THE 28TH ANNUAL INTERNATIONAL

SOLID FREEFORM FABRICATION SYMPOSIUM

– AN ADDITIVE MANUFACTURING CONFERENCE – 2017

August 7–9, 2017

Hilton Hotel Austin • Austin, Texas, USA

FINAL PROGRAM

sffsymposium.engr.utexas.edu

Organized by the Mechanical Engineering Department/Lab for Freeform Fabrication under the aegis of the Advanced Manufacturing and Design Center at The University of Texas at Austin.

Sponsored by:

NSF

Office of Naval Research ONR Science & Technology

SCHEDULE OF EVENTS

Function	Time	Location
Sunday, August 6		
Registration	2:00 pm - 5:00 pm	Hilton Austin, Salon JK Foyer
Pre-Conference Social Event	6:00 p.m. to 8:30 p.m.	Buffalo Billiards
Monday, August 7		
Registration	7:00 a.m. to 5:00 p.m.	Hilton Austin, Salon JK Foyer
Opening Remarks	8:00 a.m. to 8:15 a.m.	Hilton Austin, Salon HJK
Plenary Session and FAME Award Presentations	8:15 a.m. to 12:05 p.m.	Hilton Austin, Salon HJK
Break	9:55 a.m. to 10:25 a.m.	Hilton Austin
Lunch	12:05 p.m. to 1:30 p.m.	On Your Own
Technical Sessions	1:30 p.m. to 5:00 p.m.	Hilton Austin
Break	3:10 p.m. to 3:40 p.m.	Hilton Austin
Welcome Reception	6:00 p.m. to 6:30 p.m.	Hilton Austin, Salon HJK
9th Annual Awards Program & Banquet	6:30 p.m. to 9:00 p.m.	Hilton Austin, Salon HJK
Tuesday, August 8		
Registration	7:00 a.m. to 5:00 p.m.	Hilton Austin, Salon JK Foyer
Technical Sessions	8:15 a.m. to 12:05 p.m.	Hilton Austin
Break	9:55 a.m. to 10:25 a.m.	Hilton Austin
Lunch	12:05 p.m. to 1:40 p.m.	Hilton Austin, Salon H
Technical Sessions	1:40 p.m. to 4:00 p.m.	Hilton Austin
Poster Session with Refreshments	4:00 p.m. to 5:00 p.m.	Hilton Austin, Salon JK
Wednesday, August 9		
Registration	7:00 a.m. to 5:00 p.m.	Hilton Austin, Salon JK Foyer
Technical Sessions	8:00 a.m. to 11:50 a.m.	Hilton Austin
Break	9:40 a.m. to 10:10 a.m.	Hilton Austin
Lunch	11:50 a.m. to 1:10 p.m.	On Your Own
Technical Sessions	1:10 p.m. to 5:00 p.m.	Hilton Austin
Break	2:50 p.m. to 3:20 p.m.	Hilton Austin

TABLE OF CONTENTS

REGISTRATION

The full-conference and student registration rates include the following:

- Access to technical and poster sessions
- Sunday evening pre-conference event
- Monday evening awards banquet
- Tuesday lunch
- A flash drive copy of the post-conference proceedings

The daily registration rate includes the following:

- Access to technical and poster sessions that day
- One ticket to the social event on that day

Registration Hours

The registration desk will be located in the Salon JK Foyer of the Hilton Hotel Austin during the following hours:
Sunday, August 6: 2:00 p.m. to 5:00 p.m.
Monday, August 7: 7:00 a.m. to 5:00 p.m.
Tuesday, August 8: 7:00 a.m. to 5:00 p.m.
Wednesday, August 9: 7:00 a.m. to 5:00 p.m.

Internet Access

Complimentary wireless internet is for attendees in the Hilton Austin meeting spaces. To access the wireless internet, open the wireless menu on your device and choose the network "SFF2017" and enter the password "SFF2017."

Technical Sessions

All technical and poster presentations will be located at the Hilton Austin. See the Technical Program on pages 11-93 for locations.

PRE-CONFERENCE SOCIAL EVENT

Sunday, August 6 • 6:00 p.m. to 8:30 p.m

Buffalo Billiards
Come and meet old friends and make new ones before the "business" starts Monday! Enjoy a "Tex-Mex" style fajita buffet at Buffalo Billiards, 201 East 6th Street in downtown Austin. The restaurant is only 0.3 mi (0.5 km) from the Hilton Hotel Austin. There is no additional charge to attend for conference registrants. No transportation will be provided.

About Buffalo Billiards
From the Buffalo Billiards website: "This turn-of-the-century building was built in 1861 by the Ziller Family and named the Missouri House. Touted as Austin's first boarding house and rumored to be a brothel, many a cowboy had a good time here."

The entire venue consists of three full bars, 19 pool tables, seven shuffleboard tables, five foosball tables, 15 pinball machines, a collection of classic and modern arcade machines, and two air hockey tables. The SFF Symposium group will have the run of the place from 6:00 p.m. to 8:30 p.m.

AWARDS PRESENTATION

Monday, August 8 • Hilton Hotel Austin

6:00 p.m.	Reception & Welcome
6:40 p.m.	Special Presentation
7:00 p.m.	Dinner
8:30 p.m.	Awards Presentation
9:00 p.m.	Event Concludes

ABOUT THE SYMPOSIUM

Monday Evening Awards Banquet Presentation: Dr. Olaf Diegel

Professor Olaf Diegel is both an educator and a practitioner of product development with an excellent track record of developing innovative solutions to engineering problems.

In his role as Professor of Product Development in the Department of Design Sciences of the Faculty of Engineering at Lund University in Sweden, he is heavily involved in all aspects of product development and is widely published in the areas of additive manufacturing and rapid product development. In his consulting practice, he develops a wide range of products for companies around the world. Over the past three decades, he has developed over 100 commercialized new products including innovative new theater lighting products, security, marine products, and several home health monitoring products and, for this work, has received numerous product development awards.

Over the last 20 years, Olaf has become a passionate follower of 3D printing (additive manufacturing). He believes it is one of the technologies that has been a real godsend to innovation, as it allows designers and inventors to instantly test out ideas to see if they work. It also removes the traditional manufacturing constraints that have become a barrier to creativity, and allows us to get real products to market without the normally high costs that can become a barrier to innovation. In 2012, Olaf started manufacturing a range of 3D printed guitars and basses that has developed into a successful little side-business (and gives Olaf the therapy he needs in allowing him to make things that are a blend of high technology and traditional handcrafting).

After Olaf's presentation, the first-ever **Texas 3DP Band** (T3DPB!) will play a mini concert of "Texas Country" songs—all played with additive manufactured instruments.

CONFERENCE LUNCH EVENT

Tuesday, August 8

An informal networking lunch will provided near the meeting rooms in Salon H at the Hilton Hotel Austin at the noon break on Tuesday. Cost is included in the full-conference, student, and Tuesday registration fees. There is no organized Tuesday evening social event this year.

ABOUT THE VENUE

Symposium programming and events will take place at the four-star Hilton Hotel Austin. The Hilton Austin is located at 500 East 4th Street in downtown Austin, adjacent to the Convention Center. Exclusive shopping, amazing restaurants, and fun live music venues in the 6th Street Entertainment District and surrounding areas are all just a few steps away from the Hilton Austin. The hotel also boasts fantastic views of the Capitol of Texas and Lady Bird Lake from 31 stories up.

Self-parking ($30) and valet parking ($39) are both available at the hotel. Visit the Hilton Hotel Austin website for more details.

DINING OPTIONS
NEAR THE HILTON AUSTIN

Barbecue	Mexican	American	Italian	Seafood
Coopers (3rd/Congress) **Lamberts** (W.2nd/Guadalupe) **Iron Works** (Red River/Cesar Chavez) **Stubbs** (Red River/E.8th) **Terry Blacks** (Barton Springs Rd) **Franklin** (E.11th/Branch) **La Barbecue** (E.Cesar Chavez) **Freedman's** (W. 24th) **Micklethwait** (E.11th/Rosewood) **The Salt Lick** (Round Rock/Driftwood)	**La Condesa** (W.2nd/Guadalupe) **El Naranjo** (Rainey St.) **Manuels** (Congress/W.3rd) **Iron Cactus** (E.6th St) **Pelons** (8th/Red River) **Benjis Cantina** (W.6th/West Ave) **Uncle Julios** (Brazos/E.3rd) **El Sol Y La Luna** (6th/Red River) **Michelada's** (2nd/San Jacinto) **Matts El Rancho** (S. Lamar)	**Cannon + Belle** (Hilton Austin) **Moonshine** (4TH/Red River) **Parkside** (E.6th /San Jacinto) **Searsucker** (Colorado/W.5th) **Fixe** (W.5th/Nueces) **Max's Wine Dive** (San Jacinto/E.3rd) **Second Bar + Kitchen** (Congress/W.2nd) **Emmer & Rye** (Rainey St.) **No Va** (Rainey St.) **Swifts Attic** (3rd/Congress) **24 Diner** (S.Lamar/W. 6th)	**Italic** (W.6th/Colorado) **Botticellis** (S.Congress/Gibson) **La Traviata** (Congress/W. 4th) **Taverna** (W.2nd/Lavaca) **WinfloOsteria** (W.6th/Pressler) **Carmelos** (E.5t) **Cipollina** (W.Lynn/W. 13th) **Vespaio** (S. Congress) **Numero 28** (W. 2nd/San Antonio)	**Café Blue** (2nd/Trinity) **Eddie V's** (E. 5th/Trinity) **Capital Grille** (W. 4th/Colorado) **Trulucks** (Colorado/E.4th) **Perla's** (S. Congress/Gibson) **Surf and Turf Po Boy** (Lavaca/E. 4th) **Trio** (San Jacinto) **Clarks** (W. 6th/Blanco) **Dock and Roll** (S.1st)
Steakhouse	**Asian**	**Sushi**	**French**	**Pizza**
Eddie V's (E. 5th/San Jacinto) **Vince Young's** (2nd/San Jacinto) **Capital Grille** (W. 4th/Colorado) **Perry's** (W.7th/Colorado) **Sullivan's** (Colorado/W.3rd) **III Forks** (C. Chavez/Lavaca) **Austin Land & Cattle** (N.Lamar) **Lonesome Dove** (5th/Colorodo)	**Wu Chow** (W. 5th/San Antonio) **Kyoten** (E. 6th) **Mai Thai** (San Jacinto/E.3rd) **Sway** (S.1ST) **Elizabeth St. Café** (S.1st/W.Mary) **Koriente** (E.7th/Sabine) **Daruma Ramen** (E.6th)	**Bar-Chi** (Colorado/W.2nd) **Uchi** (S.Lamar) **Uchiko** (N. Congress) **Sushi Zushi** (W.5th) **Piranha Sushi** (San Jacinto/E.3rd) **Maiko** (W. 6th/Guadalupe) **RA** (4th/Colorado) **Lucky Robot** (S. Congress)	**Justine's Brasserie** (E. 5th) **Chez Nous** (5th/Neches) **Peche** (W.4th) **Blue Dahlia Bistro** (E.11th) **L'estelle House** (Rainey) **Elizabeth Street Café** (S. Congress/Elizabeth St) **Le Café Crepe** (2nd/San Jacinto)	**Backspace** (San Jacinto/E 6th) **Hoboken Pie** (Red River/E.8th) **Roppolo's** (6th/ Trinity) **Home Slice** (S. Congress) **Via 313** (Rainey St) **Numero 28** (W. 2nd/San Antonio)
Burgers/Sandwiches	**Vegetarian/ Vegan**	**Fusion/Misc.**	**Breakfast**	**Brunch**
Easy Tiger (E.6th/Sabine) **Casino El Camino** (E.6th/Red River) **Eureka** (6th/ Brazos) **Hopdoddy** (S.Congress) **Waller Creek Pub** (6th/ Sabine) **P Terry's** (6th/Congress) **Frank** (Colorado/W.4th)	**Koriente** (E.7th/Sabine) **Arlos (V)** (Red River) **Counter Culture Café (V)** (E. C. Chavez/Clara) **Bouldin Creek Café** (S.1st/W.Mary) **Mr. Natural** (E. C. Chavez/Chicon) **The Vegan Yacht (V)** (Spiderhouse) **(V) = Vegan**	**Austin Taco Project** (Hilton Austin) **G'RajMahal Indian** (Rainey St) **Malaga Tapas** (2nd/ San Antonio) **Clay Pit** (15th/Guadalupe) **Russian House** (E. 5th) **Buenos Aires Argentine** (E. 6th/Waller) **Bangers** (Rainey St)	**Cannon + Belle** (Hilton Austin) **24 Diner** (S.Lamar/W.6th) **Annies Cafe** (Congress/E.4th) **1886 Café** (The Driskill) **Counter Café** (E.6th) **Le Café Crepe** (2nd/San Jacinto) **South Congress Café** (South Congress) **Snack Bar** (S.Congress)	**Moonshine** (Red River/E.4th) **El Naranjo** (Rainey St) **Stubbs Gospel Brunch** (Red River) **No Va** (Rainey) **Swifts Attic** (Congress Avenue) **Taverna** (2nd/Lavaca) **Searsucker** (5th/Colorado) **Little Barrel & Brown** (S. Congress)
Cafes	**Beer/Wine/Liquor**	**Grocery/Pharmacy**	**Tour Info/Pickup**	**Address**
Starbucks (Hilton Austin) **Hounds Tooth** (E.4th/Congress) **Jo's Coffee** (2nd/Colorado)	**All American Liquors** (E 5th/Brazos) **Twin Liquors** (Red River/E.7th) **Austin Wine Merchant** (W.6th)	**CVS Pharmacy** (11th/IH35) **Royal Blue Grocery** (3rd/Brazos) **Whole Foods Market** (W.6th/Lamar)	**Austin Visitor Center** (512)-478-0098 (Red River/E.4th)	**The Hilton Austin** **500 E. 4th St** **Austin, Texas** **(512)-482-8000**

DOWNTOWN MAP

TyRex Group Ltd.

Tuesday, August 8th
Starting at 3:00 p.m.

TyRex is the parent company of a group of subsidiaries impacting AM, including Digital Light Innovations, iRex, SabeRex, ARL Testing, RF Scientific Research Funding, and Right Stuff Marketplace. For example, Digital Light Innovations' (DLi) proprietary 3DLP9000 light engine offers 4M Pixel resolution at variable wavelengths from 365-405 nm. This both broadens the material palette and enables the largest print area available for DLP-based UV vat photopolymerization. **DLi is also developing a 355nm light engine**, which will unlock new materials currently unattainable to DLP-based printing. The company's new **Carbon 3D CLIP Printer** is scheduled to be available for viewing.

TyRex is offering a tour of its north Austin facility, about 14 mi (23 km) from the Hilton Hotel Austin. NO SIGN UP IS NEEDED. Departure time for the buses from the Hilton Austin will be: 3:00 p.m.; 3:30 p.m.; 4:00 p.m.; 4:30 p.m.; and 5:30 p.m. Visitors should plan for about 2 hours from the Hilton departure to the Hilton return. Attendees will have the opportunity to tour and partake in multiple breakout discussions on additive manufacturing/3D printing and its impact on the global marketplace.

All TyRex visitors will receive a $35 gift card that is redeemable at one of a few restaurants local to the Hilton Hotel. To participate, simply go to the 5th Street entrance of the Hilton Austin (doors are located near the concierge desk and Starbucks in the hotel lobby) and hop on the bus!

All TyRex visitors will receive a $35 gift card that is redeemable at one of a few restaurants local to the Hilton Hotel. **To participate, simply go to the 5th Street entrance of the Hilton Austin (doors are located near the concierge desk and Starbucks in the hotel lobby) and hop on the bus!**

Limited Space

EOS North America Pflugerville Plant

Wednesday, August 9
11:00 a.m. to 2:30 p.m.

Last year, Additive Manufacturing (AM) pioneer, EOS North America, opened its new Technical Center in the north Austin community of Pflugerville. EOS is a global technology leader for industrial 3D printers using metals or polymers. Founded in Germany in 1989, the privately owned company is a pioneer and innovator for holistic solutions in AM.

We are offering a limited, first-come opportunity for SFF Symposium attendees to visit and tour the state-of-the-art facility on Wednesday, August 9, from 11:00 a.m. to 2:30 p.m. Attendees will tour the innovations laboratory (iLab), which contains a full range of the company's metal and polymer AM systems. A capabilities presentation will be given, and EOS experts will answer any questions you may have. Transportation and lunch will be provided.

To participate, please register in the lobby of the Hilton Hotel. This tour is limited to 60 attendees. If you sign up for the tour, you MUST be at the 5th Street entrance of the Hilton Austin (doors are located near the concierge desk and Starbucks in the hotel lobby) to board the bus **PRIOR TO THE 11:00 A.M. DEPARTURE**.

Badges

All attendees are encouraged to wear SFF Symposium registration badges at all times during the conference to ensure admission to events included in the paid fee such as technical sessions and receptions.

Americans with Disabilities Act

The federal Americans with Disabilities Act (ADA) prohibits discrimination against, and promotes public accessibility for, those with disabilities. In support of, and in compliance with ADA, we ask those requiring specific equipment or services to contact TMS Meeting Services at mtgserv@tms.org in advance.

Cell Phone Use

In consideration of attendees and presenters, we kindly request that you minimize disturbances by setting all cell phones and other devices on "silent" while in meeting rooms.

Anti-Harassment

In all activities, the SFF Symposium is committed to providing a professional environment free of harassment, disrespectful behavior, or other unprofessional conduct.

Conference policy prohibits conduct that is disrespectful, unprofessional, or harassing as related to any number of factors including, but not limited to, religion, ethnicity, gender, national origin or ancestry, physical or mental disability, physical appearance, medical condition, partner status, age, sexual orientation, military and veteran status, or any other characteristic protected by relevant federal, state, or local law or ordinance or regulation.

Failure to comply with this policy could lead to censure from the conference organizers, potential legal action, or other actions.

Anyone who witnesses prohibited conduct or who is the target of prohibited verbal or physical conduct should notify a conference staff member as soon as possible following the incident. It is the duty of the individual reporting the prohibited conduct to make a timely and accurate complaint so that the issue can be resolved swiftly.

Photography and Recording

The SFF Symposium reserves the right to all audio and video reproduction of presentations at this event. By registering for this meeting, all attendees acknowledge that they may be photographed by conference personnel while at events and that those photos may be used for promotional purposes, in and on conference publications and websites, and on social media sites.

Any recording of sessions (audio, video, still photography, etc.) intended for personal use, distribution, publication, or copyright without the express written consent of the individual authors is strictly prohibited. Attendees violating this policy may be asked to leave the session.

Antitrust Compliance

The SFF Symposium complies with the antitrust laws of the United States. Attendees are encouraged to consult with their own corporate counsel for further guidance in complying with U.S. and foreign antitrust laws and regulations.

Emergency Procedures

The chances of an emergency situation occurring at the SFF Symposium are quite small. However, being prepared to react effectively in case of an incident is the most critical step in ensuring the health and safety of yourself and those around you. Please take a few moments to review the map of the Hilton Hotel Austin printed in this program (on back cover). When you enter the building, familiarize yourself with the exits and the stairs leading to those exits. When you arrive at your session or event location, look for the emergency exits that are in closest proximity to you.

The Hilton Austin has an emergency response team in place 24 hours a day. The hotel's internal emergency number is 44 (can be dialed from any house phone). In the event of an emergency, calling the 44 emergency number will initiate the appropriate response. The hotel security department and a number of other hotel employees are also trained in CPR and First Aid.

Emergency evacuation routes and procedures are located on the inside of all guest room doors. The local fire department, police department, and paramedics are all approximately five minutes away from the conference location.

A Big Thank You to:

The **National Science Foundation** for providing meeting support (Grant Number CMMI-1639406)

The **Office of Naval Research** for providing meeting support (Grant Number N00014-17-1-2471)

Stratasys Digital Manufacturing (Jeff Rodocker, Pat Garner) for donating the FAME trophies.

TyRex Group Ltd. for partially covering beverages for the Sunday evening pre-conference gathering.

Taylor & Francis Publishing for allotting a special issue of the *Virtual and Physical Prototyping Journal* for best papers for the meeting.

The Minerals, Metals & Materials Society for allotting a special issue of the journal *JOM* for best papers with a materials theme.

International SFF Symposium Organizing Committee

Dave Bourell, Chair, UT-Austin
Joe Beaman, UT-Austin
Rich Crawford, UT-Austin
Carolyn Seepersad, UT-Austin
Scott Fish, UT-Austin

International SFF Symposium FAME Award Selection Committee

Chad Duty, Chair, University of Tennessee at Knoxville
April Cooke, Trumpf, Inc.
Nathan Crane, University of Southern Florida
David Keicher, Sandia National Labs
Tom Starr, University of Louisville

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Toshiki Niino, University of Tokyo
David Rosen, Georgia Institute of Technology
Brent Stucker, 3DSIMS
Wei Sun, Drexel and Tsinghua Universities
Ryan Wicker, University of Texas at El Paso

SPECIAL ORGANIZED SESSIONS

AM for Defense • (Monday PM)

Organized by Jennifer Wolk,
Office of Naval Research
See pages 37-38 for more details.

Hybrid Processes • (Tuesday AM/PM)

Organized by Michael Sealy,
University of Nebraska–Lincoln
See pages 51-52 and 61-62 for more details.

BEST PAPERS

- There will be a dedicated a special issue of the *Virtual and Physical Prototyping Journal* for the best seven (7) papers from the meeting (4,000 word limit).
- The TMS journal *JOM* will devote part of a special issue to the 15 best papers with a materials theme (4,000 word limit).
- The quality of the submitted manuscripts will be the primary judging criterion. Selection will be made by the Local Organizing Committee.

MANUSCRIPTS FOR THE PROCEEDINGS

Non-Reviewed

- Upload to the conference website no later than **August 31**.

Reviewed Manuscripts

- Upload final versions to the conference website no later than **August 31**.
- Mandatory Revision: please respond in comment box when uploading final manuscript to conference website.
- Reviewers: If your reviews are not received by **August 11**, the status of your manuscript will be changed from “reviewed” to “non-reviewed” status.

Proceedings Availability

- The Conference Proceedings Thumb Drive will be mailed out to all attendees no later than mid-November.
- Proceedings articles will be posted and downloadable for the general public at the conference website: **http://sffsymposium.engr.utexas.edu/archive**

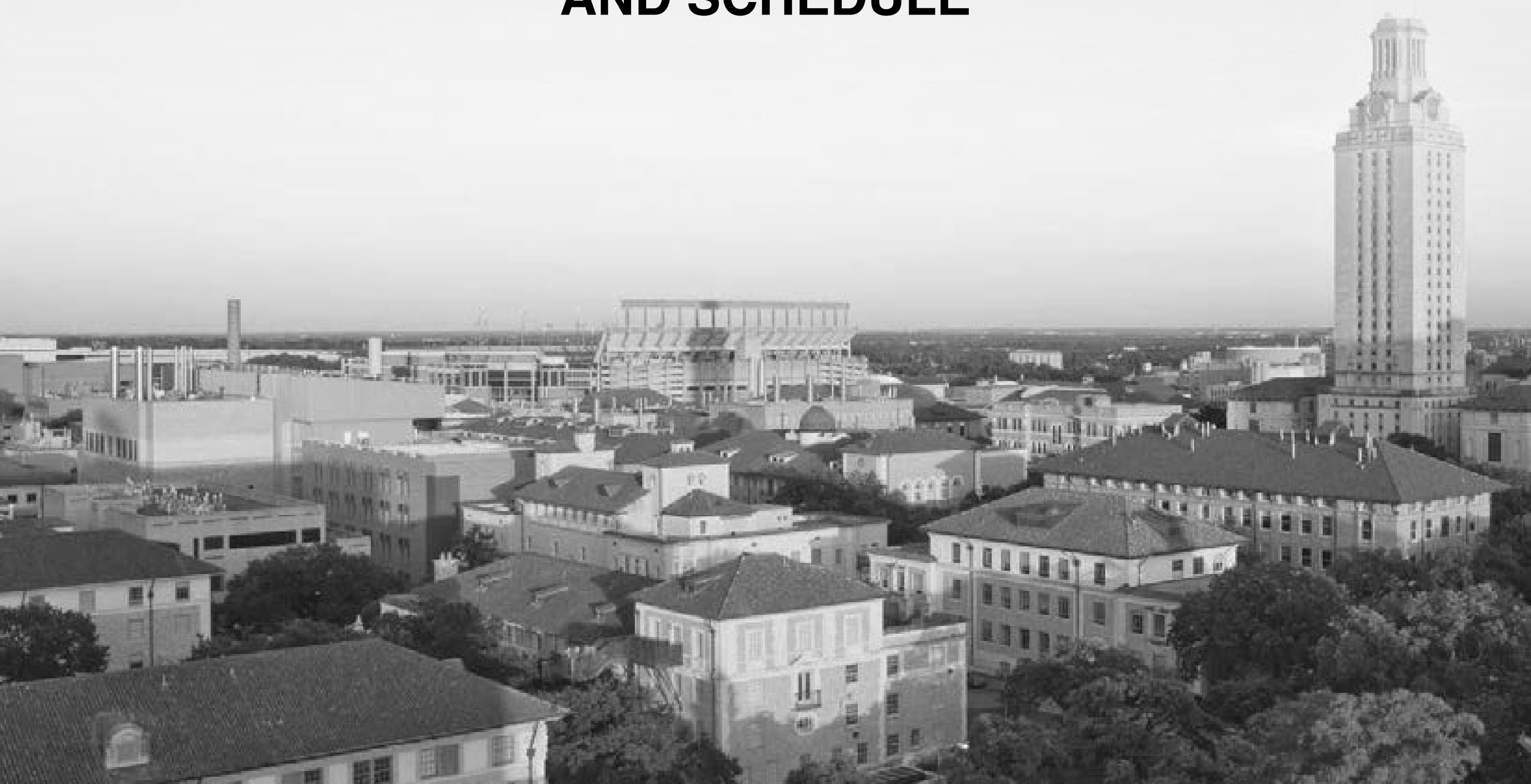
THE 28TH ANNUAL INTERNATIONAL

SOLID FREEFORM FABRICATION SYMPOSIUM

– AN ADDITIVE MANUFACTURING CONFERENCE – 2017

TECHNICAL PROGRAM

AND SCHEDULE



PROGRAM OVERVIEW

	Mon AM	Mon PM	Tue AM	Tue PM	Tue PM	Wed AM	Wed PM
	8:00 a.m. to 12:05 p.m.	1:30 p.m. to 5:00 p.m.	8:15 a.m. to 12:05 p.m.	1:40 p.m. to 4:00 p.m.	4:00 p.m. to 5:00 p.m.	8:00 a.m. to 11:50 a.m.	1:10 p.m. to 5:00 p.m.
404	Plenary Session and FAME Presentations Salon H-J-K	Process Development 2: Photopolymers and Novel Processes	Materials 4: Photopolymers	Process Development 6: Sprays and Jetting	Poster Sesson Salon J-K	Modeling 1	Modeling 2
406		Special Session: AM for Defense	Special Session: Hybrid Processes 1	Special Session: Hybrid Processes 2		Applications 9: Heat Exchangers and Smart Devices	Applications 10
408		Materials 1: Novel Polymers and Processing	Materials 3: Process Effects on Microstructure and Properties	Materials 8: Nickel 718		Materials 10: PBF: Multijet Fusion and Laser Sintering	Materials 16: Thermal Aspects and Porosity Effects
410		Materials 2: Ceramics, Intermetallics, and Multi-materials	Materials 6: Material Extrusion	Materials 9: Metallic Glass and High Entropy Materials		Applications 8	Materials 14: Novel Materials and Processes
415A-B		Physical Modeling 1: Design and Quality Control	Physical Modeling 3: Powder Beds	Physical Modeling 4: Microstructural Modeling		Physical Modeling 5: Finite Element Analysis	Applications 11: Honeycombs and Process Characterization
416A-B		Physical Modeling 2: Novel Simulation Approaches	Process Development 4: Novel Processes, Energy, Computing	Process Development 5: Material Extrusion and Surface Properties		Process Development 9: Metal Powder Processing	Process Development 11: Wire Processes and Ceramics
417A-B		Process Development 1: Laser Processing and Monitoring 1	Process Development 3: Laser Processing and Monitoring 2	Process Development 7: Novel Processes		Process Development 8: Process Effects	Process Development 10: Large Scale and Hybrid Processes
602 (Salon J on Wednesday)		Applications 1: Lattices 1	Applications 5: Residual Stress	Applications 6: Lattices 2		Biomedical Applications 1: Tissue and Cellular	Biomedical Applications 2: Scaffolds and Supports
615A-B		Applications 2: Design and Optimization	Materials 5: Nickel-based Superalloys	Materials 7: Aluminum		Materials 12: Titanium	Materials 13: Jetting and Inks
616A-B (Salon K on Wednesday)		Applications 3: Education and Future	Applications 4: Metals	Applications 7: Economics		Materials 11: 304L and Precipitation Hardened Stainless Steel	Materials 15: 316L and Other Stainless Steels

TECHNICAL SESSION GRID: MONDAY MORNING

	Plenary Session and FAME Award Presentations Salon H-J-K Phill Dickens, University of Nottingham
8:00 AM	Introductory Comments
8:15 AM	Towards Real-time Regulation of Build Geometry in a Directed Energy Deposition Additive Manufacturing System using Vision-based Feedback Control: Abdalla Nassar, Applied Research Lab, Pennsylvania University
8:35 AM	Automatic and Reusable Metal Supports for 3D Printing: Yang Xu, University of Southern California
8:55 AM	An Investigation into Spatter Creation during Selective Laser Melting: Mohsen Taheri Andani, University of Michigan
9:15 AM	Detection of Defects and Studying Effect of Defects Using X-ray Computed Tomography: Felix Kim, National Institute of Standards and Technology
9:35 AM	Predicting Meltpool-Scale Phenomena in Full-Scale Parts made using Metal Laser Sintering: Brent Stucker, 3DSIM
9:55 AM	Break
10:25 AM	Big Area Additive Manufacturing Application in Wind Turbine Molds: Brian Post, Oak Ridge National Laboratory
10:45 AM	Next Generation Aerosol-Based Printing for Production-Level Printed Electronic: David Keicher, Sandia National Laboratories
11:05 AM	FAME Outstanding Young Researcher Award Lecture: Quantifying Processing-structure-property Relationships in Additively Manufactured Metals: Allison Beese, Pennsylvania State University
11:35 AM	Freeform and Additive Manufacturing (FAME) Award II: A Journey through Time and Around the World of Solid Freeform Fabrication: Ian Gibson, Deakin University

TECHNICAL SESSION GRID: MONDAY AFTERNOON

	Process Development 2: Photopolymers and Novel Processes	Special Session: AM for Defense	Materials 1: Novel Polymers and Processing	Materials 2: Ceramics, Intermetallics, and Multi-materials	Physical Modeling 1: Design and Quality Control
	Room 404	Room 406	Room 408	Room 410	Room 415A-B
	Joe Bennett, NIST	Jennifer Wolk, Naval Surface Warfare Center	Andreas Wegner, University of Duisburg-Essen	Ramesh Subramanian, Siemens Energy	Ian Gibson, Deakin University
1:30 PM	Microheater Array Powder Sintering: A Novel Additive Manufacturing Process: Nicholas Holt, University of Arkansas	Naval Additive Manufacturing S&T: Jennifer Wolk, Naval Surface Warfare Center	Fabricating Zirconia Components with Organic Support Material by the Ceramic On-demand Extrusion Process: Wenbin Li, Missouri University of Science and Technology	Ceramic Additive Manufacturing: A Review of Current Status and Challenges: Li Yang, University of Louisville	From CAD Models to Parts: Software Development for the Wire+ Arc Additive Manufacture Process: Filomeno Martina, Cranfield University
1:50 PM	Process Modeling and In-situ Monitoring of Photopolymerization for Exposure Controlled Projection Lithography (ECPL): Jenny Wang, Georgia Institute of Technology	A Micro-Tailoring Technique to Alter the Spatial Distribution and Orientation of Particles in a Stereolithography Fabricated Composite Part and Quantification of Alignment in the Part: Larry Holmes, US Army Research Laboratory	The Application of Composite Through-thickness Assessment to Additively Manufactured Parts: Isam Bitar, University of Nottingham	Recapitulation on Laser Melting of Ceramics and Glass-ceramics: Ming Xuan Gan, Nanyang Technological University	Multi-Level Uncertainty Quantification in Additive Manufacturing: Paromita Nath, Vanderbilt University
2:10 PM	Design and Fabrication of an Experimental Microheater Array Powder Sintering Printer: Nicholas Holt, University of Arkansas	Thermal Modelling of Large Scale Polymer Additive Manufacturing: Sam Pratt, Naval Surface Warfare Center Carderock Division	FDM with Natural Fibre Reinforced PLA: Eleonora Ferraris, KU Leuven	Powder Preparation for Indirect Selective Laser Sintering of Alumina: Diptanshu, Texas A&M University	Computed Axial Lithography (CAL) for Rapid Volumetric 3D Printing: Brett Kelly, University of California, Berkeley
2:30 PM	Highly Removable Water Support for Stereolithography: Jie Jin, University of Southern California	Material Informed Digital Design Demonstration for Additive Structures: Edwin Schwalbach, Air Force Research Laboratory	Tensile Mechanical Properties of Polypropylene Composites Fabricated by Material Extrusion: David Rosen, Georgia Institute of Technology	A Modular Direct Write Additive Manufacturing Approach in the Printing of Multi-materials and Ceramics: Judi Lavin, Sandia National Laboratories	Computation of Geometry Attributes of Components' 3D Model for Additive Manufacturing: Min Zhou, China Agricultural University
2:50 PM	Acoustic Field-assisted Particle Patterning for Smart Polymer Composite Fabrication in Stereolithography: Lu Lu, University of Illinois At Chicago	Evolution of Raw Powder Characteristics through the Additive Manufacturing Reuse Cycle: Claudia Luhrs, Naval Postgraduate School	High-throughput Additive Manufacturing of Silicone Elastomers with Tunable Mechanical Properties: Noah Holzman, University of Minnesota	Additive Manufacturing of Flexible 3-3 Ferrorelectric Ceramic/Polymer Composite Based on Triply Periodic Cellular Micro-skeleton: Xuan Song, University of Iowa	Efficient Sampling for Design Optimization of an SLS Product: Nancy Xu, University of Texas at Austin
3:10 PM	Break	Break	Break	Break	Break
3:40 PM	Effect of Constrained Surface Texturing on Separation Force in Projection Stereolithography: Haiyang He, University of Illinois At Chicago	Metallic Additive Manufacturing at the Army Research Laboratory: Brandon McWilliams, US Army Research Laboratory	Adjustment of Part Properties for an Elastomeric Laser Sintering Material: Andreas Wegner, University of Duisburg-Essen	On the Effect of Building Direction on the Microstructure and Tensile Properties of SLM NiTi: Amirhesam Amerinatanzi, University of Toledo	Review of AM Simulation Validation Techniques: Aaron Flood, Missouri University of Science and Technology
4:00 PM	Fabrication and Control of a Microheater Array for Microheater Array Powder Sintering: Nicholas Holt, University of Arkansas	Design, Fabrication, and Qualification of a 3D Printed Metal Quadruped Body: Combination Hydraulic Manifold, Structure, and Mechanical Interface: Joshua T. Geating, US Naval Research Laboratory	Mechanical Properties and color of TPE parts as function of temperature history in selective laser sintering process: Christina Kummert, Paderborn University/ DMRC	Microstructural Origins of Spatially Tailored Functional Response in NiTi SMAs: Ji Ma, Texas A&M University	Analytical and Experimental Characterization of Anisotropic Mechanical Behaviour of Infill Building Strategies for Fused Deposition Modelling Objects: Marlon Cunico, University of São Paulo
4:20 PM	Projection-based Stereolithography Using a Sliding Window Screen for Simultaneous Photopolymerization and Resin Refilling: Huachao Mao, University of Southern California	Reduction Expansion Synthesis of Thin Metal Films: Jonathan Phillips, Naval Postgraduate School	Process -- Structure -- Properties Relationships of a Novel Polypropylene Laser Sintering Material: Rob Kleijnen, inspire AG	Observing the Location Dependence of Microstructure in Selective Laser Melted NiTi: Brian Franco, Texas A&M University	Flexural Behavior of FDM Parts: Experimental, Analytical and Numerical Study: Madhukar Somireddy, York University
4:40 PM	Modeling of Low One-photon Polymerization for 3D printing of UV-curable Silicones: Dong Sung Danny Kim, Texas A&M University	Fracture Behavior of Thermally Annealed, Additively Manufactured Polymers: Kevin Hart, US Army Research Laboratory	Filament Extension Atomization of Polymer Melts: A Novel Approach to Generating Powders for Selective Laser Sintering: Jerome Unidad, PARC, A Xerox Company	Selective Laser Melting of Bismuth Telluride and Half-Heusler Thermoelectric Materials: Saniya LeBlanc, The George Washington University	High-throughput Printing of Conductive Polymer Nanocomposites via Joule Preheating of the Filament: Adam Stevens, Massachusetts Institute of Technology

Physical Modeling 2: Novel Simulation Approaches	Process Development 1: Laser Processing and Monitoring 1	Applications 1: Lattices 1	Applications 2: Design and Optimization	Applications 3: Education and Future	
Room 416A-B	Room 417A-B	Room 602	Rom 615A-B	Room 616A-B	
Wayne King, Lawrence Livermore National Laboratory	Igor Yadroitsev, Central Univ of Technology, Free State	Albert To, University of Pittsburgh	Sarah Bagehorn, Airbus Group Innovations	Matt Frank, Iowa State University	
Numerical Study of Keyhole Formation in Selective Laser Melting of Ti6Al4V: Wenjun Ge, KAIST	In Process Monitoring in Metal Powder Bed Fusion Processes using Optical Coherence Tomography: Philip DePond, Lawrence Livermore National Lab	Novel Graded Honeycombs Fabricated by Material Extrusion Additive Manufacturing: Brett Compton, University of Tennessee	Feature-based Level Set Topology Optimization Applied in Additive Manufacturing: Yeming Xian, Georgia Institute of Technology	Maker Spaces and Fab Labs: Creating Student Access to 3D Printing and Digital Fabrication: Jason Weaver, Brigham Young University	1:30 PM
Thermomechanical Analysis of Direct Metal Laser Melting via Line Heat Source Model: Qian Chen, University of Pittsburgh	Characterizing the Dynamics of Laser Powder Bed Fusion Additive Manufacturing Processes by High-speed High-energy X-ray Imaging and Diffraction: Lianyi Chen, Missouri S&T	Digital Design and Manufacture of Soft Lattice Structures: Martin Dunn, Singapore University of Technology and Design	Multi-material Structural Topology Optimization under Uncertainty via a Stochastic Reduced Order Model Approach: Miguel Aguilo, Sandia National Laboratories	Launching a Masters Degree on Metal Additive Manufacture: Filomeno Martina, Cranfield University	1:50 PM
Simulation of Spot Melting Scan Strategy to Predict Columnar to Equiaxed Transition in Metal Additive Manufacturing: Yousub Lee, Oak Ridge National Laboratory	Melt Pool Study in Selective Laser Melting: Bo Cheng, University of Louisville	Embedding of Liquids into Water Soluble Materials via Additive Manufacturing for Timed Release: Callie Zawaski, Virginia Tech	Projection-based Topology Optimization Algorithms for Manufacturing Design Constraints in Powder Bed Fusion and Vat-based Additive Manufacturing: Andrew Gaynor, U.S. Army Research Laboratory	Skill-based Education of 3D Printing Technologies at DEI: Bringing Additive Manufacturing to the Classroom: Rahul Sharma, Dayalbagh Educational Inst	2:10 PM
Numerical Simulation of Temperature Fields in Powder Bed Fusion Process by using Hybrid Heat Source Model: Zhibo Luo, McGill University	Preliminary Investigation of Pulsed Thermography for Online Process Monitoring in Additive Manufacturing: James Pierce, University of South Florida	Prediction of the Elastic Response of TPMS Cellular Lattice Structures using Finite Element Method: Mohsen Taheri Andani, University of Michigan	Topology Optimization for 3D Material Distribution and Orientation for Additive Manufacturing: Douglas Smith, Baylor University	Roadmap for Multi-Material Additive Manufacturing: Amy Elliott, Oak Ridge National Laboratory	2:30 PM
A Proposed Framework for Material Jetting Process Modeling: Critical Issues and Research Directions: Chad Hume, Georgia Institute of Technology	In-process Condition Monitoring in Laser Powder Bed Fusion (LPBF): Mohammad Montazeri, University of Nebraska-Lincoln	Generation of TPMS Cellular Lattice Structures to Fill an Arbitrary Boundary: Mohsen Taheri Andani, University of Michigan	Topological Optimization and Methodology for Fabricating Additively Manufactured Lightweight Metallic Mirrors: Michael Stern, MIT Lincoln Laboratory	Roadmap for Binder Jet Additive Manufacturing: Amy Elliott, Oak Ridge National Laboratory	2:50 PM
Break	Break	Break	Break	Break	3:10 PM
Numerical Modeling of High Resolution Electrohydrodynamic Jet Printing using OpenFOAM: Maxwell Wu, University of Michigan	Linking Process Parameters to Part Defects through In-Process Sensor Signatures in Laser Powder Bed Fusion (LPBF).: Mohammad Montazeri, University of Nebraska-Lincoln	A Framework for the Design of Biomimetic Cellular Materials for Additive Manufacturing: Dhruv Bhate, Phoenix Analysis & Design Technologies, Inc. (PADT)	Topology Optimization of an Additively Manufactured Beam: Saber DorMohammadi, AlphaSTAR Corp.	Roadmap for Metal Matrix Composite Development for Binder Jetting: Amy Elliott, Oak Ridge National Laboratory	3:40 PM
A Normalized Dispensing Modeling Method for Feature Prediction in Direct Ink Writing Process: Yizhou Jiang, University of Illinois At Chicago	Effect of a Mid-build Halt on the Microstructure and Porosity in Powder Bed Fusion Stainless Steel Parts: Clara Hofmeister, Oak Ridge Institute for Science and Education	Topology Optimization of Variable-density Lattice Structure for Highly Efficient Convective Heat Transfer: Lin Cheng, University of Pittsburgh	Quantifying Accuracy of Metal Additive Processes through a Standardized Test Artifact: TJ Barton, Brigham Young University	Selective Separation Shaping (SSS) – Large Scale Fabrication Potentials: Xiang Gao, University of Southern California	4:00 PM
Computational Simulation of Additively Manufactured Marine Structures: Charles Fisher, Naval Surface Warfare Center	Performance Characterization of Process Monitoring Sensors on the NIST Additive Manufacturing Metrology Testbed: Brandon Lane, National Institute of Standards and Technology	An Evaluation of Carbon Composite Axial Lattice Structures: Pritam Poddar, Rochester Institute of Technology	Integrating Interactive Design and Simulation for Mass-Customized 3D-Printed Objects – a Cup Holder Example: Christian Altenhofen, Fraunhofer IGD	Smart Parts Fabrication using Powder Bed Fusion Additive Manufacturing Technologies: Mohammad Shojib Hossain, The University of Texas at El Paso	4:20 PM
	Laser Sintering of Polyetherethrerketone with Low-temperature Process: Fumio Ito, Institute of Industrial Science, the University of Tokyo			Design for Protection: Systematic Approach to Prevent Product Piracy during Product Development Using AM: Ulrich Jahnke, Paderborn University / DMRC	4:40 PM

	Materials 4: Photopolymers	Special Session: Hybrid Processes 1	Materials 3: Process Effects on Microstructure and Properties	Materials 6: Material Extrusion	Physical Modeling 3: Powder Beds
	Room 404	Room 406	Room 408	Room 410	Room 415A-B
	David Rosen, Georgia Institute of Technology	Michael Sealy, University of Nebraska-Lincoln	Allison Beese, Pennsylvania State University	Wenchao Zhou, University of Arkansas	Wentao Yan, Northwestern University
8:15 AM	Measuring the Curing Parameters of Photopolymers used in Additive Manufacturing: Joe Bennett, NIST	Direct Additive Subtractive Hybrid Manufacturing (DASH): An Out of Envelope Method: Matt Frank, Iowa State University	Effect of Process Parameter Variation on Microstructure and Mechanical Properties of Additively Manufactured Ti-6Al-4V: Jonathan W Pegues, Auburn University	Expanding Material Property Space Maps with Functionally Graded Materials for Large Scale Additive Manufacturing: Thomas Sudbury, Cincinnati Incorporated	A Close-up View onto the Strong Dynamics in Laser Metal Powder Bed Fusion: Saad khairallah, Lawrence Livermore National Laboratory
8:35 AM	Materials Properties Evolution during Photopolymerization: Jiangtao Wu, Georgia Institute of Technology	Metallic Components Repair Strategies using the Hybrid Manufacturing Process: Xingchang Zhang, Missouri University of Science and Technology	Predictive Modeling Tool for Performance and Life Analysis of Metal-Based Additive Manufacturing Parts: Behrooz Jalalahmadi, Sentient Science	Considering Machine- and Process-specific Influences to Create Custom-built Specimens for the Fused Deposition Modeling Process: Christian Schumacher, Paderborn University / DMRC	High-speed Imaging of the Powder-bed and Shield Gas during Metal PBF Additive Manufacture: Prveen Bidare, Heriot-Watt University
8:55 AM	A Trade-off Analysis of Recoating Methods for Vat Photopolymerization of Ceramics: Thomas Hafkamp, Eindhoven University of Technolgy	Rapid Prototyping of EPS Pattern for Complicated Casting: Ranjeet Kumar, IIT Bombay	Scanning Strategies in Electron Beam Melting to Influence Microstructure Development: Diego Bermudez, UTEP	Investigating the Effect of Nozzle Residence Time on Properties of Thermoplastic Parts Produced by Material Extrusion AM: Joseph Bartolai, The Pennsylvania State Univeristy	Discrete Element Modeling of Powder Spreading and Flow for Metal Additive Manufacturing: Dan Bolintineanu, Sandia National Laboratories
9:15 AM	Supportability of Highly Viscous Slurry in a New Stereolithography-based Ceramic Fabrication Process: Li He, University of Iowa	5-Axis Slicing Methods for Additive Manufacturing Process: Sajan Kapil, Indian Institute of Technology Bombay	Position-dependent Powder Properties in the Metal Powder Bed Laser Melting Process: Peter Koppa, Paderborn University / DMRC	Rheological Evaluation of High Temperature Polymers to Identify Successful Extrusion Parameters: Christine Ajinjeru, University of Tennessee Knoxville	Mesoscopic Multi-layer Simulation of Selective Laser Melting Process: Subin Shrestha, University of Louisville
9:35 AM	Digital Light Processing (DLP): Anisotropic Tensile Considerations: Elisa Aznarte Garcia, University of Alberta	A Hybrid Method for Additive Manufacturing of Silicone Structures: Farzad Liravi, University of Waterloo	Correlation of Engineering Properties with Modal Analysis Parameters for Metal SLM Parts: Nick Capps, Missouri University of Science and Technology	A Viscoelastic Model for Evaluating Extrusion-based Print Conditions: Chad Duty, University of Tennessee	A Study into the Effects of Gas Flow Inlet Design in a Renishaw AM250 Laser Powder Bed Fusion Machine Using Computational Modelling: Adam Philo, Swansea University
9:55 AM	Break	Break	Break	Break	Break
10:25 AM	Large-area, High-resolution Additive Manufacturing of Elastomers with Scanning Mask Projection Vat Photopolymerization: Viswanath Meenakshisundaram, Virginia Polytechnic Institute and State University	Advanced Hybrid Manufacturing: Roadmap of Technological Challenges: Guha Manogharan, Pennsylvania State University	Qualification of DMLS Ti6Al4V (ELI) Alloy for Biomedical Applications: Igor Yadroitsev, Central University of Technology, Free State	Towards a Robust Production of FFF End-user Parts with Improved Tensile Properties: Gerardo Mazzei Capote, University of Wisconsin- Madison	Comparison of 3D Microstructural Modeling for Powder Bed and Powder Fed Metal AM Methods: Theron Rodgers, Sandia National Laboratories
10:45 AM	Recyclable 3D Printing of Vitrimer Epoxy: Xiao Kuang, GEORGIA TECH	Opening the Architecture of AM with Hybrid Manufacturing Technologies: Jason Jones, Hybrid Manufacturing Technologies	Development of Sintering Parameters for Full Densification of H13 Tool Steel Printed via Binder Jet Additive Manufacturing: Amy Elliott, Oak Ridge National Laboratory	Investigating Material Degradation through the Recycling of PLA in Additively Manufactured Parts: Nicholas Meisel, Pennsylvania State University	Experiments and Modeling of End Effects of Direct Laser Deposition: Jennifer Bennett, Northwestern University
11:05 AM	3D Printable Recyclable Thermosets: Biao Zhang, Singapore Univeristy of Technology and Design	Analysis of Hybrid Manufacturing Systems Based on Additive Manufacturing Technology: Marlon Cunico, University of São Paulo	Influence of Hatch Spacing on the Superelastic Properties of a Ni-rich SLM Nitinol Shape Memory Alloy: Narges Shayesteh Moghaddam, University of Toledo	EcoPrinting: Investigating the Use of 100% Recycled Acrylonitrile Butadiene Styrene (ABS) for Additive Manufacturing: Mazher Mohammed, Deakin University	Development of Simulation Tools for Selective Laser Melting Additive Manufacturing: Yongsheng Lian, University of Louisville
11:25 AM	Determination of Complex Young's Modulus for Polymer Produced by Microstereolithography: John M Cormack, University of Texas at Austin	Synergistic Integration of Hybrid Processes and Multiple Technologies: K. P. Karunakaran, Indian Institute of Technology Bombay	Optimal Process Parameters for In Situ Alloyed Ti15Mo Structures by Direct Metal Laser Sintering: Igor Yadroitsev, Central University of Technology, Free State	Achieving Functionally-graded Material Composition through Bicontinuous Mesostructural Geometry in Material Extrusion AM: Brant Stoner, Pennsylvania State University	Modeling of Electron Beam Selective Melting: from Powder Bed Spreading to Melting: Wentao Yan, Northwestern University
11:45 AM	Understanding the Effects of Post-Processing on a High-Performance All-Aromatic Polyimide Fabricated Using Vat-Photopolymerization: Nicholas A Chartrain, Virginia Polytechnic Institute and State University		Process -- Property Relationships in Additive Manufacturing of Nylon-fiberglass Composites using Taguchi Design of Experiments: Kuldeep Agarwal, Minnesota State University, Mankato		Modelling Nanoparticle Sintering in a Microscale Selective Laser Sintering Process: Obehi Dibua, University of Texas at Austin
12:05 PM					

Process Development 4: Novel Processes, Energy, Computing	Process Development 3: Laser Processing and Monitoring 2	Applications 5: Residual Stress	Materials 5: Nickel-based Superalloys	Applications 4: Metals	
Room 416A-B	Room 417A-B	Room 602	Rom 615A-B	Room 616A-B	
Yong Chen, University of Southern California	April Cooke, NIST/University of Maryland at College Park	Tim Horn, North Carolina State University	Brent Stucker, 3DSIM	Ian Maskery, University of Nottingham	
Preliminary Study of Large Area Polymer Sintering with Projection Sintering: Justin Nussbaum, University of South Florida	Laser Power Control in SLS: Tim Phillips, University of Texas at Austin	A Modified Inherent Strain Method for Fast Prediction of Residual Deformation in Additive Manufacturing of Metal Parts: Xuan Liang, University of Pittsburgh	Characterization of Inconel Alloy 625 Fabricated Using Powder Bed-based Additive Manufacturing Technologies: Philip Morton, University of Texas El Paso	The Processing-Structure Relationship for Surface Roughness in Additively Manufactured IN 718: Joy Gockel, Wright State University	8:15 AM
Multisystem Modeling and Optimization of Solar Sintering System: Amber Dressler, University of Texas at Austin	Laser Sintering Exposure Parameter Optimizsation by CT Scan: Johannes Lohn, Paderborn University, Direct Manufacturing Research Center	On the Simulation Scalability to Predict the Distortion and Residual Stress of Bridge Structures in Selective Laser Melting: C. Li, University of Alabama	Impact of Hastelloy-X Composition on Crack Formation in Powder Bed Fusion Additive Manufacturing: Stephanie Giet, Renishaw plc	Torsional Strength of Additively Manufactured Friction Stir Welding Tools: John Linn, Brigham Young University	8:35 AM
Casting-forging-milling Composite Additive Manufacturing Technology: Zhang Haiou, Huazhong University of Science and Technology	Sintering Laser Power vs. Part Porosity Comparison using In-Situ Optical Coherence Tomography Data in Selective Laser Sintering: Adam Lewis, University of Texas at Austin	The Effect of Scanning Strategy on Residual Stress in Metal Parts Fabricated via Selective Laser Melting (SLM) Technique: Ajith Ukwattage Don, Clarkson University	Additive Manufacturing of γ' and γ'' Nickel Super alloys by Renishaw Laser Melting Machines: Ravi Aswathanarayanaswamy, Renishaw Plc	Surface Finish of Overhangs in Laser Powder Bed Fusion Additive Manufacturing of 17-4 Stainless Steel: Thien Phan, National Institute of Standards and Technology	8:55 AM
The Influence of Exposure Time on Energy Consumption and Mechanical Properties of SLM-fabricated Parts: Shuangmei Xu, Zhejiang University	Assessment of Optical Emission Analysis for In Process Monitoring of Powder Bed Fusion Additive Manufacturing: Alexander Dunbar, The Pennsylvannia State University	Effects of Scanning Strategy on Residual Stress Formation in Additively Manufactured Ti-6Al-4V Parts: Mohammad Masoomi, Auburn University	Microstructure and Indentation Hardness of SLE-Deposited Rene80 Superalloy with Post-process Heat Treatment: Andriy Dotsenko, Georgia Tech	Residual Stress Reduction in LENS 3D Printed Metal Parts: Shaun Whetten, Sandia National Laboratories	9:15 AM
Energy Coupling Efficiency and Melt Pool Dynamics Associated with the Laser Melting of Metal Powder Layers: Manyalibo Matthews, Lawrence Livermore National Laboratory	High Speed Thermal Imaging of the Melt Pool during Laser Powder Bed Fusion of Metal Alloys: Nicholas Calta, Lawrence Livermore National Laboratory	Residual Stress Analysis of Thin Wall Blade Structure Manufactured by Direct Metal Laser Sintering (DMLS): Oguz Colak, Anadolu University	Additive Manufacturing of René 142 through Scanning Laser Epitaxy (SLE): Yunpei Yang, Georgia Institute of Technology	The Use of Electropolishing Surface Treatment on IN718 Parts Fabricated by Laser Powder Bed Fusion Process: Li Yang, University of Louisville	9:35 AM
Break	Break	Break	Break	Break	9:55 AM
Syringe Dispense of Copper Paste with Formic Acid Cure: Judi Lavin, Sandia National Laboratories	The Effect of Powder on Cooling Rate and Melt Pool Length Measurements using in situ Thermographic Techniques: Jarred Heigel, National Institute of Standards and Technology	Residual Stress Analysis in Supportless Overhanging Surfaces: Ankit Porwal, IIT Kharagpur	Characterization of MAR-M247 Deposits Fabricated through Scanning Laser Epitaxy (SLE): Amrita Basak, Georgia Institute of Technology	Defect Detection in Metal SLM Parts Using Modal Analysis "Fingerprinting": James Urban, Missouri University of Science and Technology	10:25 AM
Bio-inspired Micro-scale Texture Fabrication based on Immersed Surface Accumulation Process: Xiangjia Li, University of Southern California	Monitoring of Single-track Degradation in the Process of Selective Laser Melting: Ivan Zhirnov, Moscow State University of Technology "STANKIN"	The Effect of Process Parameters and Texture Evolution on Residual Stress in Selective Laser Melting of Ti-6Al-4V: Nathan Levkulich, Wright State University	Mechanical Assessment of a LPBF Nickel Superalloy using the Small Punch Test Method: Sean Davies, Swansea University	Electrochemical Enhancement of the Surface Morphology and the Fatigue Performance of Ti-6Al-4V Parts Manufactured by Laser Beam Melting: Sarah Bagehorn, Airbus Group Innovations	10:45 AM
Review of Ultra-High Speed Imaging of Powder Bed Fusion Additive Manufacturing Processes: Gabe Guss, Lawrence Livermore National Laboratory	Machine Learning for Defect Detection for PBFAM using High Resolution Layerwise Imaging Coupled with Post-Build CT Scans: Jan U. Petrich, ARL Penn State	Residual Stress Analysis of Additively Manufactured 17-4 PH Steel: Frank Abdi, AlphaSTAR Corporation	Cracking Behavior of High Gamma Prime Ni-base Superalloys Fabricated through Additive Manufacturing: Michael Kirka, Oak Ridge National Laboratory	The Change of Thermal Properties and Microstructure of an AM Fabricated AlSi10Mg Alloy during Thermal Annealing: Pin Yang, Sandia National Laboratories	11:05 AM
Melt Pool Image Process Acceleration Using General Purpose Computing on Graphics Processing Units: Robert Sampson, TWI	Selection and Installation of High Resolution Imaging to Monitor the PBFAM Process, and Synchronization to Post-Build 3D Computed Tomography: Jacob P. Morgan, Applied Research Laboratory - The Pennsylvannia State University	Residual Stresses in Direct Metal Laser Sintered Stainless Steel Parts: Mohammad Masoomi, Auburn University	Effects of Processing Parameters on the Mechanical Properties of CMSX-4® Additively Fabricated through Scanning Laser Epitaxy (SLE): Amrita Basak, Georgia Institute of Technology	Improving Fatigue Performance of Ti6Al4V As-built Electron Beam Melting Parts using Surface Mechanical Attrition Treatment: Hengfeng Gu, North Carolina State University	11:25 AM
		Measurement and Prediction of Distortions in a 17-4 PH Stainless Steel Part Produced by Laser Powder Bed Fusion: Daniel Galles, Army Research Laboratory	Effect of Heat Treatment on the Microstructures of CMSX-4® Processed through Scanning Laser Epitaxy (SLE): Amrita Basak, Georgia Institute of Technology		11:45 AM
			Effect of Process Parameters and Shot Peening on Mechanical Behavior of ABS Parts Manufactured by Fused Filament Fabrication (FFF): Michael Sealy, University of Nebraska-Lincoln		12:05 PM

TECHNICAL SESSION GRID: TUESDAY AFTERNOON

	Process Development 6: Sprays and Jetting	Special Session: Hybrid Processes 2	Materials 8: Nickel 718	Materials 9: Metallic Glass and High Entropy Materials	Physical Modeling 4: Microstructural Modeling
	Room 404	Room 406	Room 408	Room 410	Room 415A-B
	Brian Post, Oak Ridge National Laboratory	Frank Liou, Missouri S&T	Ola Harrysson, North Carolina State University	Saniya LeBlanc, The George Washington University	Joy Gockel, Wright State University
1:40 PM	Magnetohydrodynamic Liquid Metal Droplet Jetting of 4043 Aluminum: Denis Cormier, Rochester Institute of Technology	Fabrication and Characterization of Ti6Al4V and Ti47Al2Cr2Nb Using Selective Electron Beam and Laser Hybrid Melting: Bin Zhou, Tsinghua University	Prediction of Grain Morphology in Electron Beam Melting of IN718 Superalloys: Jingfu Liu, Sentient Science	Microstructure and Mechanical Behavior of AlCoCuFeNi High-entropy Alloy Fabricated by Selective Laser Melting: Zhang Mina, University of Science and Technology	Modeling Microstructure Evolution and the Effects of Texture on Mechanical Properties in Additively Manufactured Metals: Judith Brown, Sandia National Laboratories
2:00 PM	Using Additive Manufacturing Techniques as an Alternative Method to Spray Deposit Metallized Material: Zachary Stephens, Sandia National Laboratories	Hybrid Additive Manufacturing of Steel by LENS and Laser Shock Peening: Cody Kanger, University of Nebraska - Lincoln	Quantitative Texture Prediction of Epitaxial Columnar Grains in Additive Manufacturing: Jian Liu, University of Pittsburgh	Selective Laser Melting of AlCu5MnCdVA: Formability, Microstructure, and Mechanical Properties: Zhiheng Hu, Wuhan National Laboratory for Optoelectronics	Numerical investigation of grain structure development in Laser Engineered Net Shaping: Xuxiao Li, University of Utah
2:20 PM	Modeling the Effect of Inter-layer Time on the 3D Microstructure and Residual Stress in LENS Parts: Kyle Johnson, Sandia National Laboratories	Surface Integrity of Inconel 718 by Hybrid Selective Laser Melting and Milling: Z.Y. Liu, The University of Alabama	Relationship of Powder Feedstock Variability to Microstructure and Defects in Selective Laser Melted Alloy 718: Timothy M Smith, NASA Glenn Research Center	Microstructure and Crack Distribution of Fe-based Amorphous Alloys Manufactured by Selective Laser Melting: Bo Song, Huazhong University of Science and Technology	Phase Field Modeling of Microstructure Evolution during Selective Laser Melting of Inconcel 718: Kubra Karayagiz, Texas A&M University
2:40 PM	Temperature and Humidity Variation Effect on Process Behavior in Electrohydrodynamic Jet Printing of a Class of Optical Adhesives: Patrick Sammons, University of Michigan	Development of A Hybrid Manufacturing Process for Precision Metal Parts: Frank Liou, Missouri University of Science and Technology	Influence of Dwell Time on Localized Thermal History and Properties of Directed Energy Deposition (DED)-processed Inconel 718 Thin Walls: Sarah Wolff, Northwestern University	Brittle-tough Transition through Microcrack Modulating in 3D Printing Fe-based Metallic Glass Composite: Ning Li, Huazhong University of Science and Technology	Numerical Simulation of Solidification in Additive Manufacturing of Ti-alloy by Multi-Phase-Field Method: Yusuke Shimono, Itochu Techno-Solutions Corp.
3:00 PM	Blown Powder Laser Cladding with Novel Processing Parameters for Isotropic Material Properties: Jing Liu, University of Liverpool	Design for Hybrid Additive Manufacturing by Drop Tower Testing Shot Peened Almen Strips: Haitham Hadidi, University of Nebraska - Lincoln	On the Use of X-ray Computed Tomography for Monitoring the Failure of a Two-bar Small Specimen Manufactured by Selective Laser Melting: Christopher Hyde, The University of Nottingham	Processability of Fe-based Bulk Metallic Glass using Direct Metal Laser Sintering and Electron Beam Melting: Zaynab Mahbooba, North Carolina State University	Effect of Heterogeneous Nucleation on Microstructure Modeling in Powder-bed Metal Additive Manufacturing: Jingfu Liu, Sentient Science
3:20 PM		Fatigue Behavior of Surface Treated Ti-6Al-4V Made via Electron Beam Melting as Input for Hybrid Process Planning System: Carter Keough, North Carolina State University	Corrosion Resistance Behavior Study of SLM Inconel 718 Sample under Different Surface and Heat Treatment: Florencia Edith Wiria , Simtech	Construction of Metallic Glass Structures by Laser-foil-printing Technology: Yiyu Shen, Missouri University of Science and Technology	Modelling Powder Flow in Metal Additive Manufacturing Systems: Gary Delaney, CSIRO
3:40 PM		Effects of Ambient Pressure on Laser Process of Austenite Stainless Steel: Jiang-Zhou Su, Beijing Institute of Techonology	Dissolvable Metal Supports Processes for Powder Bed Fusion Printed Inconel 718: Owen J. Hildreth, Arizona State University	Building Zr-based Metallic Glass Part on Ti-6AL-4V Substrate by Laser-foil-printing Additive Manufacturing: Yingqi Li, Missouri University of Science and Technology	
4:00 PM to 5:00 PM Poster Session See program pages for poster listings.					

TECHNICAL SESSION GRID: TUESDAY AFTERNOON

Process Development 5: Material Extrusion and Surface Properties	Process Development 7: Novel Processes	Applications 6: Lattices 2	Materials 7: Aluminum	Applications 7: Economics	
Room 416A-B	Room 417A-B	Room 602	Rom 615A-B	Room 616A-B	
Nicholas Meisel, Pennsylvania State Univ	Judi Lavin, Sandia National Laboratories	Li Yang, University of Louisville	Eleonora Ferraris, KU Leuven	Igor Yadroitsev, Central Univ of Technology, Free State	
Reducing Mechanical Anisotropy in Extrusion-Based Printed Parts: Chad Duty, University of Tennessee	A Direct 4D Printing Method Using Multimaterial 3D Printing: H. Jerry Qi, Georgia Institute of Technology	The Mechanical Performance of Triply Periodic Minimal Surface Lattice Structures: Ian Maskery, University of Nottingham	Influence of Arcam EB Parameters on Properties in Aluminum Alloy 2024: Maria Withrow, North Carolina State CAMAL	Cost-efficient Design and Machine Productivity: A Technology-spanning Approach: Christian Lindemann, Paderborn University	1:40 PM
Development of Automatic Smoothing Station Based on Solvent Vapour Attack for Low Cost 3D Printers: Marlon Cunico, University of São Paulo	Using Multi-Axis Material Extrusion Additive Manufacturing to Improve Part Mechanical Properties through Printed Surface Reinforcement: Joseph Kubalak, DREAMS Lab	Estimating Strength of Lattice Structure Using Material Extrusion Based on Deposition Modeling and Fracture Mechanics: Sang-in Park, Georgia Institute of Technology	Processing and Characterization of Aluminum 6061 using Selective Laser Melting at Elevated Temperature: Syed Zia Uddin, The University of Texas at El Paso	How Significant is the Cost Impact of Part Consolidation within Additive Manufacturing Adoption?: Alicia Stevenson, University of Nottingham	2:00 PM
Effect of Process Parameters and Shot Peening on the Tensile Strength and Deflection of Polymer Parts Made Using Mask Image Projection Stereolithography (MIP-SLA): Mohammad Montazeri, University of Nebraska - Lincoln	Reactive Inkjet Printing Approach towards 3D Silicone Elastomeric Structures Fabrication: Aleksandra Foerster, University of Nottingham	Multiscale Analysis of Cellular Solids Fabricated by EBM: Edel Arrieta, The University of Texas at El Paso	Selective Laser Melting of Al7075 by Application of Powder Bed Preheating: Raya Mertens, KU Leuven	Method for the Evaluation of Economic Efficiency of Additive and Conventional Manufacturing: Cordula Auth, TU Darmstadt	2:20 PM
Material Addition and Continuous Sculpting as an Alternate Approach to Improve Surface Quality and Dimensional Accuracy of 3D Printed Parts: Rajeev Dwivedi, STEM and Robotics Academy	Selective Separation Shaping of polymeric material: Hadis Nouri, USC	An Investigation of Property Isotropy of 3D Periodic Cellular Structure Designs: Li Yang, University of Louisville	Porosity Development and Cracking Behavior of Al-Zn-Mg-Cu Alloys Fabricated by Selective Laser Melting: Ting Qi, Wuhan National Laboratory for Optoelectronics	Comparative Costs of Additive Manufacturing vs. Machining: The Case Study of the Entire Annual Production of Forming Dies for Tube Bending: Barbara Previtali, Politecnico di Milano	2:40 PM
Predicting Sharkskin Instability in Extrusion Additive Manufacturing of Reinforced Thermoplastics: Vidya Kishore, University of Tennessee, Knoxville	Additive Manufacturing Utilizing Stock Ultraviolet Curable Silicone: Daniel Porter, Southern Methodist University	Modeling of Fracture Characteristics in 2D Brittle Lattice Structures Assisted by Additive manufacturing: Yan Wu, University of Louisville	Progress Toward the use of Elemental Aluminum-Silicon-Magnesium Mixtures in Selective Laser Melting: Christopher Roberts, University of Texas at Austin	Integrating AM into Existing Companies: Selection of Existing Parts for Increase of Acceptance: Thomas Reiher, Paderborn University / DMRC	3:00 PM
Exploring the Manufacturability and Resistivity of Conductive Filament Used in Material Extrusion Additive Manufacturing: Nicholas Meisel, Pennsylvania State University	Active-Z Printing: A New Way to Improve 3D Printed Part Strength: Jivtesh Khurana, Pennsylvania State University	A Study of the Size Effect of Fracture on Additively Manufactured Periodic Cellular Structures: Li Yang, University of Louisville	Effects of AlSi10Mg Feedstock Condition on Part Properties: Lisa Deibler, Sandia National Laboratories	Ramp-Up-Management in Additive Manufacturing – Technology Integration in existing Business Processes: Johannes Büsching, Paderborn University / DMRC	3:20 PM
	Magnetohydrodynamic Drop-on-Demand Liquid Metal 3D Printing: Viktor Sukhotskiy, Vader Systems	Mechanical Property Variation in Metal Lattice Structures: Amber Dressler, The University of Texas	Effect of Optimizing Particle Size in Laser Metal Deposition with Blown Pre-mixed Powders: Wei Li, Missouri University of Science and Technology	Rational Decision-Making for the Beneficial Application of Additive Manufacturing: Gereon Deppe, Paderborn University - DMRC	3:40 PM
4:00 PM to 5:00 PM Poster Session See program pages for poster listings.					

TECHNICAL SESSION GRID: WEDNESDAY MORNING

	Modeling 1	Applications 9: Heat Exchangers and Smart Devices	Materials 10: PBF: Multijet Fusion and Laser Sintering	Applications 8	Physical Modeling 5: Finite Element Analysis
	Room 404	Room 406	Room 408	Room 410	Room 415A-B
	Hadis Nouri, USC	Ulrich Jahnke, Paderborn University / DMRC	Taku Niino, The University of Tokyo	Jason Weaver, Brigham Young University	Wenda Tan, University of Utah
8:00 AM	Real-Time Process Measurement and Feedback Control for Exposure Controlled Projection Lithography: Xiayun Zhao, Georgia Institute of Technology	3D Printing of Humidity Sensor Based on Swelling Kinetics of Hydrogel: Xiangjia Li, University of Southern California	The Mechanical Voxel: Variable Rigidity Polymer Parts Using Multi Jet Fusion: Kristopher Erickson, HP Incorporated	State of the Art and Qualification Plans for Wire + Arc Additive Manufacture: Filomeno Martina, Cranfield University	Multivariate Calibration of a FE Melt Pool Simulator for Selective Laser Melting: Mohamad Mahmoudi, Texas A&M University
8:20 AM	Machine Learning-based Monitoring of Advanced Manufacturing: Brian Giera, LLNL	Additive Manufacturing for Embedded Microelectronics: David Keicher, Sandia National Laboratories	The Conductive Voxel: Conductive Features within Polymer Parts Using Multi Jet Fusion: Kristopher Erickson, HP Incorporated	Powder Removal Methods for Electron Beam Melting: Philip Morton, University of Texas El Paso	The Effect of Process Parameters and Mechanical Properties of Direct-energy Deposited Stainless Steel 316: Ian Gibson, Deakin university
8:40 AM	Optimization of Build Orientation for Minimum Thermal Distortion in DMLS Metallic Additive Manufacturing: Hao Peng, ITAMCO	Surface Roughness and Resolution Refinement of Vacuum Electronic Devices using Fine Distributions of OFHC Copper with Electron Beam Melting: John Ledford, CAMAL	Pre-printing Quality Assessment of LS-PA12 Parts: Validating the Energy Density Mapping Approach through the use of X-ray Computed Tomography: Michele Pavan, Materialise	Experimental and Analytical Analysis of Nanoparticle Assemblies for High-throughput Nanomanufacturing: Michael Cullinan, University of Texas Austin	Thermal modeling of 304L Stainless Steel Selective Laser Melting: Cody Lough, Missouri University of Science and Technology
9:00 AM	Using Skeletons for Void Filling in Large-Scale Additive Manufacturing: Andrew Messing, Oak Ridge National Laboratory	3D Printing of Flexible & Stretchable Electronics at Room Temperature via Liquid Metal Direct-writing: Dishit Parekh, North Carolina State University	Flow Behaviour of Laser Sintering Powders at Elevated Temperatures: Michael Van den Eynde, KU Leuven	Adhesion of Reactive Silver Inks on Indium Tin Oxide Films: Avinash Mamidanna, Arizona State University	A Finite-element Simulation of Spherical Indentation of LENS-processed 316L Stainless Steel: John Shelton, Northern Illinois University
9:20 AM	Implicit Slicing Method for Additive Manufacturing Processes: Davis W Adams, Clemson University	Integrated Additively Manufactured Hydraulic and Electronic Passageways in Novel Robotic Systems: Brian Post, Oak Ridge National Laboratory	Microwave Measurements of Nylon-12 Powder Ageing for Additive Manufacturing: Nicholas Clark, Cardiff University	Characterization of Thermal and Vapor Smoothing on Surface Roughness of Extruded Components for Printed Electronics: Clayton Neff, University of South Florida	The Effect of Polymer Melt Rheology on Predicted Die Swell and Fiber Orientation in Fused Filament Fabrication Nozzle Flow: Zhaogui Wang, Baylor University
9:40 AM	Break	Break	Break	Break	Break
10:10 AM	B-spline Based Topology Optimization for Metal Hybrid Additive-subtractive Manufacturing: Lin Cheng, University of Pittsburgh	Design and Process Considerations for Effective Additive Manufacturing of Heat Exchangers: Mohammad Masoomi, Auburn University	Improvement of Recycle Rate in Laser Sintering by Low Preheat Temperature Process: Takashi Kigure, Tokyo metropolitan industrial technology research institute	Characterization of Wirebondability to Copper Nanoparticle Traces Produced via Inkjet Printing: Daniel Revier, Texas Instruments	Multiphysics Computational Framework for Selective Laser Sintering Process of Polymers: Vinay Damodaran, University of Wisconsin Madison
10:30 AM	Mechanics of the Separation Process in Constrained-Surface Stereolithography: Abhishek Venketeswaran, University at Buffalo	Design and Additive Manufacturing of a Composite Crossflow Heat Exchanger: Tom Mulholland, University of Wisconsin - Madison	Development of an Experimental Lasersintering Machine to Process New Materials like Nylon 6: Johannes Lohn, Paderborn University, Direct Manufacturing Research Center	Thermo-mechanical Properties of 3D-printed Epoxy Nanocomposites: Nadim Hmeidat, University of Tennessee	Consideration of Fluid Physics on the Residual Stress in a Singe Track of Material: Kurtis Ford, Sandia
10:50 AM		Cooling Optimization of 3D Printed Camera Cell Cooling Housing for Machine Vision in High Temperature Condition: Chiyen Kim, UTEP	Optimization of Adhesively Joined Laser-sintered Parts: Thiemo Fieger, Daimler AG	Approaching Rectangular Extrudate in 3D Printing for Building and Construction by Experimental Iteration of Nozzle Design: Wenxin Lao, Nanyang Technological University	Simulation of Planar Deposition Polymer Melt Flow and Fiber Orientation in Fused Filament Fabrication: Blake Heller, Baylor University
11:10 AM		Thermal Concentrator Design Enabled by Multi-Material 3D Metal Printing: Tim Price, Sandia National Laboratories		Areal Surface Characterization of Laser Sintered Parts for Various Process Parameters: Patrick Delfs, Paderborn University / DMRC	Theoretical Investigation of Stiffness Properties of FDM Parts as a Function of Raster Orientation: Sanchita Sheth, University of Texas at Arlington
11:30 AM		Fabrication and Quality Assessment of Thin Fins Built Using Metal Powder Bed Fusion Additive Manufacturing: Alexander Dunbar, The Pennsylvannia State University			Computationally Efficient Finite Element (FE) Framework to Simulate Additive Manufacturing Process: Ajit Achuthan, Clarkson University

Process Development 9: Metal Powder Processing	Process Development 8: Process Effects	Biomedical Applications 1: Tissue and Cellular	Materials 12: Titanium	Materials 11: 304L and Precipitation Hardened Stainless Steel	
Room 416A-B	Room 417A-B	Salon J	Rom 615A-B	Salon K	
Abdalla Nassar, Penn State University	G. Vastola, A*STAR Institute	Wei Sun, Drexel University	Amrita Basak, Georgia Institute of Technology	Amy Elliott, Oak Ridge National Laboratory	
Ultrasonic Vibration-assisted Direct Laser Deposited TiB Reinforced Ti Composites with a Three-dimensional Quasi-continuous Network Microstructure: Fuda Ning, Texas Tech University	Continuous Laser Scan Strategy for Faster Build Speeds in Laser Powder Bed Fusion System: Ho Yeung, National Institute of Standards and Technology	Constructing Heterogeneous Tumor Models by Integrated Cell Printing System: Wei Sun, Drexel University	Active Control of Microstructure in Electron Beam Melting of Ti6Al4V: Guglielmo Vastola, A*STAR Institute of High Performance Computing	Characterization of Heat-affected Powder Generated during Selective Laser Melting of 304L Stainless Steel Powder: Austin Sutton, Missouri University of Science and Technology, Dept of Matls Science and Engrg	8:00 AM
Development of an Experimental Test Setup for In Situ Strain Evaluation during Selective Laser Melting: Erwin Krohmer, Institute for Machine Tools and Factory Management, TU Berlin	Effect of Printing Speed on Quality of Printed Parts in Binder Jetting Process: Hadi Miyanaji, University of Louisville	Biofabrication of a 3D Vascular Network Using Dynamic Optical Projection Stereolithography: Hongtao Song, Texas Tech University	Efficient Fabrication of Ti6Al4V Alloy by Means of Multi-laser Beam Selective Laser Melting: Fangzhi Li, Wuhan National Laboratory for Optoelectronics	Effects of Area Fraction and Part Spacing on Degradation of 304L Stainless Steel Powder in Selective Laser Melting: Caitlin Kriewall, Missouri University of Science and Technology	8:20 AM
In Situ Melt Pool Monitoring and the Correlation to part Density of Inconel® 718 for Quality Assurance in Selective Laser Melting: Daniel Alberts, SLM Solutions Group AG	Influence of the Ratio between the Translational and Contra-rotating Coating Mechanism on Different Laser Sintering Materials and their Packing Density: Lars Meyer, Universität Duisburg-Essen	Study of Printing Dynamics during Inkjetting of Cell-laden Bioink: Hongtao Song, Texas Tech University	Assessment of Porosity Formation in Additively-manufactured Parts via Numerical Thermomechanical Simulation: Mohammad Masoomi, Auburn University	Directional Dependence of Mechanical Properties and Defects of LENS 304L: Cole Britt, Sandia National Laboratories	8:40 AM
Influence of Process Time and Geometry on Part Quality in Low Temperature Laser Sintering: Yuki Yamauchi, Tokyo Metropolitan Industrial Technology Research Institute	Thermal History Correlation with Mechanical Properties for Polymer Selective Laser Sintering: Samantha Taylor, University of Texas at Austin	Biofabrication of 3D Vascular Constructs of Interpenetrating Network Hydrogel Using a Yield-stress Fluid Bath: Srikumar Krishnamoorthy, Texas Tech University	Effect of Heat Treatment and Hot Isostatic Pressing on the Morphology and Size of Pores in Additive Manufactured Parts: Shuai Shao, Louisiana State University	Impact of Specimen Dimensions on Miniature Tensile Characterization of Powder Bed Fabricated 304L Stainless Steel: Sreekar Karnati, Missouri University of Science and Technology	9:00 AM
Approve of Porosity for Increasing Process Speed in the Laser Melting Process of Ti6Al4V: Dominik Ahlers, Paderborn University / DMRC	A Mobile 3D Printer for Cooperative 3D Printing: Wenchao Zhou, University of Arkansas	High-resolution Electrohydrodynamic Jet Printing of Molten Polycaprolactone: Patrick Sammons, University of Michigan	Effects of Build Orientation on Fatigue Performance of Ti-6Al-4V Parts Fabricated via Laser-based Powder Bed Fusion: Brian Torries, Auburn University	Bonding of 304L Stainless Steel to Cast Iron by Selective Laser Melting: Baily Thomas, Missouri University of Science and Technology	9:20 AM
Break	Break	Break	Break	Break	9:40 AM
The Assessment of Residual Stress in Powder Bed Fusion Components Using a Novel Residual Stress Analysis Component, the Three Prong Method: Stuart Sillars, Swansea University	A Floor Power Module for Cooperative 3D Printing: Jacob Currence, University of Arkansas	Engineered Stem Cell Fibrous Substrates Using High Resolution Additive Biomanufacturing: Robert Chang, Stevens Institute of Technology	Probabilistic Fatigue Life Prediction of an SLM Ti64 Component: Peipei Li, Cornell University	Metal Matrix Nanocomposite Powders for Laser Powder Bed Fusion: Khalid Hussain Solangi, Missouri University of Science and Technology	10:10 AM
A Method for Metal AM Support Structure Design to Facilitate Removal: Niechen Chen, Iowa State University	Mechanical Properties of 304L Metal Parts made by Laser-foil Printing Process: Chia-Hung Hung, Missouri University of Science and Technology	3D Bioprinting Tissue Constructs: Matthew Moldthan, California State University Northridge	Static and Fatigue Properties of Ti-6Al-4V Deposited by the WAAM Process with and without In-process Cold Work: Filomeno Martina, Cranfield University	Effect of Zone Creation to Locally Control Microstructure in Powder Bed Fusion Stainless Steel: Andelle Kudzal, Worcester Polytechnic Insitute	10:30 AM
A Novel Strategy to Build Support-free Overhang Surface below Critical Angle in Direct Metal Laser Sintering Process: Yaswanth Nuthalapati, Indian Institute of Technology Kharagpur	The Optimal Variation in Raster Angle Per Layer for the Selective Laser Sintering of Nylon 12: Bethany King, Lancaster University	Rapid 3D Printing of Scale-up Vascularized Cell-laden Tissue: Hang Ye, University at Buffalo	Effect of Specimen Surface Area Size on Fatigue Strength of Additively Manufactured Ti-Al-4V Parts: Jonathan W Pegues, Auburn University	Impact of Energy Density on Energy Consumption and Porosity of 17-4PH Stainless Steel Fabricated by Selective Laser Melting: Tao Peng, Zhejiang University	10:50 AM
Dilution and Mixing for Functionally Gradient DED Printed Stainless Steel Components with Dissolvable Carbon Steel Supports: Owen J. Hildreth, Arizona State University	The Effect of Arc-based Direct Metal Energy Deposition on DMLS Maraging Steel: Bishal Silwal, Georgia Southern University	Fracture Mechanism Analysis of Schoen Gyroid Cellular Structures Manufactured by Selective Laser Melting: Lei Yang, HuaZhong University of Science & Technology	Small-scale Mechanical Properties of Additively Manufactured Ti-6Al-4V: Meysam Haghshenas, University of North Dakota	Mechanical Performance of Selective Laser Melted 17-4PH Stainless Steel under Compressive Loading: Panneer Selvam Ponnusamy, Swinburne University of Technology	11:10 AM
Numerical Study of Cover Gas Flow in Powder Bed-based Additive Manufacturing: Jan Frederik Hagen, Institute of Photonic Technologies, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)		Three-dimensional Printing of Cellulose-laden Ionic Liquids: Deshani Gunasekera, The University of Nottingham	Machine Learning-enabled Powder Spreading Process Maps for Metal Additive Manufacturing (AM): C. Fred Higgs III, Rice University	Effect of Load Sequences on Fatigue Life of Direct Metal Laser Sintered Parts under Variable Amplitude Loading: Sagar Sarkar, Indian Institute of Technology (IIT)	11:30 AM

	Modeling 2	Applications 10	Materials 16: Thermal Aspects and Porosity Effects	Materials 14: Novel Materials and Processes	Applications 11: Honeycombs and Process Characterization
	Room 404	Room 406	Room 408	Room 410	Room 415A-B
	Douglas Smith, Baylor University	Xuan Song, University of Iowa	Aref Yadollahi, Mississippi State University	Marlon Cunico, University of São Paulo	Maggie Yuan, Beijing Institute of Technology
1:10 PM	Time-Optimal Scan Path Planning Based on Analysis of Sliced Geometry: Anje Van Vlierberghe, Flanders Make VZW	Additive Manufacturing and Mechanical Evaluation of the Stiffness-matched Mandibular Bone Fixation Plates: Ahmadreza Jahadakbar, The University of Toledo	Using Laser Ultrasonic Testing to Detect Sub-surface Defects in Metal Laser Powder Bed Fusion Components: Sarah Everton, University of Nottingham	Crack Initiation and Growth in Selective Laser Melted Pure Molybdenum: Dianzheng Wang, Tsinghua University	Material Selection on Laser Sintered Stab-resistant Body Armor: Maggie Yuan, Beijing Institute of Technology
1:30 PM	A Slicer and Simulator for Cooperative 3D Printing: Jace McPherson, University of Arkansas	Additive Manufacturing of Porous Materials: Christopher Jones, Sandia National Laboratories	Thermal Property Measurement Methods and Analysis for AM Solids and Powders: Justin Whiting, NIST	Wire + Arc Additive Manufacture of Unalloyed Tantalum: Gianrocco Marinelli, Cranfield University	Controlling Thermal Expansion with Lattice Structures Using Powder Bed Laser Fusion: Steven Milward, Swansea University
1:50 PM	Study on STL-based Slicing Process for 3d Printing: Jing Hu, University of Colorado Denver	A Mobile Robot Gripper for Cooperative 3D Printing: Jason Steck, University of Arkansas	Ex situ Determination of Melt Pool Length Through Surface Finish Metrology in Laser Powder Bed Fusion Additive Manufacturing: Zach Reese, University of North Carolina at Charlotte	Selective Laser Melting of Pure Copper: Toshi-Taka Ikeshoji, Kindai University	Determination of a Shape and Size Independent Material Modulus for Honeycomb Structures in Additive Manufacturing: Thao Le, Arizona State University
2:10 PM	ORNL Slicer: A Novel Approach for Additive Manufacturing Tool Path Planning: Alex Roschli, Oak Ridge National Laboratory	Biomimetic Anisotropic Reinforcement Architectures by Electrically Assisted Nanocomposite 3D Printing: Yang Yang, University of Southern California	Fracture Toughness of Additive Manufactured Composite Metamaterial: Huachen Cui, Virginia Tech	Direct Writing of Films from High Speed Aerosol Deposition of Ag: Jeremiah McCallister, The University of Texas at Austin	Additively Manufactured Conformal Negative Stiffness Honeycombs: David Debeau, The University of Texas at Austin
2:30 PM	Novel Approach for Optimizing Infill Density of an Additively Manufactured Structure: Seokpum Kim, Oak Ridge National Laboratory	Technological Challenges for the Automotive Series Production in Laser Beam Melting: Felix Haeckel, BMW Group	Characterization of Ejected Particles or Spatter during Laser Powder Bed Additive Manufacturing: Maria Withrow, North Carolina State CAMAL	Effect of Bed Temperature on the on the Laser Energy Required to Sinter Copper Nanoparticles: Nilabh Roy, The University of Texas at Austin	Understanding and Improving Optical Coherence Tomography Imaging Depth in Selectively Laser Sintered Nylon 12 Parts and Powder: Adam Lewis, University of Texas at Austin
2:50 PM	Break	Qualification Challenges with Additive Manufacturing in Space Applications: Christo Dordlofva, Luleå University of Technology	Break	Break	Break
3:20 PM	Computer Aided High Complex Geometry Generation for Product Optimization with Additive Manufacturing: Thomas Reiher, Paderborn University		A Design of Experiments Approach to Observing the Effect of Primary Process Parameters on Porosity Populations and Fatigue Life in DMLS Inconel 718: Luke Sheridan, Air Force Research Laboratory	Aluminum Matrix Syntactic Foam Fabricated with Additive Manufacturing: Myranda Spratt, Missouri University of Science and Technology	Application of Integrated Computational Materials Engineering in Qualification of Additive Manufacturing Parts: Guofeng Chen, Siemens Ltd., China
3:40 PM	Multiscale Voxel-Based Design and Additive Manufacture of Composite Components: Martin Dunn, Singapore University of Technology and Design		Critical Defect Signatures and Impacts on Material Performance for Metal Laser Powder Bed Fusion: Bradley Jared, Sandia National Laboratories	Real-Time Layer-by-Layer Ultrasonic Treatment of Additively Manufactured Metallic Materials: Rasool Mazruee Sebdani, Clarkson University	Powder Bed Fusion Metrology for Additive Manufacturing Design Guidance: Jared Allison, University of Texas at Austin
4:00 PM	Software Tools for Rapid 3D Electronics Fabrication: Jake Lasley, UTEP - W.M. Keck Center for 3D Innovation		Prediction of Fatigue Lives in Additively Manufactured Alloys based on the Crack-growth Concept: Aref Yadollahi, Mississippi State University	Fabrication of Metallic Multi-material Components Using Laser Metal Deposition: Frank Brueckner, Fraunhofer IWS Dresden / TU Dresden / LTU Lulea	Geometrical Accuracy of Holes and Cylinders Manufactured with Fused Deposition Modeling: Frederick Knoop, Paderborn University / DMRC
4:20 PM			Classification Based Porosity Prediction Technique Using Melt Pool Signal: Mojtaba Khanzadeh, Mississippi State University	Design and Fabrication of Hierarchical 3D Architected Metamaterials with Programmable Damage Tolerance and Strength: Rayne Zheng, Virginia Tech	New Benchmark Part Design for Characterising Accuracy in Binder Jetting Process: Senthilkumaran Kumaraguru, Indian Institute of Information Technology, Design and Manufacturing, Kancheepuram
4:40 PM				Weldability of Additively Manufactured Metal Components: Jeffrey Rodelas, Sandia National Laboratories	

Process Development 11: Wire Processes and Ceramics	Process Development 10: Large Scale and Hybrid Processes	Biomedical Applications 2: Scaffolds and Supports	Materials 13: Jetting and Inks	Materials 15: 316L and Other Stainless Steels	
Room 416A-B	Room 417A-B	Salon J	Rom 615A-B	Salon K	
Chao Ma, Texas A&M University	Chad Duty, University of Tennessee	Natalie Rudolph, University of Wisconsin	Denis Cormier, Rochester Institute of Technology	Christopher Roberts, University of Texas at Austin	
Cost Competitive Wire Arc Additive Manufacturing (WAAM): Jonathan Hoffmann, Louisiana State University	Challenges in Making Metal Large-scale Complex Parts for Additive Manufacturing: A Case Study Based on the Additive Manufacturing Excavator (AME): Andrzej Nycz, Oak Ridge National Laboratory	A Topological Exploration of Shrinkage in Sintered Bioceramic Parts Fabricated by Vat Photopolymerization: Donald Aduba, Virginia Tech	Investigating the Impact of Functionally Graded Materials on Fatigue Life of Material Jetted Specimens: Dorcas Kaweesa, The Pennsylvania State University	Microstructure Comparison of 316L Parts Produced by Different Additive Manufacturing Processes: Mihaela Nastac, ExOne	1:10 PM
Design of a Desktop Wire-feed Prototyping Machine: Yu-Chuen Chang, The University of Texas at Austin	Changing Print Resolution on BAAM via Selectable Nozzles: Phillip Chesser, Oak Ridge National Laboratory	Additive Manufacturing and Mechanical Testing of Interpenetrating Phase Composites for High-performance Armor Applications: Zachary Cordero, Rice University	Guidelines for Developing Binder Jet Printing Parameters for Various Powder Feedstocks: Derek Siddel, Oak Ridge National Laboratory	A Parametric Study on Grain Structure in Selective Laser Melting Process for Stainless Steel 316: Dongwei Sun, University of Utah	1:30 PM
Visual Sensing and Image Processing for Error Detection in Laser Metal Wire Deposition: Adeola Adediran, Oak Ridge National Laboratory	3D LSP: Tailoring Residual Stresses in Parts by Introducing Laser Shock Peening during Selective Laser Melting: Nikola Kalentics, EPFL	Understanding and Engineering of Natural Surfaces with Additive Manufacturing: Ali Khoshkhoo, Auburn University	Binderless Jetting: Additive Manufacturing of Metal Parts via Jetting Nanoparticles: Yun Bai, Virginia Tech	Strength of Micro-Computed Tomography as an Indicator of Process History and Estimator of Mechanical Performance in Additively Manufactured Stainless Steel: Jonathan Madison, Sandia National Laboratories	1:50 PM
Multi-sensor Investigations of Optical Emissions and Their Relations to DED Processes and Quality: Christopher B Stutzman, Penn State University	Examination of Build Orientation and Its Impact on 316 Stainless Steel Dissolvable Supports: Owen J. Hildreth, Arizona State University	Additive Fabrication of Polylactic Acid/Ceramic Based Scaffolds for Maxillofacial Regeneration: Srikanthan Ramesh, Iowa State University	Electrical and Mechanical Properties of Metal Filled Conductive Material Using Fused Deposition Modeling: Sagar Navle, Texas State University	Porosity and Mechanical Properties of Selected Laser Melted 316L Stainless Steel: Trevor Verdonik, Lehigh University	2:10 PM
Fiber-fed Laser-melting Process for Printing Transparent Glass: John M. Hostetler, Missouri University of Science and Technology	Expert Survey to Understand and Optimize Workpiece Orientation in Direct Metal Laser Sintering: David Hoelzle, The Ohio State University	Binder Jet Additive Manufacturing of Stainless Steel,Tricalcium Phosphate Biocomposite for Bone Scaffold Applications: Kuldeep Agarwal, Minnesota State University, Mankato	Fabrication and Characterization of Graphite/Nylon 12 Composite via Binder Jetting Additive Manufacturing Process: Hadi Miyanaji, University of Louisville	316L Powder Reuse for Metal Additive Manufacturing: Tammy Pond, Honeywell FM&T	2:30 PM
Break	Break	Break	Break	Break	2:50 PM
Flash Laser Sintering of Ceramics: Debbie Hagen, The University of Texas at Austin	Multi-robot Arc-based Additive Manufacturing for High Material Deposition Rates: David Espalin, UTEP - W.M. Keck Center for 3D Innovation	Selective Laser Melting of Novel Titanium-Tantalum Alloy as Orthopedic Biomaterial: Florencia Edith Wiria, Singapore Institute of Manufacturing Technology	Fabricating TiC/Ni3Al Hybrid Composite Using Binder Jet Additive Manufacturing: Peeyush Nandwana, Oak Ridge National Laboratory	Competing Influence of Porosity and Microstructure on the Fatigue Property of Laser Powder Bed Fusion Stainless Steel 316L: Meng Zhang, Singapore Centre for 3D Printing, Nanyang Technological University	3:20 PM
Process Temperature Monitoring with Physics-based Compressive Sensing: Yanglong Lu, Georgia Institute of Technology	Fabrication of 3D Multi-material Parts Using Laser-based Powder Bed Fusion: Christine Anstaett, Fraunhofer IGCV	Development of Patient Specific Surgical Resection Guides Using Medical Imaging 3D Modelling and Additive Manufacturing Processes: Mazher Mohammed, Deakin University	Net Shaping of Steel-tungsten Metal Hybrid via Binder Jet Additive Manufacturing: Amy Elliott, Oak Ridge National Laboratory	Studying Chromium and Nickel Equivalency to Identify Viable Additive Manufacturing Stainless Steel Chemistries: Zachary Hilton, Missouri University of Science and Technology	3:40 PM
Alumina-zirconia Ceramics Fabricated by Ultrasonic Vibration-assisted Laser Engineered Net Shaping Process: Yingbin Hu, Texas Tech University	Multi-process Advanced Manufacturing for 3D-printed Multi-functional Devices: Jose Coronel, UTEP - W.M. Keck Center for 3D Innovation	Design Optimisation of a Thermoplastic Splint: Angus Fitzpatrick, Deakin University	Effect of Contact Angle on Reactive Ink Droplet Evolution: Avinash Mamidanna, Arizona State University	Experimental Analysis on Eradicating Porosity from Additively Manufactured Low Alloy Steels by Using Martensitic Stainless Steel Powder Reinforcement Technique: A. Farooq, IMR, Chinese Academy of Sciences	4:00 PM
		Reverse Engineering a Transhumeral Prosthetic Design for Additive Manufacturing: Breanna Rhyne, Oak Ridge National Laboratory	3D Printing of Metal Powder-based Inks via Direct Ink Writing: Robert Pack, University of Tennessee at Knoxville		4:20 PM
		Augmented Additive Manufacturing for Affordable Prosthetic Socket Printing: Nicholas Rodriguez, The University of Texas-Austin	Electrical Properties of Reactive Silver Inks on Indium Tin Oxide Films: Avinash Mamidanna, Arizona State University		4:40 PM

Plenary Session and FAME Presentations

Monday AM — Room: Salon H-J-K
August 7, 2017 — Location: Hilton Austin

Session Chair: Phill Dickens, University of Nottingham

8:00 AM Introductory Comments
Comments by Symposium Chair David Bourell

8:15 AM
Towards Real-time Regulation of Build Geometry in a Directed Energy Deposition Additive Manufacturing System using Vision-based Feedback Control: Dustin Seltzer[1]; Jeffrey Schiano[1]; *Abdalla Nassar*[1]; Edward Reutzel[1]; [1]Penn State University

Directed energy additive manufacturing presents a cost effective means for repairing wear to components that are expensive to remanufacture, such as turbine blades. However, such components have narrow tolerance bands and the required tolerances are not guaranteed when processing parameters are chosen prior to the build. To achieve the desired build quality, we propose a feedback control system that uses real-time measurements of melt-pool geometry to automatically adjust the process parameters of scan speed and laser power. This paper describes a multi-input multi-output (MIMO) controller that simultaneously regulates melt-zone width and build height. Melt-zone geometry is observed using a Camera Link camera with a field programmable gate array in order to obtain and process melt-zone images at approximately 100 frames per second. The control design is based on a MIMO dynamic model that was identified from experimental data using a least-squares estimation method.

8:35 AM
Automatic and Reusable Metal Supports for 3D Printing: *Yang Xu*[1]; Ziqi Wang[1]; Siyu Gong[1]; Yong Chen[1]; [1]University of Southern California

Three-dimensional (3D) printers such as fused deposition modeling (FDM) need to add supports to a digital model in order to be printed. The additional supports using the same or different materials have several drawbacks such as the supports are a waste of materials and the support printing and removing is time-consuming. We develop a new type of metal supports that serve as the trunks of the required supports to reduce the printed supports. When finishing the printing of a layer, the metal rods will be moved up the same layer distance as the printer head. The stop positions of the metal rods are set by metal tubes with pre-defined lengths. After the printing process, the metal rods can easily be removed and reused. A prototype FDM 3D printer has been developed to demonstrate the metal support method, and several test cases are presented to show its effectiveness and efficiency.

8:55 AM
An Investigation into Spatter Creation during Selective Laser Melting: *Mohsen Taheri Andani*[1]; Reza Dehghani[2]; Mohammadreza Karamooz Ravari[2]; Reza Mirzaeifar[3]; Jun Ni[1]; [1]University of Michigan; [2]Graduate University of Advanced Technology, Kerman; [3]Virginia Tech

Selective laser melting (SLM) as a novel metallic additive manufacturing process has drawn extensive attention recently, mainly due to its unique ability for layer-by-layer fabricating parts of various complexities. However, the fatigue response of SLM parts, due to the presence of non-melted regions into the final SLM product, is inferior as compared to that of parts manufactured by conventional methods. In this work, high-speed photography is utilized to realize the formation mechanisms and behavior of these un-melted particles during SLM fabrication. A computational image analysis framework is developed and applied to obtain the size and the number of induced unmelted regions. The morphology and the composition of un-melted particles and their influence on the surface properties of the fabricated parts are also determined in this study.

9:15 AM
Detection of Defects and Studying Effect of Defects Using X-ray Computed Tomography: *Felix Kim*[1]; Edward Garboczi[1]; Shawn Moylan[1]; John Slotwinski[2]; [1]National Institute of Standards and Technology; [2]Johns Hopkins University Applied Physical Laboratory

Reliable defect detection is a critical part of qualifying a part produced with metal Additive Manufacturing (AM). X-ray Computed Tomography (XCT) is becoming a viable inspection tool to detect defects non-destructively. XCT can not only detect defects but also quantitatively measure global porosity, individual pore size, shape, orientation and distribution. A thresholding procedure was developed to measure the global porosity and individual pore characteristics of AM parts produced with varying processing parameters (hatch speed and hatch spacing). XCT provided a complete defect structure at sub-micrometer resolution for an in-depth analysis. In addition, unique mechanical tests combined with XCT are proposed to complement standard mechanical tests to improve understanding of the effects of typical AM defects and failure mechanism. The process of developing tensile specimens incorporating natural and designed defects will be shared. The plans for in-situ mechanical test with XCT and initial mechanical test results will be provided.

9:35 AM
Predicting Meltpool-Scale Phenomena in Full-Scale Parts made using Metal Laser Sintering: *Brent Stucker*[1]; [1]3DSIM

In 2013, an estimate of the time needed to predict thermal history at 10 micron accuracy in a part that takes 50 hours to scan was presented. Using a uniform mesh, a desktop computer would take 5.7*10^18 years to solve this problem, whereas a multi-scale moving mesh would reduce that to 10^10 years. Algorithmic, mathematical and software innovations were presented that theoretically reduced that time to a matter of hours. Over 4 years a team worked to implement these innovations. The mathematical efficiency of the resultant "Thermal Solver" is better than predicted, however GPU data bandwidth limitations were worse than anticipated. Today, in anywhere from hours to a few weeks' time on a CPU, the prediction of location-specific meltpool, defect, strain, microstructure and thermal history is possible. In this talk, the path to achieve these efficiencies, the results being produced, and steps toward faster solution times will be presented.

9:55 AM Break

10:25 AM
Big Area Additive Manufacturing Application in Wind Turbine Molds: *Brian Post*[1]; Bradley Richardson[1]; Randall Lind[1]; Lonnie Love[1]; Peter Lloyd[1]; Vlastamil Kunc[1]; Breanna Rhyne[1]; Alex Roschli[1]; Jim Hannan[2]; Steve Nolet[2]; Kevin Veloso[2]; Parthiv Kurup[3]; Timothy Reno[3]; Dale Jenne[3]; [1]Oak Ridge National Laboratory; [2]TPI Composites; [3]National Wind Technology Center

Tooling is a primary target for current additive manufacturing (AM), or 3D printing, technology because of its rapid prototyping capabilities. Molds of many sizes and shapes have been produced for a variety of industries. However, large tooling remained out of reach until the development of large-scale composite AM manufacturing processes like the Cincinnati Big Area Additive Manufacturing (BAAM) system. The Department of Energy's Oak Ridge National Laboratory (ORNL) worked with TPI Composites to use the BAAM system to fabricate a wind turbine blade mold. The fabricated wind turbine blade mold was produced in 16 additively manufactured sections, was 13 meters long, had heating channels integrated into the design, and was mounted into a steel frame post fabrication. This research effort serves as a case study to examine the technological impacts of AM on wind turbine blade tooling and evaluate the efficacy of this approach in utility scale wind turbine manufacturing.

10:45 AM
Next Generation Aerosol-Based Printing for Production-Level Printed Electronic: *David Keicher*[1]; Marcelino Essien[2]; Judi Lavin[1]; Shaun Whetten[2]; Seethambal Mani[1]; [1]Sandia National Laboratories; [2]IDS

Sandia National Labs (SNL) and IDS have developed a next generation aerosol-based printing technology for printed electronics applications. This production-capable apparatus provides stable, repeatable printing of conductive, resistive, and insulating inks. This collaboration has resulted in the provision of a cartridge style print head for Direct Write Electronic (DWE) applications at a fraction of the cost of other aerosol based printing systems. The technology, Mycrojet, is based SNL patented focusing technology. The Mycrojet print head is capable of printing high-definition traces with line widths from 10 to 1000 microns. The technology has been used to print embedded sensors, 3D capacitors, resistors and direct write conductive traces. Print stability test results showing unassisted run times and continuous, unassisted printing of high-quality traces for more than eight hours will be shown with a relative standard deviation of printed traces of less than 5%. Similar results for printed resistors will also be shown.

11:05 AM Invited

FAME Outstanding Young Researcher Award Lecture: Quantifying Processing-structure-property Relationships in Additively Manufactured Metals: *Allison Beese*[1]; Zhuqing Wang[1]; Alexander Wilson-Heid[1]; Lourdes Bobbio[1]; [1]Pennsylvania State University

While additive manufacturing (AM) of metallic materials can be used to fabricate custom and complex shaped components, before AM can be adopted for use in load-bearing applications, the processing-structure-property relationships in these materials must be understood such that their mechanical properties can be reliably predicted. The rapid solidification and repeated thermal cycles the material is exposed to during AM fabrication results in heterogeneous and anisotropic microstructures that differ from those seen in traditionally cast, wrought, or annealed counterparts. This talk will focus on our efforts to experimentally identify the quantitative process-microstructure-mechanical property relationships in both monolithic and functionally graded additively manufactured components.

11:35 AM Invited

Freeform and Additive Manufacturing (FAME) Award II: A Journey through Time and Around the World of Solid Freeform Fabrication: *Ian Gibson*[1]; [1]Deakin University

When I started working at Nottingham University around 1992, there were 3 known 'Rapid Prototyping' machines in the UK as they were known then. When I moved to Hong Kong in 1994, there were 4 machines there. I moved to Singapore in 2005 and things were very different but the real boom was still to take place, which I now view from my position at Deakin University in Australia. The many, many people that are now aware of Solid Freeform Fabrication, or 3D Printing as most know it, may not realise that there were times when it was uncertain as to how this technology would develop. Maybe, with the multi-faceted opportunities that we see, the future is still uncertain, but nonetheless bright in my opinion. For this talk, I would like to provide my perspective on how the technology has developed into the multi-billion dollar industry it is today.

Applications 1: Lattices 1

Monday PM	Room: 602
August 7, 2017	Location: Hilton Austin

Session Chair: Albert To, University of Pittsburgh

1:30 PM

Novel Graded Honeycombs Fabricated by Material Extrusion Additive Manufacturing: *Brett Compton*[1]; [1]University of Tennessee

Cellular materials offer unique combinations of strength, stiffness, and low density that are unattainable in traditional engineering materials. Graded cellular materials present new opportunities to access superior combinations of static and dynamic properties over uniform cellular materials while maintaining low density. Material extrusion additive manufacturing provides an ideal method to design, fabricate, and study the mechanical properties of graded cellular materials. This talk will outline a novel method for fabricating honeycombs with gradients in both strut thickness and cell shape via material extrusion AM, and describe the resulting mechanical properties using compression testing, finite element analysis, and analytical modeling. Potential areas of application will also be discussed.

1:50 PM

Digital Design and Manufacture of Soft Lattice Structures: Oliver Weeger[1]; Narasimha Boddeti[1]; Bharath Narayanan[1]; You Jian Teoh[1]; Sai-Kit Yeung[1]; Sawako Kaijima[1]; Qi Ge[1]; *Martin Dunn*[1]; [1]Singapore University of Technology and Design

Lattice structures are frequently found in nature and engineering due to their myriad attractive properties, with applications ranging from molecular to architectural scales. While design and simulation tools for stiff lattices are common, here we present a digital design and manufacturing approach for soft lattices structures, for which applications in soft robotics, medtech, and energy harvesting/dissipation exist. Our framework admits soft lattices with curved members which can adapt to freeform geometries, and have variable, gradually changing member thickness and material, allowing the local control of stiffness. We model the lattice members as 3D curved rods and using a spline-based isogeometric method that allows the efficient simulation of nonlinear, large deformation behavior of these structures directly from the CAD geometries. Simulation results are verified against experiments with lattices realized by PolyJet polymer 3D printing, highlighting the potential for design and application of non-uniform and curved soft lattice structures.

2:10 PM

Embedding of Liquids into Water Soluble Materials via Additive Manufacturing for Timed Release: *Callie Zawaski*[1]; Evan Margaretta[2]; Andre Stevenson[3]; Allison Pekkanen[2]; Timothy Long[2]; Abby Whittington[3]; Christopher Williams[1]; [1]DREAMS Lab at Virginia Polytechnic Institute and State University; [2]Long Research Group at Virginia Polytechnic Institute and State University; [3]Whittington Research Group at Virginia Polytechnic Institute and State University

One fundamental goal of personalized medicine is to provide tailored control of the dissolution rate for an oral dosage pill. Additive manufacturing of oral dose medicine allows for customized dissolution by tailoring both geometric and printed material properties. Direct processing of medicine via filament material extrusion is challenging because many active agents become inactive at the elevated temperatures found in the melt-based process. In this work, this limitation is circumvented by incorporating the active agents via in-situ embedding into a priori designed voids. This concept of embedding active ingredients into printed parts is demonstrated by the in-situ deposition of liquid ingredients into thin-walled, water soluble, printed structures. The authors demonstrate the ability to tune dissolution time by varying the thickness of the printed part's walls using this technique.

2:30 PM

Prediction of the Elastic Response of TPMS Cellular Lattice Structures using Finite Element Method: Mohammadreza Karamooz Ravari[1]; *Mohsen Taheri Andani*[2]; [1]Graduate University of Advanced Technology, Kerman; [2]University of Michigan

Cellular lattice structures are a group of porous materials in which the cells are regularly distributed. Since the morphology of the cells are complicated, the fabrication of them was challenging using conventional methods. However, with the advent of additive manufacturing technology, more attention is focused on these class of materials because the regular geometry makes it possible to tailor the mechanical response of the structure. Among all kinds of cellular lattice structures, those based on triply periodic minimal surfaces are of great importance due to mechanical/biological properties. Since the fabrication of such structures is challenging, it is desirable to predict their mechanical response before fabrication. In this paper, finite element approach is employed to predict the elastic response of well-known Schwarz minimal surfaces named P-Type and G-Type. The results show that at the same value of porosity, the P-Type specimen provides a higher value of elastic modulus than G-Type one.

2:50 PM
Generation of TPMS Cellular Lattice Structures to Fill an Arbitrary Boundary: Mohammadreza Karamooz Ravari[1]; *Mohsen Taheri Andani*[2]; [1]Graduate University of Advanced Technology; [2]University of Michigan

Cellular lattice structures based on triply periodic minimal surfaces are good candidates for being used as bone scaffolds. Since the shape of the bone is almost arbitrary, it is desirable to develop a methodology to be able to generate a cellular lattice structure whose boundaries are coincided with that of the bone. In this paper, a method is developed to generate a TPMS cellular lattice with arbitrary boundaries. To do so, first, the point clouds of the lattice are generated and then a suitable mesh is constructed through them. Then, the same process is performed for the shape of the desired boundaries. To fill the boundary shape with pores, the Boolean difference of the boundary and porous structure is found. This method is used to construct P/G-Type porosities as pores and sphere, and heart as the boundary mesh. Additive manufacturing limitations are also considered in the development of this method.

3:10 PM Break

3:40 PM
A Framework for the Design of Biomimetic Cellular Materials for Additive Manufacturing: Teresa McNulty[1]; *Dhruv Bhate*[2]; Amy Zhang[2]; Mehlika Kiser[1]; Lara Ferry[1]; Austin Suder[2]; Sunand Bhattacharya[3]; Prasad Boradkar[1]; [1]Arizona State University; [2]Phoenix Analysis & Design Technologies, Inc. (PADT); [3]Autodesk Inc.

Cellular materials such as honeycombs and lattices are an important area of research in Additive Manufacturing due to their ability to improve functionality and performance. While there are several design choices when selecting a unit cell, it is not always apparent what the optimum cellular design for a particular application is. This becomes particularly challenging when seeking an optimal design for more than one function, or when the design needs to transition spatially between different functions. Nature abounds with examples of cellular materials that are able to achieve multifunctionality, but designers lack the ability to translate the underlying principles in these examples to their design tools. In this work, we propose a framework to bridge the connection between nature and designer. We present a classification of natural cellular materials based on their structure and function, and relate them in a manner amenable for use in guiding design for Additive Manufacturing.

4:00 PM
Topology Optimization of Variable-density Lattice Structure for Highly Efficient Convective Heat Transfer: *Lin Cheng*[1]; Joseph Brown[1]; Albert To[1]; [1]University of Pittsburgh

A novel methodology is proposed to considerably enhance the heat transfer of a given problem by optimizing the density distribution of additive manufactured lattice structure. A multiscale model is employed to derive the heat convection of lattice structure in terms of design variables, such as relative density, inlet velocity and porosity per unit length. At microscale, a full scale simulation is conducted on the lattice unit to obtain the forced convection heat transfer coefficients, while at macroscale a homogenized model is used to characterize the thermal performance of lattice material. Once the homogenized model is obtained, it is embedded into a coupled thermal-fluid governing equation and the optimization is conducted to iteratively optimize the density distribution of lattice structure until the convergence is satisfied. To demonstrate the efficiency of the proposed method, several numerical examples are provided to compare with result of full scale simulation and great agreements are observed.

4:20 PM
An Evaluation of Carbon Composite Axial Lattice Structures: *Pritam Poddar*[1]; Denis Cormier[1]; [1]Rochester Institute of Technology

Axial lattice extrusion (ALE) is an additive manufacturing technique for producing lattice structures where the extrusion toolpath is not restricted to the X-Y plane and can include printing moves with a vertical component. When the ALE feedstock includes chopped carbon fibers, vertical and diagonal struts include fibers that are axially aligned with the orientation of the struts. This greatly enhances mechanical properties of the resulting lattice structures. This paper will describe modifications to an existing fused filament extrusion machine to enable more reliable ALE operation. Mechanical properties of ALE structures produced using nylon filament with chopped carbon fibers will also be reported.

Applications 2: Design and Optimization

Monday PM — Room: 615A-B
August 7, 2017 — Location: Hilton Austin

Session Chair: Sarah Bagehorn, Airbus Group Innovations

1:30 PM
Feature-based Level Set Topology Optimization Applied in Additive Manufacturing: *Yeming Xian*[1]; David Rosen[1]; [1]Georgia Institute of Technology

This paper addresses two issues: 1. Topology optimization (TO) yields designs that may require support structures if additively manufactured, which increase material and clean-up costs. 2. Topologically optimized designs consist of discretized geometry which makes subsequent engineering difficult, hence the increasing need to somehow render TO results to parameterized CAD models. This paper presents a procedure that, during each design update, firstly identifies certain regions on the part boundary that may require support materials or may cause staircase effect during 3D printing, then replaces these boundary segments with similar-shaped printable design features. Additionally, other boundary regions are fitted simple geometric entities, so that the part boundary can be completely defined by geometric parameters of design primitives. To construct such boundary representations and perform sensitivity analysis, we combine level set functions of the design primitives using Boolean operations and R-functions, which yields a fully parameterized level set based optimization problem.

1:50 PM
Multi-material Structural Topology Optimization under Uncertainty via a Stochastic Reduced Order Model Approach: *Miguel Aguilo*[1]; James Warner[2]; [1]Sandia National Laboratories; [2]NASA Langley Research Center

This work presents a stochastic reduced order modeling approach for the solution of uncertainty aware, multi-material, structural topology optimization problems. Uncertainty aware structural topology optimization problems are computationally complex due to the number of model evaluations that are needed to quantify and propagate design uncertainties. This computational complexity is magnified if high-fidelity simulations are used during optimization. A stochastic reduced order model (SROM) approach is applied to 1) alleviate the prohibitive computational cost associated with large-scale, uncertainty aware, structural topology optimization problems; and 2) quantify and propagate inherent uncertainties due to design imperfections. The SROM framework transforms the uncertainty aware, multi-material, structural topology optimization problem into a deterministic optimization problem that relies only on independent calls to a deterministic analysis engine. This approach enables the use of existing optimization and analysis tools for the solution of uncertainty aware, multi-material, structural topology optimization problems.

2:10 PM
Projection-based Topology Optimization Algorithms for Manufacturing Design Constraints in Powder Bed Fusion and Vat-based Additive Manufacturing: *Andrew Gaynor*[1]; Terrence Johnson[1]; Andelle Kudzal[2]; Brandon McWilliams[1]; [1]U.S. Army Research Laboratory; [2]Worcester Polytechnic Institute

Topology-optimized geometries for additive manufacturing often require post-processing in order to guarantee manufacturability. This work tackles two problems in this realm: design for the maximum manufacturable overhang angle and design to eliminate internal pores. Topology optimization for overhang control through projection-based schemes has previously been formulated in 2D. The first extension of the 2D approach is a straightforward translation to 3D. The next extension of the approach remedies the issue of obtaining solutions with internal voids – in which powder or resin may be trapped and will inadvertently add to the weight of the manufactured geometry. Algorithmically, this is achieved through inverting the design problem to project void, with voids “growing” from external, user-defined surfaces, therefore necessitating that unprocessed powder or resin have a path to a surface. Solutions are manufactured on a metal powder bed fusion machine, and post-process characterization is performed to quantify adherence to imposed design rules.

2:30 PM
Topology Optimization for 3D Material Distribution and Orientation for Additive Manufacturing: *Douglas Smith*[1]; Delin Jiang[1]; [1]Baylor University

Products produced with additive manufacturing methods often have anisotropic microstructures that form as material layers are added during processing. Carbon fiber filled polymer deposited in beads with the Fused Filament Fabrication (FFF) process, for example, has been shown to have a highly anisotropic material response. This paper presents a three dimensional (3D) topology optimization method that computes the best anisotropic material distribution and direction for minimum compliance of a statically loaded AM structure. The objective function is calculated using the Finite Element Method with eight node 3D isoparametric elements, and design sensitivities with respect to both density and material orientation are calculated with the Adjoint Variable method. We employ a linear weighted sensitivity filter on the density variables to prevent the checker-boarding of the material distribution. The optimization problem is solved with a nonlinear constraint-based Matlab optimization solver. Several loaded scenarios are presented to demonstrate versatility of the optimization scheme.

2:50 PM
Topological Optimization and Methodology for Fabricating Additively Manufactured Lightweight Metallic Mirrors: *Michael Stern*[1]; Joseph Bari[1]; James Ingraham[1]; [1]MIT Lincoln Laboratory

Imaging systems for space and airborne platforms have aggressive Size Weight and Power (SWaP) requirements. High quality, lightweight optics help enable these types of systems. Today typical light weighting techniques are accomplished through removal of material in the back structure with classical machining and the use of low-density, high-stiffness materials such as beryllium. We present a novel methodology for generating lightweight metallic mirrors that are fabricated by growing an additive manufactured blank, fly cutting the surfaces to be mirrored, and post processing the faces by coating them with electroless nickel and then diamond turning. This process was used in a case study for the development of a topology optimized, low-weight and high-stiffness spinning mirror. The mirror was fabricated with selective laser melting and post processed to deliver optical quality mirror surfaces.

3:10 PM Break

3:40 PM
Topology Optimization of an Additively Manufactured Beam: Brian Torries[1]; *Saber DorMohammadi*[2]; Frank Abdi[2]; Nima Shamsaei[1]; [1]Auburn University; [2]AlphaSTAR Corp.

This study investigates the application of topological optimization in conjunction with additive manufacturing (AM) process simulation for fabricating parts that meet strict quality and performance requirements while also minimizing printed geometry. Integrated Computational Materials Engineering (ICME) and GENOA 3D commercial software were used to simulate sample fabrication and, along with commercial design optimization tools, create an optimized beam topology for simple loading conditions. Constraints were set in order to support any over-hanging material with an appropriate inclination angle. These samples were fabricated from Ti-6Al-4V using an EOS M290 direct metal laser sintering (DMLS) system with default parameters, as well as 95%, 90%, and 88% of default laser power in order to reduce the porosity in the over-heated areas. Parts were subjected to X-ray CT scanning to quantify part porosity. It was determined that the process used allowed for the fabrication of samples with optimized topology and minimal defects.

4:00 PM
Quantifying Accuracy of Metal Additive Processes through a Standardized Test Artifact: Jason Weaver[1]; *TJ Barton*[1]; Derrik Jenkins[1]; John Linn[1]; Mike Miles[1]; Robert Smith[2]; [1]Brigham Young University; [2]Rapid Qualified Products

Two limitations of AM processes when compared to CNC subtractive processes are reduced dimensional accuracy and rougher surface finish. Accuracy and surface finish of metal additive processes, such as DMLS or SLM, are generally much looser than precision turning or grinding processes. Because of this, it is important to have an understanding of an AM machine's capabilities—the designer must be satisfied with the tolerances and finishes possible, or additional post-processing must be added. One way to examine the capabilities of an AM process is by printing and measuring test artifacts. This paper examines a test artifact proposed by NIST that is intended to demonstrate many different capabilities and types of accuracy. Three identical builds are printed on a Concept Laser metal additive machine and measured. The capabilities of the machine are quantified and discussed, along with additional recommendations for improving the test structure design and the measurement process.

4:20 PM
Integrating Interactive Design and Simulation for Mass-Customized 3D-Printed Objects – a Cup Holder Example: *Christian Altenhofen*[1]; Felix Loosmann[1]; Johannes Mueller-Roemer[1]; Tim Grasser[1]; Thu Huong Luu[1]; André Stork[1]; [1]Fraunhofer IGD, Technische Universität Darmstadt

We present an approach for integrating interactive design and simulation for customizing parameterized 3D models. Instead of manipulating the mesh directly, a simplified interface for casual users allows for adapting intuitive parameters, such as handle diameter or height of our example object - a cup holder. The transition between modeling and simulation is performed with a volumetric subdivision representation, allowing direct adaption of the simulation mesh without re-meshing. Our GPU-based FEM solver calculates deformation and stresses for the current parameter configuration within seconds with a pre-defined load case. If the physical constraints are met, our system allows the user to 3D print the object. Otherwise, it provides guidance which parameters to change to optimize stability while adding as little material as possible based on a finite differences optimization approach. The speed of our GPU-solver and the fluent transition between design and simulation renders the system interactive, requiring no pre-computation.

Applications 3: Education and Future

Monday PM — Room: 616A-B
August 7, 2017 — Location: Hilton Austin

Session Chair: Matt Frank, Iowa State University

1:30 PM
Maker Spaces and Fab Labs: Creating Student Access to 3D Printing and Digital Fabrication: *Jason Weaver*[1]; [1]Brigham Young University

Hands-on experience with CAD modeling and digital fabrication, including 3D printing, is an excellent format for developing innovation and engineering skills. These tools are being increasingly offered in STEM curricula in K-12 education. In university engineering programs, it is even more essential that students have the opportunity to build these skills in both structured and unstructured learning formats. This paper examines various types of open-access student spaces for 3D printing, particularly those typically called "maker spaces," "fab labs," or "prototyping labs." Several implemented examples at universities are compared, and recommendations are made for developing a similar space at the author's university.

1:50 PM
Launching a Masters Degree on Metal Additive Manufacture: *Filomeno Martina*[1]; Didier Boisselier[2]; Eurico Assuncao[3]; David Wimpenny[4]; Moataz Attallah[5]; Vasily Ploshikhin[6]; Luisa Coutinho[7]; [1]Cranfield University; [2]IREPA lasers; [3]European Welding Federation; [4]MTC; [5]University of Birmingham; [6]University of Bremen; [7]Istituto Superior Tecnico

The ADMIRE project has one main goal: to address the death-valley among academic and industrial world, while at the same time responding to an urgent industrial need: the qualification of AM workforce. Together, four universities (Cranfield University, University of Birmingham, Bremen University and Istituto Superior Tecnico), end-users and students will design a Master degree course, entirely focussed on metal AM, according to level 7 of the European Qualification Framework, with a set of innovative features. These include a multidisciplinary scientific scope, a modular structure promoting hard and soft skills based on the Learning Outcomes described in Knowledge, Skills and Competences; it will also have learning approaches that are learner-centred, self-directed and work-based, enabling flexible learning paths, including problem-based ones.

2:10 PM

Skill-based Education of 3D Printing Technologies at DEI: Bringing Additive Manufacturing to the Classroom: *Rahul Sharma*[1]; [1]Dayalbagh Educational Institute

Additive Manufacturing (AM) education and skills are competitive edge for engineering graduates having potential to transform their careers. AM fabricators are 3D printers which allow the user to "print" a 3D object. Dayalbagh Educational Institute (DEI) has provided accessible 3DP resources for students by allowing them to "design their printers" and "print" their 3D object, learn to turn a pile of parts into an operable printer. DEI is focusing primarily to skill the youth by providing them 'hands-on' experience through values and quality as well as optimizing Bhartiya Swadeshi (Indigenous) content fulfilling local needs at low-cost and affordable by masses in India. Skill-based training of 3D printing technologies serves as a tool of transformation of budding young engineers and empowered entrepreneurs of the future. DEI is establishing a path for transition from laboratory-scale development to student innovation and entrepreneurship.

2:30 PM

Roadmap for Multi-Material Additive Manufacturing: *Amy Elliott*[1]; Lou Dadok[2]; Chris Menzel[2]; [1]Oak Ridge National Laboratory; [2]Fujifilm Dimatix

A promise of material-jet additive manufacturing (AM) is the ability to deposit multiple materials within a single part, giving printed artifacts advanced functionality not possible with traditional manufacturing. Applications for multi-material AM include smart structures, high-performance electronics, medical implants, aerospace parts, and engine components. However, the end result is limited by the resolution, material selection, and process complexity. This paper reviews the field of use for and current research in multi-material printing, as well as proposes a path forward for the deposition and solidification of dissimilar materials.

2:50 PM

Roadmap for Binder Jet Additive Manufacturing: *Amy Elliott*[1]; Peeyush Nandwana[1]; Jay Billings[1]; Tomonori Saito[1]; [1]Oak Ridge National Laboratory

Binder jetting is unique among additive manufacturing processes because of its high throughput due to batch-wise processing, compatibility of the shaping process with virtually any powdered material, and isotropic properties of the final densified artifacts. Because of these advantages, binder jetting has the potential for wide-spread adoption into high-volume manufacturing environments. Still, certain limitations in the current state of binder jet technology must be addressed for this adoption to take place. This work outlines the current condition of binder jet technology, the strategic objectives that will bring binder jetting into mass manufacturing, and the research that Oak Ridge National Lab will conduct toward these aims.

3:10 PM Break

3:40 PM

Roadmap for Metal Matrix Composite Development for Binder Jetting: *Amy Elliott*[1]; Cameron Shackleford[2]; Cindy Waters[2]; [1]Oak Ridge National Laboratory; [2]North Carolina A&T

Binder jetting works repeated;y spreading and binding layers of powder via inkjet deposition. To densify artifacts bound by binder jetting, the printed "skeleton" is sintered and then infiltrated with a secondary material via capillary infiltration, and the resulting material is a metal matrix composite (MMC). As with all AM processes, binder jetting must have a broad range of materials it can process before the technology can be fully adopted by the manufacturing industry. An opportunity exists to develop new metal matrix composites with desirable properties with binder jetting. However, there is no set of rules for selecting metal-metal or metal-ceramic pairs for capillary infiltration. This paper contains a review of the current state of materials formed by capillary infiltration and a roadmap for creating new MMC pairs. Further, some examples of MMC pairs created at Oak Ridge National Lab will be given, along with analysis of their properties.

4:00 PM

Selective Separation Shaping (SSS) – Large Scale Fabrication Potentials: Behrokh Khoshnevis[1]; *Xiang Gao*[1]; Brittany Barbara[1]; Hadis Nouri[1]; [1]University of Southern California

Selective Separating Shaping is a new additive manufacturing technique which is capable of processing polymeric, metallic, ceramic and composites including cementitious materials. In earlier experiments the capabilities of SSS in making metallic and ceramic parts have been demonstrated. The focus of the research reported in this paper has been on exploration of capabilities of SSS for creation of large-scale cementitious composite parts. A prototype machine has been used to create specimens made of regular construction cement (lime based), Sorel cement (magnesia based) and gypsum based composites. The fabrication results, surface quality and flexural strength for these experiments are presented.

4:20 PM

Smart Parts Fabrication using Powder Bed Fusion Additive Manufacturing Technologies: *Mohammad Shojib Hossain*[1]; Jose Gonzalez[1]; Ricardo Martinez Henandez[2]; Philip Morton[1]; Jorge Mireles[1]; Ahsan Choudhuri[2]; Yirong Lin[2]; Ryan Wicker[1]; [1]W.M. Keck Center for 3D Innovation; [2]The University of Texas at El Paso

Metallic components with embedded sensors or smart parts can be a beneficial tool for monitoring harsh environments in the energy, biomedical, automotive, and aerospace industries. Smart parts maintain structural integrity with added functionality of sensing temperature, pressure and structural health. A non-intrusive placement of a sensor in metallic components can be done using powder bed fusion additive manufacturing fabrication process. As a proof of concept, a cylindrical shaped smart part was fabricated individually using 2 powder bed fusion technologies, electron beam melting and selective laser melting. A paused build fabrication process was introduced for embedding sensor material. This paper focuses on the fabrication process and characterization of the smart part. The pressure and temperature sensing capabilities were tested using compressive cyclic loading and a hot plate respectively. A maximum sensing response of 3V was obtained for EBM fabricated smart part while applying compressive load.

4:40 PM

Design for Protection: Systematic Approach to Prevent Product Piracy during Product Development Using AM: *Ulrich Jahnke*[1]; Rainer Koch[2]; Anna Theresa Oppermann[2]; [1]Paderborn University / DMRC; [2]Paderborn University / C.I.K.

Although infringements of intellectual properties in terms of product piracy are growing for years and threaten investments in research and development most companies still rely on legal measures like property rights. A more preventive effect to protect against counterfeits can be achieved using technical measures complicating reverse engineering, improving traceability and assuring data protection. Additive Manufacturing can contribute a lot to the effectivity and efficiency of those technical measures but presently they are often unconsidered during product development. To support decision makers and designers through all the steps of a product development process an integrated systematic approach has been developed. Protective measures using AM are allocated to specific process steps and responsible persons in charge so that the result is a guideline for "design for protection". The main idea is to help developing piracy-robust products for that the return of investment is not threatened by counterfeits and its economical impacts.

Materials 1: Novel Polymers and Processing

Monday PM Room: 408
August 7, 2017 Location: Hilton Austin

Session Chair: Andreas Wegner, University of Duisburg-Essen

1:30 PM
Fabricating Zirconia Components with Organic Support Material by the Ceramic On-demand Extrusion Process: *Wenbin Li*[1]; Amir Ghazanfari[1]; Devin McMillen[1]; Ming Leu[1]; Gregory Hilmas[1]; [1]Missouri University of Science and Technology

Ceramic On-Demand Extrusion (CODE) is an extrusion-based additive manufacturing process recently developed for fabricating dense, functional ceramic components. This paper presents further development of this process and focuses on fabricating 3 mol% yttria-stabilized zirconia (YSZ) components that have overhangs which cannot be fabricated without using support structures. The YSZ paste is deposited through the main nozzle; polycaprolactone (PCL) pellet feedstock is melted and deposited through an auxiliary nozzle to build support structure. After a green part is printed and dried, the support structure is removed by increasing the part temperature to ~70 \176C to melt PCL. The green part is then sintered at 1550 \176C to achieve near theoretical density. The maximum angle of overhanging feature that can be fabricated without support was determined. Sample parts were fabricated and evaluated to demonstrate the effectiveness of the support material and CODE's capability of fabricating geometrically complex parts.

1:50 PM
The Application of Composite Through-thickness Assessment to Additively Manufactured Parts: *Isam Bitar*[1]; Nesma Aboulkhair[1]; Richard Leach[1]; [1]University of Nottingham

Through-thickness (Z-direction) tensile testing is a mechanical property assessment method that applies a tensile force to a test specimen whose tensile axis is perpendicular to the axis of reinforcement. Several studies have been conducted on through-thickness performance testing of carbon-fibre-reinforced polymer (CFRP) composites. However, to the author's knowledge, there is no current literature on through-thickness testing of additively manufactured (AM) composites. This study looks into the applicability of through-thickness assessment to AM CFRPs. The study utilised a Markforged Mark Two material extrusion printer to manufacture AM CFRP specimens. The matrix material of choice was nylon 12. Samples were printed exploring a range of reinforcement material content. In summary, this study presents an assessment of the applicability of through-thickness testing to AM CFRP specimens and provides an applicability assessment and a performance check on AM composite through-thickness properties.

2:10 PM
FDM with Natural Fibre Reinforced PLA: *Eleonora Ferraris*[1]; Frederik Vogeler[2]; Aart van Vuure[3]; Jan Ivens[3]; [1]KU Leuven; [2]KU Leuven Mechanical Engineering Technology TC; [3]KU Leuven Materials Technology TC

Fused deposition modelling (FDM) is a well-established technique in additive manufacturing for producing complex polymer components. Currently, FDM filaments are usually made out of pure thermoplastic materials. In this research, PLA is reinforced with short bamboo and flax fibres in order to increase the stiffness of the filament and final product. The fibres, polymer and plasticizer, were compounded and extruded as a filament. Fibres were characterized by measuring their length over diameter before and after compounding. Porosities were determined via computed tomography on both the filament and printed tensile bars, and the printing process was optimized focusing on nozzle temperature and printing speed. Also, tensile bars were printed and tested; an increased strength up to 100% and 73% could be achieved for bamboo and flax based composite products, respectively, thanks to the reinforcement of the fibres.

2:30 PM
Tensile Mechanical Properties of Polypropylene Composites Fabricated by Material Extrusion: Narumi Watanabe[1]; Meisha Shofner[1]; *David Rosen*[1]; [1]Georgia Institute of Technology

The filament deposition pattern in material extrusion results in voids and incomplete bonding between adjacent filaments, which leads to reduced mechanical properties. Further, the layer-by-layer deposition procedure typically results in mechanical property anisotropy, with better properties in the layer compared to across layers. The study reported in this paper explored various polypropylene composite formulations to accomplish several objectives: low residual stress and warpage, good mechanical properties, and reduced anisotropy. The reduction in anisotropy will be the focus of this paper as a function of thermal properties and process variable settings. A series of process simulation models was developed to explore ranges of thermal properties and process settings, which provided insights into tensile specimen behaviors. Results demonstrate that anisotropy can be reduced almost completely if the material can be formulated to have low crystallinity, low coefficient of thermal expansion, and moderate to high thermal conductivity (for a polymer).

2:50 PM
High-throughput Additive Manufacturing of Silicone Elastomers with Tunable Mechanical Properties: *Noah Holzman*[1]; [1]University of Minnesota

Large scale implementation of silicones in additive manufacturing has yet to be realized due to their diverse rheological properties and curing mechanisms. In this work, three silicone elastomers with different curing mechanisms are printed using a pneumatic liquid deposition printer. The silicones range from Shore 00-30 to A-80 hardness. Flow rates are determined for two nozzle geometries and three diameters (250-850 µm) using gravimetry and video analysis. At high flow rates, significant deviation from the linear trend between pressure and flow rate is observed due to non-Newtonian behavior. The effect of die swell is also considered. Freestanding, high aspect ratio (height/width >20) features are demonstrated at high speeds (=100 mm/s). Effects of acceleration and layer height are examined to enable high resolution layers while maintaining high flow rates. By combining printing and rheological experiments, a process map for development of liquid printing materials is established.

3:10 PM Break

3:40 PM
Adjustment of Part Properties for an Elastomeric Laser Sintering Material: *Andreas Wegner*[1]; Timur Ünlü[2]; [1]University of Duisburg-Essen; [2]ROWAK AG

Laser sintering of polymers gets more and more importance for small series production. In most cases parts are build up using polyamide 12. However, other materials are available for laser sintering, too. Elastomeric, rubber like materials are some of those alternative materials. These enable for the production of flexible parts like e.g. sealings, flexible tubes or shoe soles. They offer high part ductility and low hardness. At the chair for manufacturing technology one of these materials was developed and commercialized.Aim of the presented study was to analyze the properties of this new elastomeric laser sintering material. It was found, that Shore hardness can be modified by variation of parameter settings. Therefore the correlation between process parameters, energy input, Shore hardness and other part properties like mechanical properties were investigated. Basing on these results suitable parameter sets were established which enable for the production of parts with different Shore hardnesses.

4:00 PM

Mechanical Properties and color of TPE Parts as Function of Temperature History in Selective Laser Sintering Process: *Christina Kummert*[1]; Stefan Josupeit[1]; Hans-Joachim Schmid[1]; [1]University of Paderborn

The influence of laser sintering (SLS) parameters on PA12 part properties is well known, but research into other materials is rare. A more elastic alternative is the thermoplastic elastomer (TPE) PrimePart ST, which shows a different SLS processing behaviour. In former research a temperature measurement system was developed at the Particle Technology Group, part of the Direct Manufacturing Research Center at the University of Paderborn and is applied to TPE in the present work. The temperature history at different positions within the part cake is recorded during the whole build and cooling process. Position-dependent temperature histories are directly correlated with the color and mechanical properties of build parts. Further heat treatment of specimens in an oven confirms that discoloration of parts in different intensities has no influence on mechanical part properties.

4:20 PM

Process -- Structure -- Properties Relationships of a Novel Polypropylene Laser Sintering Material: *Rob Kleijnen*[1]; Manfred Schmid[1]; Konrad Wegener[2]; [1]inspire AG; [2]Swiss Federal Institute of Technology Zurich

One of the main contenders for becoming a viable addition to polyamide 12 as a laser sintering material is a novel polypropylene. This polypropylene powder exhibits a relatively broad particle size distribution and consists of almost perfectly spherical particles. This study focuses on the material's fundamental process-structure-properties relationships. The Successive Self-nucleation/Annealing (SSA) thermal characterization method is employed in addition to optical microscopy to clarify the distinct molecular architecture of the polymer that lends it the properties that make it suitable specifically for the laser sintering process. Such properties include a low crystallinity, a large sintering window, and the occurrence of cooling rate dependent crystalline phases. In addition, parts produced with varying energy densities and part bed temperatures are investigated to define the relations between observed microstructure, part porosity, and mechanical properties. Specific interest goes towards the causes behind the, for laser sintering unparalleled, elongation at break, which can exceed 200%.

4:40 PM

Filament Extension Atomization of Polymer Melts: A Novel Approach to Generating Powders for Selective Laser Sintering: *Jerome Unidad*[1]; Scott Solberg[1]; Arun Jose[1]; David Johnson[1]; [1]PARC, A Xerox Company

Leveraging on recent developments on PARC's Filament Extension Atomizer (FEA), we present a novel approach for generating micron-sized powders out of a wide range of thermoplastics, for use in selective laser sintering. PARC's FEA can generate aerosol out of highly viscoelastic fluids by exploiting elastocapillary thinning in the fluids as they undergo extensional flow in a roll-to-roll process. These polymer droplets are then cooled and harvested to generate nearly monodisperse powders. FEA can be easily integrated in a polymer processing line and can serve as an additional non-energy intensive unit operation for creating powders. Our approach should enable a wider application of SLS at the industrial scale by offering an alternative cost-effective way for generating powders for additive manufacturing.

Materials 2: Ceramics, Intermetallics, and Multi-materials

Monday PM	Room: 410
August 7, 2017	Location: Hilton Austin

Session Chair: Ramesh Subramanian, Siemens Energy

1:30 PM

Ceramic Additive Manufacturing: A Review of Current Status and Challenges: *Li Yang*[1]; Hadi Miyanaji[1]; [1]University of Louisville

In recent years, various additive manufacturing (AM) technologies that are capable of processing ceramic materials have been demonstrated. Among the ceramic AM systems that are based on various technologies including binder jetting, material jetting and vat photopolymerization, material availability and geometrical accuracy are rapidly improving, which allow for the direct fabrication of ceramic prototypes and structures with enhanced geometry freedom. On the other hand, most of the newly-developed ceramic AM processes rely on secondary processes to render mechanical to printed ceramic structures, which significantly offset many benefits provided by the freeform AM green ceramic part fabrication. There exist significant gap between the demonstrated capabilities by current system providers and the specific requirements of applications, which might be partially addressed via collaborations between industries and academia.

1:50 PM

Recapitulation on Laser Melting of Ceramics and Glass-ceramics: *Ming Xuan Gan*[1]; Chee How Wong[1]; [1]Nanyang Technological University

Additive manufacturing of ceramics and glass-ceramics is becoming important due to demands for high-performance applications and requirement for customisations. This is also due to the high cost incurred by conventional methods for producing prototypes and functional end parts of such inorganic materials. Despite the advantages that are already evident for direct laser melting of metals, in-process challenges such as thermal stress induced cracks and laser-material interactions have slowed down the progress and adoption of direct laser melting for these inorganic and non-metallic materials. Nevertheless, several works have been carried out to improve the process of direct laser melting of ceramics and glass ceramics despite the various challenges posed. In this article, we recapitulate past studies and update the progress on the additive manufacturing of ceramics and glass ceramics in particular by direct laser melting. In addition, we discuss the relevance of laser melting of ceramics and glass-ceramics for future roadmap.

2:10 PM

Powder Preparation for Indirect Selective Laser Sintering of Alumina: *Diptanshu*[1]; Wenchao Du[1]; Xiaorui Ren[1]; Chao Ma[1]; Zhijian Pei[1]; [1]Texas A&M University

Indirect selective laser sintering is an additive manufacturing process which produces intricate shapes out of ceramic materials. Alumina with particle of size 0.3 microns was used along with Polyamide 12 (PA 12) as the binder. Thermally induced phase separation was employed to form Polyamide/Alumina microspheres using high purity Dimethyl Sulfoxide (DMSO) as solvent. Powders containing various fractions of polyamide and alumina were produced using this method. The fraction of polyamide ranged from 20 vol. % to 60 vol. % and the associated fraction of alumina is 80 vol. % to 40 vol. %. The morphology of the particles was characterised using optical microscope and scanning electron microscope. The particles are of spherical shape. The average size was approximately 20 microns. Flowability of the particles was studied using ASTM B213-13 and was found to be satisfactory for selective laser sintering. The powders were sintered at 1600 °C, demonstrating good sinterability.

2:30 PM

A Modular Direct Write Additive Manufacturing Approach in the Printing of Multi-materials and Ceramics: *Judi Lavin*[1]; Lindsey Evans[1]; David Keicher[1]; William Reinholtz[1]; Seethambal Mani[1]; [1]Sandia National Laboratories

Additive manufacturing and direct write printing provides an opportunity to modify the current capabilities associated with traditional ceramic processing creating a more diverse and flexible technology. The flexibility available in the direct write process supports an agile assessment of materials, design and process feasibility. We have developed a modular printing platform comprised of five modules: Mycrojet, syringe-dispense, Sono-Tek aerosol spray, progressive cavity pump and extrusion dispense. Choice of module for a given print is dictated by material viscosity and desired feature size. Here a syringe dispense head is used to print parts for use as molds for capacitors. Work presented will detail the method to achieving a highly loaded polymer material with alumina and the direct write approach of printing parts. The curing and sintering of the green parts will be discussed, covering the issues associated with defects and burnoff rates in an effort to achieve defect free, viable parts.

2:50 PM
Additive Manufacturing of Flexible 3-3 Ferrorelectric Ceramic/Polymer Composite Based on Triply Periodic Cellular Micro-skeleton: *Xuan Song*[1]; Li He[1]; Wenhua Yang[2]; Zeyu Chen[3]; Lei Chen[2]; [1]University of Iowa; [2]Mississippi State University; [3]University of Southern California

3-3 ferrorelectric ceramic/polymer composites, i.e. three-dimensional (3D) interconnected piezocomposites with continuous piezoelectric ceramic skeleton, possess an excellent property combination of mechanical flexibility and piezoelectricity, compared with other materials including pure ceramics, 0-3, 1-3 and 2-2 piezocomposites. While piezoelectric performances of 3-3 piezocomposites are dependent on the meso-scale geometry of the active piezoelectric ceramic phase in the composite, current manufacturing processes are extremely limited in defining a desired meso-scale geometry in a 3-3 piezocomposite. In this research, we investigated the fabrication of 3-3 piezocomposites with predefined ceramic micro-skeletons utilizing a Suspension Enveloped Projection Stereolithography process (SEPS). Triply periodic cellular structures were used in the design of the active piezoelectric ceramic phase due to their larger elastic constants with respect to their rod-connected counterparts. Post processes including debinding, sintering, poling and polymer infiltration were presented. Mechanical and piezoelectric properties of final 3-3 piezo-composites were analyzed by experimental characterization and finite element modeling.

3:10 PM Break

3:40 PM
On the Effect of Building Direction on the Microstructure and Tensile Properties of SLM NiTi: *Amirhesam Amerinatanzi*[1]; Narges Shayesteh Moghaddam[1]; Ahmadreza Jahadakbar[1]; Hamdy Ibrahim[1]; Soheil Saedi[2]; Haluk Karaca[2]; Mohammad Elahinia[1]; [1]University of Toledo; [2]University of Kentucky

Selective laser melting (SLM) has increasingly gained attraction due to its capability to produce complex parts with high precision. One of the primary applications of AM is the production of metallic implants, including NiTi. Although the compressive behavior of AM NiTi is well understood, there has been a lack of study to cover the tensile behavior. This work is the first to study the tensile properties of SLM NiTi. First, several Ti-rich Ni50.09Ti samples were built in different directions, via a 3D Systems (Rock Hill, SC) selective laser melting PXM. The samples were subsequently tested under tensile loading using an MTS Landmark servo-hydraulic test instrument. Here, the relationships between the microstructure and shape memory properties are investigated thoroughly. It is shown that the building directions significantly affect the mechanical and microstructural behavior of SLM NiTi parts. The most favorable tensile properties are observed when the samples are fabricated horizontally.

4:00 PM
Microstructural Origins of Spatially Tailored Functional Response in NiTi SMAs: *Ji Ma*[1]; Brian Franco[1]; Kubra Karayagiz[1]; Luke Johnson[1]; Jun Liu[1]; Gustavo Tapia[1]; Alaa Elwany[1]; Raymundo Arroyave[1]; Ibrahim Karaman[1]; [1]Texas A&M University

Through Transmission Electron Microscopy (TEM) studies, we demonstrate micro- and nanoscale differences in the dislocation, second-phase, and subgrain structures caused by differences in the processing parameter during selective laser melting (SLM) of a nickel-titanium shape memory alloy. These controlled variations in microstructure can be harnessed to create location-dependent functional properties in the same part, such as solid-state actuators showing multiple shape recovery stages activated at different temperatures. However, the complex thermal history of the SLM process begets multi-scale microstructures that may be highly inhomogeneous even within a small spatial region, and creates unanticipated coupling between properties that one may which to control separately.

4:20 PM
Observing the Location Dependence of Microstructure in Selective Laser Melted NiTi: *Brian Franco*[1]; Gustavo Tapia[1]; Kubra Karayagiz[1]; Jun Liu[1]; Ji Ma[1]; Alaa Elwany[1]; Raymundo Arroyave[1]; Ibrahim Karaman[1]; [1]Texas A&M University

The thermomechanical behavior of NiTi prepared by selective laser melting differs significantly depending on the process parameters. It is well known that differences in microstructure (E.G. grain size, dislocation density, composition, precipitate structure) can cause differences in transformation and mechanical behavior. Using a variety of experimental methods, including wavelength dispersive spectroscopy, x-ray dispersive spectroscopy, scanning electron microscopy, and transmission electron microscopy, we observe how the microstructure varies depending on the sampled location relative to the melt pool. We also demonstrate how this variation is affected by changes in hatch distance.

4:40 PM
Selective Laser Melting of Bismuth Telluride and Half-Heusler Thermoelectric Materials: Haidong Zhang[1]; Shanyu Wang[2]; Ahmed El-Desouky[3]; Michael Carter[4]; Nicholas Batista[1]; Joseph Crandall[1]; Alaa Elwany[5]; Jihui Yang[2]; *Saniya LeBlanc*[1]; [1]The George Washington University; [2]University of Washington; [3]Carpenter Technology Corporation; [4]Columbia University; [5]Texas A&M University

The traditional thermoelectric device manufacturing method requires machining and assembly steps which are lengthy, waste material, and limit device geometries. In order to overcome these shortcomings, this work explored selective laser melting of thermoelectric materials. Selective laser melting was conducted on well-known thermoelectric materials such as bismuth telluride and half-Heusler materials. The processing was conducted with commercial and custom-built systems. The powder preparation and laser processing parameters were explored to construct bulk, three-dimensional parts. Chemical and physical properties were characterized. X-ray diffraction results for pre- and post-processed material demonstrate the phase changes (or lack thereof) for different material types, providing insight into which materials would need post-processing to regain the favorable phases. While microscopy and gravimetric analyses show the need for further process-property tuning, they indicate the potential for process-property-performance enhancements compared to the traditional manufacturing method. The results demonstrate the feasibility of selective laser melting for inorganic thermoelectric materials.

Physical Modeling 1: Design and Quality Control

Monday PM | Room: 415A-B
August 7, 2017 | Location: Hilton Austin

Session Chair: Ian Gibson, Deakin University

1:30 PM
From CAD Models to Parts: Software Development for the Wire+ Arc Additive Manufacture Process: Jialuo Ding[1]; Florent Michel[1]; *Filomeno Martina*[1]; Helen Lockett[2]; Stewart Williams[1]; [1]Cranfield University; [2]Open University

Wire + arc additive manufacture (WAAM) is developed for manufacture of multi-metre metallic structures. One of the major challenges of WAAM is developing software for automated building of parts. A design software will be introduced which can automatically transform the original CAD model into WAAM preform models based on the design rules. This software can also assist the decision of the build strategies with integrated cost estimation functions. A feature library has been developed which include all the basic WAAM features. All these features have been associated with experimentally proven build strategies to provide defect-free deposition. A virtual environment has been generated to simulate the movement of the machines and perform collision detection. A case study will be provided which demonstrates the process of manufacturing a real part from CAD model with the WAAM software. This will be followed by the further work and development plan of the software.

1:50 PM
Multi-Level Uncertainty Quantification in Additive Manufacturing: *Paromita Nath*[1]; Zhen Hu[1]; Sankaran Mahadevan[1]; [1]Vanderbilt University

Quantifying the uncertainty in additive manufacturing process plays an important role in the quality control of additively manufactured products. This work presents an uncertainty quantification framework to quantify the variability of macroscale material properties due to the variability in additive manufacturing process parameters and micro-scale material properties. A multi-scale multi-physics simulation model is developed first to simulate the additive manufacturing process. The melting pool profile obtained from macroscale finite element analysis is coupled with a microscale cellular automata model to predict the microstructure evolution during solidification. A homogenization method is then employed to predict the macroscale material properties based on the microstructure. Based on the simulation model, various sources of uncertainty are aggregated to quantify the variability of macroscale material properties using a Bayesian network. The contributions of various sources of uncertainty on the variability of macroscale material properties are analyzed using variance-based sensitivity analysis.

2:10 PM
Computed Axial Lithography (CAL) for Rapid Volumetric 3D Printing: *Brett Kelly*[1]; Indrasen Bhattacharya[1]; Maxim Shusteff[2]; Hayden Taylor[1]; Christopher Spadaccini[2]; [1]University of California, Berkeley; [2]Lawrence Livermore National Laboratory

Most Three-dimensional additive manufacturing processes today operate by printing voxels (3D quanta of material) serially point-by-point, layer-by-layer, to build up a 3D part. In some more recently developed techniques, for example optical printing methods based on projection stereolithography, parts are printed layer-by-layer by photocuring full 2D cross-sections of the 3d part in each print step. The method presented in this work looks toward printing of 3D geometries, of near arbitrary shape, in a single print step. This is done through a process similar to Computed Tomographic (CT) imaging, but in reverse. Three-dimensional parts are printed by sequential projection of 2D images toward a volume of photocurable resin from many angles about a central axis. In this work, we present the development of a computational algorithm to design the projections, construction of a novel volumetric 3D printing system, and 3D parts printed using this technique.

2:30 PM
Computation of Geometry Attributes of Components' 3D Model for Additive Manufacturing: *Min Zhou*[1]; [1]China Agricultural University

Additive manufacturing (AM) is a process to create objects layer-by-layer directly from a CAD model. In principle, any product even with complex structures can be created by AM technology successfully. However, restricted by equipment, material, prototyping process etc., some features with special geometry attributes may fail to be created. Therefore, it's necessary to analyze and compute the geometry attributes of a model and further simulating the printing process before manufacturing. A peeling method based on voxel model and constraint size is presented to calculate the geometries. First, the geometry features of components are classified into positive and negative features for AM. Then, the negative model is defined and identified based on voxel-based model. Furtherly, the peeling methods for the computation of positive feature and negative feature based on constraint size are developed. Finally, the error of this method is analyzed and the main advantages of the proposed method is discussed.

2:50 PM
Efficient Sampling for Design Optimization of an SLS Product: *Nancy Xu*[1]; Cem Tutum[1]; [1]University of Texas at Austin

In this work an efficient constrained-based sampling algorithm is implemented to optimize the process parameters for the polymer (powder form) based AM process. Two variations of the algorithm have been implemented and tested on a Farsoon HT251p machine using PA3300 polymer powder. The algorithm is based on building statistical predictive models of both objective (maximization of tensile strength) and constraint (avoiding of warping) functions in an iterative manner by simultaneously improving the quality of the predictive models as well as getting closer to the optimum set of process parameters. The difference in two algorithmic variations is the number of samples to update at each iteration. While the first method is based on a single sample update, the latter searches for multiple simultaneous updates to let the manufacturer try several potentially good sets of parameters in the same machine to eventually speed up the experimental evaluation procedure.

3:10 PM Break

3:40 PM
Review of AM Simulation Validation Techniques: *Aaron Flood*[1]; Frank Liou[1]; [1]Missouri University of Science and Technology

Due to the complexity of Additive Manufacturing (AM), it can require many trial runs to obtain processing parameters which produce a quality build. Because of this trial and error process, the drive for simulations of AM as grown greatly. These simulations only become useful to researchers if it can be shown that they are a true representations of the physical process to be simulated. These simulations all have different methods of validation to show that they are accurate representations of the process. This paper explores the various methodologies for validation of AM simulations, focusing mainly on the modeling of the thermal processes and final part shape. It will identify and explain the various validation techniques, specifically looking at the the accuracy and the frequency of reported use of each technique.

4:00 PM
Analytical and Experimental Characterization of Anisotropic Mechanical Behaviour of Infill Building Strategies for Fused Deposition Modelling Objects: *Marlon Cunico*[1]; Jennifer Cavalheiro[2]; [1]University of São Paulo; [2]University Federal of Parana

As consequence of the 3d printing extraordinary rising along the last years, product development fields are facing new challenges. In addition, it is notory that low cost additive manufacturing, as such fused filament fabrication (FFF), result in objects with anisotropic mechanical behaviour. Nevertheless, there is still lacking studies that highlight a proper specification of those mechanical proprieties. For that reason, the main goal of this work is to present a mechanical characterization of anisotropic behaviour of FFF objects as a function of infill strategy using a finite element method. In this work, the main effect of building parameters were investigated in addition the identification of generalized elasticity and failure mode formulations. By the end, the general reccomendation for objects building was sketched in order to support new strength based developments.

4:20 PM
Flexural Behavior of FDM Parts: Experimental, Analytical and Numerical Study: *Madhukar Somireddy*[1]; Diego de Moraes[1]; Aleksander Czekanski[1]; [1]York University

Fused deposition modelling (FDM) processed parts behave as composite laminate structures. Therefore, mechanics of composite laminates can be adopted for the characterization of mechanical behavior of the printed parts. In this study, the flexural properties of the 3D printed laminates are investigated experimentally, analytically and numerically. Each layer of the printed specimens is treated as an orthotropic material. The elastic moduli of a lamina are calculated by considering the mesostructure of the printed laminate in finite element simulation of tensile testing. These elastic moduli are employed in a constitutive matrix for the calculation of flexural stiffness of the laminate using classical laminate theory. Then 3-point bending tests are conducted on the printed laminates to calculate their flexural stiffness. The influence of road/ fiber size and lamina layup on the flexural properties are also investigated. Furthermore, failure phenomena of printed laminates under bending loads is investigated.

4:40 PM
High-throughput Printing of Conductive Polymer Nanocomposites via Joule Preheating of the Filament: *Adam Stevens*[1]; Jamison Go[2]; A. Hart[1]; [1]Massachusetts Institute of Technology; [2]MIT

Physical Modeling 2: Novel Simulation Approaches

Monday PM Room: 416A-B
August 7, 2017 Location: Hilton Austin

Session Chair: Wayne King, Lawrence Livermore National Laboratory

1:30 PM
Numerical Study of Keyhole Formation in Selective Laser Melting of Ti6Al4V: *Wenjun Ge*[1]; [1]KAIST

This study demonstrates the significant effect of process parameters on the penetration depth. The molten pool can be divided into two types: keyhole mode and thermal conduction mode. A three-dimensional laser selective model of transition from thermal conduction mode to keyhole mode is proposed. The inclusion of laser ray tracing energy deposition in the powder-scale model improves over traditional volumetric energy deposition. The effect of beam power, scan speed and linear energy on the molten pool penetration has been investigated. It shows that the linear energy plays a crucial role in the keyhole mode formation.For the same laser power, the keyhole depth is increased as the scan speed decreased. In this study, the experimental observation of keyhole in selective laser melting of Ti6Al4V is presented. In addition, the fluid flow pattern of conduction mode and keyhole mode is presented.

1:50 PM
Thermomechanical Analysis of Direct Metal Laser Melting via Line Heat Source Model: *Qian Chen*[1]; Xuan Liang[1]; Jason Oskin[1]; Lin Cheng[1]; Qingcheng Yang[1]; Albert To[1]; [1]University of Pittsburgh

Fast and accurate prediction of thermal history and distortion in laser powder bed fusion process is important to part quality and process parameter optimization. However, the small laser spot size and thin layer thickness significantly limit the process simulation speed. In this work, process simulation based on line heat source model is proposed to simulate the thermomechanical history for different scanning strategies in the direct metal laser melting process. By comparison, the line heat input model needs only 0.5% of the load steps needed for the conventional double ellipsoid or Gaussian heat source model. Due to the micrometer-sized layer thickness, it is time consuming to perform mechanical analysis for the entire build process. A distortion and residual stress prediction method is also proposed based on the one layer simulation result. Distortion simulation result and experimental measurement for a single wall are performed to demonstrate the accuracy of the proposed method.

2:10 PM
Simulation of Spot Melting Scan Strategy to Predict Columnar to Equiaxed Transition in Metal Additive Manufacturing: *Yousub Lee*[1]; Mike Kirka[1]; Naren Raghavan[2]; Ryan Dehoff[1]; [1]Oak Ridge National Laboratory; [2]University of Tennessee, Knoxville

Recently, additive manufacturing (AM) process transits from rapid prototyping to mass production as the process becomes more reliable and production cost drops rapidly. This trend triggers the process optimization in various applications. In prior literature, high fidelity numerical models have been presented to understand the solidification conditions during the process which includes heat transfer, fluid flow and beam interaction with raw material. However, most of these models are simulating few melt passes and it is computationally expensive to simulate an entire layer of the component being fabricated. In this study, we use a lower fidelity model to simulate an entire layer. We also introduce a new melt strategy to control the solidification microstructure. The response of the solidification morphology to process parameters (ex. point offset, power, spot on-time) are investigated in terms of thermal gradient G and solidification rate R. Appropriate experimental validation has been carried out through sample characterization.

2:30 PM
Numerical Simulation of Temperature Fields in Powder Bed Fusion Process by using Hybrid Heat Source Model: *Zhibo Luo*[1]; Yaoyao Fiona Zhao[1]; [1]McGill University

The performance of Powder bed fusion (PBF) processed part is mainly controlled by many process parameters. Numerical methods have been widely adopted to investigate the effects of these process parameters on temperature fields and thermal stress fields. The study of the history of temperature distribution is the basic and crucial step in the modeling of PBF process. Usually, moving Gaussian point heat source has been applied to model the temperature distribution. However, a small enough time step size is required to accurately model the real heat input, which will lead to significant computational burden. In this research, a hybrid of Gaussian point and line heat source model is developed, which makes the modeling of PBF process efficient without losing too much accuracy. In addition, an adaptive mesh scheme, which can refine and coarsen the mesh adaptively, is adopted to accelerate the simulation process.

2:50 PM
A Proposed Framework for Material Jetting Process Modeling: Critical Issues and Research Directions: *Chad Hume*[1]; David Rosen[1]; [1]Georgia Institute of Technology

Material jetting-based additive manufacturing is a promising manufacturing approach with the advantages of high resolution, speed, material flexibility, and scalability. Presently, characterization and optimization of the material jetting process requires extensive experimental study due to the limited availability of process modeling. This slows the development progress and inhibits new applications that push the limits of what is geometrically feasible. In this work, a framework for material jetting process modeling is proposed. Critical issues and research directions are outlined with particular focus on how to move from high fidelity droplet-scale modeling to global process prediction in a computationally efficient manner. By bridging the gap between physics based droplet models and part level planning, the feasibility of new designs can be more easily explored and improved process plans and structure-process relationships developed.

3:10 PM Break

3:40 PM
Numerical Modeling of High Resolution Electrohydrodynamic Jet Printing using OpenFOAM: *Maxwell Wu*[1]; Patrick Sammons[1]; Kira Barton[1]; [1]University of Michigan

Electrohydrodynamic jet (e-jet) printing is a micro-/nano-scale additive manufacturing (AM) method that has emerged in recent years as a process to rival similar technologies such as inkjet printing. By utilizing electrostatic forces to induce fluid flow, e-jet has shown the ability to fabricate high resolution features with a wide variety of materials. Because it is a relatively new AM process, the printing behavior of many different types of inks are not completely understood, as existing knowledge of the process relies almost entirely on empirical methods which can be time intensive and difficult to implement for materials that are hazardous or not readily available. This paper discusses procedures for modeling both the electric and fluid dynamics of the e-jet printing process within OpenFOAM, an open-source CFD solver. Further discussion has been provided to show simulations of the process at typical e-jet printing scales and to present existing limitations of the model.

4:00 PM

A Normalized Dispensing Modeling Method for Feature Prediction in Direct Ink Writing Process: *Yizhou Jiang*[1]; Yayue Pan[1]; [1]University of Illinois at Chicago

A dispensing modeling method for feature prediction in direct ink writing processes is presented in this paper. A normalized modeling procedure is developed for both Newtonian and non-Newtonian inks. Viscosity under various shear rate is measured for non-Newtonian inks, and the power law model fitting parameters are characterized accordingly. The cross-section geometries of directly written traces are modelled and measured. Direct ink writing processes with varied tip sizes are investigated. The developed feature prediction model has been tested and verified for direct writing processes with varied inks, and direct write tip sizes. Experimental results show that the developed model is effective and very efficient in predicting the trace geometry in direct writing processes, regardless of inks or tips. In addition, it is found that the speed ratio plays a significant role in unifying dispensing process. Further, a process planning strategy is developed to improve direct writing efficiency and accuracy.

4:20 PM

Computational Simulation of Additively Manufactured Marine Structures: *Charles Fisher*[1]; Caroline Scheck[1]; [1]Naval Surface Warfare Center

The present study is part of an integrated computational materials engineering (ICME) thrust to expand the use of computational simulations for additive manufacturing (AM) components. Previously, finite element analysis (FEA) of AM components was not able to include distortion and residual stress of the entire AM build process, yielding uncertainty in the computational models. To address this, recently developed computational tools are under a validation investigation for laser powder-bed fusion (L-PBF) builds. The on-going investigation includes physical validation of various AM parts to understand how modification of the process can improve build efficiency and reduce instances of failed builds. Additionally, the thermal modeling of the build process will likely influence the developed microstructure, thereby giving insight into how to modify build processes in order to obtain designed alloys. The project goal is to validate the computational tools to determine best practices for insertion of computational AM simulation into fabrication.

Process Development 1: Laser Processing and Monitoring 1

Monday PM — Room: 417A-B
August 7, 2017 — Location: Hilton Austin

Session Chair: Igor Yadroitsev, Central University of Technology, Free State

1:30 PM

In Process Monitoring in Metal Powder Bed Fusion Processes using Optical Coherence Tomography: *Philip DePond*[1]; Gabe Guss[1]; Sonny Ly[1]; David Deane[1]; Manyalibo Matthews[1]; [1]Lawrence Livermore National Lab

Although extremely informative and prevalent, post-build non-destructive evaluation techniques can be costly, slow, and limited in terms of accessible range into large parts. Advances in process monitoring in additive manufacturing has allowed for the investigation of morphological inconsistencies for the purpose of identification and remediation of micro and macroscopic defects during the layer to layer powder bed fusion process. In-line optical diagnostics provide the extended advantage of tracing the tool paths non-invasively during the melting process (operando) or between layers (in-situ). Compared with other techniques, optical coherence tomography (OCT), an interferometric technique, enables long working distance and with micrometer scale resolution of surface structure in metals. With the goal of interrogating deformations and defects in additively manufactured metals, we show how fast sampling 100kHz OCT, coupled with feed-forward algorithms can improve overall part quality (morphology, density, geometry, etc.) We also discuss recent work in analyzing meltpool dynamics with operando OCT.

1:50 PM

Characterizing the Dynamics of Laser Powder Bed Fusion Additive Manufacturing Processes by High-speed High-energy X-ray Imaging and Diffraction: Qilin Guo[1]; Luis Izet Escano[1]; Lianghua Xiong[1]; Cang Zhao[2]; Wes Everhart[3]; Tao Sun[2]; *Lianyi Chen*[1]; [1]Missouri University of Science and Technology; [2]Argonne National Laboratory; [3]Department of Energy's National Security Campus Managed by Honeywell FM&T

Laser powder bed fusion (LPBF) is a major additive manufacturing technique for producing complex-shaped metal parts by selective melting successive layers of metal powders using a laser beam. Understanding the physics of LPBF processes is critical for establishing location-specific processing-microstructure-property relationships in LPBF of metals. The non-transparency of metals to visible light and the highly localized (tens of micrometers) and very short (tens of microseconds) interaction of a laser beam with metal powders during LPBF pose a huge challenge to the characterization and understanding of this process. The detailed physics of the LPBF process and the mechanisms of defect formation and microstructure evolution are still not clear. In this talk, I will give an overview of our ongoing research on characterizing the dynamics of LPBF additive manufacturing processes by high-energy high-speed x-ray imaging and diffraction. The physics governing powder moving, spattering, and melt pool evolution will be discussed.

2:10 PM

Melt Pool Study in Selective Laser Melting: *Bo Cheng*[1]; James Lydon[2]; Kenneth Cooper[2]; Vernon Cole[3]; Paul Northrop[3]; Kevin Chou[1]; [1]University of Louisville; [2]Marshall Space Flight Center; [3]CFD Research Corporation

Process temperature measurement for selective laser melting (SLM) can provide critical information such as melt pool dimension for real-time part quality control. In this study, a MCS640 LumaSense thermal imager was utilized to collect process radiant temperature information during SLM fabrication using Inconel718 powder. Identified liquidus-solidus transition was used to calculate melt pool size. Speed effect on melt pool dimension has been investigated. The major findings are as follows. (1) At a beam power of 180 W, the typical melt pool has dimensions of about 0.49 mm and 0.21 mm in length and width for 400 mm/s scanning speed. (2) Droplet ejection from melt pool may affect the melt pool dimension. (3) No significant difference has been observed for melt pool size at different build height for a given scanning speed.

2:30 PM

Preliminary Investigation of Pulsed Thermography for Online Process Monitoring in Additive Manufacturing: *James Pierce*[1]; Nathan Crane[1]; [1]University of South Florida

Defect detection and quantification within a structure is a vital component in the field of manufacturing, especially online process detection. This paper will discuss the use of a Nondestructive evaluation (NDE) method known as Pulsed Thermography (PT) to detect defects and quantitatively measure their depths within a 3D printed part made from a thermoplastic, ABS. The material properties of thermoplastics allow for a low cost PT system capable of distinguishing surface characteristics of 3D printed parts and detect defects within the part. Due to the short amount of time required by the PT method there are possibilities for integrating the quality system with the 3D printing system to permit layer by layer inspection. Integration will allow for online process monitoring of subsurface layers therefore adding to the input parameters monitoring ultimately minimizing the possibility of defects within a final structure and improving the quality and reliability of printed parts.

2:50 PM

In-process Condition Monitoring in Laser Powder Bed Fusion (LPBF): *Mohammad Montazeri*[1]; Brandon Lane[2]; Jarred Heigel[2]; Prahalada Rao[1]; [1]University of Nebraska-Lincoln; [2]NIST

The goal of this work is to monitor the laser powder bed fusion (LPBF) additive manufacturing (AM) process using heterogeneous sensors. The ultimate aim is to usher a certify-as-you-build quality assurance paradigm in LPBF whereby process faults are detected through analysis of data from in-process sensors; and preventive action is subsequently taken to avert propagation of part defects. In pursuit of this goal, a commercial LPBF machine (EOS M280) at the National Institute of Standards and Technology (NIST) was integrated with three sensors, namely, a photodetector, high speed video camera, and a MWIR thermal camera with the following two-fold objectives: (1) to develop and apply a sensor-based modeling approach that invokes spectral graph theoretic Laplacian eigenvectors for monitoring LPBF process conditions; and (2) to compare the results from the three different sensors in terms of their fidelity in distinguishing between different LPBF process conditions.

3:10 PM Break

3:40 PM

Linking Process Parameters to Part Defects through In-Process Sensor Signatures in Laser Powder Bed Fusion (LPBF).: *Mohammad Montazeri*[1]; Emily Curtis[1]; Aniruddha Gaikwad[1]; Prahalada Rao[1]; Hui Yang[2]; Ted Reutzel[2]; [1]University of Nebraska-Lincoln; [2]Penn State University

The goal of this work is to detect incipient part defects, such as porosity in Laser Powder Bed Fusion (LPBF) using in-process sensors. In pursuit of this goal, the objectives of the work are two-fold: (1) understand and quantify the link between process parameters (hatch spacing, scan velocity, and laser power) on part defects through analysis of CT scan data. (2) Detect the location, size, and frequency of part defects as a function of signatures extracted from in-process images of the powder bed. This work reports experimental studies conducted on a commercial-grade LPBF machine. Statistical analysis of part CT scan images revealed that the size, frequency, and locations of defects is contingent on the scan velocity, hatch spacing, and laser power process parameters. Laser power is deemed to have the most statistically significant effect; low laser power (250 Watts) leads to an inordinate increase in defect characteristics.

4:00 PM

Effect of a Mid-build Halt on the Microstructure and Porosity in Powder Bed Fusion Stainless Steel Parts: *Clara Hofmeister*[1]; Andelle Kudzal[1]; Joshua Taggart-Scarff[1]; Ryan Rogers[2]; Jennifer Sietins[3]; Brandon McWilliams[3]; [1]Oak Ridge Institute for Science and Education; [2]Dynamic Science Inc; [3]US Army Research Laboratory

Interruption of builds during powder bed fusion (PBF) can occur if part or power failure occurs. An interruption of the build cycle can create a highly porous plane visible from the outside surface of the part known as a witness line. Witness lines are deleterious to the mechanical properties of the part, but may be avoided if the hold time in production is short. In this study, the PBF of 17-4 stainless steel powder was intentionally halted mid-build for hold times ranging from 5 min to 12 hours and then allowed to continue. Microscopy and x-ray microcomputed tomography were conducted to determine the effect of hold time on the microstructure of the newly created heat affected zone as well as the size and morphology of the porosity in each witness line. The formation of witness lines and its effect on the quality of manufactured parts will be discussed.

4:20 PM

Performance Characterization of Process Monitoring Sensors on the NIST Additive Manufacturing Metrology Testbed: *Brandon Lane*[1]; Steven Grantham[1]; Ho Yeung[1]; Clarence Zarobila[1]; Jason Fox[1]; [1]National Institute of Standards and Technology

Researchers and equipment manufacturers are developing in-situ process monitoring techniques with the goal of qualifying AM parts during a build thereby accelerating the certification process. Two primary in-situ process monitoring methods are implemented on laser powder bed fusion (LPBF) machines: layer-wise monitoring, and co-axial melt pool monitoring. Both monitoring systems are implemented on the Additive Manufacturing Metrology Testbed (AMMT) at NIST; a multi-use custom LPBF research platform where one of many research goals is to advance measurement science of AM process monitoring. This paper presents the methods used to calibrate and characterize the layer-wise and melt pool monitoring instrumentation on the AMMT. Temporal and spatial resolution measurements are demonstrated and compared. These results are analyzed in terms of their ability to measure key LPBF layer and melt pool signatures taken during a multi-layer AM build.

4:40 PM

Laser Sintering of Polyetherethrerketone with Low-temperature Process: *Fumio Ito*[1]; Toshiki Niino[2]; [1]Aspect inc.; [2]Institute of Industrial Science, the University of Tokyo

Low temperature process is a laser sintering/melting process that prevent part warpage not by preheating at a high temperature but by anchoring parts to a rigid base plate. Previously, the authors reported that using this process to fabricate high performance plastic parts causes violent phenomena such as sparkling and fuming. They also tested tophat profiled laser in the low temperature process of polyphenylenesulfide (PPS), while most of commercial systems employ Gaussian beam. As result, the problems were successfully reduced and high tensile strength and good surface smoothness were obtained.The present research investigates advantage of using tophat profiled laser in low temperature process of polyetheretherketone (PEEK), which has much higher melting point than PPS. Both of Gaussian and tophat profiled beams are tested to compare them in terms of ease of suppressing sparkling and fuming, mechanical strength and precision.

Process Development 2: Photopolymers and Novel Processes

Monday PM — Room: 404
August 7, 2017 — Location: Hilton Austin

Session Chair: Joe Bennett, NIST

1:30 PM

Microheater Array Powder Sintering: A Novel Additive Manufacturing Process: *Nicholas Holt*[1]; Austin VanHorn[1]; Mahsa Montazeri[1]; Wenchao Zhou[1]; [1]University of Arkansas

One of the most versatile additive manufacturing processes is selective laser sintering. However, it suffers from slow printing speed and high energy consumption. In this paper, we propose a novel method of additive manufacturing which replaces the laser beam with an array of microheaters as an energy source. This method, referred to as Microheater Array Powder Sintering (MAPS), has the potential to increase the printing speed by layer-wise sintering and reduce the power consumption. This paper provides a proof-of-concept for this method. First, a thin-film microheater is designed and simulated with an experimentally validated numerical model to demonstrate that it can be used as an alternative energy source. Simulation results show that heat can be effectively transferred over an air gap to raise the temperature of the powder particles to their sintering temperature. Different process parameters are discussed. An experimental MAPS system is implemented to provide a proof-of-concept.

1:50 PM

Process Modeling and In-situ Monitoring of Photopolymerization for Exposure Controlled Projection Lithography (ECPL): *Jenny Wang*[1]; Changxuan Zhao[1]; Ying Zhang[1]; Amit Jariwala[1]; David Rosen[1]; [1]Georgia Institute of Technology

Exposure controlled projection lithography (ECPL) is an additive manufacturing process in which photopolymer resin is used to fabricate three-dimensional features. During this process, UV curing radiation, controlled by a dynamic mask, is projected through a transparent substrate onto the resin. COMSOL software has been used to model the photopolymerization reaction kinetics, predicting the cured part geometry based on certain process parameters. Additionally, an Interferometric Curing Monitoring (ICM) system has been implemented to acquire real-time information about the optical properties of the cured part. Potential sources of error with the real-time monitoring system were investigated. Additionally, refractive index and degree of conversion changes were modeled throughout the reaction. Measured and simulated results were compared to understand the ICM signal with the reaction kinetics. These comparisons were used to validate the simulation model and identify system level errors that must be reconciled to improve the accuracy and precision of the ECPL process.

2:10 PM
Design and Fabrication of an Experimental Microheater Array Powder Sintering Printer: *Nicholas Holt*[1]; Steven Brown[1]; Wenchao Zhou[1]; [1]University of Arkansas

Microheater Array Powder Sintering (MAPS) is a novel additive manufacturing process which uses an array of microheaters to sinter powder particles. For MAPS to be successful, a micron scale air gap must be maintained between the heater array and the sintering material. In this paper, we present an experimental MAPS printer with airgap control for printing conductive circuits. First, we discuss design aspects necessary to implement MAPS including an overview of heater design and control, air gap, dwell time and conducting medium. We design a printhead with a scraper which spreads powder particles uniformly over a substrate and maintains an airgap between the microheaters and powder layer. Next, an XY stage is designed to allow a substrate to move underneath the printhead. Finally, the printer is built and a silver nanoparticle ink is used for testing: lines of silver nanoparticles are sintered on a film of PET plastic.

2:30 PM
Highly Removable Water Support for Stereolithography: *Jie Jin*[1]; Yong Chen[1]; [1]University of Southern California

Current stereolithography (SL) technology requires additional support structures in order to ensure a model can be fabricated. However, the support structures may be difficult to remove, and the removal of the supports may cause damage to delicate features with undesired surface marks. We developed a novel SL process using highly removable and widely available water as support. The process uses solid ice to surround the built parts in the layer-by-layer fabrication process. A cooling device is used to freeze water into ice for each layer. The photocurable resin is spread on ice surface and then solidified by projection images. Accordingly, a complex 3D object can be fabricated without using traditional support structures. After the fabrication process, the additional ice structure can easily be removed leaving no marks on the bottom surfaces. Two test cases are presented to show the effectiveness of the presented water support method.

2:50 PM
Acoustic Field-assisted Particle Patterning for Smart Polymer Composite Fabrication in Stereolithography: *Lu Lu*[1]; Yayue Pan[1]; Shan Hu[2]; [1]University of Illinois at Chicago; [2]Iowa State University

By combining various materials that serve mechanical, electrical, chemical, and/or thermal, functions with controlled local distributions, smart devices and machines with multiple functionalities can be fabricated. This paper reports a new approach for particle patterning during additive manufacturing, for the fabrication of multi-functional smart composite devices with complicated 3D structures. An acoustic field is integrated into the projection based stereolithography system to pattern different nanoparticles into dense parallel curves or networks in liquid resin. Mask image planning strategy is developed for curing particles in polymer matrix and various material processing techniques are adopted to improve the interfacial bonding. Effects of acoustic field settings and manufacturing process parameters on patterning and interfacial bonding strengths are modeled and experimentally characterized. Various particle patterning results are presented. A projection based stereolithography prototype testbed integrated with acoustophoresis has been developed. The feasibility of the proposed approach for multi-functional particle-polymer composite fabrication has been verified.

3:10 PM Break

3:40 PM
Effect of Constrained Surface Texturing on Separation Force in Projection Stereolithography: *Haiyang He*[1]; Yayue Pan[1]; Jie Xu[1]; Xiaoming Yu[2]; [1]University of Illinois at Chicago; [2]University of Central Florida

In projection stereolithography (SL) processes, the separation of a newly cured layer from the constrained surface is a historical technical barrier that greatly limits printable size, process reliability and print speed. This paper presents an approach to reduce the separation force in projection stereolithography (SL) processes by texturing the constrained surface with radial microgroove patterns. It is found that a proper design of micro patterns of the constrained surface can reduce separation forces greatly. Test cases also show that with the textured constrained surface, parts with wide solid cross sections that could not be printed using conventional methods can be manufactured successfully. In addition, a grey scale projection approach is proposed to eliminate the influence of surface texture on the surface finish of printed parts. The study shows that the presented methods are effective in reducing the separation force and hence enabling prints of objects with wide solid cross sections.

4:00 PM
Fabrication and Control of a Microheater Array for Microheater Array Powder Sintering: *Nicholas Holt*[1]; Lucas Marques[1]; Austin VanHorn[1]; Mahsa Montazeri[1]; Wenchao Zhou[1]; [1]University of Arkansas

Microheater Array Powder Sintering (MAPS) is a novel additive manufacturing process that uses a microheater array to replace the laser of selective laser sintering as the energy source. Most of the previous research on microheaters are for applications in gas sensing or inkjet printing. The operation temperature and response time of the microheater array are critical for the choice of sintering materials and printing speed for the MAPS process. In this paper, we present the fabrication, packaging, and control of a platinum microheater array that has a target operation temperature of 400°C and a response time of ~1 millisecond. First, we will present the fabrication process of a microheater array. The fabricated microheater array is then packaged for easy control and to serve as the printhead of the SRS process. A PID controller is designed to control the temperature response of the microheater. Finally, the effectiveness of the controller is evaluated.

4:20 PM
Projection-based Stereolithography Using a Sliding Window Screen for Simultaneous Photopolymerization and Resin Refilling: *Huachao Mao*[1]; Yong Chen[1]; [1]University of Southern California

Material refilling is a critical issue in Stereolithography (SL), including both laser-based SL and projection-based SL. The fabrication speed is largely slowed down by the extra time that is required for refilling liquid resin. Although several methods have been developed to reduce this extra refilling time, they are effective for shapes that have small building areas. The building speed will be significantly reduced when the shape has large cross-section areas since the liquid refilling for them is much more challenging. This paper introduces a novel SL process that can fabricate solid three-dimensional objects with any shapes and size in minutes. We incorporate a sliding window screen in the projection-based Stereolithography process, which can enable simultaneous photopolymerization and resin refilling. This innovative process can maintain the high fabrication speed, without the limitation of large cross-section area size.

4:40 PM
Modeling of Low One-photon Polymerization for 3D printing of UV-curable Silicones: *Dong Sung Danny Kim*[1]; Jakkrit Suriboot[1]; Melissa Grunlan[1]; Bruce Tai[1]; [1]Texas A&M University

Low-one photon polymerization (LOPP) enables an in-liquid curing to suspend a soft silicone object in the vat without mechanical disturbance. To further control the process for 3D printing, this research characterizes and models the LOPP behaviors of a custom-made UV-curable silicone system based on the Beer-Lambert law. LOPP requires a low-absorbance wavelength and great gradient light beam to achieve desired curing at the focusing spot; therefore, a methyl acrylate-based silicone was specifically formulated to pair with a 375 nm UV light and high numerical aperture lens in this work. The polymerization model for this silicone system was established using the critical exposure and penetration depth determined by a modified “windowpane” test. The comparison results between the model and a series of LOPP tests showed consistent trends. This model can be used to optimize the optical setup as well as silicone composition for the ideal LOPP-based 3D printing.

Special Session: AM for Defense

Monday PM Room: 406
August 7, 2017 Location: Hilton Austin

Session Chair: Jennifer Wolk, Naval Surface Warfare Center

1:30 PM Invited
Naval Additive Manufacturing S&T: *Jennifer Wolk*[1]; [1]Office of Naval Research

Additive manufacturing (AM) represents a unique intersection of design, materials, processing and properties. Microstructure and properties are inextricably linked to the part design and processing and AM is ill-suited for conventional qualification techniques. In order to change the paradigm of qualification for additive manufactured components, the Office of Naval Research is pursuing integrated computational materials engineering coupled with in-situ sensors and controls for production of metallic parts. This talk will highlight current efforts in AM research in materials and processes to meet current and emerging warfighter needs to deliver future force capabilities.

1:50 PM Invited
A Micro-Tailoring Technique to Alter the Spatial Distribution and Orientation of Particles in a Stereolithography Fabricated Composite Part and Quantification of Alignment in the Part: *Larry Holmes*[1]; Eric McDonald[2]; David Roberson; [1]US Army Research Laboratory; [2]Youngstown State University

The mechanical properties and dimensional stability of polymer composites are dictated by the orientation and distribution of filler materials within the composite. Spatial distribution and orientation are strongly dependent on the fabrication method used to create the structure, and it is strongly desirable for filler orientation, developed during manufacturing, to be controlled. Here, we describe a novel Additive Manufacturing (AM) technology and fundamental understanding that enables the control and fabrication of micro-composites with tailored and predictable filler configuration. An electric-field assisted Stereolithography Apparatus (SLA) is shown to align and orient fillers into chain-like structures that are immediately frozen into place by incident ultra-violet radiation on the polymer matrix directly after electric field alignment. Alignment and orientation are quantified using machine vision to calculate the angle of rotation of large aspect ratio filler particles. Implications of controlling alignment of filler particles include mitigating the inherently anisotropic mechanical performance of additively manufactured structures.

2:10 PM Invited
Thermal Modelling of Large Scale Polymer Additive Manufacturing: *Sam Pratt*[1]; Nathan Desloover[1]; Bryan Kessel[1]; Yared Amanuel[1]; [1]Naval Surface Warfare Center Carderock Division

The Fused Filament Fabrication process for Additive Manufacturing builds components by depositing extruded layers of thermoplastic material from a digital model. The phase change that occurs as these materials are heated and cooled introduces residual stresses that can exceed the interlayer bond strength of the material, resulting in part deformation and interface delamination. As the applications and technologies for large-scale component fabrication (build volumes exceeding 8’X20’X6’) advance, reinforced feedstock materials are being investigated as a way to minimize the effect of the residual stresses but predicting and mitigating these effects through processing parameter optimization is a challenge to consistent end-use part fabrication. This work is using in-situ thermal imaging of large-scale, thick-walled specimens to develop 3-D computational models that can predict, and measure, interlayer temperature evolution to predict material properties. This information can then be used to inform optimal toolpath design and processing parameters specific to the individual part geometry.

2:30 PM Invited
Material Informed Digital Design Demonstration for Additive Structures: Michael Groeber[1]; *Edwin Schwalbach*[1]; Michael Uchic[1]; Paul Shade[1]; William Musinski[1]; Sean Donegan[1]; Daniel Sparkman[1]; Jonathan Miller[1]; [1]Air Force Research Laboratory

Additive manufacturing presents both extreme potential and concern for component design. The ability to spatially tailor processing conditions opens the door to sophisticated designs with heterogeneous materials. Accounting for this heterogeneity, before exploiting it, requires the ability to link local processing state to properties/performance of local material. A concern with current geometry-based design approaches, such as topology optimization, is not directly accounting for material property changes as geometry updates are made. The MIDAS program addresses this challenge by generating highly-pedigreed data sets including detailed process descriptions (beam path, location specific processing conditions), post-build characterization (X-ray CT, RUS, 3D Optical, SEM) and mechanical testing (milli-tensile, in situ HEDM, notch, torsion testing). These data sets will be made available to the AM community in process-structure and structure-property material modeling challenge problems. Finally, challenge results will be used to feed novel model aggregation strategies akin to weather forecasting.

2:50 PM Invited
Evolution of Raw Powder Characteristics through the Additive Manufacturing Reuse Cycle: *Claudia Luhrs*[1]; Sam Murphy[1]; Gregory Welsh[2]; Terri Merdes[3]; Edward Reutzel[3]; [1]Naval Postgraduate School; [2]Naval Air Warfare Center Aircraft Division; [3]Applied Research Laboratory. Pennsylvania State University.

The rapid development of metal Additive Manufacturing (AM) techniques such as direct metal laser sintering processes (DMLS) promises to revolutionize the way we design, build, supply, use and maintain metal and alloy components. Through AM, complex alloy parts are fabricated layer by layer in a relatively short time with no tooling required and with the optimal amount of raw material. However, reusing the alloy particulates that stay in the system after the 3D printed part is removed will be indispensable to generate other parts and to deliver on expected cost efficiency of the AM approaches. The current research effort is focused on studying the raw powder features (i.e. particle size distribution, microstructure and chemical composition among others) through the reuse cycle and correlating them with the mechanical properties of the 3D components built from them.

3:10 PM Break

3:40 PM Invited
Metallic Additive Manufacturing at the Army Research Laboratory: *Brandon McWilliams*[1]; [1]US Army Research Laboratory

An overview of metallic additive manufacturing (AM) research at the Army Research Laboratory’s (ARL) Center for Agile Materials and Manufacturing Science will be provided. ARL is pursuing an integrated approach to metallic AM which operates at the union of materials development, advanced manufacturing, and design for AM concurrently in order to meet the future needs of the warfighter. Disruptive improvements in metallic AM components which meet property requirements for in-service use necessitate the development and integration of advanced modeling and simulation tools at each stage of the AM workflow, from feedstock development to prediction of final performance of novel and ultra-lightweight structures manufactured at the point of need. Recent developments in process modeling at the continuum and mesoscales will be highlighted as well as experimental progress in local control of microstructure and properties by design during laser powder bed fusion.

4:00 PM Invited
Design, Fabrication, and Qualification of a 3D Printed Metal Quadruped Body: Combination Hydraulic Manifold, Structure, and Mechanical Interface: *Joshua Geating*[1]; Matthew Wiese[1]; Michael Osborn[1]; [1]US Naval Research Laboratory

Additive manufacturing allows designers to make complex, efficient parts not possible by conventional manufacturing techniques. Efficiencies are achieved by combining structure, interfaces, and power distribution, while eliminating redundant structural mass and volume. This paper documents the design, fabrication, inspection and testing of complex additively manufactured metal parts. Parts utilize Al10SiMg aluminum alloy serving the multipurpose role of hydraulic manifold, mechanical interface, and structure for a meso-scale quadruped robot. These parts allow Naval Research Laboratory (NRL) engineers to design and construct a highly capable quadruped robot that is highly dynamic and lightweight. Metal parts were designed with computer aided design (CAD) and constructed using powder-bed direct laser metal sintering (DLMS). High-pressure hydraulic lines with internal fluid passageways were printed into the body assembly seamlessly creating a complex hydraulic manifold. After fabrication, a rigorous program involving post-processing, inspection, and destructive and non-destructive testing was performed to validate the design and manufacturing methods.

4:20 PM Invited
Reduction Expansion Synthesis of Thin Metal Films: *Jonathan Phillips*[1]; Chris Pelar[1]; [1]Naval Postgraduate School, EAG

We have developed a simple, inexpensive, technology for creating metal thin films, order 1 micron thick, on metal substrates. It is based on creating a multi-component physical mixture with the consistency of paste. After the paste is applied mechanically, the paste/substrate is heated in a inert atmosphere to above 500 C. Using this technique Ni films, of order 1 micron thick, were produced on an iron substrate, and only in the area in which the paste was applied. It is postulated this general approach can be applied to create more precise metal parts, and eliminate the need for high temperature laser melting.

4:40 PM Invited
Fracture Behavior of Thermally Annealed, Additively Manufactured Polymers: *Kevin Hart*[1]; Ryan Dunn[1]; Jennifer Sietins[1]; Clara Hofmeister[1]; Eric Wetzel[1]; [1]US Army Research Laboratory

Polymeric structures fabricated using Fused Filament Fabrication (FFF) suffer from poor inter-laminar fracture toughness. As a result, these materials exhibit only a fraction of the mechanical performance of those manufactured through more traditional means. Here we present a simple thermal annealing technique which dramatically increases the inter-laminar toughness of structures manufactured using the FFF technique. Single Edge Notch Bend (SENB) fracture specimens made from a variety of common FFF feedstock polymers annealed across a range of times and temperatures were used to quantify the critical elastic-plastic fracture toughness of annealed structures. In the best case, the inter-laminar toughness of annealed materials was increased by a factor of 25 over those which were not annealed. Void coalition and migration during the annealing process was analyzed using X-Ray Computed Tomography and provides insight into the toughening mechanisms provided by the annealing process.

Applications 4: Metals

Tuesday AM — Room: 616A-B
August 8, 2017 — Location: Hilton Austin

Session Chair: Ian Maskery, University of Nottingham

8:15 AM
The Processing-Structure Relationship for Surface Roughness in Additively Manufactured IN 718: Bo Whip[1]; Eric Tatman[1]; Luke Sheridan[1]; *Joy Gockel*[1]; [1]Wright State University

Additive manufacturing (AM) can create metal components with complex internal geometries where the internal surfaces cannot easily be post machined. It has been reported that fatigue failures commonly initiate on the surface of as-built material. This work investigates the relationship between process parameters, and surface roughness of Inconel 718 fabricated on a laser powderbed fusion AM machine. Samples are built with different contour laser powers and speeds to obtain a variety of surface features. The surface is characterized using both 3D surface metrology and 2D destructive cross-sections, to expose any features obscured in the 3D surface measurements. The processing-structure relationship and potential life-limiting surface features are identified. Future work will include fatigue testing of these features. Overall, the results will be used to develop the processing-structure-properties-performance relationship, which provides an understanding of process limitations and the potential for improvement of the fatigue performance in AM components.

8:35 AM
Torsional Strength of Additively Manufactured Friction Stir Welding Tools: *John Linn*[1]; Jason Weaver[1]; Mike Miles[1]; Yuri Hovanski[1]; Ben Nelson[2]; [1]Brigham Young University; [2]Quad City Manufacturing Laboratory

Friction stir welding (FSW) is an important technology in the joining industry. It offers many advantages over other welding techniques in specific applications, such as joining dissimilar materials. There is ongoing research into creating effective and application-specific tool bits for FSW. However, these tools can have complex geometries and require close dimensional accuracy. This makes new tool designs expensive to prototype and test. By using additive manufacturing, these prototype tools can be quickly and economically fabricated. In general, metal parts manufactured through additive processes tend to have less favorable material properties than equivalent parts manufactured through precision machining; however, an AM tool for FSW may still have sufficient strength for limited prototype testing. This paper describes a study of an additive manufactured FSW tool for torsional strength and considers whether it has sufficient material properties to be used in FSW applications for low-life testing and prototyping.

8:55 AM
Surface Finish of Overhangs in Laser Powder Bed Fusion Additive Manufacturing of 17-4 Stainless Steel: Jason Fox[1]; *Thien Phan*[1]; Zach Reese[2]; Mark Stoudt[1]; Lyle Levine[1]; Chris Evans[2]; Brandon Lane[1]; Shawn Moylan[1]; [1]National Institute of Standards and Technology; [2]University of North Carolina at Charlotte

The development of additive manufacturing has allowed for increased complexity of designs over traditional manufacturing; however, variations in build orientation and overhang angle lead to variations in surface finish. In this study, as-built 17-4 stainless steel samples produced by laser powder bed fusion with various overhang angles and process parameters were investigated through non-destructive surface metrology and destructive cross-sectioning analysis. Shifts between surfaces dominated by partially melted powder particles and surfaces dominated by the re-solidified melt track are seen with variation in overhang angle and can be identified through surface profile parameters, such as *Rpc*, *RSm*, and *Rc*. Analysis of cross-sections show features not easily identified through surface metrology and comparison between the destructive and non-destructive techniques is discussed. Microstructural analysis was also used to identify features in the cross-sections. Through these relationships, surface finish metrology has the potential as a process signature to determine the cause of various defects.

9:15 AM
Residual Stress Reduction in LENS 3D Printed Metal Parts: *Shaun Whetten*[1]; David Keicher[1]; [1]Sandia National Laboratories

Thermal cycling and repeated melting/solidification cycles characteristic of 3D metal printing processes causes buildup of residual stress in 3D printed parts. Using laser engineered net shaping (LENS), residual stresses are formed leading to deformation and possible cracking of the 3D printed metal components. The LENS processes offers opportunities for rapid prototyping, alternative manufacturing processes, and repair of worn/broken components so it is important to be able to minimize the effects of residual stress. Work was performed to understand the benefit of substrate heating to reduce residual stress in metal parts made using the LENS process. Components made with various levels of heating will be compared, simulations that help understand the effects of heating will be shown, and initial results will be discussed.

9:35 AM

The Use of Electropolishing Surface Treatment on IN718 Parts Fabricated by Laser Powder Bed Fusion Process: *Li Yang*[1]; Chris O'Neil[1]; Yan Wu[1]; [1]University of Louisville

In various applications of additively manufactured Ni-based superalloys, high surface finish quality is required. In this work, electropolishing surface treatment with anhydrous electrolyte solution was employed to improve the surface quality of the IN718 parts fabricated by laser powder bed fusion process. Various process parameters including electropolishing voltage, polishing time, electrolyte spacing and electrolyte flow speed were investigated for their effect on the improvement of surface roughness and surface texture characteristics. In addition, the effect of electrolyte flow uniformity on the surface quality deviation was investigated. The results provided additional insights to the recently proposed polishing methods proposed by the same group, which enables further development of process for parts with more complex geometries.

9:55 AM Break

10:25 AM

Defect Detection in Metal SLM Parts Using Modal Analysis "Fingerprinting": *James Urban*[1]; Nick Capps[1]; Brian West[1]; Troy Hartwig[2]; Toby Lund[2]; Ben Brown[2]; Robert Landers[1]; Douglas Bristow[1]; Edward Kinzel[1]; [1]Missouri University of Science and Technology; [2]Kansas City - National Security Campus

The validation of additively manufactured (AM) materials is a difficult and expensive process because the local engineering properties are a function of the thermal history. The thermal history varies with the process parameters as well as the geometries. This paper presents a case study using modal impact testing to identify defects in a realistic AM parts. A low-cost setup consisting of an impact hammer and microphone are used to identify the resonant frequencies for several nominally identical parts on a build plate. Parts with lower density (as a result of purposely varying the process parameters) are identified by a shift in the torsional mode. Results from this study are compared to Finite Element Method (FEM) models and generalized for identifying defects in parts created with AM on the basis vibration/modal "fingerprinting".

10:45 AM

Electrochemical Enhancement of the Surface Morphology and the Fatigue Performance of Ti-6Al-4V Parts Manufactured by Laser Beam Melting: *Sarah Bagehorn*[1]; Jürgen Wehr[1]; Sonja Nixon[1]; Aubin Balastrier[1]; Tobias Mertens[2]; Hans Jürgen Maier[3]; [1]Airbus Group Innovations; [2]Airbus; [3]Leibniz Universität Hannover

In the course of the industrialization of the Additive Manufacturing (AM) process of metallic components, the surface finish of the final parts is a key milestone. 'As-built' AM surfaces feature a high initial surface roughness (i.e. Ra > 10 µm), which often exceeds the specification for technical applications. In order to apply AM for highly stressed and cyclically loaded components, the as-built surface roughness needs to be reduced. Since conventional surface finishing processes as machining or blasting often show a limited applicability to complex shaped AM parts, an enhanced electrolytic polishing process was developed (3D SurFin®). Within the present study, Ti-6Al-4V AM plates and fatigue samples were produced in a powder bed laser beam system. The enhanced electrolytic polishing process led to a significant roughness decrease of approximately 84 % for a treatment time of 60 min. Also a notable improvement of the fatigue performance of 174 % was achieved after a treatment time of 40 min in comparison to the as-built reference samples.

11:05 AM

The Change of Thermal Properties and Microstructure of an AM Fabricated AlSi10Mg Alloy during Thermal Annealing: *Pin Yang*[1]; Mark Rodriguez[1]; Daniel Stefan[1]; Amy Allen[1]; Donald Bradley[1]; Lisa Deibler[1]; Bradley Jared[1]; [1]Sandia National Laboratories

Selective laser melting is widely used for additive manufacturing (AM) to fabricate intricate3D structures. Parts made by this technique are usually far from their equilibrium state. They generally possess texture, anisotropy, and residual stresses. Additionally, microstructure and lattice imperfections induced by the non-equilibrium deposition process can significantly enhance anharmonicities of lattice vibration and directly impact the thermal properties of the parts. Normally, these parts have to be thermally treated to yield desirable properties. This is particularly true for the solution treatable aluminum alloy in heat exchanger applications. This work investigates the change of microstructure and thermal properties during the annealing process for the AlSi10Mg alloy. Correction between microstructure and calculated mean-free-paths of electrons and phonons is used to identify key issues governing changes in the thermal properties during the annealing process. These implications are important to ensure the thermal performance of AM fabricated solution treatable parts for practical applications.

11:25 AM

Improving Fatigue Performance of Ti6Al4V As-built Electron Beam Melting Parts using Surface Mechanical Attrition Treatment: *Hengfeng Gu*[1]; Carter Keough[1]; Xiaotian Fang[1]; Harvey West[1]; Yuntian Zhu[1]; Ola Harrysson[1]; [1]NC State University

As-built electron beam melted parts usually exhibit an inferior fatigue life compared to casted or wrought parts, mainly due to the poor surface quality inherited from the EBM process which serves as the crack initiation/propagation spots. This paper proposed a novel method based on surface mechanical attrition treatment (SMAT) to improve fatigue performance of EBM parts. As-built Ti6Al4V EBM parts were SMAT-processed using a SPEX 8000M Mixer/Mill for various time durations, and then underwent a stress controlled low cycle four-point bending fatigue test. The results showed that fatigue life was significantly improved by introducing a gradient-structured layer (from nanocrystallined to coarse grains) on the surface that effectively prevents crack initiation/propagation. Micro hardness indentation and scanning electron microscopy were used to characterize the affected gradient-structured layer, and the strengthening mechanism was discussed. In addition, a large improvement of surface finish for the SMAT processed Ti6Al4V EBM parts was also observed.

Applications 5: Residual Stress

Tuesday AM — Room: 602
August 8, 2017 — Location: Hilton Austin

Session Chair: Tim Horn, North Carolina State University

8:15 AM

A Modified Inherent Strain Method for Fast Prediction of Residual Deformation in Additive Manufacturing of Metal Parts: *Xuan Liang*[1]; Qian Chen[1]; Lin Cheng[1]; Qingcheng Yang[1]; Albert To[1]; [1]University of Pittsburgh

Effective prediction of residual deformation is very important to guarantee the quality of metal parts produced by Additive Manufacturing (AM). However, analytical or numerical models for the AM process are complicated and time consuming thus far. The conventional inherent strain theory can predict residual distortion of the regular metal welding problem. Typically, it is not applicable to the complicated layer-by-layer laser-sintering depositing process. In this paper, the modified inherent strain method is presented to predict the residual deformation much more efficiently. Calculation of the modified inherent strain is based on small-scale thermomechanical simulation of the AM process. Next, the strains are assigned to the heat-affected zone as material thermal properties and a one-time static mechanical analysis is performed. Residual deformation obtained by the new method and the thermomechanical simulation indicates good accuracy and efficiency of the proposed method.

8:35 AM
On the Simulation Scalability to Predict the Distortion and Residual Stress of Bridge Structures in Selective Laser Melting: *C. Li*[1]; Z.Y. Liu[1]; X.Y. Fang[2]; Y.B. Guo[1]; [1]The Univ. of Alabama; [2]Shandong University of Technology

Rapid heating and cooling thermal cycle of metal materials in selective laser melting (SLM) result in high tensile residual stress which leads to part distortion. However, how to fast and accurately predict residual stress and the resulted part distortion has been remaining a critical issue. It is not practical to simulate every single scan to build up a functional part due to the exceedingly high computational cost. Therefore, scaling-up the material deposition rate via increasing heat source dimension and layer thickness would dramatically reduce the computational cost. In this study, a multiscale modeling approach has been presented to enable fast prediction of part distortion and residual stress. Case studies on residual stress and distortion of the bridge structure were predicted via deposition scalability and validated with the experimental data. The influence of laser scanning strategy on residual stress distribution and distortion magnitude of the bridge was also discussed.

8:55 AM
The Effect of Scanning Strategy on Residual Stress in Metal Parts Fabricated via Selective Laser Melting (SLM) Technique: *Ajith Ukwattage Don*[1]; Ajit Achuthan[1]; [1]Clarkson University

Linear scanning, which is the building block of an SLM process, produces a non-uniform plastic deformation field around the melt pool due to the combined effect of large thermal gradient and non-uniform thermal and mechanical boundary conditions. Residual stress in a part is due to the generation of the non-uniform plastic deformation field during the building process. The non-uniformity of the plastic deformation field can be controlled and mitigated by changing the direction of subsequent linear scans as the part is continued to build. As a result, the scanning strategies can vary widely in complexity. In this study, the computational simulation of SLM process using finite element analysis is performed to develop an in-depth understanding of the relationship between scanning strategies and residual stress. Such an understanding will help to develop optimal scanning strategy that can minimize the thermal distortion and the residual stress of parts fabricated via SLM technique.

9:15 AM
Effects of Scanning Strategy on Residual Stress Formation in Additively Manufactured Ti-6Al-4V Parts: *Mohammad Masoomi*[1]; Scott Thompson[1]; Nima Shamsaei[1]; Meysam Haghshenas[2]; [1]Auburn University; [2]University of North Dakota

Parts fabricated via directed energy additive manufacturing (AM) can experience very high, localized temperature gradients during manufacture which can lead to their possession of complex residual stress fields. In this study, a thermo-mechanical model is employed for predicting the temperature distribution and residual stress in Ti-6Al-4V parts fabricated using laser-powder bed fusion (L-PBF). Numerical results are utilized for determining relationships between local part temperature gradients with generated residual stress. In particular, the effects of part size and employed scan patterns are investigated. Residual stress predictions are compared with those measured experimentally. Results indicate that by decreasing the size of the samples, the residual stress will decrease. Additionally, residual stresses tend to decrease when each layer is sub-divided into several islands.

9:35 AM
Residual Stress Analysis of Thin Wall Blade Structure Manufactured by Direct Metal Laser Sintering (DMLS): *Oguz Colak*[1]; Lokman Yunlu[2]; [1]Anadolu University; [2]Mehmet Akif Ersoy University

Direct Metal Laser Sintering (DMLS) has great potential in manufacturing of thin Wall complex shape blade structure. Thin walled blade (TWB) structures commonly uses in micro pumps and micro turbines such as heart pumps. In this study thin walled blade of heart pump is manufactured with additive manufacturing technology. In metallic additive manufacturing high temperature gradients, as a result of the locally concentrated energy input, lead to residual stresses, crack formation and part deformations during processing or after separation from the supports and the substrate. Therefore the residual stress in DMLS heart pump blades fabricated from Ti-6Al-4V alloy is measured by X-ray diffraction technique and analyzed residual stress.

9:55 AM Break

10:25 AM
Residual Stress Analysis in Supportless Overhanging Surfaces: *Ankit Porwal*[1]; Sagar Sarkar[1]; Cheruvu Siva Kumar[1]; [1]IIT Kharagpur

Internal structures are an integral part of any part geometry. These internal structures require support to build when we use direct laser metal sintering(DMLS)and require post processing. These support and post processing represent a significant waste in terms of material, energy and time employed for their fabrication. The current study is focused on fabrication of the support less overhanging surfaces and measurement of residual stresses. The study aims to measure the change in residual stress with changing the physical structure of overhanging structure. X-Ray Diffraction and Nanoindentation methods are used to calculate the residual stress. Dross and warp are also analyzed to compare the quality of fabricating samples.Keywords: DMLS, Overhang surface, Residual Stress

10:45 AM
The Effect of Process Parameters and Texture Evolution on Residual Stress in Selective Laser Melting of Ti-6Al-4V: *Nathan Levkulich*[1]; Nathan Klingbeil[1]; Joy Gockel[1]; John Middendorf[1]; [1]Wright State University

Selective Laser Melting (SLM) is a commonly used metal additive manufacturing (AM) process that builds complex 3D components with very high dimensional control. This process has gained significant traction in the aerospace and biomedical industries. However, during SLM fabrication, large residual stresses accumulate throughout the AM build because of the large thermal gradients and fast cooling rates present. These residual stresses cause undesired distortion and in extreme cases build failure, thus making it essential to develop a methodology to reduce them. In this work, the effect of process parameters (e.g. laser power, scan speed, build height, and substrate overhang) on residual stress in the SLM of Ti-6Al-4V is quantified through non-destructive and destructive techniques. In addition, Knoop Hardness yield loci and EBSD is used to access plastic anisotropy. The experimental work completed, will create a foundation for future residual stress modeling efforts in AM.

11:05 AM
Residual Stress Analysis of Additively Manufactured 17-4 PH Steel: Saber DorMohammadi[1]; *Frank Abdi*[1]; Nima Shamsaei[2]; Scott Thompson[2]; [1]AlphaSTAR Corporation; [2]Auburn University

This study shows the development of AM process simulation to predict as-built material characteristic and final part residual stress comparing with experimental test data. A computational tool was used to simulate manufacturing process by coupling FE thermal/stress analysis with multi-scale material model. To be able to perform a simulation and obtain accurate results, a grain and grain boundary finite element representative volume element (FE RVE) was proposed and implemented. The computational method was validated against residual stress measurements to establish its thermal-structural credentials. The method was extended to predict oxidation and damage of as built parts. The samples were fabricated from 17-4 PH steel using a PHENIX PM 100 SLM system. Neutron diffraction methods were used to obtain the residual stress at selected points along different directions. Sensitivity analysis was performed to determine the effect of process parameters on residual stress for as-built parts.

11:25 AM

Residual Stresses in Direct Metal Laser Sintered Stainless Steel Parts: Morteza Ghasri Khouzani[1]; *Mohammad Masoomi*[2]; Ronald Rogge[3]; Scott Thompson[2]; Nima Shamsaei[2]; Meenakshisundaram Ravi Shankar[1]; [1]University of Pittsburgh; [2]Auburn University; [3]Canadian Nuclear Laboratories

High temperature gradients associated with direct metal laser sintering (DMLS) process may induce large residual stresses within the as-built parts. In this study, disk-shaped 316L stainless steel components with various dimensions were additively manufactured using the DMLS technique. Neutron diffraction was used to profile the residual stresses in the samples before and after removal of the build plate and support structures. Large tensile in-plane stresses (up to ˜ 400 MPa) were measured near the disk top surfaces before the removal, while the stress magnitude decreased from the disk canter to the edges. The stress gradient was steeper for the disks with smaller diameters and heights. The data were then used for validation of a computational model for predicting residual stresses in additively manufactured components. The correlation between residual stress data and thermal history of the parts is discussed.

11:45 AM

Measurement and Prediction of Distortions in a 17-4 PH Stainless Steel Part Produced by Laser Powder Bed Fusion: *Daniel Galles*[1]; Andelle Kudzal[1]; Ryan Rogers[1]; Brandon McWilliams[1]; [1]Army Research Laboratory

Laser powder bed fusion (LPBF) is an additive manufacturing technique that produces parts in a layer-by-layer fashion using a sliced CAD file. This method can produce complex geometries that are difficult to manufacture using traditional processes. Unfortunately, rapid heating and cooling incurred during printing generates thermal stresses, which in turn lead to distortions and residual stresses in the as-printed part. In this study, experiments and simulations are conducted in order to predict distortions that arise during the LBPF process and after build plate removal. For the experiments, geometrical variations of a simple arch are printed using two laser scan strategies, generating various amounts of distortion. For the simulations, a one way temperature displacement coupling is adopted, in which predicted temperatures are inputted into a finite element stress analysis. Mechanical properties are estimated from the literature. Good agreement is achieved between the measured and predicted distortions.

Materials 3: Process Effects on Microstructure and Properties

Tuesday AM | Room: 408
August 8, 2017 | Location: Hilton Austin

Session Chair: Allison Beese, Pennsylvania State University

8:15 AM

Effect of Process Parameter Variation on Microstructure and Mechanical Properties of Additively Manufactured Ti-6Al-4V: *Jonathan Pegues*[1]; Kelvin Leung[2]; Azadeh Keshtgar[2]; Luca Airoldi[2]; Nicole Apetre[2]; Nagaraja Iyyer[2]; Nima Shamsaei[1]; [1]Auburn University; [2]Technical Data Analysis, Inc.

As additively manufactured (AM) parts become viable options for various structural applications, it is essential to fully understand how various process parameters affect their subsequent mechanical behavior. In this study, a process simulation package is utilized to model the heat transfer during the laser-based powder bed fusion (L-PBF) process. Along with mechanical properties, the model is capable of estimating porosity, density, and microstructural evolution during the rapid cooling phases associated with L-PBF. Simulation results were validated using experimentally measured mechanical properties of L-PBF Ti-6Al-4V specimens. Tensile tests and microscopy were conducted for determining the effects of process parameters (i.e. laser power, laser scan speed, hatch distance) on microstructure, strength and ductility of fabricated parts. Predictions from process simulations were compared with experimental results. Validated process simulation packages, used and developed herein, can provide a low-cost means for the quality control of AM parts.

8:35 AM

Predictive Modeling Tool for Performance and Life Analysis of Metal-Based Additive Manufacturing Parts: *Behrooz Jalalahmadi*[1]; Nathan Bolander[1]; Jingfu Liu[1]; [1]Sentient Science

Use of additive manufacturing (AM) processes to make different engineering components has been increased over the past years. However, there is not a well-established standard for qualifications of these components and industry relies mainly on experimental testing. Sentient incorporates its DigitalClone-Component (DCC) modeling technology to simulate AM build process considering the parameters involved during the build process to generate the microstructure of AM part which is the outcome of the build process. DCC is a computational physics-based modeling tool to simulate microstructure of different components and their behavior, calculate internal stresses caused by applied loading conditions, accumulate internal damages resulting in crack nucleation and propagation, and investigate the performance. This new AM model accounts for the effect of microstructure on performance of AM components, but also predicts their fatigue life. We also study the effect of different material properties, microstructural features and geometry details on fatigue life of AM parts.

8:55 AM

Scanning Strategies in Electron Beam Melting to Influence Microstructure Development: *Diego Bermudez*[1]; Cesar Terrazas[1]; Philip Morton[1]; Ryan Wicker[1]; [1]W. M. Keck Center for 3D Innovation

A dual scanning strategy was implemented using an Arcam A2 electron beam melting (EBM) additive manufacturing (AM) system to selectively influence microstructural variations within a single fabricated component. The methodology consisted of two melt steps, a regular hatch and a point-wise melt. The implementation of this scanning strategy caused different solidification conditions on the two regions scanned resulting in a refined microstructure at the location scanned with the point-wise strategy whereas a more regular size microstructure developed in the rest of the structure. These results were confirmed by microstructural observations performed using an optical microscope and the microstructure sizes measured using image segmentation. Testing of tensile specimens in the Z direction, created using this technique, will be reported. The ability provided by EBM AM manufacturing, through this methodology, to selectively control the microstructure can be used for practical applications such as the engineering of material with specific properties.

9:15 AM

Position-dependent Powder Properties in the Metal Powder Bed Laser Melting Process: *Peter Koppa*[1]; [1]DMRC

Additive manufacturing of metal powder requires during the entire process a reliable powder surface before laser exposure. The distribution of powder size and the bulk density influences crucial the part quality. This properties are dependent on the particle size distribution, powder humidity, particle material and the recoating technology. Latest measurements showed that it is possible to improve this powder layer surface quality significantly with an upgrade of the usual slide recoater. Due to this fact it is possible to recoat faster with a better quality and to recoat with bad flowable powders.

9:35 AM

Correlation of Engineering Properties with Modal Analysis Parameters for Metal SLM Parts: *Nick Capps*[1]; Brian West[1]; James Urban[1]; Troy Hartwig[2]; Toby Lund[2]; Ben Brown[2]; Robert Landers[2]; Douglas Bristow[1]; Edward Kinzel[1]; [1]Missouri University of Science and Technology; [2]Kansas City - National Security Campus

Selective Laser Melting (SLM) creates metal parts by fussing powder layer-by-layer. It provides significant design flexibility and the possibility of low-volume production. The engineering properties of the printed metal are a function of the local thermal history. This creates challenges for validating additively manufactured (AM) parts. This paper correlates the engineering properties (density, modulus, yield strength and ultimate strength) for tensile test specimens created with different process parameters with the resonant frequencies determined using modal testing. The paper shows that yield and ultimate strengths for these specimens can be accurately determined using modal analysis and that this correlation is significantly better than for density or stiffness alone.

9:55 AM Break

10:25 AM

Qualification of DMLS Ti6Al4V (ELI) Alloy for Biomedical Applications: *Igor Yadroitsev*[1]; P. Krakhmalev[2]; I. Yadroitsava[1]; A. Du Plessis[3]; [1]Central University of Technology, Free State (CUT); [2]Karlstad University; [3]Stellenbosch University

Ti6Al4V (ELI) samples were manufactured by Direct Metal Laser Sintering (DMLS) in vertical and horizontal directions and subjected to various heat treatment. Detailed analysis of porosity, microstructure, residual stress, tensile properties, fatigue and fractured surfaces was done based on computed tomography scans, scanning electron microscope and X-ray diffraction methods. Types of fractures and tensile fracture mechanisms in DMLS Ti6Al4V (ELI) alloy were studied at pre-strained samples. Peculiarities of the microstructure and corresponding mechanical properties were compared with standard specification for conventional Ti6Al4V alloy (grade 5 and grade 23) for surgical implant applications. Conclusions regarding mechanical properties and heat treatment of DMLS Ti6Al4V (ELI) for biomedical applications were made.

10:45 AM

Development of Sintering Parameters for Full Densification of H13 Tool Steel Printed via Binder Jet Additive Manufacturing: Peeyush Nandwana[1]; Derek Siddel[1]; *Amy Elliott*[1]; [1]Oak Ridge National Laboratory

H13 tool steel is commonly used as die and mold material for aluminum and magnesium castings owing to its high hardenability and toughness at relevant temperatures. Conventionally, the dies are fabricated via machining that limits the complexity of the geometries that can be fabricated. Binder jet additive manufacturing is a viable technique to fabricate near net shapes with complex geometries. However, the green density is usually very low, which would render the H13 green part unfit for use as dies. Therefore, there is a need to develop a sintering schedule to attain full densification of H13 components. The results from solid state sintering and supersolidus liquid phase sintering along with associated shrinkages will be discussed. The study will provide insights and input towards development of a predictive tool to determine associated shrinkage, thereby allowing for appropriate design modifications to attain the near net shape with high dimensional tolerance.

11:05 AM

Influence of Hatch Spacing on the Superelastic Properties of a Ni-rich SLM Nitinol Shape Memory Alloy: *Narges Shayesteh Moghaddam*[1]; Amirhesam Amerinatanzi[1]; Ahmadreza Jahadakbar[1]; Soheil Saedi[2]; Haluk Karaca[2]; Mohammad Elahinia[1]; [1]University of Toledo; [2]University of Kentucky

The focus of this study is to tailor the hatch spacing of SLM fabrication in a way to tune the superelastic properties of NiTi component. To this aim, several NiTi cylindrical components were fabricated using Ni50.8Ti powder via SLM PXM by Phenix/3D Systems, using previously obtained optimum values for laser power, scanning speed, and layer thickness, but different hatch spacing. Then, the microstructure, transformation temperatures, hardness, and superelastic response of NiTi samples were studied. The results showed smaller grains and higher densities in the samples fabricated with lower hatch spacing. The grains were observed to be enlarged in size with increasing the hatch spacing. Moreover, the transformation temperatures (TTs) and the Vicker hardness were observed to be lower for the samples processed with higher hatch spacing. Finally, the superelasticity behavior of the samples was also shown to be degraded with higher values for hatch spacing.

11:25 AM

Optimal Process Parameters for In Situ Alloyed Ti15Mo Structures by Direct Metal Laser Sintering: T.C. Dzogbewu[1]; *Igor Yadroitsev*[1]; P. Krakhmalev[2]; I. Yadroitsava[1]; A. Du Plessis[3]; [1]Central University of Technology, Free State; [2]Karlstad University; [3]Stellenbosch University

Direct Metal Laser Sintering has the advantage to produce objects with complex geometry. In-situ alloying is of great interest since it provides a promising opportunity to create gradient materials with variable properties. Understanding of the effects of each process parameters on the synthesized material is paramount to successful manufacturing advanced implants with mechanical properties close to the mechanical properties of bones. Ti15Mo was chosen as a promising ß-type alloy for biomedical applications. Single tracks were produced on titanium substrate by in-situ alloying of pure Ti and Mo powders. Geometrical characteristics of single tracks were investigated at wide range of laser powers and scanning speeds. Threshold of enthalpy ratio to transition from conduction to keyhole mode was found. To study the distributions of molybdenum, nano-CT scans were performed. Effects of hatch distance and scanning strategy on the layer surface morphology were investigated. Microstructure and mechanical properties of as-built specimens were analyzed.

11:45 AM

Process -- Property Relationships in Additive Manufacturing of Nylon-fiberglass Composites using Taguchi Design of Experiments: *Kuldeep Agarwal*[1]; Matthew Houser[1]; Sairam Vangapally[1]; Arun Vulli[1]; [1]Minnesota State University, Mankato

Composite Filament Fabrication (CFF) process, similar to Fused Deposition Modeling (FDM) can extrude fiber along with plastic. The process has two nozzles, one that can extrude Nylon and another can extrude fiber such as Fiberglass or Kevlar. Mechanical properties of parts produced by this process are dependent on process parameters. To determine the effect of process parameters and design parts for optimal properties, the relationship needs to be determined. This research works with Nylon-Fiberglass composite and focuses on five different process parameters and their effect on properties such as tensile strength, elastic modulus and elongation. 36 experiments based on Taguchi DOE methodology are conducted and analysis of variance of results is used to find important parameters. Results show that some process parameters are more significant than others in affecting the properties. It is found that the fiber volume % in the composite plays the most significant role in mechanical properties.

Materials 4: Photopolymers

Tuesday AM Room: 404
August 8, 2017 Location: Hilton Austin

Session Chair: David Rosen, Georgia Institute of Technology

8:15 AM

Measuring the Curing Parameters of Photopolymers used in Additive Manufacturing: *Joe Bennett*[1]; [1]NIST

A testing methodology was developed to expose five commercially available photopolymer resins and measure the cured material to determine two key parameters related to the photopolymerization process: E_c (critical energy to initiate polymerization) and D_p (penetration depth of curing light). Three different methods for determining the thickness of the cured resins - exposed to light at two wavelengths and varying power densities and energies - were evaluated. Caliper measurements, stylus profilometry, and confocal laser scanning microscopy showed similar results for hard materials while caliper measurement of a soft, elastomeric material proved inaccurate. Working curves for the photopolymers showed unique behavior both within and among the resins as a function of curing light wavelength. The observed variations, if unknown to the user and not controlled for, would clearly affect printed part quality. This points to the need for a standardized approach for determining and disseminating these, and perhaps, other key parameters.

8:35 AM
Materials Properties Evolution during Photopolymerization: *Jiangtao Wu*[1]; Zeang Zhao[1]; H. Jerry Qi[1]; [1]Georgia Institute of Technology

The photopolymerization which changes liquid monomer solution into solid polymer by using the light activated chemical reaction is widely used in many engineering fields such as dental restoration and 3D printing. The physical properties of the cured polymer change dramatically during the photopolymerization process. Considering the non-uniform conversion of the monomer and nonhomogeneous material properties, the internal stress caused by the volume shrinkage could be a severe problem. We investigated the photopolymerization reaction kinetics and material properties evolution during curing process by theoretical modeling and experiments. The degree of conversion of monomers is used to describe the mechanical properties of cured polymer at different curing state. The internal stress of a photopolymerized sample caused by the volume shrinkage is investigated by FEM simulation. The bending curvature induced by the internal stress are investigated by experiment and modeling. The results indicate that the model can describe the mechanics during photopolymerization.

8:55 AM
A Trade-off Analysis of Recoating Methods for Vat Photopolymerization of Ceramics: *Thomas Hafkamp*[1]; Gregor van Baars[2]; Bram de Jager[1]; Pascal Etman[1]; [1]Eindhoven University of Technolgy; [2]TNO

Technical ceramic parts can be produced by curing ceramic-filled resins in the vat photopolymerization (stereolithography) process. Scaling up to larger ceramic product sizes and higher product quality calls for the integration of more sensing, actuation and closed-loop control solutions while taking a systems engineering approach. This paper gives a comprehensive overview of methods to deposit a layer of (ceramic-filled) resin, better known as recoating. The aim of this work is to perform a trade-off analysis of recoating methods to enable the selection of the method that best meets the requirements for scaling up the printable object size in the ceramic vat photopolymerization process.

9:15 AM
Supportability of Highly Viscous Slurry in a New Stereolithography-based Ceramic Fabrication Process: *Li He*[1]; Xuan Song[1]; [1]University of Iowa

In recent years, ceramic fabrication using stereolithography (SLA) has attracted a lot of interest due to relatively high accuracy and density that can be achieved in final part production. One of the main challenges in ceramic SLA is that support structures are required to build overhanging features. Since support structures have to be manually removed after fabrication, fracture tips are typically introduced at the location where a support structure was originally built. Fracture tips may decrease surface quality, introduce stress concentration and consequently increase the probability of component damage. In this research, we developed a Suspension Enclosing Projection-stereolithography process (SEPS), which employs highly viscous ceramic slurry as feedstock materials, and explored use of the unique non-Newtonian rheological behavior of the materials in supporting overhanging features without building extra support structures. Several test cases suggest that using highly viscous slurry with suitable rheological properties to support overhanging features is feasible.

9:35 AM
Digital Light Processing (DLP): Anisotropic Tensile Considerations: *Elisa Aznarte Garcia*[1]; Cagri Ayranci[1]; A.J. Qureshi[1]; [1]University of Alberta

Digital light processing (DLP) 3D printing is an additive manufacturing (AM) process used to produce layered parts via photopolymerization. Anisotropy is a common characteristic of parts produced by DLP. Furthermore, printing conditions affect widely the resulting mechanical properties. This paper shows the effect of three printing factors on the final mechanical properties of specimens manufactured using DLP 3D printing. A series of ISO complaint tensile test specimens were designed, printed and tested. The properties analyzed were the Elastic Modulus, Ultimate Tensile Strength, Ultimate Strain and Printing Time. Preliminary findings on design guidelines for Vat Photopolymerization processes are presented in addition to the economic effect of the studied parameters in terms of the total printing time.

9:55 AM Break

10:25 AM
Large-area, High-resolution Additive Manufacturing of Elastomers with Scanning Mask Projection Vat Photopolymerization: *Viswanath Meenakshisundaram*[1]; Philip Scott[2]; Justin Sirrine[2]; Christopher Williams[1]; Timothy Long[2]; [1]Design, Research and Education for Additive Manufacturing Systems Laboratory, Department of Mechanical Engineering and Macromolecules Innovation Institute, Virginia Tech, Blacksburg, VA 24061; [2]Long Research Group, Department of Chemistry and Macromolecules Innovation Institute, Virginia Tech, Blacksburg, VA-24061

Acrylate-based resins are the most prevalent materials in vat-photopolymerization because their fast-cure kinetics and mechanical stiffness allow for the manufacturing of high-resolution parts. However, due to their brittle nature, these photopolymers are primary used for prototyping purposes only. In an effort to expand the materials catalog, and thus the application space, for vat-photopolymerization, the authors present three vat-photopolymerizable elastomers: styrene butadiene (SBR), hydroxyl-terminated polybutadiene (HTPB), and siloxanes. Further, the authors describe the fabrication of large-area, high-resolution elastomeric components with a scanning-mask projection vat-photopolymerization machine. Process parameters and resultant mechanical properties of the three printed elastomeric materials are reported. Finally, the strategies for additive manufacturing of similar families of elastomers are discussed.

10:45 AM
Recyclable 3D Printing of Vitrimer Epoxy: *Xiao Kuang*[1]; Qian Shi[1]; H. Qi[1]; [1]Georgia Institute of Technology

3D printed thermosets are inherently non-recyclable due to their permanently crosslinked networks. It is desirable to develop recycling approaches for 3D printed parts in view of increasing polymer wastes. Here, we present a new thermosetting vitrimer epoxy ink and a 3D printing method that can 3D print epoxy into parts with complicated 3D geometries, which can be recycled into a new ink for next round of 3D printing. A high-viscous ink was printed at an elevated temperature into complicated 3D structures, followed by an oven cure using a two-step approach. To recycle, the printed epoxy parts are fully dissolved in an ethylene glycol in a sealed container at a high temperature. The dissolved polymer solution is reused for the next printing cycle using the similar printing conditions for four times retaining good printability. In addition, the vitrimer epoxy can be used for pressure-free repairs for the 3D printed parts.

11:05 AM
3D Printable Recyclable Thermosets: *Biao Zhang*[1]; Qi Ge[1]; Martin Dunn[1]; [1]Singapore University of Technology and Design

Thermoseting materials have superior dimensional stability and mechanical performance at high temperatures as compared to thermoplastics which render them ideal in many technological applications. However, once thermosets form 3D shapes, e.g., through UV radiation triggered formation of covalent bonds, they cannot be reshaped or reprocessed. This leads to material waste and potentially serious environmental impacts with the continuous increase in consumption of 3D printing materials. Here we develop a family of new 3D printable recyclable thermosets. They work by UV curing during projection microstereolithography to create complex 3D shapes, followed by postcuring to enable transesterification-based bond exchange reactions that create a set of dynamic covalent bonds (DCBs). These DCBs can then be broken and reformed upon heating which essentially makes a thermoset act like a thermoplastic, rendering it reprocessable. Here we demonstrate the workings of this new family of materials via 3D printing and recycling a series of 3D components.

11:25 AM

Determination of Complex Young's Modulus for Polymer Produced by Microstereolithography: Clinton Morris[1]; *John Cormack*[1]; Michael Haberman[1]; Carolyn Seepersad[1]; [1]University of Texas at Austin

Microstereolithography is capable of producing polymer parts with a total size on the order of millimeters with high resolution. Material properties of the cured polymers can vary depending on build parameters like time of exposure and part geometry. Current techniques for determining the material properties of these polymers are limited to static measurements via micro/nanoindentation, leaving the dynamic response undetermined. Frequency-dependent material parameters, such as the complex Young's Modulus, have been determined for other materials by measuring the wave speed and attenuation of an ultrasonic pulse through the materials. This method is now applied to determine the frequency-dependent material parameters of polymers manufactured using microstereolithography. Because the ultrasonic wavelength is comparable to the part size, a model that accounts for both geometric and viscoelastic effects is used in the inverse problem.

11:45 AM

Understanding the Effects of Post-Processing on a High-Performance All-Aromatic Polyimide Fabricated Using Vat-Photopolymerization: *Nicholas Chartrain*[1]; Viswanath Meenakshisundaram[2]; Maruti Hegde[3]; Susheel Sekhar[4]; Christopher Williams[2]; Timothy Long[3]; Danesh Tafti[4]; [1]Design, Research and Education for Additive Manufacturing Systems Laboratory, Department of Materials Science and Engineering and Macromolecules Innovation Institute, Virginia Tech; [2]Design, Research and Education for Additive Manufacturing Systems Laboratory, Department of Mechanical Engineering and Macromolecules Innovation Institute, Virginia Tech; [3]Long Research Group, Department of Chemistry and Macromolecules Innovation Institute, Virginia Tech; [4]High Performance Fluid-Thermal Science and Engineering Laboratory, Department of Mechanical Engineering and Macromolecules Innovation Institute, Virginia Tech

Polyimides are class of thermoplastics or thermosets that exhibit exceptional mechanical, thermal, and dielectric properties. Poly(4,4'-oxydiphenylene-pyromellitimide), branded as Kapton™ film by DuPont, is one of the most well-known polyimides due, in part, to its excellent solvent resistance and thermal stability between -270 °C and 400 °C. However, the polymer's allaromatic backbone make it notoriously difficult to process, particularly into three-dimensional parts. The authors recently demonstrated the ability to fabricate three-dimensional parts from poly(4,4'-oxydiphenylene-pyromellitimide), using vat-photopolymerization. To fabricate functional parts from polyimides, it is necessary to understand how the printing, drying, and imidization steps affect the final part. In this work, we investigate the effects of these processes on print accuracy, part shrinkage, and achievable feature size.

Materials 5: Nickel-based Superalloys

Tuesday AM
August 8, 2017

Room: 615A-B
Location: Hilton Austin

Session Chair: Brent Stucker, 3DSIM

8:15 AM

Characterization of Inconel Alloy 625 Fabricated Using Powder Bed-based Additive Manufacturing Technologies: *Philip Morton*[1]; Jose Gonzalez[1]; Jorge Mireles[1]; Ryan Wicker[1]; [1]W. M. Keck Center for 3D Innovation

Growth within the additive manufacturing (AM) field is dependent on system development and application exploration. As AM technology is gradually implemented by companies to fabricate metallic components, it is important to understand the capabilities and limitations of each technology to justify future investments and ensure effective performance in particular applications. Powder-bed based AM technologies, including binder jetting (BJ), electron beam melting (EBM), and selective laser melting (SLM) have shown promise for fabrication of complex end use metallic parts. This research is focused on characterization and comparison of components fabricated by powder bed-based AM technologies, using the three aforementioned technologies. The characterization study looked at Inconel 625 and included microstructural analysis pertaining to the respective technologies and mechanical properties obtained by each. Mechanical properties including, ultimate tensile strength (UTS), yield strength, % elongation, and modulus of elasticity, were compared, and all three technologies met minimal baselines as defined by ASTM F3056-14.

8:35 AM

Impact of Hastelloy-X Composition on Crack Formation in Powder Bed Fusion Additive Manufacturing: *Stephanie Giet*[1]; Jonathan Munday[1]; Ravi Aswathanarayanaswamy[1]; [1]Renishaw plc

In this study, we show how certain compositions provide crack-free as-built samples over a set of fixed energy inputs when fabricated using a Renishaw AM400 additive manufacturing machine. We also assess the impact of high temperature substrates on the finished samples. Crack length, number, and density distribution are assessed using optical microscopy and SEM analysis. The microstructure and the hardness of solidified samples in as-built condition was compared with that of conventionally fabricated heat treated samples. Powders are also characterised to assess the impact of their physical properties on melting.

8:55 AM

Additive Manufacturing of γ' and γ'' Nickel Superalloys by Renishaw Laser Melting Machines: *Ravi Aswathanarayanaswamy*[1]; Nneji Kemakolam[1]; Laura Pickard[1]; [1]Renishaw Plc

In this study the melting characteristics of additively manufactured γ' CM247LC and γ'' Inconel 718 and 625 alloys were analysed. When a high γ' CM247LC was melted, thermal cracks were observed whereas for the sluggish γ''' alloys no cracks were observed. The crack density was sensitive to the process parameters and layer thickness chosen. By reducing the layer thickness (from 60 µm to 30 µm) and by optimising the laser process parameters, crack density was reduced. For the optimised samples, no cracks were observed in the core (at 75x magnification) after hot iso-static pressing (HIPing). When a small delay was introduced between each solidification, crack orientation became random. Re-melting between layers resulted in the coarsening of the cracks. Keeping the powder bed at few hundred degrees (≈ 450 °C) was not sufficient to stop the crack formation.

9:15 AM

Microstructure and Indentation Hardness of SLE-Deposited Rene80 Superalloy with Post-process Heat Treatment: *Andriy Dotsenko*[1]; Amrita Basak[1]; Ranadip Acharya[1]; Suman Das[1]; [1]Georgia Tech

Heat treatment procedures are routinely done to tailor the microstructure and properties of superalloy components. The work presented here investigates the effects of post-process heat treatment on the microstructure and indentation hardness properties of the René 80 samples fabricated using the scanning laser epitaxy (SLE) process. The thick, single-layer samples produced with SLE feature full density, crack-free René 80 deposits. Characterization of the as-deposited and the heat treated samples is performed using optical microscopy (OM), scanning electron microscopy (SEM), and Vickers microhardness measurements. Results are presented along with a discussion on the next phase of analysis and modeling of microstructure evolution within the process-parameter space. This work is sponsored by the Office of Naval Research through grants N00014-11-1-0670 and N00014-14-1-0658.

9:35 AM

Additive Manufacturing of René 142 through Scanning Laser Epitaxy (SLE): *Yunpei Yang*[1]; Amrita Basak[1]; Suman Das[1]; [1]Georgia Institute of Technology

This work aims to establish process-structure-property relationships for nickel-base superalloy, René 142 deposited using a laser powder bed fusion (LPBF)-based additive manufacturing process, scanning laser epitaxy (SLE). A numerical model combining heat transfer and microstructure evolution is developed to capture the relationship between the process parameters and the microstructures. The model is validated for a range of processing parameters. The results show excellent agreement in predicting the microstructure evolution in SLE. The deposit region is further characterized using optical microscopy, scanning electron microscopy, and Vickers microhardness measurements. The results show that the higher microhardness is correlated with higher □' volume fraction in the deposit. This work is sponsored by the Office of Naval Research through grant N00014-14-1-0658.

9:55 AM Break

10:25 AM
Characterization of MAR-M247 Deposits Fabricated through Scanning Laser Epitaxy (SLE): *Amrita Basak*[1]; Suman Das[1]; [1]Georgia Institute of Technology

This paper aims to characterize the microhardness and the process-induced residual stress in nickel-base superalloy MAR-M247 fabricated using a laser-powder bed fusion (LPBF)-based additive manufacturing (AM) process, scanning laser epitaxy (SLE). The SLE fabricated MAR-M247 samples are investigated using optical microscopy, scanning electron microscopy, energy dispersive x-ray spectroscopy, x-ray diffraction, and Vickers microhardness measurements. The results show that the average Vickers microhardness values do not have any significant variation with changes in SLE processing parameters. However, the microhardness values are unevenly distributed and show variations along the build direction and the laser movement direction. However, overall the hardness values are within ±2 sigma limits for all the SLE deposited MAR-M247 samples. The effect of heat treatment on the microhardness and the residual stress is also investigated. The results show that the residual stress decreased after the heat treatment. This work is sponsored by the Office of Naval Research through grant N00014-14-1-0658.

10:45 AM
Mechanical Assessment of a LPBF Nickel Superalloy using the Small Punch Test Method: *Sean Davies*[1]; Spencer Jeffs[1]; Robert Lancaster[1]; Gavin Baxter[2]; [1]Swansea University; [2]Rolls-Royce plc

With the continuous drive of the aerospace industry to introduce Additive Layer Manufacturing (ALM) into next generation turbine engines, the requirement to understand their mechanical performance has grown. However, limitations in material availability due to the nature of the process can restrict the scope for conventional mechanical testing. The Small Punch test (SPT) provides an effective tool of ranking the performance of ALM processed alloys, credited to the small volumes of material utilised and the ability to sample localised regions. This technique has been applied to the nickel superalloy C263, manufactured via Powder Bed Direct Laser Deposition (PB-DLD) in different build orientations and subjected to contrasting post process treatments. To fully understand the effects of these process variables on the mechanical response of PB-DLD alloys, empirical correlations have been derived between SPT and uniaxial data to demonstrate the suitability of this novel approach in characterising the properties of ALM structures.

11:05 AM
Cracking Behavior of High Gamma Prime Ni-base Superalloys Fabricated through Additive Manufacturing: *Michael Kirka*[1]; Duncan Greeley[1]; Yousub Lee[1]; Ryan Dehoff[1]; [1]Oak Ridge National Laboratory

High gamma prime containing nickel base (Ni-base) superalloys comprise an alloy family that has great potential to benefit from the geometric complexity additive manufacturing allows. However, for all the beneficial properties high gamma prime superalloys have, the classification as traditionally non-weldable presents challenges. The focus of this work is to understand and identify the mechanisms through which high gamma prime Ni-base superalloys crack in during the electron beam melting process. While, additive manufacturing is similar to welding and the mechanisms of cracking in superalloy welds is well understood, the influence of repeated thermal gyrations from layer addition and passage of the heat source presents challenges in understanding the occurrence and how to mitigate the cracking through thermal management and ingenious scan strategies of the electron beam. The focus of the discussion will be centered on the Ni-base superalloys Inconel 738 (~50% gamma prime) and CM247 (~70% gamma prime).

11:25 AM
Effects of Processing Parameters on the Mechanical Properties of CMSX-4® Additively Fabricated through Scanning Laser Epitaxy (SLE): *Amrita Basak*[1]; Kyriaki Kalaitzidou[1]; Suman Das[1]; [1]Georgia Institute of Technology

The work aims to characterize the effects of processing parameters on the mechanical properties of CMSX-4® fabricated using a laser-powder bed fusion (LPBF)-based additive manufacturing (AM) process, scanning laser epitaxy (SLE). The laser power, the scan speed, and the number of repeat scans are varied in SLE. These parameters are combined to define a new measure such as the energy density. Microstructures of the samples are investigated using optical microscopy and scanning electron microscopy. Uniaxial tension tests are performed on samples in longitudinal direction. The yield strength, ultimate tensile strength, modulus and ductility values are extracted. This work is sponsored by the Office of Naval Research through grant N00014-14-1-0658.

11:45 AM
Effect of Heat Treatment on the Microstructures of CMSX-4® Processed through Scanning Laser Epitaxy (SLE): *Amrita Basak*[1]; Suman Das[1]; [1]Georgia Institute of Technology

Engineered components made of superalloys routinely undergo heat treatment procedures to tailor their microstructures and properties. In this study, the effect of heat treatment on the microstructures and microhardness of single-crystal nickel-base superalloy CMSX-4® is investigated. Samples of CMSX-4® are fabricated using scanning laser epitaxy (SLE), a laser powder bed fusion (LPBF)-based additive manufacturing process. Microstructural characterizations of the as-deposited and the heat treated CMSX-4® samples are performed using optical microscopy, scanning electron microscopy, x-ray diffraction, and Vickers microhardness measurements. The results show that the microstructure becomes homogeneous with reductions in the eutectic volume fraction for the heat-treated samples. The microhardness values also improve after the heat treatment. This work is sponsored by the Office of Naval Research through grant N00014-14-1-0658.

12:05 PM
Effect of Process Parameters and Shot Peening on Mechanical Behavior of ABS Parts Manufactured by Fused Filament Fabrication (FFF): Cody Kanger[1]; Haitham Hadidi[1]; Sneha Akula[1]; Chandler Sandman[1]; Jacob Quint[1]; Mahdi Alsunni[1]; Ryan Underwood[1]; Cody Slafter[1]; Jason Sonderup[1]; Mason Spilinek[1]; John Casias[1]; Prahalada Rao[1]; *Michael Sealy*[1]; [1]University of Nebraska-Lincoln

The goal of this research was to understand the relationship between three fused filament fabrication process parameters (layer height, infill angle, and outer shell quantity) on the tensile strength of shot peened ABS polymer parts produced on a Hyrel System 30M FFF printer. This is an important area of research because polymers have historically been limited to non-load bearing applications due to low strengths and stiffness. Improving mechanical properties is typically accomplished by changing the structure or chemical composition of the polymer. An alternative approach commonly used on metals is surface treatments. Shot peening is a surface treatment to improve the near-surface mechanical properties by imparting compressive residual stress. In polymer additive manufacturing, it was hypothesized that shot peening significantly affected the mechanical behavior at various FFF print process parameters. Results showed that tensile strength decreased for every printing recipe (except one) while the elongation usually increased.

Materials 6: Material Extrusion

Tuesday AM Room: 410
August 8, 2017 Location: Hilton Austin

Session Chair: Wenchao Zhou, University of Arkansas

8:15 AM

Expanding Material Property Space Maps with Functionally Graded Materials for Large Scale Additive Manufacturing: *Thomas Sudbury*[1]; Chad Duty[2]; [1]Cincinnati Incorporated; [2]University of Tennessee

Big Area Additive Manufacturing (BAAM) is a large scale extrusion-based print system that exceeds the throughput of conventional printers by five hundred times. In addition, BAAM uses pelletized feedstocks, which allows for site-specific definition of material composition and provides an unprecedented variety of material options. This study applies Ashby's concept of a material property space map to a variety of materials suitable for printing on BAAM. Ashby maps plot the performance of various materials across multiple parameters (such as strength, density, stiffness, etc) allowing for direct comparison of non-dimensional performance criteria. This study uses Ashby maps to identify opportunities for the use of functionally graded materials on BAAM to achieve structural performance not yet available with conventional printers and homogeneous materials.

8:35 AM

Considering Machine- and Process-specific Influences to Create Custom-built Specimens for the Fused Deposition Modeling Process: *Christian Schumacher*[1]; Volker Schöppner[2]; [1]Paderborn University, Direct Manufacturing Research Center (DMRC); [2]Paderborn University, Kunststofftechnik Paderborn (KTP)

Compared to conventional polymer processing technologies the material selection in the Fused Deposition Modelling (FDM) process is restricted. To expand the range of materials the requirements for the material properties and the semi-finished products (filaments) must be clarified. Therefor a machine- and process-independent rating of the processability is necessary. The established standards for the tensile strength test apply to specimens with nearly isotropic mechanical properties. The FDM-process generates anisotropic parts. The properties are mainly influenced by the machine quality and the data processing. It is not possible to test a material for FDM independently from the machine and the data processing. In this paper, machine and process specific influences are investigated. Considering these influences a custom-built specimen is created to test the tensile strength of the welding seams for polyamide 6. This proceeding allows the machine- and process-independent rating of the processability in terms of tensile strength for different materials.

8:55 AM

Investigating the Effect of Nozzle Residence Time on Properties of Thermoplastic Parts Produced by Material Extrusion AM: *Joseph Bartolai*[1]; Timothy Simpson[1]; [1]The Pennsylvania State Univeristy

It has been shown that there are large differences in mechanical properties between thermoplastic parts produced using conventional manufacturing methods and those produced using material extrusion additive manufacturing (AM). When factors known to affect the strength of these parts, such as the strength of the welded interfaces between adjacent deposition roads and the void space created inside each part, are taken into account; there is still a small amount of error in strength calculations. This study isolates the effect of nozzle residence time on the mechanical properties of material extrusion AM parts by producing specimens using two different filament feedstock diameters. All other process factors known to affect the strength of material extrusion parts, including nozzle temperature, deposition feed rate, road width, composition and/or rheological differences in feedstock material, and build orientation were identical for both specimen groups. The isolated effect of nozzle residence time on mechanical strength is presented.

9:15 AM

Rheological Evaluation of High Temperature Polymers to Identify Successful Extrusion Parameters: *Christine Ajinjeru*[1]; Chad Duty[1]; [1]University of Tennessee Knoxville

With the advancements in additive manufacturing (AM), several high-temperature thermoplastics are being explored as potential AM feedstocks. Some of these high-performance thermoplastics include; polyetherimides (PEI), polyphenylsulfones (PPSU/F), polyetherketoneketones (PEKK) and polyphenylene sulfide (PPS) as well as their reinforced composites. Most of these advanced resins tend to be more expensive than commodity plastics such as acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), and their processing parameters have not been determined for most AM systems. This paper introduces a method for identifying appropriate processing conditions for extrusion-based AM deposition systems, in which a material is forced through an orifice at a given flow rate. The pressure required to extrude a shear-thinning thermoplastic at a given shear rate is calculated based on viscoelastic properties of the polymer melt and compared against maximum system pressure to predict successful extrusion. An evaluation of several candidate materials is presented across a variety of extrusion-based platforms.

9:35 AM

A Viscoelastic Model for Evaluating Extrusion-based Print Conditions: *Chad Duty*[1]; Christine Ajinjeru[1]; Vidya Kishore[1]; Brett Compton[1]; Nadim Hmeidat[1]; Xun Chen[2]; Peng Liu[2]; Ahmed Hassen[2]; John Lindahl[2]; Vlastimil Kunc[2]; [1]University of Tennessee; [2]Oak Ridge National Laboratory

Extrusion-based printing systems have improved significantly over the past several years, allowing for higher throughput, higher temperatures, and larger components. At the same time, advanced materials are being introduced on the market that can provide improved performance over a range of operating conditions. Often these materials incorporate fiber reinforcements, reactive resins, and additives to control reaction kinetics, flow rheology, or thermal stability. This study presents a general framework for evaluating the printability of various candidate materials based on a basic viscoelastic model. The model addresses fundamental requirements for extrusion-based printing, including pressure-driven flow, bead formation, bead functionality, and component-level functionality. The effectiveness of this model for evaluating the impact of compositional variations and identifying appropriate processing conditions will be demonstrated for specific materials on direct write, fused filament fabrication, and large-scale extrusion platforms.

9:55 AM Break

10:25 AM

Towards a Robust Production of FFF End-user Parts with Improved Tensile Properties: *Gerardo Mazzei Capote*[1]; Alec Redmann[1]; Carsten Koch[2]; Natalie Rudolph[1]; [1]University of Wisconsin- Madison; [2]RWTH Aachen University

The relatively low cost of Fused Filament Fabrication (FFF) printers and wide variety of materials -spanning multiple functionalities and prices- make this process interesting for production of functional parts. However, FFF produced objects underperform in terms of mechanical properties when compared to injection molding. Therefore, a study of tensile properties of FFF produced parts was conducted according to the ASTM D638 standard, using a commercial and an in-house produced ABS filament. Initial tests using commercial ABS revealed poor reproducibility of results, which were analyzed in detail in this study. This led to designing a formal bed levelling procedure for the printer, evaluating effects of printer configuration and material quality as well as exploring modifications to the ASTM test procedure. As a result, test specimens with properties close to injection molding parts were produced. Therefore, the different impact factors will be discussed and the new procedures will be presented.

10:45 AM

Investigating Material Degradation through the Recycling of PLA in Additively Manufactured Parts: Daniel Tanney[1]; *Nicholas Meisel*[1]; Jacob Moore[2]; [1]The Pennsylvania State University; [2]Penn State Mont Alto

The field of additive manufacturing (AM) has been expanding rapidly with the decreasing cost of desktop-scale material extrusion AM systems. As the cost of AM systems decreases, more users are investing in the technology, including universities, which have turned to AM as an option for providing wide-scale access to prototyping technology. However, this type of wide-access printing generates significant waste due to cast-off support material as well as failed prints from inexperienced users or print errors. This paper investigates the feasibility of recycling this cast-off material through the relationship between the mechanical properties of recycled PLA and the number of lifecycles it has experienced on a desktop material extrusion machine. A three-stage shredding, extrusion, and spooling system is used to recycle the PLA material from cast-off build material. Additionally, the research investigates how adding virgin pellets to pellets of the recycled material in various ratios can affect tensile strength.

11:05 AM

EcoPrinting: Investigating the Use of 100% Recycled Acrylonitrile Butadiene Styrene (ABS) for Additive Manufacturing: *Mazher Mohammed*[1]; Anirudra Das[1]; Eli Gomez-Kervin[1]; Daniel Wilson[1]; Ian Gibson[1]; [1]Deakin University

Many commonly found polymers have the potential to be recycled, such as Acrylonitrile Butadiene Styrene (ABS), a prevalent 3D printing material. In this study we examine the potential of using 100% recycled ABS to form filaments for use in Fused Deposition Modelling (FDM) 3D printing. We then characterise the resulting changes in the printing quality and mechanical properties, over a single recycling cycle. We found that ABS can undergo recycling and reforming into consistent printer filaments without the addition of virgin material. However, notable changes in polymer characteristics were observed, reflected by degradation in mechanical properties during tensile tests and a decrease in the polymer melt flow, which required reduced raster speed to achieve repeatable prints. Despite these limitations, we demonstrate that recycling and reprinting is possible with acceptable loss of material integrity, and could provide unique opportunities for sustainable use of waste ABS using 3D printing technology.

11:25 AM

Achieving Functionally-graded Material Composition through Bicontinuous Mesostructural Geometry in Material Extrusion AM: *Brant Stoner*[1]; Joseph Bartolai[1]; Dorcas Kaweesa[1]; Nicholas Meisel[1]; Timothy Simpson[1]; [1]Pennsylvania State University

Functionally-graded materials (FGMs) are materials that gradually change composition through their volume, which allows certain areas of a part to be optimized for specific performance requirements. While certain additive manufacturing (AM) process types such, as material jetting and directed energy deposition, are capable of creating FGMs, they tend to be costly and limited. This paper presents a novel solution to the creation of FGMs: creating the material gradient by varying the mesostructural size and thickness of bicontinuous, multi-material geometries. By using bicontinuous geometric structures, each component material exists as a continuous discrete body. The use of these discrete structures allow FGMs to be produced by a wider range of AM processes. The gradient is created by varying the volume fraction occupied by the structure inside the part. This paper explores the use of this technique to create FGMs with material extrusion AM. Properties of these bicontinous structures are experimentally characterized.

Physical Modeling 3: Powder Beds

Tuesday AM — Room: 415A-B
August 8, 2017 — Location: Hilton Austin

Session Chair: Wentao Yan, Northwestern University

8:15 AM

A Close-up View onto the Strong Dynamics in Laser Metal Powder Bed Fusion: *Saad khairallah*[1]; Sonny Ly[1]; Gabe Guss[1]; Alexander Rubenchik[1]; Sheldon Wu[1]; Gustavo Tapia[2]; Alaa Elwany[2]; Manyalibo Matthews[1]; Wayne King[1]; [1]Lawrence Livermore National Laboratory; [2]U. of Texas A&M

A mesoscopic high fidelity simulation model is developed to understand the main physics in Laser Powder Bed Fusion. The model is applied to understand spattering, which can introduce defects as parasite deposits on the melt track as well change locally the powder distribution and its flowability. Different modes of spattering and spatter formation mechanisms are described and compared to experiments. The model is also used to create a surrogate model, using Gaussian process, that predicts melt pool dimensions of single tracks, for a given combination of laser power and scan speed, and therefore infer a process window specifying conduction versus the undesirable keyhole regime of operation. Prepared by LLNL under Contract DE-AC52-07NA27344. IM LLNL-ABS-727083.

8:35 AM

High-speed Imaging of the Powder-bed and Shield Gas during Metal PBF Additive Manufacture: *Prveen Bidare*[1]; Ioannis Bitharas[1]; Rachel Jennings[2]; R. Mark Ward[2]; Moataz M. Attallah[2]; Andrew J. Moore[1]; [1]Heriot-Watt University; [2]University of Birmingham

We have used an in-house developed open architecture metal powder bed fusion (PBF) system to record high-speed image sequences of the melt pool and powder bed during additive manufacture. Results are presented for single tracks and for area scans during the manufacture of multiple layer components, for both top-views (viewing direction ~20° to vertical) and side-views (viewing direction ~10° to horizontal). The results provide information on the motion of the particles in the powder bed and of the inert atmosphere that has not been observed previously, and the main features have been described by a finite element model. The model is further validated by the first reported schlieren imaging of the shield gas flow during PBF. These results provide useful information for process planning, including on dynamic packing density, powder denudation, the production of metal vapour and spatter direction, and variations in laser absorption in to the powder bed.

8:55 AM

Discrete Element Modeling of Powder Spreading and Flow for Metal Additive Manufacturing: *Dan Bolintineanu*[1]; Jeremy Lechman[1]; [1]Sandia National Laboratories

We present discrete element method (DEM) simulations pertaining to the processing and spreading of metal powders in the context of additive manufacturing. The parameter space includes a large number of process features (e.g. powder layer thickness, spreader height above the powder bed, spreader type) as well as particle properties (e.g. particle shape and size distribution, particle-particle contact parameters). We use simulations to explore the sensitivity of various features of the packed powder bed to these parameters. Particle friction, cohesion and size distribution are all shown to have a strong effect on the structure of the powder bed, especially its surface characteristics. We report simulations of various flow measurements that can be directly related to common experimental powder characterization techniques, including angle of repose, Hall flow, and powder rheology. The particle-level detail in these simulations can provide quantitative insight into powder selection and handling decisions for additive manufacturing.

9:15 AM

Mesoscopic Multi-layer Simulation of Selective Laser Melting Process: *Subin Shrestha*[1]; Kevin Chou[1]; [1]University of Louisville

Selective Laser Melting (SLM) is a layer by layer deposition process and it is desired to study the material accumulation and interaction to layer addition. In this regard, a mesoscopic multilayer numerical model with volume of fluid (VOF) method is developed using ANSYS/FLUENT. At first, a sequential powder addition algorithm is applied to generate first layer of randomly distributed non-uniform particles over a powder bed. A moving volumetric heat source is then applied to melt the single track in powder layer which is defined by specifying temperature dependent material properties. After a single scan in first layer is completed, the surface data is acquired to re-apply sequential powder addition algorithm over the deformed surface to generate second layer of powder. In this study, the melt flow has been simplified and is driven primarily by constant surface tension applied over melt pool and the obtained track width from simulation is in good agreement with experiment in literature.

9:35 AM
A Study into the Effects of Gas Flow Inlet Design in a Renishaw AM250 Laser Powder Bed Fusion Machine Using Computational Modelling: *Adam Philo*[1]; Chris Sutcliffe[2]; Stuart Sillars[1]; Johann Sienz[1]; Stephen Brown[1]; Nicholas Lavery[1]; [1]Swansea University; [2]Renishaw Additive Manufacturing Products Division

In powder-based additive manufacturing systems an inert gas flow is used to avoid oxidation of the metal alloy but is also used to remove unwanted by-products produced during the process.The current study analyses the gas flow experienced over the processing area in a Renishaw AM250 metal powder bed fusion machine via How Wire Anemometry (HWA) testing. A Computational Fluid Dynamics (CFD) model was developed in ANSYS FLUENT to simulate the argon gas flow coupled with a Discrete Phase Model (DPM) representing the expulsion of spatter. The model was then used to explore the effect of different inlets designs to improve flow uniformity over the processing area and increase the proportion of removed by-product. Results demonstrate how CFD is being used to optimise inlet positions and gas flow velocities providing design rules used for the new generation of machines which can contribute to even better mechanical properties.

9:55 AM Break

10:25 AM
Comparison of 3D Microstructural Modeling for Powder Bed and Powder Fed Metal AM Methods: *Theron Rodgers*[1]; Kyle Johnson[1]; Fadi Abdeljawad[1]; Jonathan Madison[1]; [1]Sandia National Laboratories

Powder-based metal additive manufacturing can be broadly categorized into powder-bed or powder-fed techniques. Both methods can be used to produce parts of similar size and geometry with comparable expectations of in-service performance. However, many process parameters exist in substantially different regimes between methods. For example, powder-fed methods have larger and slower moving molten zones compared to powder-bed methods. Here, the SPPARKS Monte Carlo suite is used to simulate three-dimensional microstructures for equivalent geometries fabricated by both methods. Differences in as-solidified microstructures are quantified and compared to experiment. Results will be presented in the context of processing parameter sensitivities with an emphasis on modeling challenges specified to each method. Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

10:45 AM
Experiments and Modeling of End Effects of Direct Laser Deposition: *Jennifer Bennett*[1]; Wentao Yan[2]; Sarah Wolff[2]; Kornel Ehmann[2]; Wing Kam Liu[2]; Jian Cao[2]; [1]Northwestern University, DMG MORI; [2]Northwestern University

Because additively manufactured components are built in a layer-by-layer fashion, a recurring defect in a particular location on each layer can propagate and significantly deteriorate the dimensional integrity of the final component. A prominent recurring defect in directed energy deposition (DED) is the difference of clad height at the start and stop of a single clad. The focus of this work is to qualitatively illustrate the physical mechanisms of start/stop defects by combining simulations and experiments. Clad height measurements at the start, end and mid point of single clads were used to establish a relationship between process parameters, solidification rate and clad geometry. This relationship verified the particle-scale modeling that illustrates the physical mechanisms at the start and stop of a clad. By simulating the evolution of powder particles in the DED process, an improved understanding of these mechanisms will allow for the minimization and mitigation of these defects.

11:05 AM
Development of Simulation Tools for Selective Laser Melting Additive Manufacturing: Thomas Nolan[1]; *Yongsheng Lian*[1]; Mark Sussman[2]; [1]University of Louisville; [2]Florida State University

In this paper we report our development of a fast simulation tool with dynamic mesh adaptation and massive parallelism to simulate the evolution of thermal fields during metal Selective Laser Melting (SLM) additive manufacturing (AM) processes. The simulation suite is based on a first-principles approach to simulate complex AM processes at the entire built part/component level. The developed model takes into account of heating, melting, powder-to-solid volumetric consolidation, cooling, as well as solidification and shrinkage that are often ignored in current simulation tools. The reported work is our first step toward the development of a complete software suite that can be executed rapidly on workstations and clusters with accelerators. The simulation tool can provide AM practitioners and researchers from industry and academic a fast and accurate simulation-based approach to replace current trial-and-error based practices in industry for process and material development

11:25 AM
Modeling of Electron Beam Selective Melting: from Powder Bed Spreading to Melting: *Wentao Yan*[1]; Wing Liu[1]; [1]Northwestern University

Electron Beam Selective Melting (EBSM) is promising, but many factors influence the manufacturing process, which poses a significant challenge to the quality repeatability. To comprehensively understand the EBSM process, we develop and integrate two models: a powder spreading model simulating a rake being pushed over powder particles using the Discrete Element Method and a powder melting model using the Finite Volume Method. These two models exchange 3D geometrical data to reproduce the selective melting process along various scan paths in multiple layers. By incorporating the experimentally measured powder size distribution, the rake-powder interactions and a heat source model derived from electron-material interactions, the integrated models account for the influence of the powder spreading machinery and electron beam gun, thereby linking equipment, process and structures. Moreover, the multiple-layer multiple-track simulation results further advance our understanding of how current and previous tracks and layers interact with each other to build complex products.

11:45 AM
Modelling Nanoparticle Sintering in a Microscale Selective Laser Sintering Process: *Obehi Dibua*[1]; Anil Yuksel[1]; Nilabh Roy[1]; Chee Foong[2]; Michael Cullinan[1]; [1]University of Texas at Austin; [2]NXP Semiconductors

An important aspect of making microscale selective laser sintering (μ-SLS) a viable commercial process is having the ability to predict the structural properties of sintered parts. This prediction is made possible through accurate models. The majority of SLS models simulate sintering as a melting process which is accurate for microparticles. When particles tend to the nanoscale, the sintering process becomes dominated by grain boundary and surface diffusion between particles. Though there are currently research efforts on modeling the sintering behavior between nanoparticles, these efforts revolve around simulations with only a few particles. This paper presents an approach to modelling diffusion between nanoparticles in full sized beds made up of hundreds of particles. The simulations presented in this paper are done using Phase Field Modelling and can be used to predict properties such as the porosity, shrinkage and relative density of sintered parts, which can then be compared against experimental data.

Process Development 3: Laser Processing and Monitoring 2

Tuesday AM — Room: 417A-B
August 8, 2017 — Location: Hilton Austin

Session Chair: April Cooke, National Institute of Standards and Technology/University of Maryland at College Park

8:15 AM
Laser Power Control in SLS: *Tim Phillips*[1]; Lixun Zhang[1]; Scott Fish[1]; Joseph Beaman[1]; [1]University of Texas at Austin

Selective Laser Sintering (SLS) of polymers is a common technique for creating structural plastic components in additive manufacturing. As a result, the mechanical strength of SLS parts is often of concern and mechanical testing has revealed a large variation in mechanical properties of components within the same build. It is believed that this variation is a result of poor temperature control during the sintering process. The proposed control method involves using an infrared camera to measure initial powder temperature before computing an optimal laser power profile to sinter the powder. By controlling the laser energy, it is expected that a more uniform temperature can be achieved and variation in mechanical properties can be reduced. The feed-forward control method is presented along with preliminary results.

8:35 AM
Laser Sintering Exposure Parameter Optimizsation by CT Scan: *Johannes Lohn*[1]; Michael Eschenbücher[2]; Hans-Joachim Schmid[3]; [1]Paderborn University / DMRC; [2]Paderborn University; [3]Paderborn University / Particle Technology Group (PVT)

Laser sintering (SLS) of PA12 based materials is state of the art and the material range is limited. The Direct Manufacturing of functional products by SLS requires the qualification of new materials. Since 2008, the Group of Particle Technology is a part of the Direct Manufacturing Research Center at the University of Paderborn. During several research projects a wide knowledge base on SLS has been built up and a SLS test equipment has beed developed. SLS is used to build high dense parts with strong mechanical properties. The porosity and the mechanical properties depend on the selected exposure strategy and energy density. During this research the correlation between exposure strategy, porosity and mechanical properaties is investigated by CT-Scan. Single Tracks, single layers, walls and solids are built and analysed by CT Scan. Additionally tensile tests are performed and the relation between exposure strategy, porosity and mechanical properties is analysed.

8:55 AM
Sintering Laser Power vs. Part Porosity Comparison using In-Situ Optical Coherence Tomography Data in Selective Laser Sintering: *Adam Lewis*[1]; Austin McElroy[1]; Thomas Milner[1]; Scott Fish[1]; Joseph Beaman[1]; [1]University of Texas at Austin

Additional types of process sensors could be useful in further improving consistency of Selectively Laser Sintered (SLS) parts. Optical Coherence Tomography (OCT) has shown promise as a new SLS process sensor which can yield depth resolved data not attainable with conventional sensors. This study investigates the use of OCT as a tool to measure part porosity. Various laser powers were used during the build and the in-situ OCT data corresponding to the various laser powers are compared. The finished part was then imaged using X-ray Computed Tomography (XCT). Porosity data was obtained and is compared with the OCT data.

9:15 AM
Assessment of Optical Emission Analysis for In Process Monitoring of Powder Bed Fusion Additive Manufacturing: *Alexander Dunbar*[1]; Abdalla Nassar[1]; [1]The Pennsylvannia State University

Developing methods which allow real-time monitoring of Powder Bed Fusion Additive Manufacturing (PBFAM) processes is key to enabling in situ assessments of build quality (e.g. lack of fusion and porosity). Here, we investigate the use of optical emission spectroscopy and high-speed (100 kHz) measurement of select wavelength emissions, based on a line-to-continuum approach, to determine if a correlation between PBFAM process inputs, sensor outputs, and build quality exists. Using an open protocol system interfaced with a 3D Systems ProX200 machine, sensor data was synchronized with the scanner position and the laser state, during buildup of Inconel-718 components under varying powers, scan speeds, and hatch spacing parameters. Sensor measurements were then compared against post-build computed tomography scans. We show evidence that sensor data, when combined with appropriate analyses, are related to both processing conditions and build quality.

9:35 AM
High Speed Thermal Imaging of the Melt Pool during Laser Powder Bed Fusion of Metal Alloys: *Nicholas Calta*[1]; Gabriel Guss[1]; Clara Druzgalski[1]; Sonny Ly[1]; Michael Crumb[1]; Manyalibo Matthews[1]; [1]Lawrence Livermore National Laboratory

The temperature distribution, peak temperatures, and cooling rates in and around the melt pool during a laser powder bed fusion build have profound effects on final microstructure and defect formation. Despite their importance to process modelling, these parameters remain poorly understood due to the high spatial and time resolution required to probe them on length and time scales relevant to melt pool fluctuations. Here we present 20 kHz thermal imaging of the melt pool viewed coaxially to the beam using a two-color thermographic approach. This approach avoids many of the confounding experimental factors typically associated with thermal imaging using a single wavelength. We present trends in the thermal profile, such as peak temperature and thermal gradient around the melt pool, as a function of laser scanning parameters. We also discuss these experimental results in the context of melt pool-scale models.Prepared by LLNL under Contract DE-AC52-07NA27344.

9:55 AM Break

10:25 AM
The Effect of Powder on Cooling Rate and Melt Pool Length Measurements using in situ Thermographic Techniques: *Jarred Heigel*[1]; Brandon Lane[1]; [1]National Institute of Standards and Technology

High-speed thermal cameras enable in situ measurement of the temperatures in and around melt pools generated during powder bed fusion processes. From these measurements, the melt pool length and cooling rates of the solidifying material are calculated and used to monitor the process and to validate thermal models. Unfortunately, pre-placed powder layers complicate the measurement and negatively impact the measurement error. For instance, powder particles that are regularly ejected from the melt pool can increase its apparent size and shape, making process monitoring strategies that rely on melt pool size susceptible to error. The objective of this work is to present high speed (1800 frames per second) thermographic measurements of single and multiple line scans on plates with and without powder layers using a variety of processing conditions and to discuss the impacts of powder on the measurement.

10:45 AM
Monitoring of Single-track Degradation in the Process of Selective Laser Melting: *Ivan Zhirnov*[1]; Maria Doubenskaia[2]; Dmitry Kotoban[1]; [1]Moscow State University of Technology “STANKIN”; [2]Université de Lyon, Ecole Nationale d’Ingénieurs de Saint-Etienne (ENISE), Saint-Etienne, France

Selective laser melting machines provide the optimal working parameters for manufacturing during the process. However, the laser interaction with metal powder is an unstable. The gasdynamic flows make powder particles move and escape from the melting pool. This phenomenon leads to an irregular distribution of the material volume being remelted. Since the energy is constant during the process, single-tracks with different geometry are appeared and their superposition forms the 3D-object. To detect the process abnormality of stable track formation there was developed a control system based on morphological analysis of thermal image obtained by IR-camera. The temperature field distribution along the image matrix’s row with the maximum temperature was used as influencing factor on stable track formation. The roughness was reduced from 39.9 to 6.6 µm by using control system with the same process parameters. The obtained results can be applied in industrial SLM machines with integrated active control system.

11:05 AM
Machine Learning for Defect Detection for PBFAM using High Resolution Layerwise Imaging Coupled with Post-Build CT Scans: *Jan Petrich*[1]; Christian Gobert[1]; Shashi Phoha[1]; Abdalla Nassar[1]; Edward Reutzel[1]; [1]ARL Penn State

This paper develops a methodology based on machine learning to detect defects during PBFAM processes using data from high resolution images. The methodology is validated experimentally using both a support vector machine (SVM) and a neural network (NN) for binary classification. High resolution images are collected each layer of the build, and the ground truth labels necessary for supervised machine learning are obtained from a 3D computed tomography (CT) scan that is processed using image processing tools—extended to 3D—in order to extract xyz position of voids within the component. Anomaly locations are transferred from the CT domain into the image domain using an affine transformation. Multi-dimensional features are extracted from the images using data surrounding both anomaly and nominal locations. Using cross-validation strategies, accuracies approaching 90% are achieved.

11:25 AM
Selection and Installation of High Resolution Imaging to Monitor the PBFAM Process, and Synchronization to Post-Build 3D Computed Tomography: *Jacob Morgan*[1]; John Morgan[1]; Donald Natale[1]; Robert Smith[1]; Wesley Mitchell[1]; Alexander Dunbar[1]; Edward Reutzel[1]; [1]Applied Research Laboratory - The Pennsylvannia State University

Industrial application of PBFAM continues to expand, and there is growing interest in use of sensors to monitor the process. Sensor data collected during the build provides insight into process physics, and may also lead to a reduction in overall fabrication time and cost by offering an alternative to extensive post-build nondestructive inspection for quality control. Ultimately, sensor data may serve as feedback for real time control systems that automatically repair flaws before they are buried by subsequent layers. In this work, high resolution images are explored as a means of monitoring the PBFAM process inside a 3D Systems ProX320. Key design considerations for camera selection and integration are discussed, and methods and algorithms are developed to calibrate and map image data to laser scan vectors. Images are stacked and exported to standardized 3D data formats to enable easy inspection and comparison to post-build 3D computed tomography scans.

Process Development 4: Novel Processes, Energy, Computing

Tuesday AM — Room: 416A-B
August 8, 2017 — Location: Hilton Austin

Session Chair: Yong Chen, University of Southern California

8:15 AM
Preliminary Study of Large Area Polymer Sintering with Projection Sintering: *Justin Nussbaum*[1]; Garrett Craft[1]; Alexander Murphy[1]; Julie Harmon[1]; Nathan Crane[1]; [1]University of South Florida

Projection sintering (patent pending) is a novel additive manufacturing (AM) technology recently developed at the University of South Florida, which uses a high power projector to fuse an entire layer of powder simultaneously. Projection sintering offers many advantages over traditional AM technologies by providing a means to create high strength thermoplastic components with the ability to finely control the heating profile over a large area with extreme resolution. This technology uses longer than typical exposure times (>1 s) but by patterning a large area, it's capable of high production rates. Long exposure times allow for a minimal overshoot of the material's melting temperature, thus decreasing the degradation of the polymer. These results along with processing parameter optimization are presented to show how this technology is capable of producing components with highly increased strength and ductility when compared to any other polymer AM technology.

8:35 AM
Multisystem Modeling and Optimization of Solar Sintering System: Clinton Morris[1]; David Debeau[1]; *Amber Dressler*[1]; [1]University of Texas at Austin

In developing countries, the production of building materials such as tile and brick, require large amounts of non-renewable energy and/or time to produce. Previous work has shown that solar sintering machines are capable of producing ceramic parts in a viable amount of time using only solar energy. The systems focus sunlight on a bed of sand where the intensity is sufficient for sintering. Then by moving the sand bed, parts of complex geometry are formed. This study aims to identify optimal operating parameters for the solar sintering system by solving a multi-objective, multisystem model. The subsystems considered are the dynamics of the sand bed, optics of focusing sunlight, and heating of the sand bed. To reduce the computational expense, a Kriging surrogate model was employed to model the heating of the sand bed. Finally by performing a tradeoff analysis of production time and part quality, candidate operating parameters were identified.

8:55 AM
Casting-forging-milling Composite Additive Manufacturing Technology: *Zhang Haiou*[1]; Li Runsheng[1]; Wang Guilan[1]; Tang Shangyong[1]; Wang Rui[1]; Fu Youheng[1]; Wang Xiangping[1]; [1]Huazhong University of Science and Technology

The current metal additive manufacturing has some drawbacks, such as poor performance in producing forgings, low accuracy and efficiency, and high cost. This paper proposes a new technology called casting-forging-milling composite(CFMC) additive manufacturing, which uses the efficient and cheap arc as the heat source. Synchronous arc welding and continuous semi-solid in-situ forging is achieved with micro-roller. Milling is incorporated into this process to remove defects and complete the part.Workpieces with equiaxed fine-grained microstructure and better performance than forgings have been obtained using CFMC. Testing shows that the mechanical performance exceeds the standards for forgings and most indicators are above the average levels. Trial products include titanium alloy aeronautical parts, a stainless steel propeller, and an aero-engine transition section which has passed the European standard x-ray inspection and test. The streamlined and low-cost manufacturing process achieved by using metal wire, integrated equipment and low pressure makes CFMC a green manufacturing model.

9:15 AM
The Influence of Exposure Time on Energy Consumption and Mechanical Properties of SLM-fabricated Parts: *Shuangmei Xu*[1]; Tao Peng[1]; Hong Zhang[1]; [1]Zhejiang University

Selective laser melting (SLM) is a relatively mature metal additive manufacturing process. Many process parameters can be configured to reduce fabrication time, which directly relates to energy consumption, while achieving acceptable part properties. Exposure time, the laser beam dwelling time at a point, is a key parameter in pulse-laser SLM processes. It is used to calculate scanning velocity. Here, we focus on this parameter and investigate its influence on energy consumption and mechanical property in fabricating 316L stainless steel. Energy consumption increases with exposure time, but specifically, it was found that the increase of exposure time led to higher power rather than longer fabrication time. This may be affected by laser jumping time. Mechanical properties measured, including tensile, flexural and torsional strength, and density, shown a positive correlation with exposure time. It is therefore possible to optimize energy consumption for acceptable properties based on exposure time within a specified range.

9:35 AM
Energy Coupling Efficiency and Melt Pool Dynamics Associated with the Laser Melting of Metal Powder Layers: *Manyalibo Matthews*[1]; Johannes Trapp[2]; Gabe Guss[1]; Sheldon Wu[1]; Alexander Rubenchik[1]; [1]Lawrence Livermore National Laboratory; [2]TU Dresden

Accurate prediction of the material response associated with any laser materials processing technology depends on precise knowledge of the energy coupling efficiency and mechanism active during the laser-matter interaction. Micro-calorimetry and high speed imaging are used to characterize energy coupling mechanisms in laser powder bed fusion additive manufacturing, yielding insights to the morphology-driven changes in effective absorptivity. Material-dependent keyhole formation onset and melt pool dynamics are investigated as a function of laser parameters. Ultra-high speed videography and finite element simulations are used to support the absorptivity measurements and gain further insight into energy coupling mechanisms.

9:55 AM Break

10:25 AM
Syringe Dispense of Copper Paste with Formic Acid Cure: *Judi Lavin*[1]; David Keicher[1]; Marcelino Essien[2]; Seethambal Mani[1]; [1]Sandia National Laboratories; [2]IDS

Direct write additive manufacturing printing approaches provide an opportunity to explore a wide range of materials using a variety deposition modules to impact electronics industry among others. Particularly applications involving space constraints and demanding conformality are best suited to benefit from this direct write approach. Specifically, in this case the use of a syringe dispense print head in the printing of copper pastes for electronic interconnects is carried out. This presentation will cover ongoing work in the printing of copper paste, achieving robust adhesion to the substrate while maintaining a degree of flexibility, all the while, working towards achieving as low a resistivity as possible. The relatively unexplored approach of curing copper under a formic acid environment will be discussed.

10:45 AM

Bio-inspired Micro-scale Texture Fabrication based on Immersed Surface Accumulation Process: *Xiangjia Li*[1]; Yang Yang[1]; Yong Chen[1]; [1]University of Southern California

Biomimetic functional textures are attracting increasing attention for the relevant technological applications. The promising functional properties can be improved by adding biomimetic textures. However, it is difficult to fabricate biomimetic functional textures on the pre-existing three-dimensional (3D) objects by the traditional fabrication techniques, especially it is challenging to build micro-scale textures on macro-scale freeform surfaces. In this paper, we present a surface-projection-based accumulation process, in which the curing tools are immersed inside liquid resin to fabricate such bio-inspired micro-scale textures on a given 3D object. The immersed surface accumulation process (ISAP) can build the micro-scale textures at high-resolution (3um) within seconds. The superhydrophobic micro-textures and fog collection micro-texture fabricated by ISAP are demonstrated in this paper. The multiple capabilities integrated within these bio-inspired micro-scale textures highlight the technical flexibility and broad applicability of our newly developed AM process in engineering advanced functional application.

11:05 AM

Review of Ultra-High Speed Imaging of Powder Bed Fusion Additive Manufacturing Processes: *Gabe Guss*[1]; Sonny Ly[1]; Sasha Rubenchik[1]; Saad Khairallah[1]; Andy Anderson[1]; Wayne King[1]; Ibo Matthews[1]; [1]Lawrence Livermore National Laboratory

The high scan speeds (~1 m/s) and small laser irradiated length scales (~100 \956m) associated with powder bed fusion additive manufacturing naturally imply a high-speed process with melt pool fluctuations occurring at frequencies approaching 1 MHz. To understand the dynamic processes occurring in the melt pool, e.g., surface shape and flow velocity, an imaging system with frame rates up to 10 MHz was employed. 500 W pulsed illumination and high magnification microscopy were combined to image the melt pool, during various stages of single-track processing, e.g., laser turn off at the end of the track. These results are shown to validate high performance computing simulations of the process. *Prepared by LLNL under Contract DE-AC52-07NA27344.*

11:25 AM

Melt Pool Image Process Acceleration Using General Purpose Computing on Graphics Processing Units: *Robert Sampson*[1]; [1]TWI

Additive manufacturing (AM) processes are incredibly complex, and the intricate web of changing process parameters can result in poor repeatability and structural consistency. New geometric designs result in an initial iteration process to optimise build parameters, which subsequently uses up resources. A deep understanding of process parameters in AM, and the ability to control and manipulate said parameters, will lead to advanced AM capabilities.Non-contact devices are typically required to measure the build characteristics such as melt pool geometry and temperature, which give a greater understanding of the complex AM process. This paper will look to view the molten metal pool that is formed in the Direct Energy Deposition (DED) process using CMOS cameras. This paper displays a new method of using General Purpose computing on Graphics Processing Units (GPGPU) to accelerate the image processing technique for such applications.

Special Session: Hybrid Processes 1

Tuesday AM — Room: 406
August 8, 2017 — Location: Hilton Austin

Session Chair: Michael Sealy, University of Nebraska-Lincoln

8:15 AM Invited

Direct Additive Subtractive Hybrid Manufacturing (DASH): An Out of Envelope Method: *Matt Frank*[1]; Ola Harrysson[2]; Richard Wysk[2]; Niechen Chen[1]; Harshad Srinivasan[2]; Guangyu Hou[1]; Carter Keough[2]; [1]Iowa State University; [2]North Carolina State Univeristy

A Direct Additive and Subtractive Hybrid (DASH) manufacturing system using both additive and then subtractive processing has been developed. The approach includes the development of a software system to link additive and subtractive manufacturing, using extensions to the AMF format, to maintain product design features along with their tolerance specifications. It also introduces the idea of sacrificial fixtures that are automatically designed into the parts to allow subsequent fixturing in the CNC mill. Once in the milling machine, a part localization system identifies the part and its location, along with capturing the geometry of any remaining AM support material left on the part. Finally, all CNC code is automatically generated and the finishing process can be executed in a lights-out operation. This work provides a drastic reduction in post processing time and cost. It further enables expansion of metal AM and uniquely addresses the challenge of out-of-envelope hybrid manufactured parts.

8:35 AM Invited

Metallic Components Repair Strategies using the Hybrid Manufacturing Process: *Xingchang Zhang*[1]; Wenyuan Cui[1]; Wei Li[1]; Frank Liou[1]; [1]Missouri University of Science and Technology

The hybrid manufacturing process which integrates additive manufacturing with subtractive machining is competitive and promising in component repair. To automate this process, detecting the missing volume and generating the deposition tracks is the key. In this study, strategies for repairing defects on flat and non-flat surfaces were investigated. A cost-effective reverse engineering tool was utilized to reconstruct STL models of damaged objects. Point data of the fracture surface on flat surfaces was obtained to generate the tool path for material building up. For defects on non-flat surfaces, the damaged model was best-fitted with the nominal model. Then both models were sliced and by using area comparison method, the defective domain was detected. Then a series of projection rays were utilized to slice the damaged cross-sections to extract the repair volume. Finally, repair experiments were performed to assess the repair quality through repair automation.

8:55 AM

Rapid Prototyping of EPS Pattern for Complicated Casting: *Ranjeet Kumar*[1]; Sajan Kapil[1]; Seema Negi[1]; Nihal Gehlot[1]; Suhas Hurli Gopalakrishna[2]; K.P. Karunakaran[1]; [1]IIT Bombay; [2]VIT University Vellore

In Rapid Prototyping (RP) process the 3D object is approximated into several 2D slices. All these slices are of a uniform thickness hence called uniform slicing of zeroth order approximation. Such a system always suffers with the staircase defects. Very thin slices have to be used to minimize these defects, which increase the production time. In this work, a RP system called Segmented Object Manufacturing (SOM) is used to produce the Expanded Polystyrene (EPS) pattern, which uses adaptive slicing with higher order approximation. This system uses the concept of visible slicing in which a complicated object is produced by converting it into the accessible (visible) segments. This is a hybrid system for producing EPS patterns which utilizes the advantages from subtractive and additive processes. These EPS patterns found their application in Evaporative Pattern Casting (EPC). EPS bracket is produced by SOM machine to prove the capability of the system.

9:15 AM
5-Axis Slicing Methods for Additive Manufacturing Process: *Sajan Kapil*[1]; Seema Negi[1]; Jitendra Sonwane[1]; Arun Sharma[1]; Ranjeet Bhagchandani[1]; K. P. Karunakaran[1]; [1]Indian Institute of Technology Bombay

In metallic Additive Manufacturing (AM) processes such as Hybrid Layered Manufacturing (HLM), it is difficult to remove the support material used for realizing the overhanging/undercut features. Multi-axis kinematics can be used to eliminate the requirement of the support mechanism. In this work, two slicing methods have been proposed which utilize the benefits of multi-axis kinematics to eliminate the support mechanism. In the first method, planar slicing is used and the overhanging/undercut features are realized while keeping the growth of the component in the conventional Z-direction. In the second method, non-planar slicing is used, and the growth of the component need not necessarily be in the Z-direction; it can also be conformal to the selected feature of the component. Both these methods are explained through a case study of manufacturing an impeller by the HLM process.

9:35 AM
A Hybrid Method for Additive Manufacturing of Silicone Structures: *Farzad Liravi*[1]; Varun Jacob-John[2]; Ali Toyserkani[1]; Mihaela Vlasea[1]; [1]University of Waterloo; [2]University of British Columbia

Silicone (polysiloxane) is used in a wide range of medical applications which require the fabrication of complex material- and functionally-graded structures. Additive Manufacturing (AM) provides a robust solution to the production of such heterogeneous structures. However, AM of silicone elastomers has been proved to be difficult mostly due to their high viscosity. Hence, no consistent method for AM of silicone has been suggested before. In this research, a hybrid AM technique combining powder-bed binder-jetting (PB-BJ) and micro-dispensing will be introduced for high-speed fabrication of parts from silicone powder. The material system involves a silicone powder (~35 um), an aqueous liquid binder (viscosity ~12 mPa.s), and a heat-curable silicone (viscosity ~25 Pa.s). Standard cylindrical parts were printed which demonstrated necessary resilience and geometrical accuracy for biomedical applications. Moreover, the mechanical, internal, and surface characterization of the printed parts as well as the rheological properties of the silicone powder will be presented.

9:55 AM Break

10:25 AM Invited
Advanced Hybrid Manufacturing: Roadmap of Technological Challenges: *Guha Manogharan*[1]; Brett Conner[2]; Richard Wysk[3]; Ola Harrysson[3]; [1]Pennsylvania State University; [2]Youngstown State University; [3]North Carolina State University

Additively manufactured (AM) metallic components offer a pathway to shorter lead times, affordable low volume production and complex uniquely-customized products. Unfortunately for most metal AM components, material properties, surface finish and tolerances are not sufficient for use within assemblies. Post-processing (e.g., secondary operations after AM, such as machining, heat-treatment, HIP, grinding, micro-finishing and abrasive polishing) can be used to address many of these requirements. Since 2015, The Consortium for Advanced Hybrid Manufacturing - Integrating Technologies (CAM - IT), a NIST AMTech program has been developing a roadmap of technological challenges required to enable adoption of metal AM through seamless integration with conventional value chains. Specifically, the six detailed critical swim lanes identified from CAM-IT's four road-mapping workshops are presented. We envision that this unique roadmap will provide a structured network of metal AM, hybrid experts and users who can formulate, support and address the needs and strategies for hybrid manufacturing.

10:45 AM Invited
Opening the Architecture of AM with Hybrid Manufacturing Technologies: *Jason Jones*[1]; [1]Hybrid Manufacturing Technologies

Self-contained system architectures have dominated Additive Manufacturing (AM) since its inception. While ideal for prototyping applications, this has inadvertently lead to a) the development of AM largely in isolation from mainstream manufacturing techniques and b) fostered the segregation of disparate AM techniques. The rise of hybrid CNCs with integrated AM capabilities has made significant strides toward assimilating AM with mainstream manufacturing (a). This foundational development now provides a suitable platform for integrating multiple types of AM in a single system (b). This presentation highlights the world's first commercial approach to opening the architecture of AM, enabling on-demand deployment of heretofore segregated AM technologies including metal and polymer deposition in a single setup. The author asserts that the combination of multiple additive, subtractive and inspection/sensing techniques on the same platform paves the way toward digital fabrication of smart products. Open architecture AM tools are poised to accelerate this great endeavor.

11:05 AM
Analysis of Hybrid Manufacturing Systems Based on Additive Manufacturing Technology: *Marlon Cunico*[1]; Dalton Kai[2]; [1]University of São Paulo; [2]Pontifical Catholic University of Parana

Along the last year, additive manufacturing technologies has been proving to be a real game changer in several market segments. Nevertheless, the main foundation of production and flexible manufacturing systems generally considers classical technologies. For that reason, the present work aim to propose and investigate manufacturing systems which includes additive manufacturing technologies as part of the main or secondary production flow. As result, it was identified that several marketing segments, types of components and different annual volumes tend to be better attended by hybrid flexible manufacturing systems which includes additive manufacturing technologies.

11:25 AM Invited
Synergistic Integration of Hybrid Processes and Multiple Technologies: *K. P. Karunakaran*[1]; Alain Bernard[2]; Sajan Kapil[1]; Jitendra Sonwane[1]; Seema Negi[1]; Arun Sharma[1]; Rakesh Kumar[3]; [1]Indian Institute of Technology Bombay; [2]Ecole Centrale de Nantes; [3]Fr. C. Rodrigues Institute of Technology

No process is omnipotent; each has a narrow window of applications owing to its strengths and limitations. Strategies [addition/subtraction], energy sources [arc/LASER/Electron Beam], layer types [uniform/adaptive; planar/conformal; edge order], kinematics [3-axis/5-axis; serial/parallel] and removal mechanisms [ablation/shearing] are complementary processes to be synergistically combined to exploit their advantages while bypassing their limitations. Furthermore, stress relieving [pre-/post-heating/peening] and inspection are the technologies to be seamlessly integrated in a transfer system to minimize material movement. Laminated Object Manufacturing (LOM), Solid Ground Curing (SGC) and Shape Deposition Manufacturing (SDM) were hybrid systems combining addition and subtraction. Hybridization in the authors' Multi-Station Multi-Axis Hybrid Layered Manufacturing (MSMA-HLM) has gone far beyond. It uses 5-axis LASER cladding to build boundaries in thin layers and fills the thick interior using 2.5-axis MIG cladding. They have built the impeller blades in conformal layers. MSMA-HLM has stations for pre-heating & peening and inspection. MSMA-HLM is close to commercialization.

Applications 6: Lattices 2

Tuesday PM	Room: 602
August 8, 2017	Location: Hilton Austin

Session Chair: Li Yang, University of Louisville

1:40 PM
The Mechanical Performance of Triply Periodic Minimal Surface Lattice Structures: *Ian Maskery*[1]; [1]University of Nottingham

Three-dimensional lattices have applications across a range of fields including structural lightweighting, impact energy absorption and biomedicine. In this work, lattices based on triply periodic minimal surfaces were produced by additive manufacturing and examined with a combination of experimental and computational methods. The lattice types were the gyroid, diamond and primitive. This investigation elucidates their deformation mechanisms and provides numerical parameters crucial in establishing relationships between their cell geometries and mechanical performance. The primitive lattice was found to have a relative modulus over 100 percent greater than those of the other two types. The compressive deformation process of the primitive lattice was also considerably different from those of the other two, exhibiting strut stretching and buckling, while the gyroid and diamond lattices deformed in a bending-dominated manner. Finite element predictions of the deformation of the lattices were in close agreement with experimental observations.

2:00 PM
Estimating Strength of Lattice Structure Using Material Extrusion Based on Deposition Modeling and Fracture Mechanics: *Sang-in Park*[1]; David Rosen[1]; [1]Georgia Institute of Technology

Geometrical complexity in lattice structure yields large bounding surfaces to be approximated during additive manufacturing (AM) processes. In material extrusion, approximation of geometries using finite-sized thin filaments introduces defects such as voids and gaps in as-fabricated geometries. This initiates cracks between layers and increases possibility of failure by crack propagation. As a result, a lattice structure fabricated by material extrusion tends to fail at significantly lower stress, which is estimated without consideration of fracture mechanism. The goal of this research is to estimate strength of a lattice structure by quantifying bonding strength among layers in material extrusion. To achieve this, the bonding strength is determined based on a deposition process modeling scheme and fracture mechanics analysis. A two-layer deposition model is generated, and the effective interlayer-bonding strength is calculated using numerical fracture mechanics analysis and T-peel test. The resulting strength is incorporated into the property-estimation procedure.

2:20 PM
Multiscale Analysis of Cellular Solids Fabricated by EBM: *Edel Arrieta*[1]; Jorge Mireles[2]; Calvin Stewart[2]; Cesar Carrasco[2]; Ryan Wicker[2]; [1]The University of Texas at El Paso ; [2]The University of Texas at El Paso

Powder bed fusion permits the creation of cellular lattice metals, whose response can be manipulated from different approaches. Whereas the existing research is somehow limited for these metals, it mostly focuses on very specific topics such as microstructure, geometry and orientation. However, the response of these metametals can be seen as the result of a multiscale interaction between multiple factors ranging from the microstructure of the constitutive solid up to the cell topology. This work is intended as a one-stop document for a new branch of material designers, the major factors found affecting the material response are classified, discussed and merged in a multiscale analysis supported by evidence from a series of experiments on EBM Ti-6Al-4V specimens, for the comprehensive understanding of the explored lattice designs. Illustrative examples of how the stress-strain curves are helpful in diagnosing design features to start reverse engineering processes are included.

2:40 PM
An Investigation of Property Isotropy of 3D Periodic Cellular Structure Designs: *Li Yang*[1]; [1]University of Louisville

In the design of periodic cellular structures, there exist various isotropic unit cell designs that possess identical theoretical mechanical properties along three or multiple principal symmetry directions. Although such definition of “isotropy” differs from the traditional definition that is used for solid materials, it is often considered to represent the equivalent design implications in many applications. In this study, the mechanical properties of various 2D and 3D periodic cellular structures under uniaxial stress along different non-principal directions were investigated. The relationships between the cellular unit cell geometries, structural size, loading orientation and the mechanical properties of the cellular structures made of perfect elastic-plastic material were discussed, which provide insights into the future design of cellular structures when utilizing homogenization treatments.

3:00 PM
Modeling of Fracture Characteristics in 2D Brittle Lattice Structures Assisted by Additive manufacturing: *Yan Wu*[1]; Li Yang[1]; [1]University of Louisville

The failure characteristics of lattice structures are of significant importance in various lightweight applications such as aerospace and biomedicine. In this study, several 2D lattice structures with different number of unit cells that represent different geometrical characteristics and deformation mechanisms were investigated for their fracture behaviors. The fracture characteristic of the cellular samples was studied experimentally through tensile testing. The fracture propagation patterns of different lattice designs were investigated by high-speed camera, and consequently analyzed via analytical model in order to evaluate the effect of finite unit cells on the fracture characteristics of these cellular structures. The results were further compared with the classic cellular fracture theory by Gibson and Ashby. The comparison results suggest that for small number of unit cells designs the homogenized fracture model does not provide accurate crack propagation predictions.

3:20 PM
A Study of the Size Effect of Fracture on Additively Manufactured Periodic Cellular Structures: *Li Yang*[1]; Yan Wu[1]; [1]University of Louisville

The size effect of periodic cellular structures affects not only the elastic properties of these structures but also their stress status, which is closely associated with the structural fracture behaviors. In this work an experimental based study was carried out to evaluate the size effect of fracture characteristics on different cellular structures (re-entrant auxetic, BCC and octet-truss) fabricated via electron beam melting (EBM) additive manufacturing (AM) system using Ti6Al4V as material. Various characteristics, including fracture initiation sites, stress-strain pattern and energy absorption of the cellular structures with various overall sizes were analyzed and compared with limited simulation results, which provide insight into the relationship between the cellular structure size design and its fracture behaviors.

3:40 PM
Mechanical Property Variation in Metal Lattice Structures: *Amber Dressler*[1]; Carolyn Seepersad[1]; [1]The University of Texas

Direct metal laser sintered lattice structures offer favorable tradeoffs between strength and weight, which are of interest to designers. However, manufacturing defects present throughout the lattices create significant variability in mechanical properties and part performance. The goal of this research is to improve the understanding of how defects impact mechanical properties to enhance designers’ ability to design metal lattice structures reliably. To accomplish this, two sets of lattice specimens of various sizes will be manufactured, tested, and analyzed. The first set will isolate individual lattice struts while the second set will investigate periodically repeated unit cells in the form of octet truss lattices. Non-destructive and destructive test methods will be used to search for correlations between processing parameters, part parameters, defects, and part performance.

Applications 7: Economics

Tuesday PM	Room: 616A-B
August 8, 2017	Location: Hilton Austin

Session Chair: Igor Yadroitsev, Central University of Technology, Free State

1:40 PM
Cost-efficient Design and Machine Productivity: A Technology-spanning Approach: *Christian Lindemann*[1]; Rainer Koch[1]; [1]Paderborn University

Additive Manufacturing technologies offer a high potential for the economic use in an industrial environment. This includes costing aspects, the technical possibilities and barriers. Costing aspects are important along the overall product design process and decisions to be made during this process have wide-ranging consequences. For the optimal design of technical products, the product requirements are as important as the consideration of a cost-efficient manufacturing. Due to this reason, the designers need assistance and tools to support and justify their decisions during the product design process. This paper shows tools for a cost-efficient product development framework, especially for the early phases of the product design process. The paper discusses an approach to compare productivity rates of the AM production equipment and explains how to utilise them in an optimal way. Technical innovations like multi laser systems will be discussed.

2:00 PM
How Significant is the Cost Impact of Part Consolidation within Additive Manufacturing Adoption?: *Alicia Stevenson*[1]; Martin Baumers[1]; Joel Segal[1]; Sarah Macdonell[2]; [1]University of Nottingham; [2]Malvern Instruments Ltd.

Successful implementation of advanced manufacturing technologies requires a robust pre-installation phase involving evaluation and justification of potential benefits. However, despite part consolidation (PC) being described as one of the major benefits of additive manufacturing (AM), there has been very little quantification of its potential impact on costs. This makes it difficult for organisations to consider all the benefits of AM adoption. A case study research approach has been used to develop an empirical cost model based on PC for the development and production stages of a product, which can be adapted by organisations during their own pre-installation stage. The case studies involve re-design of existing sub-assemblies within a laboratory instrument producer, and the resulting cost model has been trialled using empirical data. The results show that AM has the potential to considerably reduce part count by up to 93% and associated costs by up to 85%. The significant cost saving occurs where PC results in the consolidation of numerous components thereby eliminating considerable cost elements.

2:20 PM
Method for the Evaluation of Economic Efficiency of Additive and Conventional Manufacturing: *Cordula Auth*[1]; Alexander Arndt[1]; Reiner Anderl[1]; [1]Department of Computer Integrated Design (DiK), Technische Universität Darmstadt, 64287 Darmstadt, Germany

The advantages of individuality and complexity for free are commonly known in the field of additive manufacturing, but, nevertheless, they compete with advantages of conventional manufacturing methods. On the one hand, a small size production can be economically viable through additive manufacturing. On the other hand, conventional manufacturing methods are well known and optimized, so that they have low cost per unit. Therefore, to evaluate the economic efficiency various criteria are needed to compare additive and conventional manufacturing methods. In the following part comparative criteria and influence factors for economic efficiency are identified and described. Besides general aspects personal reasons may influence a manufacturing decision. Therefore, the identified criteria are used to build a method which helps the user to decide on a manufacturing method depending on personal preferences. The structure and use of this method is described in the second part. After this, an outlook and conclusion is given.

2:40 PM
Comparative Costs of Additive Manufacturing vs. Machining: The Case Study of the Entire Annual Production of Forming Dies for Tube Bending: *Barbara Previtali*[1]; Ali Gokhan Demir[1]; Marco Bucconi[1]; Andrea Crosato[2]; Mauro Penasa[2]; [1]Politecnico di Milano; [2]BLM Group

Additive processes for metallic components have nowadays economic sense when they substitute conventional processes that make use of molds and dies to produce casting or semi-finished parts with high added value. Common examples are: i) components in aerospace or energy sectors obtained by investment casting in high-temperature alloys; ii) personalized prostheses and implants in biocompatible metals in the biomedical sector. In both cases, the annual batch size is low and often is limited to single or few pieces. The paper explores the economic feasibility of SLM additive process when producing tube-forming tools. The analyzed industrial case addresses the whole annual production of massive steel tools for the bending of tubes, traditionally made by milling from solid block. The aim of this work is to identify the levers of the process that make additive production advantageous, even in more traditional sectors like mechanics and for very common materials like tool steel.

3:00 PM
Integrating AM into Existing Companies: Selection of Existing Parts for Increase of Acceptance: Anne Kruse[1]; *Thomas Reiher*[1]; Rainer Koch[2]; [1]Paderborn University / DMRC; [2]Paderborn University / C.I.K.

For bringing AM-technology closer to designers, it is necessary to show them those of their existing conventionally manufactured parts that can be produced with AM. A part selection methodology, developed in several projects, supports designers in the decision whether a part is suitable for AM or not. Due to the potential of AM, which was especially seen in the aerospace industries, many criteria of the methodology were initially adapted for this industry. Furthermore the methodology is based on a quantified weighting system, which comes to a certain subjectivity. For future use, a development towards a less subjective methodology should be accomplished. Through a more detailed adaption for individual industries and a simplification of the input mode, the objectivity of the criteria can be increased. Likewise, the input time can be reduced by simplifying the questioning. A more efficient part selection will be achieved by a better weighting system.

3:20 PM
Ramp-Up-Management in Additive Manufacturing – Technology Integration in existing Business Processes: *Johannes Büsching*[1]; Rainer Koch[2]; [1]Paderborn University / DMRC; [2]Paderborn University / C.I.K.

In conventional manufacturing, ramp-up-management describes the planning and organization of the period between finished product development and the achievement of full production capacity for defined products. This classification has to be adapted and restructured by means of product independent and tool-free production in additive manufacturing. Therefore ramp-up-management already starts with decisions on the extent of the use of additive manufacturing, includes the building of technology-know-how as well as the technology integration into processes and infrastructure of the company and ends with the attainment of a sufficient process reliability for the AM-machine. This paper focuses on technology integration in processes and infrastructure, which is part of the German research project OptiAMix. In this project, new systems for process state analysis adapted to additive manufacturing and methods for the optimal integration of additive manufacturing are developed. Furthermore ways of using the synergies of existing infrastructures and new innovative production technologies are determined.

3:40 PM
Rational Decision-Making for the Beneficial Application of Additive Manufacturing: *Gereon Deppe*[1]; Rainer Koch[2]; Martin Kaesberg[3]; [1]Paderborn University - DMRC; [2]Paderborn University - C.I.K.; [3]Paderborn University

Additive Manufacturing is a technology that offers a high potential for industrial companies. Nevertheless, companies lack experience with this new technology and face the problem to identify processes where a successful and beneficial application can be achieved. They have to be supported in this analysis with a decision support tool which is capable to compare different manufacturing or repair approaches in order to determine the optimal solution for the correspondent use case. This is not always driven solely by costs but can also be critically affected by further influencing factors. This is why the decision support takes into account also time and quality alongside the costs. For a time-critical spare part supply, for example within aerospace sector, they are substantial for taking a decision. The presented decision support features a multi-attribute decision-making approach for selecting the most appropriate process, either Additive Manufacturing, conventional technologies or an external procurement.

Materials 7: Aluminum

Tuesday PM — Room: 615A-B
August 8, 2017 — Location: Hilton Austin

Session Chair: Eleonora Ferraris, KU Leuven

1:40 PM
Influence of Arcam EB Parameters on Properties in Aluminum Alloy 2024: *Maria Withrow*[1]; Chris Rock[2]; Tim Horn[2]; Harvey West[2]; [1]NC State CAMAL; [2]Center of Additive Manufacturing and Logistics

Aluminum 2024 is an age hardenable cast-wrought alloy with excellent strength and low weight but has been slow to be adopted in additive manufacturing processes due to material compatibility issues. In this study Al 2024 was manufactured through electron beam melting (EBM) at a build temperature of 525C to produce dense parts. Build parameters had a noticeable influence on the chemistry, grain morphology, CuAl2 precipitation, and density of the samples. Solution studies of selected specimens were also performed and compared with wrought Al 2024 to determine the influence of EBM on CuAl2 solution and formation.

2:00 PM
Processing and Characterization of Aluminum 6061 using Selective Laser Melting at Elevated Temperature: *Syed Zia Uddin*[1]; Philip Morton[1]; Ryan Wicker[1]; [1]The University of Texas at El Paso

Parameter development study for pre-alloyed aluminum 6061 powder was carried out using AconityONE, (Aconity3D, Aachen, Germany) a laser based powder bed fusion technology with induction heating capability of the build platform. 10x10x10 mm cubes were used for parameter development with variation in laser-power, scanning speed and hatch spacing. Relative density of 96% was achieved with 30μm layer thickness. However, formation of solidification cracks was observed in post fabrication metallographic analysis, which would greatly inhibit component performance. Additional parameters such as platform temperature and layer thickness were tested with single and double melting of the layers to minimize cracking. This research was significant in its approach of using high temperature induction heating for SLM processing that had been absent thus far in selective laser melting (SLM) technologies. Further research will be continued to minimize crack formation and build fully dense parts.

2:20 PM
Selective Laser Melting of Al7075 by Application of Powder Bed Preheating: *Raya Mertens*[1]; Sam Buls[1]; Jan Van Humbeeck[1]; Jean-Pierre Kruth[1]; Kim Vanmeensel[1]; Brecht Van Hooreweder[1]; [1]KU Leuven

Selective Laser Melting (SLM) of Al7075 gained a lot of interest over the last years because of the large demand for high strength aluminum alloys from automotive and aerospace industry. Processability of this aluminum alloy by SLM is however limited due to crack formation. The large thermal stresses that occur during and after SLM and cause cracking, can be limited by application of powder bed preheating. This research shows a different crack behavior in parts produced with powder bed preheating at 400°C in comparison with parts produced without preheating. Furthermore, it was found that the scan strategy applied when using preheating, largely influences thermal gradients. These thermal gradients could be linked to the grain structure obtained in the parts and to crack formation. In this research, an optimal scan strategy is found that leads to a fine grained microstructure and inhibits crack formation in Al7075 SLM samples.

2:40 PM
Porosity Development and Cracking Behavior of Al-Zn-Mg-Cu Alloys Fabricated by Selective Laser Melting: *Ting Qi*[1]; Haihong Zhu[1]; Jie Yin[1]; Baijin Chen[2]; Zhiheng Hu[1]; Xiaoyan Zeng[1]; [1]Wuhan National Laboratory for Optoelectronics; [2]State Key Laboratory of Material Processing and Die and Mould Technology

Selective laser melting (SLM) of the 7xxx series Al alloy (Al-Zn-Mg-Cu) faces more challenge than other series aluminum alloy such as Al-Si system because of the high hot-cracking sensitivity. The porosity development and crack behavior of Al-Zn-Mg-Cu alloys fabricated at various scanning speeds in SLM process, as well as the influence of molten pool geometry were systematically investigated in this paper. Results show that the relative density over 99% can be achieved when the applied scanning speed is 100 mm/s. However, cracks are observed in almost all the as-deposited samples. The morphology, distribution and density of cracks were varied with the different molten pool geometry and scanning speed.

3:00 PM
Progress Toward the use of Elemental Aluminum-Silicon-Magnesium Mixtures in Selective Laser Melting: *Christopher Roberts*[1]; David Bourell[1]; [1]University of Texas at Austin

The variety of materials suitable for metal additive manufacturing (AM) is quite limited. In particular, only one near-eutectic aluminum alloy, AlSi10Mg, is in widespread commercial use despite the plethora of wrought and cast aluminum alloys commonly utilized in traditional manufacturing. The use of elemental mixtures has been proposed as a means to greatly expand the materials processing space for SLM allowing for the accelerated adoption of additive manufacturing technologies within industry. An overview of this approach as well as progress toward developing an aluminum-silicon-magnesium mixture mimicking the composition of AA6061 will be presented. Different powder mixing techniques, the use of intermediate compounds, specifically Mg_2Si, and a variety of processing conditions have been evaluated through metallographic analysis and EDS.

3:20 PM
Effects of AlSi10Mg Feedstock Condition on Part Properties: *Lisa Deibler*[1]; Benjamin Brown[2]; Jay Carroll[1]; [1]Sandia National Laboratories; [2]Kansas City National Security Campus

The condition of powder feedstock in selective laser melted parts is a key parameter in determining their final properties. In AlSi10Mg we have found that chemical changes to the powder due to powder reuse and handling make a significant difference in material properties, particularly affecting tensile ductility levels. The desired outcome of this research is an understanding of porosity effects on ductility, the causes of fine-scale porosity observed in this material, and a set of guidelines for aluminum powder handling or pre-treatment to avoid the formation of fine porosity. Powder morphology, surface chemistry, and bulk chemistry are being investigated, along with the ability and propensity for the powder to absorb moisture. Results of powder analysis from the affected builds will be presented, shedding light on the mechanism causing the porosity.

3:40 PM
Effect of Optimizing Particle Size in Laser Metal Deposition with Blown Pre-mixed Powders: *Wei Li*[1]; Jingwei Zhang[1]; Xinchang Zhang[1]; Sreekar Karnati[1]; Frank Liou[1]; [1]Missouri University of Science and Technology

Laser Metal Deposition is an effective process to fabricate Functionally Graded Materials with pre-mixed powders. Since the supplied powder mixture's dynamic flow movement in powder feeder pipe directly affects the composition, investigation on its property is greatly needed. This paper employed experimental method to reveal an important phenomenon: pre-mixed powder separation in powder feeder pipe, which causes severe deviation between designed composition and real composition. A novel particle size optimization method was introduced as solution to eliminate the powder separation. Cu and 4047 Al powders were mixed to do two experiments. The powder mixture transported following powder feeder pipe, and patterned in an epoxy resin coating after exiting nozzle. Different powder's volume percentages were plotted by quantifying different particles' distribution in the pattern. The first experiment result indicated the existence of powder separation. By optimizing the particle size, the pre-mixed powder separation was effectively solved in the second experiment result.

Materials 8: Nickel 718

Tuesday PM — Room: 408
August 8, 2017 — Location: Hilton Austin

Session Chair: Ola Harrysson, North Carolina State University

1:40 PM
Prediction of Grain Morphology in Electron Beam Melting of IN718 Superalloys: *Jingfu Liu*[1]; Behrooz Jalalahmadi[1]; [1]Sentient Science

Metal additive manufacturing (AM) becomes increasingly popular in fabricating complex, light-weight, and high-efficiency components in aerospace industry, while tailoring microstructure of additive metallic components is still a challenge. Microstructure characteristics in the rapid solidification process usually vary with process conditions, but the root cause is not clear yet. In this study, a coupled cellular automata (CA) - finite element (FE) model is presented to simulate microstructure evolution in electron beam melting (EBM) of IN718 superalloys. A 3-dimentional FE model was developed to simulate temperature history of building a L-shape part up to 8 layers. A 2-dimentional CA model was then used to simulate grain evolution at different cross-sections. Results indicate that grain morphology and grain size vary with locations due to different thermal gradients. Also, process conditions (e.g. scanning speed, hatch spacing, and scan rotation) have significant effects on dendrite orientation and grains size, which was further validated by experiments.

2:00 PM
Quantitative Texture Prediction of Epitaxial Columnar Grains in Additive Manufacturing: *Jian Liu*[1]; Qian Chen[1]; Yunhao Zhao[1]; Wei Xiong[1]; Albert C. To[1]; [1]University of Pittsburgh

The goal of this work is to establish the link between the microstructure (texture) and the process parameters of metal AM processes. A quantitative method based on the epitaxial growth of columnar grains within and across melt pools is proposed to predict the texture formation during a metal AM process. Both analytical modeling and FEM simulation have been used to predict the geometry and thermal profile of the quasi-steady melt pool. The thermal gradient distribution within the 3D melt pool determines the crystallography direction and growth direction of the columnar grains within each deposited single and multiple tracks. The single and multiple tracks with the predicted geometry are amalgamated together to represent the bulk part, and the epitaxial growth of grains across the boundary of neighboring tracks are quantitatively modeled. The proposed method is calibrated and validated by experimental studies of metal AM processed Inconel 718.

2:20 PM
Relationship of Powder Feedstock Variability to Microstructure and Defects in Selective Laser Melted Alloy 718: *Timothy Smith*[1]; Chantal Sudbrack[1]; [1]NASA Glenn Research Center

Powder-bed additive manufacturing processes use fine powders to build parts layer by layer. For selective laser melted (SLM) Alloy 718, the powders that are available off-the-shelf are in the 10-45 or 15-45 micron size range. A comprehensive investigation of sixteen powders from these typical ranges and two off-nominal-sized powders is underway to gain insight into the impact of feedstock on processing, durability and performance of 718 SLM space-flight hardware. This talk emphasizes an aspect of this work: the impact of powder variability on the microstructure and defects observed in the as-fabricated and fully heat treated material, where lab-scale components were built using vendor recommended parameters. These typical powders exhibit variation in composition, percentage of fines, roughness, morphology and particle size distribution. How these differences relate to the melt-pool size, porosity, grain structure, precipitate distributions, and inclusion content will be presented and discussed in context of build quality and powder acceptance.

2:40 PM
Influence of Dwell Time on Localized Thermal History and Properties of Directed Energy Deposition (DED)-processed Inconel 718 Thin Walls: *Sarah Wolff*[1]; Jennifer Bennett[1]; Puikei Cheng[1]; Orion Kafka[1]; Jian Cao[1]; [1]Northwestern University

Rapid directional solidification during Directed Energy Deposition (DED) determines the unique phase changes, grain structure and mechanical behavior of the resulting component. Changes in process parameters, including the dwell time between the build of each layer, determines the thermal history of a component. This study investigates two Inconel 718 walls, one built with no dwell time and the other with one minute of dwell between each layer. An infrared (IR) camera captured the thermal history of both walls. The thermal histories reveal that the wall built with one minute dwell underwent greater solidification cooling rates. Microscopy, micro-Laue X-ray diffraction and micro-hardness testing show differing dendritic and grain morphology, averaged residual strain and micro-hardness at localized areas of the walls. This study investigates the relationships between thermal history, microstructure and mechanical behavior. A deeper understanding of these relationships will improve DED process design.

3:00 PM
On the Use of X-ray Computed Tomography for Monitoring the Failure of a Two-bar Small Specimen Manufactured by Selective Laser Melting: *Christopher Hyde*[1]; Adam Thompson[1]; Richard Leach[1]; Ravi Aswathanarayanaswamy[2]; Ian Maskery[1]; Christopher Tuck[1]; Adam Clare[1]; [1]The University of Nottingham; [2]Renishaw

Additive manufacturing technologies are highly versatile, capable of producing components with previously impossible complex geometries. However, when additive manufacturing is used to produce parts for critical applications (such as in the aerospace sector), the parts are limited by poor mechanical properties; largely as a result of porosity and lower material homogeneity than found in, for example, a wrought equivalent. Presented here is a method for identifying material defects, such as porosity, and for monitoring the progress of these defects towards failure during a mechanical test. An Inconel 718 two-bar specimen, produced by laser powder bed fusion, has been applied to a "staged" mechanical test, and X-ray computed tomography used to measure the sample at the end of each "stage". The X-ray computed tomography data has then been used to provide a history of failure sites prior to failure.

3:20 PM
Corrosion Resistance Behavior Study of SLM Inconel 718 Sample under Different Surface and Heat Treatment: Baicheng Zhang[1]; *Florencia Edith Wiria*[1]; Mingzhen Xiu[2]; Mui ling Sharon Nai[1]; Chen-nan Sun[1]; Jun Wei[1]; [1]Simtech; [2]NTU

Inconel 718 is one of the important alloys widely used in the aerospace and marine industries due to its high mechanical strength and good corrosion resistance. Inconel parts fabricated using the Selective Laser Melting (SLM) technology had exhibited superior mechanical properties with manufacturing flexibility. In this study, a pitting corrosion test was conducted on SLM Inconel 718 samples under surface electro-polishing and different heat treatment conditions (peak temperature in the range from 1040 °C to 1200 °C). From the results, it was observed that with appropriate heat treatment, the corrosion resistance of the printed parts improved (pitting voltage of as-printed part increased from 560 mV to 613 mV after heat treatment). Moreover, surface electro-polishing was also found to play a key role in improving the corrosion resistance of printed parts. The pitting voltage of the printed sample after electro-polishing increased to 839.5 mV. However, for printed samples subjected to heat treatment over 1200 °C, no obvious pitting voltage peak was observed resulting in corrosion resistance failure.

3:40 PM
Dissolvable Metal Supports Processes for Powder Bed Fusion Printed Inconel 718: Christopher Lefky[1]; *Owen Hildreth*[1]; [1]Arizona State University

This work describes, for the first time, dissolvable metal supports for Powder Bed Fusion (PBF) processed Inconel 718. Similar to our stainless steel dissolvable supports process, the surface of Inconel components were sensitized using sodium hexaferrocyanide during the post-print thermal annealing process to change the composition and corrosion susceptibility. For this work, the diffusion constant of carbon in PBF processed Inconel 718 is measured along with the electrochemically measured corrosion parameters of the unsensitized and sensitized material in a variety of electrolytes. Electrolyte and applied potential down-selection will be detailed along with the resulting microstructure and roughness changes in the components after support dissolution.

Materials 9: Metallic Glass and High Entropy Materials

Tuesday PM — Room: 410
August 8, 2017 — Location: Hilton Austin

Session Chair: Saniya LeBlanc, The George Washington University

1:40 PM
Microstructure and Mechanical Behavior of AlCoCuFeNi High-entropy Alloy Fabricated by Selective Laser Melting: *Zhang Mina*[1]; Zhou Xianglin[1]; Zhu Wuzhi[1]; Li Jinghao[1]; [1]University of Science and Technology

High-entropy alloys (HEAs) are becoming novel research frontiers in the metallic materials community. Additive manufacturing (AM) technique, such as selective laser melting (SLM) is a modern method for materials fabrication and formation. In this study, AlCoCuFeNi HEA parts were fabricated by SLM using pre-alloyed powders prepared by atomization process. The effect of processing parameters on microstructures, and microhardness of SLM-fabricated HEA parts were systematically investigated. Results showed that input laser energy density involved in laser power and scan speed played a significant role in the densification behavior. A near-full 99.03% density was achieved as an energy density of 102.5 J/mm3. The alloys consist of simple body-centred cubic (BCC) structure and exhibited the highest microhardness up to 541.17 HV0.2 due to the BCC solid solution strengthening. The study revealed that SLM is advantageous to produce the high-entropy alloy with high density, good mechanical properties and even complicated shapes.

2:00 PM
Selective Laser Melting of AlCu5MnCdVA: Formability, Microstructure, and Mechanical Properties: *Zhiheng Hu*[1]; Haihong Zhu[1]; Ting Qi[1]; Hu Zhang[1]; Changchun Zhang[1]; Xiaoyan Zeng[1]; [1]Wuhan National Laboratory for Optoelectronics

Selective laser melting (SLM) is an additive manufacture (AM) technique that uses powders to fabricate 3D parts directly. Many researchers are interested in the formability and properties of the established materials manufactured by SLM. The proposed paper illustrates the formability, microstructure and mechanical properties of selective laser melted AlCu5MnCdVA. In this research, crack-free samples with relative density of nearly 100% were produced by SLM from gas atomized powders. Typical columnar crystal and inhomogeneous element distribution were obtained. The mechanical properties were test for the SLMed samples.

2:20 PM
Microstructure and Crack Distribution of Fe-based Amorphous Alloys Manufactured by Selective Laser Melting: *Bo Song*[1]; Yuanjie Zhang[1]; Qingsong Wei[1]; Yusheng Shi[1]; [1]Huazhong University of Science and Technology

In this study, Fe-based amorphous alloys with a length and width of 10 mm and height of 6 mm were prepared by selective laser melting (SLM). X-ray diffraction, differential thermal analysis and Scanning Electron Microscope were used to investigated the effect of scan space and strategy on the crystallization, microstructure, crack distribution and density. The content of amorphous calculated by differential thermal analysis is up to 93%. There is an obviously trend to lower crack distribution and higher density with an appropriate scan spaces and strategies. With the increasing scan space, the density increased first, then gradually decreased, while the crack decreased and then increasing with the scan space.

2:40 PM
Brittle-tough Transition through Microcrack Modulating in 3D Printing Fe-based Metallic Glass Composite: *Ning Li*[1]; Jianji Zhang[1]; Wei Xing[1]; Di Ouyang[1]; Lin Liu[1]; [1]Huazhong University of Science and Technology

The ability to understand and control microcrack is crucial to selective laser melting of brittle Fe-based metallic glasses. Systematical experiments combined with finite element simulation revealed that these micro-crakcs are induced by huge thermal stress and cannot be eliminated by process optimization. To conquer this challenge, we introduced ductile powders into pure Fe-based amorphous powder. The intriguing finding is that the ductile powders not only reduce the thermal stress, but increase the fracture toughness of the 3D Printing Fe-based metallic glass composites (maximum value of about 46 MPa m1/2), that is far larger than the fracture toughness of pure Fe-based amorphous alloy (2.2 MPa m1/2), indicates a brittle-tough transition. The present results not only offer in-depth understanding of the physical origin of micro-cracks, but also provide promising methods to control and suppress micro-cracks in the 3D printing of bulk metallic glasses.

3:00 PM
Processability of Fe-based Bulk Metallic Glass using Direct Metal Laser Sintering and Electron Beam Melting: *Zaynab Mahbooba*[1]; Lena Thorsson[2]; Mattias Unosson[2]; Timothy Horn[1]; Harvey West[1]; Ola Harrysson[1]; [1]North Carolina State University; [2]Sindre Metals

Bulk metallic glasses (BMGs) are among the strongest engineering materials known today. Fe-based BMGs are of increasing research interest due to their superior mechanical, magnetic and chemical properties, and low manufacturing cost. Existing manufacturing techniques limit thickness and geometry of BMGs. This work examines the processability of two Fe-based BMG alloys using direct metal laser sintering and electron beam melting. The BMG fabricated using the EOSINT M 280 exceeds the critical casting thickness by greater than 15 times in all dimensions. Process requirements to produce fully dense and amorphous material using powder bed AM will be discussed. Opportunities for novel and unique applications of metallic glass are achievable through appropriate material design and optimization of existing AM processes.

3:20 PM
Construction of Metallic Glass Structures by Laser-foil-printing Technology: *Yiyu Shen*[1]; Yingqi Li[1]; Hai-Lung Tsai[1]; [1]Missouri University of Science and Technology

Metallic glasses (MGs) have superior mechanical properties such as high tensile strength, hardness, and corrosion resistance, as compared to crystalline metals. Although newly developed MGs have significantly reduced critical cooling rates down to less than 10 K/s, products of MGs are still limited to simple geometries such as foils/plates or rods with thin section-thickness which is mainly caused by the decrease of thermal conductivities of the new MGs. Recently, we developed a new laser-foil-printing (LFP) additive manufacturing technology which welds foils, layer by layer, to construct desired 3D structures. With the LFP and Zr-based amorphous foils, 3D, large amorphous structures with complex geometry have been successfully manufactured. To better understand the time-evolution of crystalline phase, we integrate the heat transfer model with the classic nucleation theory (CNT) based crystal nucleation/growth model to study the crystalline phase evolution as a function of time during laser welding at different locations including the fusion zone (FZ) and heat-affected zone (HAZ). The modeling predictions compared favorably with the experimental results. The reported susceptibility to crystallization in HAZ was discussed and explained.

3:40 PM
Building Zr-based Metallic Glass Part on Ti-6AL-4V Substrate by Laser-foil-printing Additive Manufacturing: *Yingqi Li*[1]; Yiyu Shen[1]; Ming Leu[1]; Hai-Lung Tsai[1]; [1]Missouri University of Science and Technology

Through using Zr intermediate layers, Zr52.5Ti5Al10Ni14.6Cu17.9 metallic glass (MG) parts are successfully built on Ti-6Al-4V substrate by laser-foil-printing (LFP) additive manufacturing technology in which MG foils are laser welded layer-by-layer onto the substrate. The printed MG part is free of porosity, cracking and crystallization, and its properties are very similar to the original MG material. The Zr intermediate layers are aimed at preventing direct interaction between the first layer of MG foil and the Ti substrate; otherwise, the welded MG foils would peel off from the substrate due to the formation of brittle intermetallic compounds. With the use of Zr intermediate layers, the bonding strength of the printed MG part and the Ti substrate can reach 758 MPa owing to the formation of a-Zr phase.

Physical Modeling 4: Microstructural Modeling

Tuesday PM — Room: 415A-B
August 8, 2017 — Location: Hilton Austin

Session Chair: Joy Gockel, Wright State University

1:40 PM
Modeling Microstructure Evolution and the Effects of Texture on Mechanical Properties in Additively Manufactured Metals: *Judith Brown*[1]; Joseph Bishop[1]; Theron Rodgers[1]; Kyle Johnson[1]; [1]Sandia National Laboratories

A process-structure-property modeling approach is developed to study texture evolution in additively manufactured (AM) structures and welds and the resulting effects on mechanical properties. Microstructure evolution is modeled using a Kinetic Monte Carlo framework, which determines grain orientations as a function of thermal gradients in the melt pool and the orientations of neighboring solidified grains. Computational homogenization of stochastic volume elements is explored as a method to determine effective macroscale properties that can be used in engineering-scale material models but also include some representation of the microscale features. For part-scale AM structures, an a posteriori error-estimation framework is used to quantify modeling errors resulting from various approximations of the material properties and variability of local textures within the build.

2:00 PM
Numerical investigation of grain structure development in Laser Engineered Net Shaping: *Xuxiao Li*[1]; Wenda Tan[1]; [1]University of Utah

Very different grain sizes, shapes, and orientations have been found in parts fabricated by Laser Engineering Net Shaping (LENS) process, but the grain texture development in LENS process is not fully understood. A multi-scale model is established to investigate this issue. A macro-scale model is used to simulate the thermo-fluid phenomena in the molten pool. A meso-scale cellular automata (CA) model is used to simulate the epitaxial and competitive growth through which textured grains are formed. Nucleation is included in the model to predict the potential columnar-to-equiaxed transition (CET). The simulation results show that the scanning strategy and the molten pool shape can significantly vary the 3D grain texture. With properly selected scanning parameters, less textured grains with smaller sizes can be obtained, which can help to improve the mechanical properties of the built parts.

2:20 PM
Phase Field Modeling of Microstructure Evolution during Selective Laser Melting of Inconel 718: *Kubra Karayagiz*[1]; Thien Duong[1]; Luke Johnson[1]; Brian Franco[1]; Gustavo Tapia[1]; Mohamad Mahmoudi[1]; Ji Ma[1]; Ibrahim Karaman[1]; Alaa Elwany[1]; Raymundo Arroyave[1]; [1]Texas A&M University

Predicting the microstructure of SLM-fabricated parts is very challenging due to the complex thermal histories that result from rapid heating-cooling cycles upon successive passes of the laser beam, both within-layer and layer-to-layer. . In the present work, we develop a coupled physics-based framework for simulating the microstructure during SLM of Inconel 718. First, the thermal history is simulated using a finite element (FE) model, serving as input to the coupled phase-field (PF) microstructure evolution model to predict rapid solidification process during SLM. In particular, dendritic structure and solute segregation are investigated and validated through comparison with experiments.

2:40 PM
Numerical Simulation of Solidification in Additive Manufacturing of Ti-alloy by Multi-Phase-Field Method: *Yusuke Shimono*[1]; Mototeru Oba[1]; Sukeharu Nomoto[1]; Kenta Yamanaka[2]; Yuichiro Koizumi[2]; Akihiko Chiba[2]; [1]Itochu Techno-Solutions Corp.; [2]Institute for Materials Research, Tohoku Univ.

Multi-phase-field method (MPFM) coupled with calculation of phase diagrams (CALPHAD) is a powerful tool for simulation of solidification microstructure evolution in engineering casting conditions. MPFM equations were introduced by assuming quasi-equilibrium in the interface. On the other hand, there are few attempts adapting MPFM for solidification in additive manufacturing (AM) because it is considered to be a strong non-equilibrium process. In other words, it was considered for the classical solidification theory based on the local equilibrium assumption not to be applied to this process. However, some researchers have reported experimental observations of columnar-to-equiaxed transition in solidification conditions of AM. These suggest MPFM might be able to adapt to solidification simulation of this process. We tackled the issue of applicability of MPFM for solidification simulation in AM of Ti-alloy. It is confirmed that solidification simulation using MPFM can provide observation of columnar-to-equiaxed transition and establish solidification map in AM process condition.

3:00 PM
Effect of Heterogeneous Nucleation on Microstructure Modeling in Powder-bed Metal Additive Manufacturing: *Jingfu Liu*[1]; Behrooz Jalalahmadi[1]; [1]Sentient Science

Computational modeling is an efficient approach to understand the microstructure evolution in metal additive manufacturing. Several approaches (such as Monte Carlo method, phase field method, and cellular automata method) have been proposed to simulate grain evolution in rapid solidification process, but the effects of heterogeneous nucleation on grain morphology have not been investigated yet. In this study, the effect of different nucleation configurations on grain morphology prediction was investigated. A coupled cellular automata (CA) -finite element (FE) model was used to simulate grain morphology in selective laser melting of AlSi10Mg alloys. Predicted results show that a higher nucleation density on fusion line results in more columnar grains, while higher nucleation in the melt pool leads to more equiaxed grains. Also, epitaxial grain growth occurs when heterogeneous nucleation density was below a critical value. It is necessary to tailor the nucleation configuration to accurately predict grain morphology in microstructure modeling.

3:20 PM
Modelling Powder Flow in Metal Additive Manufacturing Systems: *Gary Delaney*[1]; Stefan Gulizia; C. Oh[1]; Vincent Lemiale; A. Murphy[1]; S. Cummins[1]; P. Cleary[1]; Vu Nguyen; M. Sinnott[1]; Dayalan Gunasegaram; P. Cook[1]; [1]CSIRO

In powder-bed based metal additive manufacturing applications, the addition of the powder layers is the crucial first step in building up of the part in 3D and has a significant impact on final part quality. A common technique employed is to add successive layers of metal powder by raking a new layer across the existing surface. Understanding this raking process and how the properties of the powder particles (e.g. size, shape, density, interaction properties) and process parameters (e.g. height of powder layer, rake geometry, rake speed) affect the properties of the bed after raking is crucial in optimizing the performance of the system and ensuring the quality of the 3D-printed part. We will present results of a computational model of this raking process using the discrete element method (DEM). This model directly incorporates the powder's particle size distribution, particle shapes and experimental measurements of the powder flowability. We have applied this model to simulating raking of both Arcam Titanium powder and CSIRO Manipulated Titanium Powder and it is being applied in improving the performance of existing 3D powder-bed systems and exploring new rake designs and powder morphology combinations in order to deliver products with improved performance. We will also describe how this model fits within a complete modelling framework we are developing for the other key physical processes in powder based metal additive manufacturing including the transfer of energy from the laser or electron beam to the metal, the melting and solidification of the powder, the flow of liquid metal in the melt pool, the heat transfer from the melt pool to the surrounding powder and solid metal, the evolution of the microstructure of the component, and the residual stress and deformation of the component that result from the non-uniform heating and cooling.

Process Development 5: Material Extrusion and Surface Properties

Tuesday PM Room: 416A-B
August 8, 2017 Location: Hilton Austin

Session Chair: Nicholas Meisel, Pennsylvania State University

1:40 PM
Reducing Mechanical Anisotropy in Extrusion-Based Printed Parts: *Chad Duty*[1]; Jordan Failla[1]; Seokpum Kim[2]; John Lindahl[2]; Brian Post[2]; Lonnie Love[2]; Vlastimil Kunc[2]; [1]University of Tennessee; [2]Oak Ridge National Laboratory

The mechanical performance of 3D printed components is highly dependent upon the orientation of the part relative to the build plane. Specifically for extrusion-based printing systems, the bond between successive layers (z-direction) can be 10-25% weaker than in the printed plane (x-y plane). As advanced applications call for fiber reinforced materials and larger print systems (such as the Big Area Additive Manufacturing system) extend the layer time, mechanical performance in the z-direction can decrease by 75-90%. This paper presents a patent-pending approach for improving mechanical performance in the z-direction by depositing material vertically across multiple layers during the build. The "z-pinning" process involves aligning voids across multiple (n) layers, which are then back-filled in a continuous fashion during the deposition of layer (n+1). The "z-pinning" approach will be demonstrated for neat and fiber reinforced materials on a variety of extrusion-based printing platforms.

2:00 PM
Development of Automatic Smoothing Station Based on Solvent Vapour Attack for Low Cost 3D Printers: *Marlon Cunico*[1]; Patrick Cavalheiro[2]; Jonas Carvalho[1]; [1]University of São Paulo; [2]Concep3D

Along the last years, 3d printing has been playing a new and important role in several market segments. As consequence, finishing methods have been developed and applied in order to improve surface roughness and mechanical strength. One of these methods is the solvent vapour attack. Nonetheless, this process is still manual and might lead to object deformation or structural damages. For that reason, the main goal of this work is to present a new approach that was implemented in automatic smoothing station. In this new approach, a close-looping control system identifies the vapour attack level in addition to controlling drying time and number of times that cycle is repeated. By the end, this proposal was identified to advances in 3d printing field, being a next step for domestic and distribuited manufacturing.

2:20 PM
Effect of Process Parameters and Shot Peening on the Tensile Strength and Deflection of Polymer Parts Made Using Mask Image Projection Stereolithography (MIP-SLA): *Mohammad Montazeri*[1]; Guru Madireddy[1]; Emily Curtis[1]; Jonathan Berger[1]; Nicholas Underwood[1]; Yousuf Al Khayari[1]; Beau Marth[1]; Ben Smith[1]; Steven Christy[1]; Kole Krueger[1]; Michael Sealy[1]; Prahalada Rao[1]; [1]University of Nebraska-Lincoln

Mask Image Projection Stereolithography (MIP-SLA) is an additive manufacturing technique in which a liquid photopolymer resin is hardened from exposure to ultraviolet (UV) light. Shot peening is a surface treatment to improve the mechanical properties of components. The goal of this work is to quantify the effect of SLA print process parameters, namely layer height and UV exposure, and shot peening on the longitudinal tensile strength of ASTM D638 Type 5 test artifacts. Test parts were created using a central composite experimental plan on a B9 Creator desktop SLA machine. Deflection of the pseudo Almen strips after shot peening was measured using a digital camera. Post-shot peening tensile strength was measured for the ASTM D638 Type 5 parts. Shot peening generally decreased the strength of MIP-SLA parts.

2:40 PM
Material Addition and Continuous Sculpting as an Alternate Approach to Improve Surface Quality and Dimensional Accuracy of 3D Printed Parts: *Rajeev Dwivedi*[1]; [1]STEM and Robotics Academy

In the additive and subtractive manufacturing processes, feature addition is enabled by relative motion of additive and subtractive end effector with respect to the substrate. Popular 2-1/2 axis approach and the size of material delivery probe limit the resolution of features. For the 3d Printing processes that are based on the phase transformation, there is additional opportunity to modify the molten material by shaping it as needed a priori solidification. Also, referred to as “continuous sculpting” such a process reduces the stair-case effect, improves the geometry and hence lesser post processing steps. This paper reports the initial implementation and findings of the process.

3:00 PM
Predicting Sharkskin Instability in Extrusion Additive Manufacturing of Reinforced Thermoplastics: *Vidya Kishore*[1]; Christine Ajinjeru[1]; Peng Liu[2]; John Lindahl[2]; Ahmed Hassen[2]; Vlastimil Kunc[2]; Chad Duty[1]; [1]University of Tennessee, Knoxville; [2]Manufacturing Demonstration Facility, Oak Ridge National Laboratory

The development of large scale extrusion additive manufacturing systems such as the Big Area Additive Manufacturing (BAAM) system has enabled faster printing with throughput as high as 50 kg/h and the use of a variety of thermoplastics and composites with filler loading as high as 50%. This combination of high rates and reinforcement can give rise to a phenomenon known as “sharkskin” instability, which refers to extrudate surface distortions typically in the form of roughness or mattness, and is commonly observed in traditional extrusion processes. The onset of this instability depends upon the viscoelastic properties of the material and also processing parameters such as throughput, shear rates, extruder die geometry and temperature. For printed parts, such instabilities are undesirable and detrimental to mechanical properties. This work examines the effect of process parameters on the rheological properties of some BAAM thermoplastics and composites to predict the occurrence of sharkskin during printing.

3:20 PM
Exploring the Manufacturability and Resistivity of Conductive Filament Used in Material Extrusion Additive Manufacturing: Harry Gao[1]; *Nicholas Meisel*[1]; [1]The Pennsylvania State University

Additive manufacturing (AM) has the unique ability to build multifunctional parts with embedded electronics without the need for post-print assembly. However, many existing forms of multifunctional AM are not easily accessible to hobby-level users. Recently, conductive filaments have become increasingly available for material extrusion desktop printers. Ideally, the use of these filaments would allow conductive circuitry to be printed simultaneously with the rest of the structure, thus enabling inexpensive, multifunctional structures. Unfortunately, the extent to which filament resistivity is significantly impacted by AM process parameters and part geometry is not fully understood. In this paper, a design of experiments approach is used to evaluate the behavior of two commercially-available conductive filaments under a variety of parameters. It is found that nozzle temperature, layer height, and orientation significantly affect resistivity in various ways. The knowledge from this research will allow users to design better multifunctional parts that have reduced resistivity.

Process Development 6: Sprays and Jetting

Tuesday PM	Room: 404
August 8, 2017	Location: Hilton Austin

Session Chair: Brian Post, Oak Ridge National Laboratory

1:40 PM
Magnetohydrodynamic Liquid Metal Droplet Jetting of 4043 Aluminum: *Denis Cormier*[1]; Khushbu Zope[1]; [1]Rochester Institute of Technology

Magnetohydrodynamic (MHD) liquid metal droplet jetting is a new metal additive manufacturing process developed by Vader Systems. The process first feeds metal wire into a reservoir where it is melted. The molten metal flows into an ejection chamber where electromagnetic fields from coil windings induce Lorentz forces that cause rapid jetting of discrete molten metal droplets through a ceramic orifice at a rate of approximately 1 kHz. This paper will provide an overview of this promising new metal additive process. It will then describe the microstructure and properties of 4043 Al structures produced using the very first Vader Systems MK1 machine. As the deposited metal structures are produced from the impingement of discrete droplets upon a substrate, the resulting microstructure is quite different from that which is typically observed in powder bed consolidation techniques such as DMLM and EBM.

2:00 PM
Using Additive Manufacturing Techniques as an Alternative Method to Spray Deposit Metallized Material: *Zachary Stephens*[1]; [1]Sandia National Laboratories

Metallization is a core manufacturing capability relevant in several industrial applications. The industrial focus is on obtaining a consistently uniform metal coating which typically correlates directly with overall performance for those applications. In order to address the reproducibility objectives, automated deposition capabilities are very attractive. Using additive manufacturing techniques and a commercially available ultrasonic spray nozzle, a metallized ink spray deposition method will be presented. The deposition process, critical process parameters, and select optimization techniques will be discussed. The advantages of spray deposition in a manufacturing environment will also be highlighted.

2:20 PM

Modeling the Effect of Inter-layer Time on the 3D Microstructure and Residual Stress in LENS Parts: *Kyle Johnson*[1]; Theron Rodgers[1]; Donald Brown[2]; Bjorn Clausen[2]; Olivia Underwood[1]; Jonathan Madison[1]; Kurtis Ford[1]; Joseph Bishop[1]; [1]Sandia National Laboratories; [2]Los Alamos National Laboratory

Processing history plays a key role in thermal gradients experienced by additively manufactured parts, which affects the resulting microstructure and residual stress profile. Building multiple parts simultaneously adds a delay between the deposition of each layer, allowing for additional cooling in comparison to a single part build. This work investigates the effect of this additional cooling by modeling the fabrication of 304L stainless steel cylinders with different inter-layer process times using the LENS process. The spatial and temporal evolutions of thermal history, residual stress, and microstructure are modeled using the Sierra finite element code and SPPARKS Monte Carlo suite. Predictions are compared to experiments and differences caused by the two processing methods are quantified and compared. Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

2:40 PM

Temperature and Humidity Variation Effect on Process Behavior in Electrohydrodynamic Jet Printing of a Class of Optical Adhesives: *Patrick Sammons*[1]; Ritika Sabal[1]; Sahit Bollineni[1]; Kira Barton[1]; [1]University of Michigan

Electrohydrodynamic jet (e-jet) printing is an emerging additive manufacturing process that utilizes an electric field to eject material from a micro-/nano-scale microcapillary nozzle. Due to its contemporary nature and the complex physics which govern the process, little is known about printing behavior sensitivity with respect to environmental condition variability. The aim of this work is to construct a systematic experimental design to test and evaluate the relationship between two environmental variables, temperature and relative humidity, and key process metrics initiating ejection voltage, printing frequency, and volume of material ejected. A factorial statistical design of experiments is used to investigate the parameter space. Results are used to identify temperature and humidity ranges that give robust printing regimes for a specific class of optical adhesives. Best-fit curves are determined for several of the input-output relationships, which provide a predictive model for the ink behavior.

3:00 PM

Blown Powder Laser Cladding with Novel Processing Parameters for Isotropic Material Properties: *Jing Liu*[1]; Eamonn Fearon[2]; Geoff Dearden[1]; Stuart Edwardson[1]; [1]University of Liverpool; [2]Advanced Laser Technology Ltd

A limitation for blown powder laser additive manufacturing in many applications is the material properties of parts made tend to show anisotropy due to directional solidification of the microstructure.Recent work reported here has identified novel low power processing conditions that yield equiaxed grain structures in 316L stainless steel and thus potentially eliminate material anisotropy. Initial observations show that the process window is affected by build height,substrate choice,powder, powder delivery rates, laser power and processing speed. A system has been developed to give precision layer height control via nozzle design and low powder delivery rates through an in-house design of powder hopper.Mechanical tests have been conducted under the novel processing parameters.Large amounts and uniform distribution of equiaxed structures compared to standard process conditions in 316L are found significantly.Moreover,cladding has been successfully produced with significantly low power around 350W,thus potentially improving process efficiency and set-up costs.

Process Development 7: Novel Processes

Tuesday PM — Room: 417A-B
August 8, 2017 — Location: Hilton Austin

Session Chair: Judi Lavin, Sandia National Laboratories

1:40 PM

A Direct 4D Printing Method Using Multimaterial 3D Printing: Zhen Ding[1]; Chao Yuan[2]; Oliver Weeger[1]; Martin Dunn[1]; *H. Jerry Qi*[2]; [1]Singapore University of Technology and Design; [2]Georgia Institute of Technology

4D Printing is a term that was recently coined to describe the switching of the shape of a 3D printed part via an environmental stimulus. In this paper, we propose a new direct 4D printing approach with shape memory polymers (SMPs) where we integrate the programming steps into the 3D printing process. As a result, the 3D printed component can directly change its shape rapidly upon heating. This second shape largely remains stable in later variations in temperature, such as cooling back to room temperature. Furthermore, a third shape can be programmed by thermomechanical loading, and the material will always recover back to the permanent (second) stable shape upon heating. We also created a theoretical model that incorporates the key elements, including the material behaviors during the processing/programming and deployment phases and 3D printing processing parameters. The model was then used to guide to design complicated shape changes.

2:00 PM

Using Multi-Axis Material Extrusion Additive Manufacturing to Improve Part Mechanical Properties through Printed Surface Reinforcement: *Joseph Kubalak*[1]; Alfred Wicks[2]; Christopher Williams[1]; [1]DREAMS Lab; [2]Mechatronics Lab

Due to the layer stacking inherent in traditional three-axis material extrusion (ME) additive manufacturing processes, a parts mechanical strength is limited in the print direction due to weaker interlayer bond strength. Often, this requires compromise in part design through either the addition of material in critical areas of the part, reducing end-use load cases based on printing orientation, or by entirely forgoing ME as a manufacturing option. To address this limitation, the authors look to use multi-axis deposition toolpaths to deposit material along the part's surface. Specifically, the authors employ a custom 6-DoF robotic arm ME system to provide surface reinforcement, similar to carbon fiber composite layup, in a single-step manufacturing process. In this paper, vertical tensile bars are fabricated through stacked XY layers, which is then followed by depositing material directly onto the surface. Experimental results demonstrate reinforced interlayer bonds, an increased yield strength, and a more isotropic response.

2:20 PM

Reactive Inkjet Printing Approach towards 3D Silicone Elastomeric Structures Fabrication: *Aleksandra Foerster*[1]; Ricky Wildman[1]; Richard Hague[1]; Christopher Tuck[1]; [1]University of Nottingham

Production of 3D silicone structures with tailored architectures has a wide number of applications including soft robotics and stretchable electronics. This work investigates a method based on a reactive inkjet printing approach to produce 3D silicone structures. Printing parameters including pressure, temperature, nozzle diameter for jetting SE1700 ink to produce silicone structures were optimised. Additives, silicone oil and vinyl terminated polydimethysiloxane were added to the main SE1700 formula to evaluate mechanical properties of the final parts. Characterisation was performed to understand the change in a sample's properties in relation to different formulations. Silicone structures with different porosities were printed and the mechanical properties were investigated. It has been demonstrated that 3D silicone structures can be produced using reactive inkjet printing approach. The presented method allowed tailoring of the mechanical properties of silicones without increasing the viscosity properties of the base material by adjusting the silicone formula and using different structures.

2:40 PM
Selective Separation Shaping of polymeric material: *Hadis Nouri*[1]; Behrokh Khoshnevis[1]; [1]USC

Selective Separating Shaping or SSS is a new powder-based additive manufacturing technique developed to build low cost, high resolution 3D objects. In this process, parts are formed by means of thin wall of separation material deposited on part boundary profile. This process has been primarily applied to metal, ceramic and cement-based material and test cases were successfully built. There has been no study on fabrication of parts using polymeric material and the goal of this research is to extend application of SSS for fabrication of polymer parts. Nylon 6,6 has been selected as base powder material and several test cases were fabricated to identify key factors in success of this process. Design of experiments have been performed and interaction between separation material and base material was investigated. In addition to that, different heating mechanisms were studied to achieve better control over shrinkage and maintain an effective binding between layers.

3:00 PM
Additive Manufacturing Utilizing Stock Ultraviolet Curable Silicone: *Daniel Porter*[1]; Adam Cohen[1]; Paul Krueger[1]; David Son[1]; [1]Southern Methodist University

Extrude and Cure Additive Manufacturing (ECAM) is a method that enables 3D printing of common thermoset materials. Ultraviolet (UV)-curable silicone is an example of a thermoset material with a large number of industrial and medical applications. 3D printed silicone prototype parts are obtained using a custom high pressure ram, valve, and UV exposure system.This paper will address issues with printing stock UV curable silicone such as electrostatic repulsion, in-nozzle curing, and extrudate sagging. One solution that addresses two issues is adding carbon black to the mixture to reduce electrostatic repulsion while also inhibiting UV cure depth, hence preventing material from curing in the nozzle. Evidence shows that too much carbon black can be detrimental to the structural stiffness of the resulting part.

3:20 PM
Active-Z Printing: A New Way to Improve 3D Printed Part Strength: *Jivtesh Khurana*[1]; Shantanab Dinda[1]; Timothy Simpson[1]; [1]Pennsylvania State University

Research suggests that topology and build parameters in Fused Filament Fabrication (FFF) play a vital role in determining mechanical properties of parts produced by this technique. In particular, the use of 2D layers printed parallel to the build surface produces high anisotropy in parts making them the weakest when loaded perpendicular to the layer interfaces. We investigate a novel approach that uses non-planar 3D layer shapes, Active-Z printing, to improve mechanical strength through alignment of localized stress tensors parallel to the deposition paths. Sinusoidal layer shapes are used with varying amplitude, frequency and orientation. Designed experiments are conducted to correlate effect of varying shape and orientation of sinusoidal layer shapes on flexural strength of parts. Results are used to decide parameters to be studied further and characterize their effect on the strength of parts.

3:40 PM
Magnetohydrodynamic Drop-on-Demand Liquid Metal 3D Printing: *Viktor Sukhotskiy*[1]; Ioannis Karampelas[2]; Gourav Garg[3]; Aditi Verma[3]; Michael Tong[3]; Scott Vader[1]; Zachary Vader[1]; Edward Furlani[3]; [1]Vader Systems; [2]Flow Science; [3]University at Buffalo

We present a novel method for drop-on-demand (DOD) printing of 3D solid metal structures using liquid metal droplets. This method relies on magnetohydrodynamic (MHD)-based droplet generation. Specifically, a pulsed magnetic field, supplied by an external coil, induces a MHD-based force density within a liquid metal filled ejection chamber, which causes a droplet to be ejected through a nozzle. Three-dimensional (3D) solid metal structures of arbitrary shape can be printed via layer-by-layer patterned deposition of droplets with drop-wise coalescence and solidification. We introduce this prototype MHD printing system along with sample printed structures. We also discuss the underlying physics governing drop generation and introduce computational models for predicting device performance.

Special Session: Hybrid Processes 2

Tuesday PM — Room: 406
August 8, 2017 — Location: Hilton Austin

Session Chair: Frank Liou, Missouri University of Science and Technology

1:40 PM
Fabrication and Characterization of Ti6Al4V and Ti47Al2Cr2Nb Using Selective Electron Beam and Laser Hybrid Melting: *Bin Zhou*[1]; Jun Zhou[1]; Hongxin Li[1]; Dechen Zhao[1]; Feng Lin[1]; [1]Tsinghua University

A hybrid process, which combines electron beam selective melting(EBM) and selective laser melting(SLM), is proposed in this study. Laser is led into the vacuum chamber through the lens so that laser can be used to fabricate the metal powder at the same time with electron beam. In this study, Laser is used to fabricate the contour of the parts both inside and outside. Electron beam is used to preheat the metal powder to the specified temperature and to fabricate the interior of the parts. It can be sure that through the hybrid process we can fabricate the parts with both better surface quality, higher precision and higher efficiency. Ti6Al4V and Ti47Al2Cr2Nb parts were fabricated using selective electron beam and laser hybrid melting. The results are that as-fabricated parts have better surface quality than the parts fabricated only using EBM process and have almost the same tensile strength.

2:00 PM Invited
Hybrid Additive Manufacturing of Steel by LENS and Laser Shock Peening: *Cody Kanger*[1]; Guru Madireddy[1]; David Sokol[2]; Michael Sealy[1]; [1]University of Nebraska-Lincoln; [2]LSP Technologies

Hybrid additive manufacturing (Hybrid-AM) processes is the combination of two or more processes or energy sources that are fully coupled and synergistically affect the quality or performance of a printed part. A promising secondary process to improve the layer-by-layer mechanical properties is laser shock peening (LSP). LSP was applied in 5, 10, and 15 increment layer intervals during LENS printing of steel to investigate the effect microhardness and thermal cancellation. One of the greatest challenges of hybrid-AM using LENS is thermal cancellation whereby the heat from subsequent printing thermally wipes away any beneficial mechanical properties from LSP.

2:20 PM Invited
Surface Integrity of Inconel 718 by Hybrid Selective Laser Melting and Milling: D. Brown[1]; C. Li[1]; *Z.Y. Liu*[1]; X.Y. Fang[2]; Y.B. Guo[1]; [1]The Univ. of Alabama; [2]Shandong University of Technology

While selective laser melting (SLM) offers design freedom of metal parts while consuming much less materials, there exist a number of limitations including high surface roughness, low dimensional accuracy, and high tensile residual stresses. In order to make functional parts with high form accuracy and superior surface integrity, an as-SLM part needs finish machining to remove the deposited surface material. The combination of machining and SLM creates a hybrid manufacturing route to overcome the SLM inherited problems. However, little study has been done to characterize surface integrity of an as-SLM part followed by machining (e.g., hybrid SLM-milling). In this paper, surface integrity including surface roughness, microstructure, and microhardness have been characterized for IN718 samples processed by the hybrid process. Microhardness varies with the scan direction and the use of coolant in the subsequent milling. It has been found that surface integrity can be significantly improved by the hybrid SLM-milling route.

2:40 PM Invited
Development of A Hybrid Manufacturing Process for Precision Metal Parts: Leon Hill[1]; Todd Sparks[1]; *Frank Liou*[1]; [1]Missouri University of Science and Technology

This paper will summarize the research and development of a hybrid manufacturing process to produce fully dense metal parts with CNC level precision. High performance metals, such as titanium alloys, nickel superalloys, tool steel, stainless steels, etc., can benefit from this process. Coupling the additive and the subtractive processes into a multi-axis workstation, the hybrid process, can produce and repair metal parts with accuracy. The surface quality of the final product is similar to the industrial milling capability. It will certainly impact the future rapid manufacturing industry. To achieve such a system, issues, including the modeling of the metal deposition process and the automated process planning of the hybrid manufacturing process, will be discussed.

3:00 PM Invited
Design for Hybrid Additive Manufacturing by Drop Tower Testing Shot Peened Almen Strips: *Haitham Hadidi*[1]; Michael Sealy[1]; [1]University of Nebraska-Lincoln

Hybrid additive manufacturing processes are the use of additive manufacturing with one or more secondary processes or energy sources that are fully coupled and synergistically affects part quality, functionality, and/or process performance. A secondary process that can favorably enhance mechanical properties of additive parts is shot peening (SP). SP impinges a target with stochastically dispersed, high velocity beads and can be applied in preferential layer intervals during additive manufacturing. This hybrid approach leads to better impact and ballistic protection by varying material elasticity, toughness, and fracture strain. The goal of this research was to test the impact strength of various sequences of SP and non-SP Almen strips in order to better understand how to design a hybrid-AM process that incorporates a mechanical surface treatment. The results suggest that preferential layer sequences exist that better absorb energy upon impact.

3:20 PM Invited
Fatigue Behavior of Surface Treated Ti-6Al-4V Made via Electron Beam Melting as Input for Hybrid Process Planning System: *Carter Keough*[1]; Harvey West[1]; Richard Wysk[1]; Ola Harrysson[1]; [1]North Carolina State University

Current metal additive manufacturing (AM) systems are often incapable of producing parts with industry specified tolerances due to the inherent process accuracy and use of support structures. Because of this, additional surface processing is often required to bring the part geometry to specification. The Digital Additive and Subtractive Hybrid (DASH) process addresses these limitations through the integration of existing subtractive manufacturing (SM) and AM systems using in-process measurement and automated process planning. Substantial production savings can be obtained in the DASH system, if the surface of the AM part more closely matches the final requirements. Surface modification, through chemical or mechanical treatments, can achieve this, however these processes can impact fatigue performance and machinability. In this work, the effects of surface characteristics on fatigue behavior of additively built Ti-6Al-4V in as-built, chemically finished, and mechanically finished conditions are investigated and the implications of these results are described.

3:40 PM
Effects of Ambient Pressure on Laser Process of Austenite Stainless Steel: Zhi-Jing Zhang[1]; *Jiang-Zhou Su*[1]; Xin Jin[1]; Zhi-Peng Ye[2]; Mu-Zheng Xiao[1]; Yi-Chong Yang[1]; [1]Beijing Institute of Technology; [2]China Electronic Product Reliability and Environmental Testing Research Institute

Defects such as oxidation, cracks and pores deteriorate the mechanical properties of metal additive manufacturing parts, yet the propagation of these defects is not fully understood. Ambient pressure, an important factor in metal additive manufacturing, has not been thoroughly investigated, especially in terms of its impact on defects. In this study, we design and employ a laser process workstation containing a pressure vessel and conduct a series of preliminary experiments on melting and solidification of austenite stainless steel under different ambient pressures ranging from 0.01 kPa to 45 bar. Metallographic results show that an increase in the ambient pressure can greatly degrade cracks and pores of molten pools and that a finer grain is obtained under higher ambient pressure. In addition, a hyperbaric condition can inhibit the spatter of metallic particles and eliminate oxidation in the laser process.

Poster Session

Tuesday PM — Room: Salon J-K
August 8, 2017 — Location: Hilton Austin

3D Printing of Ceramic Suspensions Using Microstereolithography toward Water and Gas Filtration: Keyton Feller[1]; *Donald Aduba*[2]; Christopher Williams[2]; [1]University of Wisconsin Platteville; [2]Virginia Tech

This study investigated ceramic suspension behavior and geometric designs to process and fabricate efficient, tunable and porous cylindrical filter to offer uses as removing heavy metals from water and air. This work utilizes mask-projection microstereolithography (MPμSL) to print 60 weight percent calcium phosphate particles suspended in photo-curable resin which is then sintered, and measured for dimensional shrinkage and mechanical properties.

A Two-dimensional Simulation of Grain Structure Growth within Substrate and Fusion Zone during Direct Metal Deposition: *Jingwei Zhang*[1]; Wei Li[1]; Frank Liou[1]; Joseph Newkirk[1]; [1]Missouri University of Science and Technology

In this paper, a predictive model based on a cellular automaton (CA)-finite element (FE) method has been developed to simulate thermal history and microstructure evolution during metal solidification for a laser-based additive manufacturing process. The macroscopic FE calculation that is validated by thermocouple experiment is designed to update the temperature field and a high cooling rate. A cellular automata-finite element (CAFE) method is developed to describe grain growth in the fusion zone. In the mesoscopic CA model, heterogeneous nucleation sites, grain growth orientation and rate, epitaxial growth, remelting of preexisting grains, metal addition, grain competitive growth, and columnar to equiaxed phenomena were simulated. The developed “decentered polygon” growth algorithm is appropriate for the non-uniform temperature field. Finally, the single and multiple layer direct metal deposition (DMD) experiment is conducted to validate the characteristics of grain features.

Accuracy and Variation in Small Channels Produced by Bronze Infiltration of Binder Jet Prints: *Christopher Shafer*[1]; Amy Elliott[1]; Derek Siddel[1]; Gurneesh Jatana[1]; William Partridge[1]; [1]Oak Ridge National Laboratory

Fully-dense metallic artifacts are created via binder jetting of metal powder followed by infiltration with a secondary material. For certain applications, channels within a part are needed and the accuracy of the printing process must be understood. In this work, research was conducted to develop design guidelines and explore the variables in sintering and infiltration that affect small, inner-channel diameters. 420 stainless steel was printed in tube geometries of varying diameters and then infiltrated with bronze. The resulting channel dimensions were measured and compared with the nominal design.

Additive Manufacturing of High Entropy Alloys: A Review: *Wenyuan Cui*[1]; Xinchang Zhang[1]; Frank Liou[1]; [1]Missouri S&T

High entropy alloys have attracted increasing interest due to their unique compositions, microstructures and mechanical properties. Additive manufacturing has been recognized a promising technology to fabricate the high entropy alloys in the recent years. The purpose of this paper is to review the current research progress in high entropy alloys by additive manufacturing process. It will first highlight the important theory of the high entropy alloys. The next aspect is the summarized current additive manufacturing methods applied for the high entropy alloys. At last, the correlation between the microstructures and the mechanical properties of the high entropy alloys will be examined and discussed.

An Online Surface Defects Detection System for AWAM Based on Deep Learning: *Shangyong Tang*[1]; Guilan Wang[1]; Haiou Zhang[1]; Rui Wang[1]; [1]Huazhong University of Science and Technology

Defects detecting layer by layer in arc welding based additive manufacturing (AWAM) is a big challenge as it affects the successive layer quality of the products. Most of the work on layer quality defection were focused on 3D profile measurement and X-ray spectroscopy method but it is inefficient, expensive with poor adaptability. In this work, an online intelligent surface defects detection system for AWAM was developed through deep learning algorithm and support vector machine method. To achieve a reliable surface feature of the welding beads, a vision sensor was used to get the image of the shaped surface synchronously. The system was trained offline and online to acquire knowledge of the welding beads which were classified into five patterns as normal, pore, hump, depression and undercut. An online defection test result showed 95.29% accuracy. The system was verified to be practical with high accuracy and efficiency for the surface defects.

Applied Solvent-based Slurry Stereolithography Process to Fabricate High Performance Ceramic Earrings with Exquisite Details: *Jia-Chang Wang*[1]; Hitesh Dommati[1]; [1]National Taipei University of Technology

This paper discusses the application of Slurry based Stereolithography additive manufacturing process in the fabrication of complex earring models, without any support structures requirement, using High-Performance Ceramic (HPC) materials. The earring model chosen in this study is a Rose flower with blossomed petals. The petals have edge thickness in microns and extreme overhangs with a custom text and logo on the bottom. Using any other ceramic additive manufacturing process, it requires support structures to build this model. The support removal in such minute structures is not easy and not always successful. Using Solvent based Slurry Stereolithography (3S) process, models with the micron details and overhangs can be easily built. This is enabling the neat and clean post-processing procedure to maintain the exquisite details and also gain high surface quality. The ceramic material used in this application is alumina. With some additives, it will show in different colors like sapphire. The resultant flowers are vividly shown in white, pink, green, and blue. In this study, it is also discussed about the slurry process, Stereolithography system, and proven applications of the 3S process.

Casting Low Density Lattice Structures with 3D Printed Sand Molds: *Jason Walker*[1]; Alexander Fitzgerald[1]; Eric Haake[1]; Matthew Manna[1]; Matthew Osiniak[1]; Mackenzie Scrocco[1]; Kayla Theisler[1]; Eric MacDonald[1]; Brett Conner[1]; [1]Youngstown State University

This research investigates the use of binder jetting additive manufacturing for producing sand molds for low density metal cast structures. By eliminating the use of patterns and utilizing direct-from-CAD production of sand molds, previously impossible geometries can be sand cast while simultaneously reducing lead times. This work focuses on developing the ability to cast highly complex lattice structures using 3D printed sand molds – a feat that could not be achieved with traditional sand casting methods. Low density lattice structures can be used in a variety of applications including lightweighting, energy absorption, and heat dissipation. However, such structures are inherently complex and pose significant challenges to fabrication. Here, lattice structures were designed with an architecture derived from gyroid triply periodic minimal surfaces. This presentation will the demonstrate the feasibility of using 3D printed sand molds to create complex parts and represents a significant advance in the state-of-the-art of metal casting.

Characterization of Melt Pool Morphology for Electron Beam Melting Processes of Ti6Al4V, Inconel 625, and Inconel 718 Alloy Systems: *Hengfeng Gu*[1]; Timothy Horn[1]; Ola Harrysson[1]; Sneha Narra[2]; Jack Beuth[2]; [1]North Carolina State University; [2]Carnegie Mellon University

Developing process parameters for electron beam melting is a time- and cost-consuming process which involves a significant amount of effort on experiments. To accelerate the EBM parameter development process, this paper investigated melt pool morphologies from single bead experiments to quickly determine key process parameter ranges for the EBM process. Single bead experiments with/without a layer of powders on the build plate were carried out in an Arcam Q10Plus EBM system using 24 sets of power and scan speed parameter combinations for Ti6Al4V, Inconel 625, and Inconel 718 alloy systems. Surface morphologies of single beads were measured and melt pool cross sections for each single bead was characterized. The experimental results were analyzed and discussed based on process parameter envelope for each alloy system. It was found that melt pool morphology is greatly influenced by the choice of process parameters, which would provide guidelines for future EBM process parameter optimization.

Data Driven Approach to Create a Geometry Independent Surrogate Model for Thermal History in Additive Manufacturing: *Mriganka Roy*[1]; Olga Wodo[1]; [1]University at Buffalo SUNY

Additive manufacturing has potential to build the part of any complex geometry. In order to capitalize on this potential the properties of the part must be evaluated, preferably during the printing process. This can be achieved either by in-situ control of the process, or by physical modeling of the deposition process. Both approaches must be geometry aware and have either online capabilities or be computationally affordable. In this work, we build a geometry independent surrogate model to predict thermal history of the printed part. We first build the full physics model of heat transfer during layer by layer deposition using finite element method, and next we leverage Neural Network to build the surrogate model. We demonstrate the capabilities of our model to construct the thermal history for any point with acceptable accuracy in almost real time. This model opens the possibility for property aware process planning and in-situ monitoring.

Defects Detection of Laser Metal Deposition Using Acoustic Emission Sensor: *Haythem Gaja*[1]; Frank Liou[1]; [1]Missouri University of Science and Technology

Laser metal deposition (LMD) is an advanced additive manufacturing (AM) process used to build or repair metal parts layer by layer for a range of different applications. Any presence of deposition defects in the part produced causes change in the mechanical properties and might cause failure to the part. In this work, defects monitoring system was proposed to detect and classify defects in real time using an acoustic emission (AE) sensor and an unsupervised pattern recognition analysis as well as a principal component analysis. Time domain and frequency domain, and relevant descriptors were used in the classification process to improve the characterization and the discrimination of the defects sources. The methodology was found to be efficient in distinguishing two types of signals that represent two kinds of defects. A cluster analysis of AE data is achieved and the resulting clusters correlated with the defects sources during laser metal deposition.

Design and Preliminary Evaluation of a Deployable Mobile Makerspace for Informal Additive Manufacturing Education: *Swapnil Sinha*[1]; Kelsey Rieger[1]; Aaron Knochel[1]; Nicholas Meisel[1]; [1]The Pennsylvania State University

Additive Manufacturing (AM) has played an integral part in the growth of Makerspaces as democratization of manufacturing continues to evolve. AM has also shown potential in enabling the successful amalgamation of art (A) with science, technology, engineering, and math (STEM) disciplines, giving new possibilities to STEAM subjects and its implementation. This paper presents the conceptual design and development of a deployable, mobile makerspace curriculum focused on AM education for a diverse range of participant backgrounds, ages, and locations. The aim is to identify effective means of informal learning to broaden participation and increase engagement with STEAM subjects through the context of AM. The curriculum is envisioned as “material-to-form,” offering separate modules that present opportunities for self-directed learning through all the stages of design, material use, and manufacturing associated with AM. Pilot studies of the curriculum were performed to identify potential changes to improve the effectiveness of the mobile makerspace.

Design of a Projection Sintering Test Platform: Christopher Gardiner[1]; Hani Alhazmi[2]; Coralis Madera[2]; Alex Murphy[2]; *Justin Nussbaum*[2]; Efe Yayoglu[2]; N. Crane[2]; [1]University of South Florida; [2]University of South Florida

In projection sintering, a projector sinters full layer cross sections in a single exposure. This poster describes a small scale test platform for implementing this technology with polymer powders. A benefit of this over traditional SLS is the ability to control sintering rates; in particular a much slower sintering rate is possible. This system utilizes a movable heated build volume with closed loop temperature control, within an intermediate temperature build chamber to minimize thermal gradients within the powder volume. The projector and thermal camera for process monitoring are kept above the build chamber in ambient air, transmitting and receiving radiation through quartz glass. A quartz lamp also provides radiation to the powder surface to raise the temperature prior to sintering. The projector only has power to sinter 20 x 30 mm areas, but with the X-Y movement it’s possible to tile multiple images together to create larger parts.

Development of a Desktop Metal Printer: *Yongsheng Lian*[1]; Samuel Williams[1]; Thomas Nolan[1]; [1]University of Louisville

A desktop metal printer is developed as a student design project. The printer is based on a off the shelf 3D printer. Modifications are made so that the printer can work with metal filament. We choose Sn60Bi40 alloy for testing because it is available in wire form 1.575 mm and 3.00 mm with melting region between 138oC and 170°C. In this temperature region the material provides plasticity between solid and liquid regions. A three-dimensional tool has been manufactured with the modified 3D printer. Our tensile test showed that the crude tensile specimen produced with induction heating yields tensile strength about 10% of the raw material tensile strength.

Directional Dependence of Mechanical Properties and Defects of LENS 304L: *Cole Britt*[1]; [1]Sandia National Laboratories

Sandia National Laboratories has invested in developing a next generation LENS system to advance the state of the art in LENS technology. The first material being used in that system is 304L stainless steel. To optimize process conditions, tensile bars were made to evaluate material properties of the printed structures. Blocks of stainless 304L steel were printed using Laser Engineered Net Shaping (LENS) and machined into tensile samples. Half of the samples were pulled in a direction transverse to the build plane while the second half was pulled in a direction parallel to the build plane. The directional dependence of the material properties on build direction were observed. Analyses of fracture surfaces and cross sections were conducted. Builds were repeated to minimize direction dependence and understand repeatability. Testing results for both sets of tensile bars will be discussed.

Enhanced Reliability and User Interface for Low-cost FDM 3D Printers: *Yasushi Mizuno*[1]; Bruce Tai[1]; [1]Texas A&M University

As additive manufacturing becomes a part of engineering education, low-cost FDM machines have been prevalent in engineering institutions. However, unlike industrial AM machines, these affordable FDM machines have a high failure rate of printing and are sometimes complicated to use. To improve the low-cost printers, an integrated system is designed in this study consisting of three major features, a built-in microcomputer, failure prevention schemes, and a new support material combination. A series of randomized samples were tested and results showed that failure prevention schemes, including platform error compensation, self-nozzle cleaning, and filament runout sensor could effectively suppress major failure modes caused by an unlevel platform, contaminated nozzles, and material interruption. The water-soluble PETG was found to be an ideal support material paired with PLA, enabling the high-fidelity machine type of support in these printers. This research has revealed several opportunities to enhance the current FDM printers.

Evolution of Raw Powder Characteristics through the Additive Manufacturing Reuse Cycle: Claudia Luhrs[1]; *Sam Murphy*[1]; David Buitrago[1]; Gregory Welsh[2]; Terri Merdes[3]; Edward Reutzel[4]; [1]Naval Postgraduate School; [2]Naval Air Warfare Center Aircraft Division; [3]Applied Research Laboratory. Pennsylvania State University.; [4]ARL Penn State

The rapid development of metal Additive Manufacturing (AM) techniques such as direct metal laser sintering processes (DMLS) promises to revolutionize the way we design, build, supply, use and maintain metal and alloy components. Through AM, complex alloy parts are fabricated layer by layer in a relatively short time with no tooling required and with the optimal amount of raw material. However, reusing the alloy particulates that stay in the system after the 3D printed part is removed will be indispensable to generate other parts and to deliver on expected cost efficiency of the AM approaches. The current research effort is focused on studying the raw powder features (i.e. particle size distribution, microstructure and chemical composition among others) through the reuse cycle and correlating them with the mechanical properties of the 3D components built from them.

Fabrication of an Engine Cylinder Head via Binder Jet Additive Manufacturing: *Derek Siddel*[1]; Christopher Shafer[1]; Michael Kass[1]; Steven Whitted[1]; Munidhar Biruduganti[2]; Amy Elliott[1]; [1]Oak Ridge National Laboratory; [2]Argonne National Laboratory

Research in engine efficiency requires customization in engine components, particularly in the valve block for sensor integration. Large and complex metal objects like this are typically formed via casting; however, the time to develop and the freedom of design of casting are prohibitive for low-volume production. In this work, binder jetting was utilized to create a valve block from stainless steel infiltrated with bronze. The performance of the engine block will be discussed and design rules for binder jetting of engine components will be reviewed.

Fatigue Behavior of Additive Manufactured Parts in Different Process Chains: An Experimental Study: Eckart Uhlmann[1]; *Georg Gerlitzky*[1]; Claudia Fleck[2]; [1]Institute for Machine Tools and Factory Management (IWF), Technical University Berlin; [2]Department of Materials Engineering, Technical University Berlin

Metal based Additive Manufacturing (AM) has experienced dynamic growth in recent years. However, the global distribution of Additive Manufacturing is limited by the fact the produced parts suffer from bad surface quality and the material properties concerning fatigue life are still an object of current investigations which limits possible applications of AM parts. Due to this fact metal AM processes are often followed by a post process to ensure a better surface quality. In this paper the authors present a work which unites different post processes and fatigue life of additive manufactured parts. First, parts are produced with Selective Laser Melting and then post processed with vibratory finishing and turning. Subsequently, surface roughness, high cycle fatigue and fracture behavior and microstructure have been characterized. Finally the results for the different post processing states have been compared and surface properties and microstructure have been correlated with the fatigue properties.

Flexible and Stretchable Ionic Liquid Based Pressure Sensor Fabrication via Direct-print Photopolymerization: *Md Omar Faruk Emon*[1]; Faez Alkadi[1]; Jae-Won Choi[1]; [1]The University of Akron

An increasing interest in stretchable pressure sensors has been noticed due to their potential applications in wearable electronics, robotics, and prosthetics. It is believed that 3D Printing is the most suitable manufacturing process for those stretchable multi-layer and multi-material sensors. While traditional manufacturing techniques fail to achieve them, 3D printing can fabricate any complex shape and provide scope for free-form fabrication and customization in design. Here we present the development of multi-layer stretchable pressure sensors using ionic liquids and carbon nanotubes via direct-print photopolymerization process. Each sensor consists of five thin layers, where the intermediate layer is an ionic liquid based piezoresistive film. This layer is sandwiched between two carbon nanotube based stretchable electrodes and finally, top and bottom insulation layers. Fabricated sensor was connected to a half Wheatstone bridge circuit and evaluated under compressive force. Results show that sensors containing multiple sensing units can measure force and their locations.

Influence of Shot Peening on Mechanical Behavior and Toughness of ABS Parts Manufactured by Fused Filament Fabrication (FFF): Haitham Hadidi[1]; *Cody Slafter*[1]; Jason Sonderup[1]; Mason Spilinek[1]; John Casias[1]; Prahalada Rao[1]; Michael Sealy[1]; [1]University of Nebraska-Lincoln

Polymers have historically been limited to non-load bearing applications due to low strengths and stiffness. Improving mechanical properties is typically accomplished by changing the structure or chemical composition of the polymer. An alternative approach commonly used on metals is surface treatments. Shot peening is a surface treatment to improve the near-surface mechanical properties by imparting compressive residual stress. In polymer additive manufacturing, it is hypothesized that the influence of shot peening on mechanical behavior and toughness are affected by print process parameters. The goal of this research is to understand the relationship between three fused filament fabrication process parameters (layer height, infill angle, and outer shell quantity on the tensile strength and impact toughness of shot peened ABS polymer parts produced on a Hyrel System 30M desktop FFF printer.

Influence of Shot Peening on Tensile Strength and Deflection of Polymer Parts Made using Mask Image Projection Stereolithography (MIP-SLA): Guru Madireddy[1]; *Emily Curtis*[1]; Nicholas Underwood[1]; Jonathan Berger[1]; Yousuf Al Khayari[1]; Michael Sealy[1]; Prahalada Rao[1]; [1]University of Nebraska-Lincoln

Surface treatments are known to improve the performance of parts by enhancing mechanical properties in the surface layers. A common mechanical surface treatment is shot peening. Shot peening induces compressive residual stresses into surface layers of parts by directing a stochastic stream of beads at high velocities under controlled coverage conditions. Although commonly used in metals, the effects of shot peening polymers are relatively unknown. The goal of this work is to ascertain the effect of glass bead shot peening on the tensile strength and transverse deflection of parts made using mask image projection stereolithography (MIP-SLA). In this paper, Almen strips and ASTM D638 Type 5 samples were printed using a B9Creator desktop MIP-SLA printer. Deflection of the Almen strips after shot peening was measured using a digital camera. Post-shot peening tensile strength was measured for the ASTM D638 Type 5 parts.

Interface Bonding and Fracture Behavior of Direct Laser Deposited AISI 4140 Powder on AISI 4140 Substrate: *Hoyeol Kim*[1]; Zhichao Liu[1]; Weilong Cong[1]; Hong-Chao Zhang[1]; [1]Texas Tech University

AISI 4140 has been widely used for many industrial applications due to its good balance of strength, toughness and wear resistance. Under the harsh working conditions, the surfaces of critical components made of this alloy steel undergo severe damage, which ultimately leads to the complete failure. Recently, laser engineered net shaping has been used to repair high-value components due to excellent metallurgical bonding to the substrate with a small heat affected zone compared to other surface coating processes. To date, however, there has been a paucity of research on LENS-deposited AISI 4140 powder on AISI 4140 substrate in the literature. Therefore, the aim of this study is to investigate the compatibility of LENS-deposited AISI 4140 powder with AISI 4140 substrate with a focus on interface bond performance and fracture behavior of the hybrid fabricated specimens. Fractography and failure mechanisms will be discussed in detail.

Investigation of Build Strategies for A Hybrid Manufacturing Process Progress on Ti-6Al-4V: *Lei Yan*[1]; Leon Hill[1]; Joseph Newkirk[1]; Frank Liou[1]; [1]Missouri University of Science and Technology

The various processing parameters of a hybrid manufacturing process, including deposition and machining, is being investigated with a Design of Experiment (DOE). The intent was to explore the effect of different build strategies on the final part's Vickers hardness, tensile test, fatigue life, and microstructure. From this experiment, the processing parameters can be linked to various mechanical properties. This will lead to the ability to create a combination of deposition and machining parameters, which will result in improved mechanical properties.

Investigation of Mechanical Properties for Hybrid Deposition and Micro-rolling of Bainite Steel: Youheng Fu[1]; *Haiou Zhang*[1]; Guilan Wang[1]; Huafeng Wang[1]; [1]Huazhong University of Science and Technology

Wire and arc additive manufacturing (WAAM) is a novel technology with high efficiency and low cost for mass popularity. Whereas, the lack of deposition accuracy and microstructure performances are still restricting its ongoing development. In this paper, hybrid deposition and micro-rolling (HDMR) process has been used to eliminate the anisotropy in WAAM bainitic steel samples. For the problems of deficient deformation and larger remelting area due to deeper penetration and higher temperature gradient, an initially optimized micro-rolling morphology has been proposed. The results show: the tensile strength of finished part are 1275MPa, 1256MPa, 1309MPa for transverse (X), longitudinal (Y), horizontal (Z) directions respectively. The elongation of three directions are 17.4%, 16.6%, 17.7% respectively. The impact toughness is 99J/cm2 and the average grain size reaches about 7μm. Compared to the traditionally heavy rolling equipment, micro roller this paper used has transformative cost advantage to achieve high values of comprehensive mechanical properties.

Layer-to-Layer Control of Laser Metal Deposition: *Michelle Gegel*[1]; Robert Landers[1]; Douglas Bristow[1]; [1]Missouri University of Science and Technology

Laser Metal Deposition (LMD) is a metal additive process that uses blown powder to deliver material into a laser-generated melt pool. During part builds, fluctuating process parameters and varying environmental conditions often result in height deviations within a printed layer. Under certain conditions minor height deviations that develop within a given layer will propagate through to subsequent layers and amplify as the part continues to build. The objective of this work is to prevent the accumulation and amplification of defects by implementing closed-loop feedback control. An LMD system has been developed that incorporates a laser line scanner for feedback sensing and has an open-architecture machine control. In between layers of the build process, line scan measurements are acquired, height information is extracted, and a repetitive control structure is employed to update process parameters for the next layer. The effectiveness of this controller is tested on a variety of part geometries.

Long-term Effects of Temperature Exposure on SLM 304L Stainless Steel: *Tarak Amine*[1]; Caitlin Kriewall[1]; Joseph Newkirk[1]; [1]Missouri University of Science and Technology

Austenitic stainless steel is extensively used in industries that operate at elevated temperatures. This work investigates the high temperature microstructure stability as well as the elevated temperature properties of stainless steels (304L) fabricated with the Selective Laser Melting (SLM) process. Significant microstructural changes were seen after a 400 ºC aging process for as little as 25 hours. This dramatic change in the microstructure would not be expected based on the ferrite decomposition studied in conventional 304L materials. It appears as though the as-built AM alloy has a much faster kinetic response to the heat treatment at 400 ºC. An investigation of the structures which occur, the kinetics of the various transformations and the mechanical properties will be presented. The impact of this on the application of SLM 304L will be discussed.

Metal Matrix Composites formed by Titanium Carbide and Aluminum Net Shaped via Binder Jetting: *Cameron Shackleford*[1]; Josh Arnold[2]; Peeyush Nandwana[2]; Amy Elliott[2]; Cindy Waters[1]; [1]North Carolina A&T; [2]Oak Ridge National Laboratory

Binder jet additive manufacturing has low operating costs and high throughput, which means it is poised for high-volume manufacturing environments. However, the limited material selection for binder jetting hinders the technology's adoption into these environments. To expand the material selection, Oak Ridge National Lab has found a valuable assortment of materials that are either already being utilized in industry or have high utility properties that can potentially be produced via binder jetting. One of those materials is titanium carbide (TiC) infiltrated with aluminum (Al), which offers outstanding hardness and refractory properties at a low cost. In this work, TiC is infiltrated with Al via binder jetting of a TiC skeleton and subsequent capillary infiltration with aluminum. This paper presents the infiltration process and the resulting material properties of the metal matrix composite.

Molten Pool Behavior of Al2O3 in Single-track and Single-layer during Selective Laser Melting: *Kai Zhang*[1]; Tingting Liu[1]; Wenhe Liao[1]; Changdong Zhang[1]; Daozhong Du[1]; Yi Zheng[1]; [1]Nanjing University of Science and Technology

Selective laser melting (SLM) of ceramics is garnering the interest of many researchers, because it can fabricate high precision complex ceramic parts directly. However, due to high melting point and brittleness, SLM of ceramics is difficult. To understand the relationship between molten pool behavior and final Al2O3 part quality, the single-track and single-layer experiments were conducted, and the molten pool data was collected by photodiode and thermal imager. It was found that, due to the high laser energy, the powders from left, right and front side were easily drawn into the molten pool, yielding the unfavorable melt tracks which had a large width and height. The higher of the laser power was, the bigger fluctuation range of the signals was, the less stable of the molten pool became. By comparing the reference data, some defects could be detected and the relationship between molten pool behavior and these defects was built.

Multi-Tool Additive Manufacturing System: Grady Wagner[1]; Lindsey Bass[1]; *Daniel Rau*[1]; Scott Ziv[1]; Mitchell Wolf[1]; David Wolf[1]; Viswanath Meenakshisundaram[1]; Yun Bai[1]; Christopher Williams[1]; [1]Virginia Tech Department of Mechanical Engineering

Additive manufacturing (AM) makes complex parts with a single class of material. Each AM technology encompasses specific techniques and requires diverse components to selectively form each layer, which has segregated AM research by respective technologies. Multimaterial AM exists, but it is the same class of material with the same deposition tool. To fully benefit from AM, researchers must explore the combination of multiple AM modalities and materials such that a multifunctional part may be fabricated using strengths of multiple technologies. While the methods for fabricating each layer differ, all of the AM technologies share the fundamental layer-based approach. By recognizing this universal similarity coupled with the desire to make multifunctional parts, a single system has been created to combine five different AM modalities. In this paper, the authors discuss the design and development of a multi-tool AM system that includes binder jetting, material jetting, vat photopolymerization, paste extrusion, and filament extrusion. Examples of multifunctional, multimaterial parts fabricated by multiple AM processes in a single integrated process are demonstrated.

Multiscale Study of the Electron Beam Selective Melting: Morphologies and Material Properties: *Ya Qian*[1]; Wentao Yan[1]; Feng Lin[1]; Mo Li[2]; [1]Tsinghua University; [2]Institute of Georgia Technology

In terms of Electron Beam Selective Melting (EBSM) technique, the melting and deposition process has been a challenge for precisely observing or exploring. The mesoscopic model has been developed to simulate the instantaneous process and investigate the linkage between different processing parameters and surface finish. The relation between melting pool size and input parameters is extracted and illustrated, within a broad range. The balling effect is categorized to Rayleigh instability and wetting induced result. The hump is characterized as the mismatch between beam moving and fluid flattening. Moreover, the molecular dynamics method is used to calculate material thermos properties and inter-particle behaviors. Most property parameters calculated agree well with records but some like melting point and conductivity are deviated. The atoms interaction potential is another issue to be improved for calculation. The particle boundary sintering or expansion is still under research. Size effect is an active factor during the process.

Optimising Thermoplastic Polyurethane for Desktop Laser Sintering: *Ian Richards*[1]; Thomas Nethercott-Garabet[1]; Isam Bitar[1]; Fiona Salmon[1]; [1]Centre for Additive Manufacturing, University of Nottingham

Laser Sintering is an industrially relevant Additive Manufacturing technique, which has become more accessible due to the introduction of desktop systems. However, useable materials are currently limited to several grades of nylon, and so the aim of this study was to explore potential new materials for desktop-laser sintering. UNEX thermoplastic polyurethane powder was characterised in terms of thermal properties, particle characteristics and bulk powder flow efficiency. To facilitate laser absorption at 445nm, graphite was added to UNEX thermoplastic polyurethane; the addition of graphite also significantly improved bulk powder flow efficiency. UNEX thermoplastic polyurethane was successfully processed using desktop-laser sintering, and the resulting parts possess mechanical properties comparable to commercially available thermoplastic polyurethane (Elongation at Break: 139%, Tensile Modulus: 48.7Mpa, Ultimate Tensile Strength: 7.9Mpa, Shore Hardness: 75). Flow efficiency and mechanical properties were retained in twice recycled powder. This research has established a viable new material for use in desktop-laser sintering.

Printing of Neutron Collimators via Binder Jet Additive Manufacturing: *Derek Siddel*[1]; Anibal Ramirez-Cuesta[1]; Matthew Stone[1]; Amy Elliott[1]; David Anderson[1]; [1]Oak Ridge National Laboratory

Collimators are crucial for shielding neutrons from background noise (i.e. neutrons coming from other sources than the sample being studied) and must be made from materials that can absorb neutrons, such as boron, cadmium, lithium, and gadolinium, in complex geometries. Boron carbide is a suitable material because of its high neutron-absorption rate. However, it is difficult to shape into collimator geometries via traditional means. Because collimators do not see significant mechanical loads, a functional collimator can be created by shaping boron carbide powder into a loosely bound state via binder jetting. In this work, process settings were developed to shape boron carbide powder feedstock into collimator geometries via binder jetting, and the resulting green part strength and collimator functionality were explored.

Processing Sugar on a Desktop Powder Bed Fusion System: Arthur Coveney[1]; Chung Han Chua[1]; Marina Mitrousi[1]; *Ellen Webster*[1]; [1]University of Nottingham

This poster investigates the feasibility of the use of sugars for processing in a Powder Bed Fusion system. The sugars; Glucose, Fructose, Sucrose and Golden Caster (95% Sucrose, 5% molasses) were explored. Intrinsic properties of the materials were measured with Differential Scanning Calorimetry, Thermogravimetric Analysis, and the absorption of wavelengths between the ultraviolet and visible range. The extrinsic properties measured were the particle size and powder rheology. The Powder Bed Fusion instrument used was the Sintratec Kit by Sintratec. PA12 with a carbon black additive is an optimised material for the Sintratec Kit and is used as a baseline material to compare the sugars to. Golden Caster was selected for processing because of its high absorption of the laser, $36.2 \pm 0.2\%$ with respect to PA12, and its narrow melting temperature range.

Novel Filament Composition for Fused Deposition of Ceramics: *Austin Martin*[1]; Noor Shoaib[1]; Stephen Baier[1]; Katrice Williams[1]; Fatih Dogan[1]; Harlan Brown-Shaklee[2]; [1]Missouri University of Science and Technology; [2]Sandia National Laboratories

Fused deposition of ceramics (FDC) of advanced components remains an enticing process for artists, hobbyists, low production volume shops, and advanced prototyping firms. However, the limited availability of easily printable and affordable materials currently limits the maturity of ceramic printing. In this study, we developed and produced a 55 volume % Al2O3 loaded polymer filament and demonstrated filament compatibility with low-cost fused deposition modeling (FDM) printers. Following printing, polymers were removed via binder burnout and the resulting ceramics were sintered at 1560°C. Linear shrinkage of 16-18% during sintering indicates that significant densification occurs in the x,y, and z planes. Prints were examined with μ-CT scanning. This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Real-Time Metrology for Photopolymer Additive Manufacturing with Exposure Controlled Projection Lithography: *Xiayun Zhao*[1]; David Rosen[1]; [1]Georgia Institute of Technology

As additive manufacturing (AM) is poised for growth and innovations, measurement science has been identified as a research priority to accelerate its commercialization and adoption. The Exposure Controlled Projection Lithography (ECPL) is an AM process, in which controlled ultraviolet irradiation projected from beneath a stationary substrate cures photopolymer resin into 3D parts such as micro lenses. To improve the process accuracy and precision with closed-loop control, an interferometric curing monitoring and measurement (ICM&M) method is developed. This study reports a comprehensive research on the ICM&M sensor model and algorithms. Experimental results reveal ICM&M characteristics including traceability, and show that it can provide a cost-effective real-time full-field measurement for ECPL cured heights with excellent accuracy and reliability. The scientific and engineering outcomes from this research will help enhance modeling of nonlinear photopolymerization processes, and provide a paradigm of real-time measurement feedback control for generic additive manufacturing processes.

Screening New Polymers for Powder Bed Fusion (PBF) Additive Manufacturing (AM) via Calorimetric Optical Absorption Measurements: *Camden Chatham*[1]; Viswanath Meenakshisundaram[1]; Christopher Williams[1]; [1]DREAMS Lab at Virginia Polytechnic Institute and State University

The use of an infrared laser to selectively fuse polymer particles is what differentiates powder bed fusion (PBF) additive manufacturing (AM) from other AM technologies. Therefore, the optical absorbance properties of the build material at relevant peak laser wavelengths is key for the efficient conversion of light energy into heat energy useful for fusion. Although studied for metallic build materials, the efficiency of neat polymeric materials and powder mixtures incorporating flow agents and absorbing particulates to convert the CO2 laser energy into energy for particle fusion is absent from the literature. The authors present a calorimetric methodology for determining the energy absorption efficiency of polymeric powders useful for direct incorporation into current PBF models including the energy melt ratio (EMR). This measurement expands the EMR toward a more comprehensive rapid screening method for identifying polymers for PBF and demonstrates the significance of optical material properties when fabricating end-use parts.

Thermal Simulation and Experiment Validation of Cooldown Phase of Selective Laser Sintering (SLS): Yi Ji[1]; *Samantha Taylor*[1]; Scott Fish[1]; Joseph Beaman[1]; [1]The University of Texas at Austin

Thermal stresses, induced by inhomogeneous temperature distribution inside a part during the cooldown phase of selective laser sintering, can be a major cause of part rejection for geometric deviation from its as-built specification. A validated cooldown simulation can provide predictions of temperature distribution in both parts and part cake which may enable alternative cooling profiles to reduce the likelihood of such rejections. This work describes experiments and comparative simulations developed to validate a sample tool for developing cool down control profiles in an SLS machine. In the experiments, thermocouples were inserted inside the part cake to monitor temperature at preselected locations during cooldown. The results from initial experiments and simulations were compared at these locations, to obtain improved estimates of uncertain powder conductivity and convective heat transfer parameters. The resulting simulation was then compared with independent experiments to evaluate the accuracy of such simulations. Though diffusion time in the part cake prevents active closed loop control in cooldown based on thermal measurements at the part, the simulation can be used to determine an open loop control profile for the build box heaters based on temperature gradient and resultant stresses inside the part.

Tailoring Commercially Pure Titanium Using Mo2C During Selective Laser Melting: *Xiaopeng Li*[1]; Sasan Dadbakhsh[2]; Kim Vanmeensel[2]; Jef vleugels[2]; Jan Van Humbeeck[2]; Jean-Pierre Kruth[2]; [1]The University of New South Wales; [2]KU Leuven

Commercially pure (CP) Ti, Ti alloys and Ti composites have applications in a wide spectrum of industries. With the merits of emerging additive manufacturing technique, e.g. layer-wise fabrication nature and rapid solidification rate, the fabrication of Ti composites with tailorable microstructure and hence controllable properties is possible. In this work, a Ti composite was fabricated through selective laser melting (SLM) of CP Ti with Mo2C. The influence of SLM parameters on the phase formation, microstructure and mechanical properties of the fabricated Ti composite was investigated. The results showed that tailorable microstructure and enhanced mechanical properties of the Ti composite can be achieved via SLM. This work provides fundamental and important information on fabrication of Ti composites with controllable microstructure and mechanical properties through SLM of CP Ti with ceramic particle additions.

The Generation of Quadrilateral Elements for Complicated Paths in Additive Manufacturing Aimed at Thermodynamic Analysis: *Wang Rui*[1]; Haiou Zhang[1]; Guilan Wang[1]; Shangyong Tang[1]; Runsheng Li[1]; [1]Huazhong University of Science and Technology

In wire arc welding Additive Manufacturing (WAAM), filling paths have a strong influence on the deformation of fabricated part. Many researchers employ FEM to analyze the effects of different filling strategies. However, they mainly majored in regular simple path (e.g. line and circle).This paper presents the method to generate meshes in deposition region of complicated path which can be used in FEM. First, the deposition region of each path is created by offsetting the paths inward and outward. Afterwards, quadrilateral meshes are constructed within each region. Deposition region is approximated by meshes. Then, the order of activating meshes in "birth and death method" is determined. This order is coincident with deposition sequences. Finally, the data of elements and activate order is transformed into ANSYS to calculate the temperature and stress distribution, and distortion during deposition. The analysis results can be adopted to evaluate and optimize the paths in order to decrease deformation.

Understanding the Digital Thread: Investigating the Amount of Data and File Types Generated during Additive Manufacturing: *Zackary Snow*[1]; Brant Stoner[2]; Timothy Simpson[1]; [1]The Pennsylvania State University; [2]The Pennsylvania State University

Over the last decade, additive manufacturing (AM) has progressed from a process used for prototyping to a viable manufacturing process. AM has become a suitable solution to many applications in the automotive, medical, and aerospace industries. Despite recent progress, little attention has been given to the data generated during the AM process. References are made to the "digital thread" in AM, but no end-to-end examples exist that document the complexity of the digital thread. This paper strives to fill this gap and investigate the current state of data generated during AM. First, the AM process is reviewed and an overview of the sources of data generation during the AM process is presented. A case study is then used to demonstrate data generation in metal laser-based powder bed fusion. The paper concludes with a comparison to traditional manufacturing methods and suggestions for handling AM data.

Understanding the Effect of Process Parameters on Tensile Strength and Dimensional Accuracy of ABS Parts Made using Fused Filament Fabrication (FFF): *Sneha Akula*[1]; Cody Kanger[1]; Chandler Sandman[1]; Jacob Quint[1]; Mahdi Alsunni[1]; Ryan Underwood[1]; Prahalada Rao[1]; Michael Sealy[1]; [1]University of Nebraska-Lincoln

Democratization of additive manufacturing and the wide variety of affordable 3D printers has led to large variations in the strength and accuracy of polymer components. Professionals, hobbyist, and students without engineering or additive manufacturing backgrounds are capable of adjusting multiple print settings that result in statistically different tensile strengths and dimensionally inaccurate parts. With the ever-growing expansion of affordable 3D printers in K-12 classrooms and enthusiasts' garages, there exists a need to better understand the influence of print settings on strength and accuracy of polymer parts. The goal of this research is to understand the effect of three fused filament fabrication parameters (layer height, infill angle, and outer shell quantity) on dimensional accuracy and tensile strength of ABS produced on a Hyrel System 30M. ASTM D638 Type 4 samples were used to measure tensile strength, and a test artifact based on NAS 979 (circle-square-diamond) was used to measure dimensional accuracy.

Understanding the Effect of Process Parameters on Tensile Strength of Polymer Parts Made using Mask Image Projection Sterelithography (MIP-SLA): *Mohammad Montazeri*[1]; Beau Marth[1]; Ben Smith[1]; Steven Christy[1]; Kole Krueger[1]; Michael Sealy[1]; Prahalada Rao[1]; [1]University of Nebraska-Lincoln

Mask Image Projection Stereolithography (MIP-SLA) is an additive manufacturing technique in which a liquid photopolymer resin is hardened from exposure to ultraviolet (UV) light. MIP-SLA systems are used for their high print speed and dimensional accuracy compared to other additive manufacturing processes. The goal of this work is to quantify the effect of SLA print process parameters, namely layer height and UV exposure, on the longitudinal tensile strength of ASTM D638 Type 5 test artifacts. Test parts were created using a central composite experimental plan on a B9Creator desktop SLA machine.

Design and Fabrication of Functionally Graded Material from Ti to γ-TiAl by Laser Metal Deposition: *Xueyang Chen*[1]; Lei Yan[1]; Joseph Newkirk[1]; Frank Liou[1]; [1]Missouri University of Science and Technology

Functionally graded material (FGM) is one kind of advanced material characterized by a gradual change in properties as the position varies. The spatial variation of compositional and microstructure over volume is aimed to control corresponding functional properties. In this research, when 100% γ-TiAl was directly deposited on pure Ti substrate, cracks were formed within the γ-TiAl layer. Then a six-layer crack-free functionally graded material of Ti/TiAl was designed and fabricated by laser metal deposition (LMD) method, with composition changing from pure Ti on one side to 100% γ-TiAl on the other side. The fabricated FGM was characterized for material properties by a variety of techniques. The chemical compositions, microstructure, phases, and hardness of the composite were characterized by Scanning Electronic Microscope (SEM), Optical Microscope (OM), Energy Dispersive X-ray Spectroscopy (EDS), and hardness testing. The microstructure and chemical compositions in different layers were studied.

FPGA-based Solution for High-speed Control of a Laser Powder Bed Fusion Testbed: *Jorge Neira*[1]; Ho Yeung[1]; Brandon Lane[1]; [1]National Institute of Standards and Technology

The AMMT (which stands for Additive Manufacturing Metrology Testbed) at NIST is a custom-built system for additive manufacturing (AM) research applications. This system replicates a laser powder bed fusion (LPBF) AM process, including high-power focused laser and scanner, and metal powder and layer forming capabilities. This presentation demonstrates a unique, fully customized FPGA-based hardware/software solution for high-speed control of the laser power, laser focus, and scan position. In addition, the design allows for high-speed, synchronous acquisition of laser power, position, and external sensor feedback, which can either be stored as AM build process monitoring data, or future research in control algorithms for real-time feedback control. Schematics of the system and controlling software are presented, along with measure performance parameters and results from validation testing. Future development directions and implementation options are discussed.

Framework for Design and Manufacture Integration of 3D Printing of Products with Functionally Graded Properties: *Mukul Sahu*[1]; [1]IIT Kharagpur

Developing optimized and industry standard approaches to eradicate challenges from design stage to manufacturing stage of manufacturing heterogeneous objects is the major thrust area. Currently mesh data is usually saved in industry standard STL format and any other Design Parameters /Mechanical Properties are difficult to handle and are mostly handled using vendor specific software. For. Example: Nano Scribe uses DeScribe [4] for similar purpose. While this kind of approach has worked well but it becomes highly crucial to have a more uniform and general solution to handle the complex process of additive manufacturing .Here an attempt has been made to use AMF/3MF and create a supporting software that acts as a pipeline between Design stage and manufacturing stage. It provides features like visualizing AMF and provides interface to edit other Design Parameters. It provides option to specify different zones in a geometric model of the object.

Integrated Locating Features for Precision Machining and Assembly of Additively Manufactured Components: *Ryan Penny*[1]; [1]Massachusetts Institute of Technology

The use of additive manufacturing (AM) to create high-performance components is often confronted by the discrepancy between process capabilities and required dimensional tolerances, necessitating post-processing by machining. To address this challenge, we describe the use of integral kinematic couplings (KCs) to enable fixturing of AM components during post-processing, and for construction of modular AM assembles. As a representative test geometry, classic three-ball / three-groove KCs are printed using four commonly available AM processes for plastics and metals. We study how the coupling accuracy, repeatability, and interchangeability are influenced by material properties, surface quality, and loading conditions. From this, we derive guidelines for incorporation of KCs into AM components, and reflect on the influence of AM process capabilities on the locating performance. Finally, we demonstrate the use of AM KCs in the fabrication of a modular 3D printed microscope.

Applications 8

Wednesday AM — Room: 410
August 9, 2017 — Location: Hilton Austin

Session Chair: Jason Weaver, Brigham Young University

8:00 AM
State of the Art and Qualification Plans for Wire + Arc Additive Manufacture: *Filomeno Martina*[1]; Jialuo Ding[1]; Stewart Williams[1]; [1]Cranfield University

WAAM has shown clear benefits in terms of substantial reductions in lead-times and manufacturing costs up to 70%, as well as multi-material or graded manufacturing capabilities. This paper will present the recent work performed within the WAAM Maturation (WAAMMat) consortium, with regards to part building, material processed, commercial exploitation of the process and, crucially, the qualification approach for class A structural components embraced by WAAMMat's industry members from the aerospace, defence, oil&gas, nuclear, automotive, energy sectors. In particular, the recent build of the world's largest AM part, a 6-metre, 300-kg aluminium spar structure will be presented, also with a series of critical large titanium structures. The manufacture of refractory-metals (W, Mo, Ta) will be covered too, with particular regards to multi-material graded structures. Finally, the qualification approach based on qualification of the thermal field, and on sophisticated process monitoring and control methods will be announced.

8:20 AM
Powder Removal Methods for Electron Beam Melting: *Philip Morton*[1]; David Saenz[1]; Jorge Mireles[1]; Ahsan Choudhuri[2]; Ryan Wicker[1]; [1]W. M. Keck Center for 3D Innovation; [2]UTEP-Mechanical Engineering

Electron beam melting (EBM) is a powder-bed fusion additive manufacturing technology which selectively melts metallic powder at an elevated temperature. One feature of EBM is the sintered powder which is formed during the layer preheating step. This is advantageous to the fabrication process by reducing the occurrence of residual stresses. Conversely, the powder can be difficult to remove from intricate cavities and channels. Residual powder, if not removed, can pose a safety risk or inhibit component performance specifically in flowing fluid applications. Articles were designed and fabricated to evaluate powder removal methods. The effects of feature size and wall thickness on powder removal capacity were tested. The methods were incrementally applied to the article and weigh change was measured. The Arcam PRS system, chemical etching, liquid nitrogen, ultrasonic vibration, sand blasting, and rubber mallet were the methods evaluated. The most effective were found to be ultrasonic vibration and liquid nitrogen.

8:40 AM
Experimental and Analytical Analysis of Nanoparticle Assemblies for High-throughput Nanomanufacturing: Anil Yuksel[1]; Jayathi Murthy[2]; *Michael Cullinan*[1]; [1]University of Texas Austin; [2]University of California Los Angeles

Understanding nanoparticle metal materials have been under attention due to their unique thermal, mechanical and optical properties which makes them attractive for many applications in micro-nano electronics. As the nanoparticle's behavior at the nanoscale is dominated by cohesive forces, generation of the nanoparticle assemblies for high-throughput nanomanufacturing becomes vital. In this study, we investigate cohesive force effect on metal nanoparticle assembly generation with statistical distribution and compare with SEM results. This will help to create desired nanoparticle assemblies for additively manufactured micro-nano electronic components.

9:00 AM
Adhesion of Reactive Silver Inks on Indium Tin Oxide Films: *Avinash Mamidanna*[1]; April Jeffries[1]; Mariana Bertoni[1]; Owen Hildreth[1]; [1]Arizona State University

Many emerging optoelectronic technologies require low temperatures to accommodate use of thermally sensitive substrates. Reactive inks enable fabrication of highly conductive features at low temperatures using Drop-on-demand (DOD) printing. DOD printing is a useful additive manufacturing tool which enables the user to deposit materials of any complex geometry at any desired location. In this work, the authors evaluate the adhesion performance of these reactive metal inks on Indium Tin Oxide (representative of the top layer of Silicon-Hetero-junction solar cells). A 180 °, ASTM standard peel testing method was used to evaluate the adhesion performance of these metal reactive ink contacts on ITO. Failure analysis was done on the metal fingers for varying amount of metal in each contact line to study and quantify the different adhesion failure modes of these metal reactive inks on ITO. We learned that there was more adhesive failure between the printed silver and the ITO substrate as the amount of silver increased. This novel approach introduces new techniques to deposit front contacts on solar cells and understand their adhesion properties.

9:20 AM
Characterization of Thermal and Vapor Smoothing on Surface Roughness of Extruded Components for Printed Electronics: *Clayton Neff*[1]; Darrell Griffin[1]; Eduardo Rojas[1]; Justin Nussbaum[1]; Thomas Weller[1]; Nathan Crane[1]; [1]University of South Florida

Additive manufacturing of thermoplastics via extrusion can produce substrates for printed electronics. However, the surface roughness of plastic extrusion reduces effective electric conductivity and can introduce anisotropy, especially in radio frequency (RF) devices. Vapor smoothing absorbs a solvent to lower the viscosity of the surface layer so that it can flow under surface tension. However, solvent absorption changes the surface composition slightly, can be hazardous, and not feasible with all thermoplastics. A new method—termed thermal smoothing—introduced here utilizes a heat source to locally re-flow the material thus minimizing the roughness of the undulating surfaces without the drawbacks of vapor smoothing. This research compares the surface roughness impacts of both smoothing processes profilometry and scanning electron microscope (SEM) images. Both smoothing processes enhance the surface of extruded components. This work also reports the influence of surface smoothing on the DC and high frequency conductivity of micro-dispensed conductors.

9:40 AM Break

10:10 AM

Characterization of Wirebondability to Copper Nanoparticle Traces Produced via Inkjet Printing: *Daniel Revier*[1]; Benjamin Cook[1]; Sadia Naseem[1]; Mahmud Chowdhury[1]; [1]Texas Instruments

Additive manufacturing (AM) techniques such as inkjet printing and 3D printing have emerged as low cost, high performance technologies for electronics fabrication. Initial applications cover sensors, antennas, frontends, and packages for systems from DC to millimeter wave frequencies. Yet these techniques do not exist in a vacuum and must work well with traditional manufacturing processes. Wirebonding is critical in semiconductor electronics packaging and is highly sensitive to material variation. Interactions between wirebond metals (e.g. gold) and inkjet printed metallic nanoparticle inks (e.g. copper) are studied. The wirebond process was optimized for high bond strength and bond conductivity to match industry standards. Recommended wirebonding parameters for a given wire-ink pair are provided and show encouraging results for integrating AM into the semiconductor packaging process.

10:30 AM

Thermo-mechanical Properties of 3D-printed Epoxy Nanocomposites: *Nadim Hmeidat*[1]; Brett Compton[1]; [1]University of Tennessee

Additive manufacturing (AM) methods have considerably impacted manufacturing world-wide, enabling the rapid fabrication of complex components that would not be possible in any other way. To fully utilize this manufacturing flexibility, new feedstock materials are needed that possess high strength, high stiffness, and low density to compete with existing engineering materials. This work focuses on recent efforts in characterizing the effects of functionalized nanoclay on the rheological properties of epoxy resins, and the thermo-mechanical properties of the resulting 3D-printed epoxy/clay nanocomposites, fabricated using direct-write AM. The rheological properties of ink formulations containing up to 12.5wt% nanoclay are measured using parallel plate rheometry, and thermo-mechanical properties of printed composites are measured using 3-pt flexural testing and dynamic mechanical analysis (DMA). Up to 140 MPa flexural strength is achieved in printed composites, with Tg values ranging from 140-160 degrees C.

10:50 AM

Approaching Rectangular Extrudate in 3D Printing for Building and Construction by Experimental Iteration of Nozzle Design: *Wenxin Lao*[1]; Mingyang Li[1]; Lorenzo Masia[1]; Ming Jen Tan[1]; [1]Nanyang Technological University

In Extrusion based 3D Printing technology, the voids could be reduced and the surface finish of printed parts could be improved with extrudate shape optimization. For large-scale 3D Printing technology like 3D Printing for Building and Construction, reducing printed layer height would increase the fabrication time drastically, while having few effect on voids reduction and surface finish improvement. In this paper, an iterative experimental approach to achieve the optimized nozzle design for rectangular shaped extrudate was proposed. Two nozzle prototypes were manufactured by Fused Deposition Method and implemented for experimental tests, then a new nozzle design was created based on the experimental extrudate shapes. This process iterated until a good rectangular extrudate shape was obtained. Printing tests were conducted with the optimized nozzle, which showed the designed nozzle could help to eliminate the voids among the printed parts and guarantee good surface finish without losing the speed of printing.

11:10 AM

Areal Surface Characterization of Laser Sintered Parts for Various Process Parameters: *Patrick Delfs*[1]; Hans-Joachim Schmid[2]; [1]Paderborn University / DMRC; [2]Particle Technology Group

Laser sintered polymer parts consist of rough surfaces due to the layered manufacturing and adherence of incomplete molten particles. The absolute roughness depend on various process parameters like build angle, spatial position, build temperature, exposure order and layer time. Analyses with the help of several areal roughness values of DIN EN ISO 25178-2 considering these parameters are introduced in this paper. Multiple build jobs with 120 µm layer thickness and PA2200 powder were built on an EOS P396 machine using the same build job design with varying process parameters. An individual sample part was designed to receive lots of surface topography information with optical 3D measurements. The results show roughness dependencies for 0° to 180° build angles in 15° steps and eleven distributed in-plane and three axial direction positions depending on different build temperatures and layer times. Limitations of the varied parameters are finally derived for the manufacturing of improved surface qualities.

Applications 9: Heat Exchangers and Smart Devices

Wednesday AM August 9, 2017 — Room: 406 — Location: Hilton Austin

Session Chair: Ulrich Jahnke, Paderborn University / DMRC

8:00 AM

3D Printing of Humidity Sensor Based on Swelling Kinetics of Hydrogel: *Xiangjia Li*[1]; Benshuai Xie[1]; Yang Yang[1]; Yong Chen[1]; [1]University of Southern California

Increasing interest in wearable sensors has heightened the need for multi-functional material and novel manufacturing methods suitable to monitor and detect the activities of human body; however, most of them are single dimensional sensitive to the environment. In this paper, a conductive biocompatible composite hydrogel capable of detecting humidity was developed by using the conductive carbon Nanotube and poly(ethylene diacrylate) (PEGDA) solution. Based on the swelling property, the resistant of carbon nanotube (CNT)-based hydrogel strips changes significantly due to the deformation of strips under different humilities. Furthermore, multi-layers of carbon nanotube based hydrogel strips are printed on the stretchable photopolymer that can identify position effectively based on the resistance changes in different strips. The work presented here has profound implications for future studies of 3D printed biocompatible multi-functional sensors in detecting activities of human body.

8:20 AM

Additive Manufacturing for Embedded Microelectronics: *David Keicher*[1]; Marcelino Essien[2]; Judi Lavin[1]; Shaun Whetten[1]; Zach Beller[1]; [1]Sandia National Laboratories; [2]IDS

Additive Manufacturing (AM) of mechanical structures is becoming a mature technology area. Direct Write Electronics (DWE) is maturing to the point where applications are beginning to emerge. An area of great potential lies in the overlapping application space between these two technologies where electronics can be printed layer by layer within a printed 3D structure. Work has begun to explore this application space to understand how to create functionalized structures for state of health monitoring or for the further miniaturization of microelectronic components. Areas of exploration include AM integration of passive electronics onto AM printed ceramic packages and the integration of stress and temperature sensors within 3D printed polymer structures. Issues associated with development in this technology area will be discussed along with novel solutions aimed at addressing some of these topics.

8:40 AM

Surface Roughness and Resolution Refinement of Vacuum Electronic Devices using Fine Distributions of OFHC Copper with Electron Beam Melting: *John Ledford*[1]; Harvey West[1]; Ilbey Karakurt[2]; Diana Gamzina[3]; N. C. Luhmann[4]; Liwei Lin[2]; Tim Horn[1]; [1]CAMAL; [2]University of California, Berkeley; [3]SLAC; [4]University of California, Davis

Recently, direct metal additive manufacturing has been projected to fabricate complex, high power, radio frequency (RF) components. Compared to other existing additive manufacturing processes, EBM is ideal for OFHC Cu due to the relatively high vacuum conditions to maintain purity, high ambient temperature to eliminate thermally induced stresses, and the high efficiency of EB over laser based technologies. In this study we have utilized a smaller powder size fraction and layer thickness to reduce the surface roughness of the as-manufactured RF components. These results can help lead to the use of broader powder size distributions in the EBM process. By re-engineering the EBM machine with a new build tank and better vacuum capability we are able to produce high purity, fully dense OFHC Cu RF components with small feature sizes. Oxygen content, vacuum compatibility, electrical conductivity, and density were used as measures of success in this study.

9:00 AM

3D Printing of Flexible & Stretchable Electronics at Room Temperature via Liquid Metal Direct-writing: *Dishit Parekh*[1]; Collin Ladd[1]; Lazar Panich[1]; Khalil Moussa[2]; Michael Dickey[1]; [1]North Carolina State University; [2]3D Systems, Inc.

Present metal additive manufacturing methods tend to be expensive and energy-intensive requiring high sintering temperatures and vacuum, making them difficult to integrate with different polymeric, organic, soft and biological materials. Here, we present a simple approach to print low melting point gallium-based alloys at room temperature. Due to the instantaneous formation of a thin (~3 nm), passivating surface oxide skin, we can direct-write planar as well as out-of-plane, mechanically stable conductive microstructures down to a resolution of ~10 microns, on-demand, using a customized 3-axis pneumatic dispensing robot. We have demonstrated rapid prototyping of functional electronics such as flexible and stretchable radio-frequency antennas for communication, inductive coils for power transfer, and thermoelectric generators for energy-harvesting applications. We can also pattern 3D multilayered microchannels with microvasculature using these printed liquid metals as a sacrificial template, that can be employed in various lab-on-a-chip sensing devices to enable inexpensive fabrication of personalized healthcare sensors.

9:20 AM

Integrated Additively Manufactured Hydraulic and Electronic Passageways in Novel Robotic Systems: *Brian Post*[1]; Bradley Richardson[1]; Randall Lind[1]; Lonnie Love[1]; [1]Oak Ridge National Laboratory

Additive manufacturing (AM), commonly referred to as 3D printing, was originally used for rapid prototyping. However, research into new technologies has allowed AM to become applicable far beyond prototype fabrication. The Department of Energy's Oak Ridge National Laboratory (ORNL), sponsored by the Office of Naval Research, has designed and developed an anthropomorphic seven-degree-of-freedom (DOF) dual arm hydraulic manipulator using metal AM technologies. All electrical and fluidic passageways were designed and printed into each arm. With the integrated hydraulic passageways, no hoses are required for actuation of each arm. A combination of face seals and rotary unions allow the passage of fluids from one link of the arm to another. The integrated electronic passageways allow for a control architecture that was based on a distributed controls approach. These manipulator arms provide valuable insight into AM's robotic applications.

9:40 AM Break

10:10 AM

Design and Process Considerations for Effective Additive Manufacturing of Heat Exchangers: Amanda Sterling[1]; Jonathan Pegues[1]; Huseyin Ozdes[1]; *Mohammad Masoomi*[1]; Nima Shamsaei[1]; Scott Thompson[1]; [1]Auburn University

Design and process considerations for the effective powder bed fusion (PBF) of single-phase heat exchangers and hermetic micro-to-mini channel devices for thermal management and energy harvesting are discussed. Using tools such as process simulation, scanning electron microscopy, neutron radiography and surface profilometry, the PBF of functional heat pipes, as well as their post-PBF attributes, are detailed. The effect of process parameters, part-to-bed orientation, powder entrapment and more, on the final part functionality and heat transfer ability are described. Heat transfer enhancement, material selection, de-powdering methods and hermeticity challenges are also highlighted. Results demonstrate that the relatively rough channel surfaces produced via PBF can serve as secondary wicking structures for decreasing the heat transfer required to initiate fluid motion within. Ongoing challenges relevant to producing and improving micro-to-mini channel devices using additive manufacturing are presented along with other possible topics of research in this area.

10:30 AM

Design and Additive Manufacturing of a Composite Crossflow Heat Exchanger: *Tom Mulholland*[1]; Rachel Felber[1]; Natalie Rudolph[1]; [1]University of Wisconsin - Madison

Additive manufacturing (AM) with composite materials reveals new possibilities for direct manufacturing of end-use products, breaking the paradigm of 3D printing as only a prototyping or pre-production technique that has been the norm for many AM technologies. A crossflow air-to-water heat exchanger (HX) was designed for manufacturing via fused filament fabrication (FFF). Design iterations improved the manufacturability, considering issues such as geometric fidelity, watertightness, print time, support material, and manufacturing cost. Carbon fiber fillers enhanced the thermal conductivity of the base polyamide resin, allowing for thermal HX performance comparable to conventional aluminum finned tube heat exchangers. The anisotropic thermal conductivity impacts the heat exchanger performance. The design and manufacturing challenges reveal additional routes to continued performance gains as the HX is scaled up to an 8 kilowatt product.

10:50 AM

Cooling Optimization of 3D Printed Camera Cell Cooling Housing for Machine Vision in High Temperature Condition: *Chiyen Kim*[1]; Jose Coronel[1]; David Espalin[1]; Ryan Wicker[1]; Mireya Perez[1]; Diana Gandara[1]; Diana Ibarra[1]; [1]University of Texas El Paso

Combining multiple processes for hybrid additive manufacturing requires accurate geometrics to ensure the workpiece is placed correctly on the different stations. Previous research employed machine vision to measure positions and facilitate registration. However, the initial machine vision system encountered difficulties with operating within the high temperature environment of the printing chamber. To utilize machine vision technology safely, it was required that an air cooled housing isolated the camera module from the temperature of the envelope to maintain it within operating range. It is common to utilize ready-made products for operating cameras at a specific thermal range. However, complexities arise as analysis of flow and heat exchange must be considered for the optimal operation of the system to desired specifications. The use of 3D printing allows for a cooling housing to be fabricated by saving production cost and increasing design flexibility. Using the Multi3D System, a 3D printed air cooled housing for a camera cell module was manufactured. A new method to find the optimal air flow rate without heat and flow analysis was observed. Since dark current is the most common heat reaction in the CCD (charge-coupled device) camera, investigation of the dark current effect was performed and the results will be discussed.

11:10 AM

Thermal Concentrator Design Enabled by Multi-Material 3D Metal Printing: *Tim Price*[1]; David Keicher[1]; Shaun Whetten[1]; [1]Sandia National Laboratories

Additive manufacturing provides an opportunity to create hardware not readily produced using traditional manufacturing approaches. These unique applications provide an opportunity to introduce additive manufacturing into production where the technology has significant value added. Recent work on a fail-safe component provided an opportunity to take advantage of the ability to use the LENS process to 3D print multimaterial structures. This work involved design and development of stainless steel/copper structure to collect and channel thermal energy from a heated surface and into a component meant to fail when heated. The unique structure was able to collect, channel and concentrate the thermal energy to locally heat the fail-safe component to a given temperature in approximately half of the time of a single material structure. Results of this development including thermal modeling, print geometry and measured thermal response of the printed test hardware will be discussed.

11:30 AM
Fabrication and Quality Assessment of Thin Fins Built Using Metal Powder Bed Fusion Additive Manufacturing: *Alexander Dunbar*[1]; Gabrielle Gunderman[1]; Morgan Mader[2]; Edward Reutzel[1]; [1]The Pennsylvannia State University; [2]Honeywell

Powder bed fusion additive manufacturing is well suited for the fabrication of metallic components with thin features that would be otherwise impractical using other manufacturing methods. As component designs begin to take full advantage of the capabilities of additive manufacturing, so must the capability of measurement techniques used in assessment of quality increase. The characterization of quality may be application specific, requiring different metrics for different uses, e.g. impact on thermal vs. mechanical considerations. Here, thin fins are built with a wide range of processing conditions to test the limits of thin, metallic structures using PBFAM. These thin fins are inspected using novel computed tomography (CT) based measurement and analysis techniques to assess their build quality. Within the process parameters tested, fins were successfully built thinner than the quoted manufacturer minimum wall thickness. The quality of these fins was assessed utilizing post-build non-destructive evaluation techniques developed herein.

Biomedical Applications 1: Tissue and Cellular

Wednesday AM
August 9, 2017

Room: Salon J
Location: Hilton Austin

Session Chair: Wei Sun, Drexel University

8:00 AM
Constructing Heterogeneous Tumor Models by Integrated Cell Printing System: *Wei Sun*[1]; Tiankun Liu[1]; Rui Yao[1]; Yuan Pang[1]; [1]Drexel University

In this study, a new 3D Bioprinting system was introduced to print cell/biomaterials and to pattern specific cells to construct heterogeneous tumor microenvironment. This was achieved by integrating cell plotting and alternating viscous and inertial force jetting (AVIFJ): hydrogels containing high cell density could be printed by cell plotting, while droplets with single cell could be located precisely by AVIFJ. Simple 3D structures containing tumor cells and droplet arrays were first printed to ensure the feasibility of the bioprinting system and then heterogeneous tumor model containing tumor spheres and stromal cells were printed. The width of the hydrogels and the diameter of the droplets could be controlled and modified. The viability of Hela cells was above 90% immediately after bioprinting. And the results based on integrated bioprinting suggested the droplets were located around the pre-formed tumor spheres as designed.

8:20 AM
Biofabrication of a 3D Vascular Network Using Dynamic Optical Projection Stereolithography: *Hongtao Song*[1]; Changxue Xu[1]; [1]Texas Tech University

Bioprinting has been widely used to construct artificial tissues and organs layer by layer by precisely controlling the deposition of biological materials and living cells. However, it has been recognized that one of the critical limitations in tissue engineering is lack of a blood vessel system which is used to supply tissues and organs with oxygen and nutrients. Hence, biofabrication of vascular networks is a first step towards successful bioprinting of tissues and organs. In this paper, a 3D bioprinting system based on dynamic optical projection stereolithography has been adopted to fabricate 3D vascular networks. Fibroblasts have been encapsulated into the fabricated 3D vascular networks, and the post-printing cell viability has been evaluated. As a proof of concept study, the resulting fabrication knowledge helps print tissue-engineered vascular network with complex geometry.

8:40 AM
Study of Printing Dynamics during Inkjetting of Cell-laden Bioink: Mengyun Zhang[1]; *Hongtao Song*[1]; Changxue Xu[1]; [1]Texas Tech University

Bioprinting is considered as a promising technique in tissue engineering and regenerative medicine with the aim of developing biological substitutes to restore, replace or regenerate defective tissues and organs. Inkjet printing is one of the primary manufacturing technologies due to its scale-up potential, simple setup, and good process controllability. However, when the bioink containing living cells is used for printing, the uniform cell distribution, defined as the cell number in each droplet/microsphere, is still a big challenge, which significantly affects the post-printing cell viability and cell proliferation. In this paper, the experimental and computational results of cell distribution are combined to analyze the printing dynamics of cell-laden bioink during DOD inkjetting. The resulting knowledge will benefit efficient and effective fabrication of 3D cellular constructs with uniform cell distribution.

9:00 AM
Biofabrication of 3D Vascular Constructs of Interpenetrating Network Hydrogel Using a Yield-stress Fluid Bath: *Srikumar Krishnamoorthy*[1]; Changxue Xu[1]; [1]Texas Tech University

3D bioprinting based on layer-by-layer manufacturing mechanism has been emerging as a promising solution to fabricate 3D functional tissues and organs for regeneration and replacement of defective, diseased or missing tissues and organs. However, vascularization is always the biggest challenge. This paper introduces a yield-stress fluid bath to fabricate 3D vascular constructs of interpenetrating network hydrogel with living cells encapsulated. The rheology of the yield-stress fluid bath has been characterized. The operating conditions including the nozzle speed and inlet pressure have been optimized for good filament formation. Finally, 3D cellular tubes have been successfully fabricated after a two-step crosslinking process, and cell viability has also been evaluated. This proposed fabrication approach enables effective and efficient biofabrication of 3D complex vascular network.

9:20 AM
High-resolution Electrohydrodynamic Jet Printing of Molten Polycaprolactone: Ryan Tepper[1]; *Patrick Sammons*[1]; Kira Barton[1]; [1]University of Michigan

Polycaprolactone (PCL) is a biocompatible and biodegradable polymer that is commonly used in drug delivery systems, medical structures, and tissue engineering applications. Typical additive manufacturing methods of PCL structures for tissue engineering applications either require harsh organic solvents or are only capable of producing relatively large feature sizes, which are not compatible with many of the desired applications. Electrohydrodynamic jet (e-jet) printing, an additive manufacturing process which uses an electric field to induce jetting from a microcapillary nozzle, is an attractive method for producing PCL tissue engineering structures due the achievable resolution and the ability to print highly viscous inks. In this work, experimental investigation into the ability to print pure, molten PCL using the e-jet process is carried out. A characterization of the process input which yield suitable printing regimes is presented. Demonstration of the achievable resolution with e-jet printing is presented in the form of printed, high-resolution structures.

9:40 AM Break

10:10 AM
Engineered Stem Cell Fibrous Substrates Using High Resolution Additive Biomanufacturing: *Robert Chang*[1]; Filippos Tourlomousis[1]; [1]Stevens Institute of Technology

Reliably engineering scalable 3D biological substrates as physiologically relevant structured materials with single cell resolution poses a significant manufacturing challenge. The lack of suitable technologies, along with the recently reported problem of heterogeneity in mesenchymal stem cell (MSC) populations, have impeded the clinical translation of MSCs-based therapies. To address this significant bottleneck, an additive melt electrospinning writing process is advanced to fabricate 3D fibrous substrates within a tight cellular dimensional scale window (1-50 µm). MSCs are then seeded on the various produced substrate dimensionalities. The MSC differentiation status is characterized during a time course study using quantitative indirect immunofluorescent staining. Early morphometric profiling of shape-bearing focal adhesion proteins is performed through single-cell automated image analysis and to yield a predictive model of MSC differentiation status. The in vitro methodological framework presented herein aims to establish a well-characterized homogeneous population of MSCs in 3D format for clinical delivery.

10:30 AM
3D Bioprinting Tissue Constructs: Juan Xing[1]; Xianli Luo[1]; *Matthew Moldthan*[1]; Bingbing Li[1]; [1]California State University Northridge

One of the foremost challenges of 3D bioprinting is the formation of viable and structurally sound tissues and organs. Creating tissue engineering constructs (TECs) capable of producing structurally stable, cell-laden tissues is the first step towards printing organs and tissues viable for human transplantation. We were able to fabricate these tissues by using a custom-made 3D bioprinter to print a composite hydrogel, serving as a cell carrier material, together with biodegradable polymers in conjoined patterns on a sacrificial hydrogel. We were able to achieve the desired anatomical shapes by feeding CAD model to computer, and then translating that model into customized Gcode, which instructs the microfabrication printer nozzles to dispense the cell-laden hydrogel at specific locations. Microchannels were integrated into the tissue to promote proper vascularization and to facilitate the diffusion of nutrients to the cells thereby overcoming the standard diffusion limit and maximizing cell survival.

10:50 AM
Rapid 3D Printing of Scale-up Vascularized Cell-laden Tissue: *Hang Ye*[1]; Nanditha Anandakrishnan[1]; Chi Zhou[1]; Ruogang Zhao[1]; [1]University at Buffalo

In this work, we propose a continuous bioprinting approach which enables high-efficiency fabrication of human-scale engineered hydrogel tissue. This approach is essentially a constrained surface projection-based stereolithography process. The low separation force and the high material replenishment rate result from the low viscosity of hydrogel allows high-speed production of soft tissues. The polymerization behavior for different materials and compositions is also investigated in order to achieve a fine vertical resolution. We demonstrate that a 3.5 cm × 2.2 cm × 1.4 cm vascularized liver model with encapsulated 3T3 fibroblasts and HepG2 cells can be fabricated within 5 minutes. During a 7-day period culture, it shows that more than 90% of the cells are viable during the 7-day period.

11:10 AM
Fracture Mechanism Analysis of Schoen Gyroid Cellular Structures Manufactured by Selective Laser Melting: *Lei Yang*[1]; Chunze Yan[1]; Yusheng Shi[1]; [1]HuaZhong University of Science & Technology

Ti-6Al-4V triply periodic minimal surface (TPMS) structures with biomorphics scaffold designs are expected to be the most promising candidates for many biological applications such as bone implants. Fracture is the main failure mode of Ti-6Al-4V cellular structures at room temperature. However, there is currently less investigation on general analysis about the fracture mechanism of Ti-6Al-4V TPMS cellular structures. In this work, a typical TPMS structure, Schoen Gyroid, was designed and porous Ti6Al4V Schoen Gyroid specimens were manufactured using Selective laser melting (SLM). Finite element analysis (FEA) method was employed to calculate the stress distribution under compression. The FEA results are used to predict the fracture positions, fracture zones as well as fracture mode. The uniaxial compression experiments were conducted and compared with the FEA results. The experimental and simulation results show high consistency.

11:30 AM
Three-dimensional Printing of Cellulose-laden Ionic Liquids: *Deshani Gunasekera*[1]; Yinfeng He[1]; Christopher Tuck[1]; Anna Croft[2]; Ricky Wildman[1]; [1]Centre for Additive Manufacturing (CfAM), The University of Nottingham; [2]Department of Chemical and Environmental Engineering, The University of Nottingham

In this study, a biomaterial based ink made up of cellulose and ionic liquid; 1-butyl-3-methylimidazolium acetate ($[C_4C_1Im][OAc]$) was used in three dimensional (3D) printing with a PICO Pulse deposition system from Nordson. Printing parameters were optimized by varying pressure, temperature, pulse time and droplet spacing. The quality of the droplets, lines and films printed at each condition were used to identify suitable printing conditions for the ink. 3D printed patterns in cellulose were regenerated using different anti-solvent baths and analysed with state-of-the-art analytical techniques. This work demonstrates the application of PICO Pulse jetting system in 3D printing cellulose-laden ionic liquids.

Materials 10: PBF: Multijet Fusion and Laser Sintering

Wednesday AM — Room: 408
August 9, 2017 — Location: Hilton Austin

Session Chair: Taku Niino, The University of Tokyo

8:00 AM
The Mechanical Voxel: Variable Rigidity Polymer Parts Using Multi Jet Fusion: *Kristopher Erickson*[1]; Lihua Zhao[1]; Aja Hartman[1]; Howard Tom[1]; Kristopher Li[1]; Paul Olubummo[1]; [1]HP Incorporated

Multi Jet Fusion (MJF) is a polymer powder based 3D printing technology used to produce high mechanical performance polymer parts with faster print speeds at reduced costs. The MJF technology utilizes jetted agents for defining part regions at a voxel-level. Mechanical Tailoring Agents (MTAs) have been designed to work with HP's MJF technology and can be deposited during the print process for voxel-level control over mechanical properties. Certain portions of the printed part can be made more rigid, more ductile, or left with the native material properties. Usage of MTAs works seamlessly with the MJF print process, so high print speed, resolution and mechanical performance 3D printed polymer parts are made. We demonstrate both parts with a range of mechanical properties from a singular powder build material as well as parts with different mechanical properties at different portions of the part.

8:20 AM
The Conductive Voxel: Conductive Features within Polymer Parts Using Multi Jet Fusion: *Kristopher Erickson*[1]; Sterling Chaffins[1]; Yan Zhao[1]; Aja Hartman[1]; Lihua Zhao[1]; Howard Tom[1]; [1]HP Incorporated

Multi Jet Fusion (MJF) is a polymer powder based 3D printing technology used to produce high mechanical performance polymer parts with faster print speeds at reduced costs. The MJF technology utilizes jetted agents for defining part regions at a voxel-level. Conductive Agents (CAs) have been designed to work with HP's MJF technology and can be deposited during the print process for voxel-level control of conductivity. Use of the CAs allows for conductive traces, vias, and contacts to be made anywhere within the printed part. Details around the process for creating a strain gauge device will be presented, which is used to quantify the load applied onto it for external readout. Usage of CAs works seamlessly with the MJF print process, so high print speed, resolution and mechanical performance 3D printed polymer electronic devices result.

8:40 AM

Pre-printing Quality Assessment of LS-PA12 Parts: Validating the Energy Density Mapping Approach through the use of X-ray Computed Tomography: *Michele Pavan*[1]; Tom Craeghs[1]; Jean-Pierre Kruth[2]; Wim Dewulf[2]; [1]Materialise; [2]KU Leuven

Laser sintering of polymers is progressively used to produce end-user functional parts with complex geometries. However, obtaining the required densities and dimensions in all the features contained in these complex geometries require a good process knowhow about the scanning strategy to adopt. During the process, the melting of the polymeric powder is achieved thanks to the energy delivered by the CO2-laser, which leads to progressive flow and densification of the material. The final part density and dimensions, strongly depend on the way the energy is delivered on the powder bed. The new approach proposed in this work, combines all the laser-scanning parameters into a local Energy Density mapping, highlighting the regions where the energy input differs from the optimal one. The data obtained through characterization of the parts by X-ray Computed Tomography are correlated with the local energy density deviations, establishing a clear link between the two approaches.

9:00 AM

Flow Behaviour of Laser Sintering Powders at Elevated Temperatures: *Michael Van den Eynde*[1]; Peter Van Puyvelde[1]; [1]KU Leuven

Adequate powder flowability is an indispensable property for any powder intended for laser sintering. Characterisation of which powders meet the flow requirements to form smooth and thin powder layers in a sintering device is, however, not trivial. Many factors, such as particle shape, moisture content and temperature play an important role. The effect of all these parameters is not always well understood and, moreover, the influence of some parameters, such as temperature, is often omitted in many lab-scale experiments.This research looks at powder flowability of various polymeric powders and aims to gain a more fundamental insight in the effect of temperature on powder flow. Various lab-scale measurements, such as the dynamic angle of repose, powder rheometry and a spreading experiment, are performed at elevated temperature. DSC measurements provide further information on thermal effects and moisture content is monitored to ensure a fair comparison to flow at room temperature.

9:20 AM

Microwave Measurements of Nylon-12 Powder Ageing for Additive Manufacturing: *Nicholas Clark*[1]; Franck Lacan[1]; Adrian Porch[1]; [1]Cardiff University

With repeated recycling, nylon powders used in Selective Laser Sintering are known to degrade and ultimately cause mechanical performance and surface finish deterioration in produced parts. In order to maintain consistent production and to reduce cost by minimising waste powder, it is desirable to monitor this degradation. However, any techniques used must be inexpensive, quick and simple in order to maintain industrial relevance; dielectric measurements by microwave cavity perturbation can offer these advantages. Here, samples are taken from a working SLS machine and their permittivity measured using microwave cavity perturbation. A 2% reduction in effective dielectric constant and an 8% reduction in effective dielectric loss is observed between new powder and recycled feedstock. Furthermore, in-situ measurements simulating build chamber conditions show a similar trend.

9:40 AM Break

10:10 AM

Improvement of Recycle Rate in Laser Sintering by Low Preheat Temperature Process: *Takashi Kigure*[1]; Toshiki Niino[2]; [1]Tokyo metropolitan industrial technology research institute; [2]Institute of Industrial Science, the University of Tokyo

Laser sintering process selectively solidifies its powder bed to obtain designated parts and leaves the rest unsolidified. When the remained powder is recycled, a certain amount of fresh powder is added to moderate the effect of deterioration by preheating in the previous batch. In terms of economy, improvement of the recycle rate of used powder is one of the big challenges. The authors are developing a novel laser sintering process that prevents part being processed from warping not by preheating the powder bed but by anchoring the parts to a rigid base plate. Since the new process, namely low temperature process, can lower the bed temperature than normal *high temperature process*, it is expected to reduce deterioration of the used powder. In present research, processablity of recycled powder is evaluated by its MFR, and it is shown that operation at a high recycle rate more than 90% is possible.

10:30 AM

Development of an Experimental Lasersintering Machine to Process New Materials like Nylon 6: *Johannes Lohn*[1]; Hans-Joachim Schmid[2]; Christina Kummert[2]; [1]Paderborn University/DMRC; [2]Paderborn University, DMRC

Selective Laser Sintering (SLS) is an Additive Manufacturing technology which allows the production of functional polymer parts. Conventionally, mainly Nylon 12 (PA 12), Polyamide 11 (PA 11), glass- or aluminum filled materials are used. Those materials do not always meet the requirements for direct production of serial parts by laser sintering. For the so called “Direct Manufacturing” of high quality, functional parts, the laser sintering process needs to be further developed and the choice of materials and needs to be expanded. During this research, a laser sintering machine for material qualification has been built up. The advantages are an optimized software solution, an innovative optical system with an adjustable laserspot, an alternative powder coating system and an improved temperature control. The functionality of the test equipment is proved with the standard material PA2200 and the new laser-sintering-material, Polyamide 6X (PA6X) is investigated. The required process parameters for processing PA6X are derived and the mechanical properties are determined by tensile tests.

10:50 AM

Optimization of Adhesively Joined Laser-sintered Parts: *Thiemo Fieger*[1]; Dominik Nugara[1]; Jens Huebner[1]; Gerd Witt[2]; [1]Daimler; [2]University of Duisburg-Essen

As additive manufacturing technologies are advancing in quality and economic feasibility, joining and assembly is becoming increasingly important for industrial users. In this study, the performance of four adhesives for polyamide 12 specimen is analyzed. Testing of bonding relevant factors, such as the surface energy of the solid substrates, is conducted. Tensile shear tests show an early adhesive failure of the joint polyamide 12 specimen. To increase the polar bonding forces and the surface energy of the solid substrate, pretreatments such as atmospheric plasma, chemical, corona and flame treatment are applied. As an alternative to increase the bonding strength of the joints, the effects of design changes of the bonding area are looked at. A summary of the impact of all pretreatments and design changes is given and the suitability of each application is assessed.

Materials 11: 304L and Precipitation Hardened Stainless Steel

Wednesday AM — Room: Salon K
August 9, 2017 — Location: Hilton Austin

Session Chair: Amy Elliott, Oak Ridge National Laboratory

8:00 AM
Characterization of Heat-affected Powder Generated during Selective Laser Melting of 304L Stainless Steel Powder: *Austin Sutton*[1]; Caitlin Kriewall[1]; Ming Leu[1]; Joseph Newkirk[1]; [1]Missouri University of Science and Technology

The selective laser melting (SLM) process is an additive manufacturing (AM) technique that uses a laser to fuse successive layers of powder into near fully dense components. Due to the large energy input from the laser during processing, vaporization and instabilities in the melt pool occur causing the formation of condensate and laser spatter, collectively known as heat-affected powder. Since heat-affected powder settles into the powder bed, the properties of the unconsolidated powder may be altered compromising its reusability. In this study, characterization of 304L heat-affected powder was performed through particle size distribution measurements, x-ray diffraction, metallography, energy-dispersive spectroscopy mapping, and visualization of grain structure with the aid of a focused-ion beam. The results show morphological, microstructural, and surface chemistry differences between the starting powder and heat-affected powder formed during processing, which aid in the understanding of laser spatter and condensate that form in the SLM process.

8:20 AM
Effects of Area Fraction and Part Spacing on Degradation of 304L Stainless Steel Powder in Selective Laser Melting: *Caitlin Kriewall*[1]; Austin Sutton[1]; Sreekar Karnati[1]; Joseph Newkirk[1]; Ming Leu[1]; [1]Missouri University of Science and Technology

In selective laser melting (SLM) systems, a large portion of powder remains unconsolidated and therefore recycling powder could make SLM more economical. Currently, a lack of literature exists specifically targeted at studying the reusability of powder. Furthermore, the definition of powder reusability is complex since powder degradation depends on many factors. The goal of the current research is to investigate the effects of area fraction and part spacing on the degradation of 304L powder in SLM. An experimental study was conducted where various area fractions and part distances were chosen and powder characterization techniques for determination of particle size distributions, tap and apparent densities, and x-ray diffraction were employed to track evolving powder properties for the purpose of reuse. The results show that the recyclability of 304L powder depends on the utilization of the build area causing varying degrees of particle size coarsening and delta ferrite formation.

8:40 AM
Directional Dependence of Mechanical Properties and Defects of LENS 304L: David Keicher[1]; *Cole Britt*[1]; [1]Sandia National Laboratories

Sandia National Laboratories has invested in developing a next generation LENS system to advance the state of the art in LENS technology. The first material being used in that system is 304L stainless steel. To optimize process conditions, tensile bars were made to evaluate material properties of the printed structures. Blocks of stainless 304L steel were printed using Laser Engineered Net Shaping (LENS) and machined into tensile samples. Half of the samples were pulled in a direction transverse to the build plane while the second half was pulled in a direction parallel to the build plane. The directional dependence of the material properties on build direction were observed. Analyses of fracture surfaces and cross sections were conducted. Builds were repeated to minimize direction dependence and understand repeatability. Testing results for both sets of tensile bars will be discussed.

9:00 AM
Impact of Specimen Dimensions on Miniature Tensile Characterization of Powder Bed Fabricated 304L Stainless Steel: *Sreekar Karnati*[1]; Jack Hoerchler[1]; Frank Liou[1]; Joseph Newkirk[1]; [1]Missouri University of Science and Technology

Miniature tensile specimens of 304L stainless steel (SS) with varying aspect ratios were fabricated using powder bed additive manufacturing (AM) process. The tensile characteristics measured from these specimens were analyzed to assess the impact of specimen dimensions. The study found no impact upon varying dimensions on yield and ultimate strength measurements. However, a significant impact was observed on strain and reduced area measurements. This data was also used to perform Weibull statistics to estimate the stochastic performance of the material. Fractography was performed to identify the types of flaw distributions. A comparative study with specimens fabricated from hot-rolled 304SS was also performed. The Weibull parameters were used to compare the variability within hot-rolled and AM 304L-SS. This study indicates miniature tensile testing is a robust characterization technique for obtaining representative material properties

9:20 AM
Bonding of 304L Stainless Steel to Cast Iron by Selective Laser Melting: *Baily Thomas*[1]; Austin Sutton[1]; Ming Leu[1]; Nikhil Doiphode[2]; [1]Missouri University of Science and Technology; [2]Cummins Inc.

A major limitation of cast iron is its weldability to dissimilar materials due to hot cracking caused by low ductility. A potential remedy could be the Selective Laser Melting (SLM) process using a pulsed laser, where only small weld pools are created, reducing the overall energy input. The present paper describes an investigation to join 304L stainless steel with cast iron. Small weld pools are created by this process, thereby reducing the overall energy input. In this study, 304L Stainless Steel particles were melted on a grey cast iron substrate by the SLM process. Parameter values were chosen to test different energy densities on the tensile strength of the bond created. Characterization of the bonded area included energy-dispersive spectroscopy (EDS) mapping for obtaining insight into the elemental diffusion, and metallography for visualization of the microstructure. A range of energy densities was identified for eliminating bond delamination and maximizing strength.

9:40 AM Break

10:10 AM
Metal Matrix Nanocomposite Powders for Laser Powder Bed Fusion: *Khalid Hussain Solangi*[1]; Lianyi Chen[1]; [1]Missouri University of Science and Technology

Metal powders with uniformly dispersed ceramic nanoparticles and suitable size and shape for additive manufacturing processes are highly demanded for additive manufacturing of metal matrix nanocomposites. However, it is difficult to manufacture metal matrix nanocomposite powders with both uniform dispersion of nanoparticles and optimized size and shape for additive manufacturing. Here we report the manufacturing processes to fabricate 304L matrix nanocomposite powders with uniformly dispersed nanoparticles and suitable size and shape for laser powder bed fusion. The characteristics of the powders and the manufacturing methods developed for fabricating the powders will be presented. The mechanisms of nanoparticle dispersion and powder size evolution will be discussed. Our research provides a promising way to produce metal matrix nanocomposite powders for additive manufacturing.

10:30 AM
Effect of Zone Creation to Locally Control Microstructure in Powder Bed Fusion Stainless Steel: *Andelle Kudzal*[1]; Clara Hofmeister[2]; Daniel Galles[2]; Chad Hornbuckle[3]; Brandon McWilliams[4]; Jianyu Liang[1]; [1]Worcester Polytechnic Institute; [2]Oak Ridge Institute for Science and Education; [3] US Army Research Laboratory; [4]US Army Research Laboratory

The microstructure and mechanical properties for powder bed fusion (PBF) additively manufactured 17-4 stainless steel parts are controllable by adjusting the laser processing parameters to locally control the thermal history. The powder bed energy density was manipulated such that the scan strategy was heterogeneous within a layer of the part to induce locally varying thermal histories, allowing for control of phase transformation kinetics and grain size. Microstructures were examined using optical microscopy, scanning electron microscopy, and x-ray diffraction and compared to reference samples produced using a homogeneous scan strategy. Finite element analysis was conducted of the PBF process to quantify the relative local heating and cooling rates and compared to experimental observations. Porosity was quantified using x-ray-microcomputed tomography to measure the effect of locally controlled regions on defect formation at zone boundaries. Locally changing the thermal history can create zones with decreased grain size and increased concentrations of retained austenite.

10:50 AM

Impact of Energy Density on Energy Consumption and Porosity of 17-4PH Stainless Steel Fabricated by Selective Laser Melting: *Tao Peng*[1]; Chao Chen[2]; [1]Zhejiang University; [2]Central South University

Selective laser melting is one of the most widely used additive manufacturing processes in producing high density metal parts. Energy density, a widely used parameter combination, has been recognized to have a relationship with part formation quality, but such a relationship is extremely complex. This work utilizes energy density to evaluate energy consumption in fabricating pore-free 17-4PH stainless steel parts. A parametric process energy model was developed, and the impact of energy density on the porosity was analyzed with the data from experiments and existing works. An effective energy-optimal zone was determined, where near-full density part can be fabricated with energy density of 44-87 J/mm3. Although further increasing energy density (up to 600 J/mm3) introduces no significant porosity (up to 5%), it is not energy-effective. It is recommended to investigate reasonably higher laser power with faster scan speeds, delivering energy to a thicker layer with relatively wider hatch space.

11:10 AM

Mechanical Performance of Selective Laser Melted 17-4PH Stainless Steel under Compressive Loading: *Panneer Selvam Ponnusamy*[1]; Syed Masood[1]; Tracy Dong Ruan[1]; Suresh Palanisamy[1]; Rizwan Abdul Rahman Rashid[1]; Omar Ahmed Mohamed[1]; [1]Swinburne University of Technology

Selective Laser Melting (SLM) is a powder-bed type Additive Manufacturing (AM) process, where metal powder melting is followed by rapid solidification to yield metallic components.The mechanical performance of the components is greatly influenced by various SLM process parameters such as laser power, scan speed, scan pattern, hatch distance, build orientation, layer thickness and defocus distance.Studies on compressive properties of stainless steel parts by SLM have received relatively little attention.In this study, an investigation was conducted to assess the influence of laser power, build orientation, layer thickness and defocus distance on the mechanical behaviour of selective laser melted 17-4PH stainless steel parts under quasi-static compression. Fractional factorial design was used to optimise the four process parameters to obtain maximum compressive strength and yield strength with least porosity.Results are supported by microhardness and microstructure observations.

11:30 AM

Effect of Load Sequences on Fatigue Life of Direct Metal Laser Sintered Parts under Variable Amplitude Loading: *Sagar Sarkar*[1]; Cheruvu Siva Kumar[1]; Ashish Kumar Nath[1]; [1]Indian Institute of Technology

To predict the service life of any manufactured components, its mechanical strength needs to be tested experimentally simulating the actual service conditions. The fatigue life of Direct Metal Laser Sintered (DMLS) parts under variable loading conditions is least investigated. In the present study fatigue life of widely used 15-5 PH stainless parts fabricated using DMLS process has been investigated under variable loading conditions with zero mean stress. Results shows that the number of cycles to failure does not change much (from 15350 to 14404 cycles) when a block of cyclic stresses of higher amplitude (100 cycles, stress amplitude 900 MPa) are applied first followed by a block of lower amplitude stress (300 cycles, stress amplitude 700 MPa), and when the load sequence is reversed. The load sequence has insignificant effect on the cumulative damage too. The mode of failures has been studied using Scanning Electron Microscope images of fracture surfaces.

Materials 12: Titanium

Wednesday AM
August 9, 2017

Room: 615A-B
Location: Hilton Austin

Session Chair: Amrita Basak, Georgia Institute of Technology

8:00 AM

Active Control of Microstructure in Electron Beam Melting of Ti6Al4V: *Guglielmo Vastola*[1]; Gang Zhang[1]; Qing Xiang Pei[1]; Yong-Wei Zhang[1]; [1]A*STAR Institute of High Performance Computing

Because of its complexity, powder-bed fusion additive manufacturing is very sensitive to process parameters such as beam power and scan speed. As a result, the process window to produce fully-dense parts with ASTM-grade mechanical properties is narrow. In such scenario, envisioning further control of mechanical properties is very challenging. In fact, the cooling rates and thermal gradients are incompatible with a mild microstructure without compromising on part density and surface roughness. As a departure from traditional attempts to control microstructure by changing the process parameters, we propose the introduction of a thermoelectric module (TEM) as an active device inside the build chamber. We show that by injecting or extracting heat through the TEM device, the volume fraction of martensite can be controlled. As a result, microstructure can be controlled locally while retaining the beam power and scan speed optimal for part density and surface finish.

8:20 AM

Efficient Fabrication of Ti6Al4V Alloy by Means of Multi-laser Beam Selective Laser Melting: *Fangzhi Li*[1]; Zemin Wang[1]; Xiaoyan Zeng[1]; [1]Wuhan National Laboratory for Optoelectronics

A self-developed four-laser beam selective laser melting (SLM) system was used to fabricate Ti6Al4V alloy samples in this study. The relative density, micro-hardness and mechanical properties of all isolated processing areas were compared under optimized processing parameters to ensure the consistency of this system. Microstructures in overlap areas are dominated by columnar grains along the building direction and matensitic needles a´ inclined at about ± 45° to the building direction, which are similar with those in isolated areas. Mechanical properties in overlap areas are also not inferior to those in isolated areas. The results prove the feasibility to fabricate large-scale components with a uniform microstructure and mechanical property by this SLM system. By the use of four lasers, this system can provide a high building rate of 80 cm3/h.

8:40 AM

Assessment of Porosity Formation in Additively-manufactured Parts via Numerical Thermomechanical Simulation: *Mohammad Masoomi*[1]; Scott Thompson[1]; Nima Shamsaei[1]; Kyungmin Ham[2]; Shuai Shao[2]; [1]Auburn University; [2]Louisiana State University

Laser powder bed fusion (L-PBF) has proven to be an effective means for fabricating high-value, customized components for industrial use. However, such components are prone to possessing porosity due to lack of fusion and melt pool superheating. Such porosity can adversely affect the mechanical performance and reliability of these parts in application. In this study, Ti-6Al-4V, cylindrical specimens are fabricated using L-PBF with various sets of process parameters and scan strategies. The porosity distributions in these as-built specimens are examined and characterized using X-ray computed tomography. The simulated, spatiotemporal temperature distributions within inspected parts during their L-PBF are compared with measured pore distributions and morphologies to elucidate process-structure relationships. Simulated temperature responses are obtained through continuum-based, finite element analysis (FEA). Results indicate that porosity traits are relatable to instantaneous melt pool temperatures and peak cooling rates.

9:00 AM
Effect of Heat Treatment and Hot Isostatic Pressing on the Morphology and Size of Pores in Additive Manufactured Parts: Bin Zhang[1]; Kyungmin Ham[1]; *Shuai Shao*[1]; Nima Shamsaei[2]; Scott Thompson[2]; [1]Louisiana State University; [2]Auburn University

Additive manufactured parts suffer from porosity, among other defects. The slit-shaped pores due to lack of fusion are the most detrimental to fatigue and mechanical properties. Their sharp edges generate severe stress concentration and serve as preferred sites for crack initiation. The sharp edges also have low formation energy of surface adatoms, increasing their tendency to spheroidize under elevated temperatures, such as during heat treatment (HT). In hot isostatic pressing (HIP), the combined action of high temperature/pressure also reduces the size of the pores. In this work, the effect of HT and HIP on morphology/size of the pores in Ti-6Al-4V parts manufactured from laser-based powder bed fusion is investigated. Using X-ray computed tomography combined with scanning electron microscopy, the evolution of porosity under controlled exposures to elevated temperature and/or pressure during HT/HIP are analyzed. The results are used to validate a porosity evolution model based on density functional theory.

9:20 AM
Effects of Build Orientation on Fatigue Performance of Ti-6Al-4V Parts Fabricated via Laser-based Powder Bed Fusion: *Brian Torries*[1]; Nima Shamsaei[1]; Scott Thompson[1]; [1]Auburn University

The effects of build orientation on the mechanical properties of additively manufactured Ti-6Al-4V using a Laser-Based Power Bed Fusion (L-PBF) process are investigated under monotonic tensile and uniaxial strain-controlled cyclic loadings. Ti-6Al-4V rods were manufactured in vertical, horizontal, and 45º angle orientations. The specimens were then machined and polished along the gage section in order to reduce the effects of surface roughness on fatigue behavior. Fully-reversed uniaxial fatigue tests were performed at various strain amplitudes with frequencies adjusted to maintain an average constant strain rate throughout testing. Results indicate slight variation in the tensile and fatigue behavior of specimens fabricated in the different orientations investigated. The microstructural properties of all types of specimens are obtained using optical and scanning electron microscopy with fractography performed after mechanical testing. The experimental program utilized and results obtained will be presented and discussed.

9:40 AM Break

10:10 AM
Probabilistic Fatigue Life Prediction of an SLM Ti64 Component: *Peipei Li*[1]; Derek Warner[1]; Nam Phan[2]; [1]Cornell University; [2]Naval Air Systems Command

Understanding the mechanical reliability of parts produced by selective laser melting (SLM) is key to fully realizing the potential of SLM technology. Given the layer-by-layer nature of the SLM process, the presence and characteristics of microscopic defects can be highly variable and depend on the part geometry, making reliability predictions at the component-scale difficult. In this spirit, we have developed a component-scale, high cycle fatigue model that predicts failure probability as a function of (1) the applied loading, (2) part geometry, and (3) a probabilistic field of microscopic defects. As an initial application, the model was calibrated to fatigue test results of SLM Ti64 witness coupons and used to predict the fatigue failure of a cyclically loaded aerospace component tested in the laboratory. Following this validation, the model is now being used to assess the component-scale impact of changes in processing and post-processing parameters on high cycle fatigue performance.

10:30 AM
Static and Fatigue Properties of Ti-6Al-4V Deposited by the WAAM Process with and without In-process Cold Work: *Filomeno Martina*[1]; Jialuo Ding[1]; Abdul Syed[2]; Xiang Zhang[2]; Stewart Williams[1]; [1]Cranfield University; [2]Coventry University

Additive manufacturing (AM) processes have received notable attention in the past two decades. Metal AM can be categorised broadly into powder-based and wire-based processes. Wire+arc additive manufacture (WAAM) belongs to the latter. WAAM can produce components using a variety of so-called "deposition strategies", namely single bead, parallel beads, oscillated bead. Deposits made with each of these have been characterised by the static and dynamic viewpoints. The results of tensile, fatigue crack growth rate, high cycle fatigue at different stress concentrations, fracture toughness will be presented for specimens produced with and without cold work. Properties better than forged material have been achieved from all points of view. Anisotropy was eliminated. In conclusion, the WAAM process is capable of producing defect-free structures in Ti64 using a variety of deposition strategies, thus enabling the manufacture of large-scale structural components in a cost effective way and with substantially reduced lead times.

10:50 AM
Effect of Specimen Surface Area Size on Fatigue Strength of Additively Manufactured Ti-Al-4V Parts: *Jonathan Pegues*[1]; Michael Roach[2]; R. Williamson[2]; Nima Shamsaei[1]; [1]Auburn University; [2]University of Mississippi Medical Center

As additive manufacturing becomes an increasingly popular method for advanced manufacturing of components, there are many questions that need to be answered before these parts can be implemented for structural purposes. One of the most common concerns with additively manufactured parts is the reliability when subjected to cyclic loadings which has been shown to be highly sensitive to defects such as pores and lack of fusion between layers. It stands to reason that larger parts will inherently have more defects than smaller parts which may result in some sensitivity to surface area differences between these parts. In this research, Ti-6Al-4V specimens with various sizes were produced via a laser-based powder bed fusion method. Uniaxial fatigue tests based on ASTM standards were conducted to generate fatigue-life curves for comparison. Fractography on the fractured specimens was performed to distinguish failure mechanisms between specimen sets with different sizes.

11:10 AM
Small-scale Mechanical Properties of Additively Manufactured Ti-6Al-4V: *Meysam Haghshenas*[1]; O Totuk[2]; M. Masoomi[3]; S. Thompson[3]; Nima Shamsaei[3]; [1]University of North Dakota; [2]Cankaya University; [3]Auburn University

This article aims at studying microstructure and nano/micro-scale mechanical responses of Ti-6Al-4V fabricated using a Laser-based Powder Bed fusion (L-PBF) method. To this end, an instrumented depth-sensing nanoindentation system has been used to assess hardness, Young's musluous, strain rate sensitivity and rate dependent plastic deformation of the alloy at different build orientations (in the Z-plane and X-plane) at ambient temperature. Indentation tests were conducted at constant proportional loading rates of 0.005, 0.05, 0.5, and 1 mN/s in a depth-controlled (hind=2000 nm) testing regime. The microstructure characterizations were performed using optical and scanning electron microscopy to assess the correlations to the mechanical properties achieved by the nanoindentation testing to better establish structure-property relationships for L-PBF Ti-6Al-4V. It is expected that the fine microstructure, developed by fast solidification during the L-PBF process, to directly contribute to the nanoindentation measurements at different strain rates.

11:30 AM
Machine Learning-enabled Powder Spreading Process Maps for Metal Additive Manufacturing (AM): Wentai Zhang[1]; Akash Mehta[1]; Prathamesh Desai[1]; *C. Fred Higgs III*[2]; [1]Carnegie Mellon University; [2]Rice University

The metal powder-bed AM process involves two main steps: spreading of powder layer and selective fusing or binding the spread layer. Most AM research is focused on powder fusion. Powder spreading is more rarely studied but is of significant importance considering the quality of the final part and total build time. It is thus essential to understand how to modify the spread parameters like spreader speed, to generate layers with desirable roughness and porosity. Modeling framework employing Discrete Element Method (DEM) is applied to simulate the spreading process, which is difficult to be studied experimentally, of Ti-6Al-4V powder onto substrates having different roughness values. Since the DEM simulations are computationally expensive, machine learning was employed to interpolate between the highly non-linear results obtained by running a few DEM simulations. Eventually, a spreading process map is generated to determine which spreader parameters can achieve the best surface roughness and porosity.

Modeling 1

Wednesday AM — Room: 404
August 9, 2017 — Location: Hilton Austin

Session Chair: Hadis Nouri, USC

8:00 AM
Real-Time Process Measurement and Feedback Control for Exposure Controlled Projection Lithography: *Xiayun Zhao*[1]; David Rosen[1]; [1]Georgia Institute of Technology

The Exposure Controlled Projection Lithography (ECPL) is an additive manufacturing process that can cure microscale photopolymer parts on a stationary substrate with patterned ultraviolet beams underneath. An in-situ interferometric curing monitoring and measuring (ICM&M) system is developed to measure the ECPL process output of cured height profile. This study develops a real-time feedback control system that utilizes the online ICM&M feedback for automatically and accurately cure a part of targeted height. The experimental results directly validate the ICM&M system's real-time capability in capturing the process dynamics and in sensing the process output, and evidently demonstrate the feedback control system's satisfactory performance in achieving the desired height despite the presence of ECPL process uncertainties, ICM&M noises and computing interruptions. A comprehensive error analysis is reported, implying a promising submicron control with enhanced hardware. Generally, the study establishes a paradigm of improving additive manufacturing with a real-time closed-loop measurement and control system.

8:20 AM
Machine Learning-based Monitoring of Advanced Manufacturing: *Brian Giera*[1]; Aaron Wilson[1]; Sachin Talathi[1]; Phillip Depond[1]; Gabe Guss[1]; Manyalibo Matthews[1]; [1]Lawrence Livermore National Laboratory

We develop and implement machine learning (ML) algorithms for the purposes of automated quality assessment within a variety of advanced manufacturing (AM) systems. We discuss ML-based algorithms capable of automated detection in a host of AM technologies such as Selective Laser Melting and Direct Ink Write and also microfluidic platforms that are used for feedstock production. The common thread within these systems is that routinely collected sensor data (e.g. high-speed video, pressure gauges, etc.) contains pertinent information about the state of the system that can be converted into actionable information in real-time via ML. Successful implementation of these machine learning algorithms will reduce time and cost during process by automating quality assessment and lead to process control. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

8:40 AM
Optimization of Build Orientation for Minimum Thermal Distortion in DMLS Metallic Additive Manufacturing: *Hao Peng*[1]; Morteza Ghasri Khouzani[2]; Shan Gong[2]; Ross Attardo[3]; Peter Ostiguy[3]; Bernice Aboud[3]; Joseph Budzinski[3]; Charles Tomonto[3]; Joel Neidig[1]; Ravi Shankar[2]; Richard Billo[4]; David Go[4]; David Hoelzle[5]; [1]ITAMCO; [2]University in Pittsburgh; [3]Johnson & Johnson; [4]University of Notre Dame; [5]The Ohio State University

The additive manufacturing (AM) process direct metal laser sintering (DMLS) can quickly produce complex parts. However, thermal stress in DMLS may induce thermal distortion and cause build failure. This manuscript presents an optimization algorithm for the build orientation in DMLS to minimize thermal distortion. The algorithm is built on the foundation of two coupled thermal and thermo-mechanical models developed in our previous work. The DIRECT search method and a universal objective function for thermal distortion were used. Constraints were included to rule out build orientations resulting in overheating or excessive oxidation. The optimization algorithm was tested on a rectangular bar and a complex, contoured part. Both parts were printed using an EOS M290 machine, and measured by a coordinate measuring machine. In comparison to build orientations chosen by two novice operators, the optimized build orientations gave significant reduction in the thermal distortion and number of print trials before print success.

9:00 AM
Using Skeletons for Void Filling in Large-Scale Additive Manufacturing: *Andrew Messing*[1]; Alex Roschli[1]; Brian Post[1]; Lonnie Love[1]; [1]Oak Ridge National Laboratory

In additive manufacturing (AM), slicing software is used to generate tool paths that are then converted to G-Code, which tells the 3D printer how to build a part. Toolpaths are generated using closed-loop paths. Sometimes the space left for a closed-loop is not sized perfectly. This can lead to overfill or underfill issues. Therefore, skeletonization of a polygon seeks to resolve this issue by creating an open-loop path to fill the voids between adjacent toolpaths. A straight skeleton was used to explore this work. Straight skeletonization represents the topological skeleton of a shape through line segments. After skeletonization, the extrusion rate can be varied to adjust bead width more precisely to fill the gap.

9:20 AM
Implicit Slicing Method for Additive Manufacturing Processes: *Davis Adams*[1]; Cameron Turner[1]; [1]Clemson University

All additive manufacturing processes involve a distinct preprocessing stage in which a set of instructions, or GCode, that control the process specific manufacturing tool are generated, otherwise known as slicing. In regards to fused deposition modeling, the GCode defines many crucial parameters which are needed to produce a part, including tool path, infill density, layer height, feed rate, tool head and plate temperature. The majority of current commercial slicing programs generate tool paths explicitly, and do not consider particular geometric properties of parts, such as thin walls, small corners and round profiles that can result in critical voids leading to part failure. This work replicates an implicit slicing algorithm in which functionally derived infill patterns are overlaid onto each layer of a part, reducing the possibility of undesired voids and flaws. This work also further investigates the effects that varying implicitly derived infill patterns have on a part's mechanical properties through tensile testing dog bone specimens with three different infill patterns and comparing ultimate stress and elastic modulus properties.

9:40 AM Break

10:10 AM
B-spline Based Topology Optimization for Metal Hybrid Additive-subtractive Manufacturing: JiKai Liu[1]; *Lin Cheng*[1]; Albert To[1]; [1]University of Pittsburgh

Hybrid additive-subtractive manufacturing is an emerging technology, which is capable of fabricating complex raw part through additive manufacturing (AM) and then finishing the part to meet surface and dimensional requirements through subtractive machining. However, the key issue is the difficulty in post-machining topology optimized AM parts due to their highly complex shapes. To overcome this difficulty, this research contributes a B-spline based topology optimization method capable of interfacing commercial CAD/CAM systems and accounting for post-machining requirements. Specifically, both the B-spline control points and feature modeling history will be adopted as the shape and topology variables, where the 'feature modeling history' topological derivative concept is novel and highlighted. Both the B-spline information and feature modeling history are important assets to interface CAD for user-friendly post-editing; and the topology optimized AM component would be composed of both freeform surfaces and machining-friendly surfaces, which fits the scope of hybrid additive-subtractive manufacturing.

10:30 AM
Mechanics of the Separation Process in Constrained-Surface Stereolithography: *Abhishek Venketeswaran*[1]; Sonjoy Das[1]; [1]University at Buffalo

A crucial step in additive manufacturing (AM) technologies based on constrainedsurface stereolithography (SLA) process is the separation of the cured part from the resin vat by pulling it up. An essential obstacle to separate the fabricated part is overcoming a significant suction force which results from the flow of the uncured liquid resin into the intermediate gap between the cured part and the vat. A commonly adopted technique to ease the separation process is to coat the surface of the bottom of the vat with a thin inert, transparent, oxygen permeable and compliant film (such as Teflon and PDMS films). While this practical resolution is very effective in separating the printed parts, there are many instances of breakage and damage of the printed parts leading to significant material waste and loss of production time. The present work investigates the separation process from the purview of mechanistic principles by focusing on how incompressible liquids interact with soft and hard materials. The proposed fluid-structure interaction model will be useful to study dependence of the separation process on various control parameters (e.g., pulling-up velocity, dead-zone thickness, mechanical properties of the coating) of the SLA-based AM process such as continuous printing.

Physical Modeling 5: Finite Element Analysis

Wednesday AM — Room: 415A-B
August 9, 2017 — Location: Hilton Austin

Session Chair: Wenda Tan, University of Utah

8:00 AM
Multivariate Calibration of a FE Melt Pool Simulator for Selective Laser Melting: *Mohamad Mahmoudi*[1]; Gustavo Tapia[1]; Brian Franco[1]; Ji Ma[1]; Ibrahim Karaman[1]; Raymundo Arroyave[1]; Alaa Elwany[1]; [1]Texas A&M University

Predicting melt pool geometry and temperature profiles is a key step towards understanding metal AM processes and potentially enabling tailoring the microstructure and properties of AM-fabricated parts. Finite Element (FE) thermal models have commonly been used for simulating melt pool dynamics under different process parameters. Nonetheless, similar to most complex physics-based models, melt pool simulations depend on a number of physical parameters whose values are typically unknown or hard to measure. This paper presents a two-stage Bayesian approach to conduct calibration of FE model parameters such that model predictions are in agreement with experimental measurements. First, multivariate Gaussian processes are used to construct a surrogate of the FE model to enable generating simulations needed to conduct calibration. In the second stage, experimental measurements of melt pool geometry and peak temperature were obtained using a commercial SLM system and Ti6Al4V powder to compute the posterior distributions of the calibration parameters.

8:20 AM
The Effect of Process Parameters and Mechanical Properties of Direct-energy Deposited Stainless Steel 316: Mojtaba Izadi[1]; Aidin Farzaneh[1]; *Ian Gibson*[1]; Bernard Rolfe[1]; [1]Deakin University

Process parameters in Direct Energy Deposition (DED) Additive Manufacturing are playing an important role in order to fabricate desired parts. In this research, we studied the effect of 3 process parameters, namely laser power, scan speed and powder feed rate. Based on variation of these parameters, we examined macrostructure and mechanical properties of stainless steel 316 fabricated parts, employing an orthogonal L9 array using the Taguchi technique. The results showed laser power to be the most effective factor whereas scan speed and powder feed rate were respectively less effective. In addition, effect of height of deposition was also considered. The results indicated change in macrostructure with increasing height. Finally, validation of a previously defined energy density equation for the DED process was studied. The results clearly showed the current energy density equation cannot fully represent a relation between input energy and output geometry, macrostructure, and mechanical properties.

8:40 AM
Thermal modeling of 304L Stainless Steel Selective Laser Melting: *Cody Lough*[1]; Lan Li[1]; Russell McDonald[1]; Robert Landers[1]; Douglas Bristow[1]; Edward Kinzel[1]; [1]Missouri University of Science and Technology

This paper describes the continuum thermal modeling of the Selective Laser Melting (SLM) process for 304L stainless steel using Abaqus. Temperature dependent thermal properties are obtained from literature and validated using laser flash testing. The thermal model predicts the temperature history for multi-track scans under different process parameters (laser power, step size, hatch spacing) which is used to extract the melt-pool size, solidification rate and temperature gradients. These are compared to experimental results obtained from a Renishaw AM250 in terms of the melt pool size, grain structure, and in-situ temperature measurements using a Short Wave Infrared (SWIR) thermal camera. These experimental results are used to tune unknown simulation parameters required by the continuum model (e.g., the optical penetration depth and thermal conductivity multiplier for the molten region) and yield predictive simulations.

9:00 AM
A Finite-element Simulation of Spherical Indentation of LENS-processed 316L Stainless Steel: *John Shelton*[1]; Sri Sai Kartheek Meka[1]; [1]Northern Illinois University

A finite-element simulation approach is used to numerically study normal indentation of LENS-processed 316L stainless steel by a rigid sphere. Experimentally-obtained process parameters are used to define the material properties of the modeled indented material. The effects of elasticity, plasticity, and adhesion are investigated and results are compared with theoretical Hertzian contact theory predictions. Additionally, experimentally-obtained indentation test results obtained from Rockwell B hardness tests were used as an additional comparison to these finite element simulation results.

9:20 AM
The Effect of Polymer Melt Rheology on Predicted Die Swell and Fiber Orientation in Fused Filament Fabrication Nozzle Flow: *Zhaogui Wang*[1]; Douglas Smith[1]; [1]Baylor University

Short carbon fibers suspended in the polymer feedstock enhances the mechanical performance of products produced with Fused Filament Fabrication (FFF). As the melted filament is extruded and deposited on a moving platform below, the velocity gradients within the polymer melt flow orientates the fibers, which has a direct effect on the mechanical properties of FFF bead. This paper numerically simulates the nozzle flow, including the extrudate swell at the nozzle exit, with generalized-Newtonian and viscoelastic rheology models to predict die swell and fiber orientation. We employ the simplified viscoelastic model in ANSYS Polyflow to evaluate the polymer melt velocity field and die swell. Fiber orientation tensors are computed along streamlines using the Fast Exact Closure and Folgar-Tucker isotropic rotary diffusion. The predictions indicate that the die swell computed with the viscoelastic model is larger than those yielded by the Newtonian flow model, and the rheology model significantly effects fiber orientation.

9:40 AM Break

10:10 AM
Multiphysics Computational Framework for Selective Laser Sintering Process of Polymers: *Vinay Damodaran*[1]; Pavana Prabhakar[1]; [1]University of Wisconsin Madison

In this paper, we present a validated 3D finite element model of the Selective Laser Sintering (SLS). In SLS, polymer powder is selectively melted and fused using a laser energy source. The rapid heating and cooling rates in the material provide faster print times, but also induce large residual stresses in the final part that can cause the part to warp, thus reducing the performance of the final part. The model considers state and temperature dependent material properties like density, heat capacity, thermal conductivity, and the latent heat associated with the crystallization of the polymer. Stress evolution during solidification and cooldown will be incorporated into the model. In particular, the focus will be on stresses caused due to shrinkage, thermal expansion, and phase change. The influence of various process parameters such as laser power, scan speed, scanning path, etc. on the fabricated material will be explored.

10:30 AM

Consideration of Fluid Physics on the Residual Stress in a Singe Track of Material: *Kurtis Ford*[1]; Kyle Johnson[1]; Mario Martinez[1]; Joseph Bishop[1]; [1]Sandia National Laboratories

The thermal history of a part is incorporated into a FEA model by birthing elements at a calibrated temperature and then cooling them down. Typically, the fluid mechanics and heat transfer of the melt pool are overlooked or averaged into the solid elements. In this work, a solid mechanics model is coupled to a fluid simulation of a melt pool in a single track and then cooled down. The final stress of the bead is compared to the stress that is predicted if the fluid interactions are neglected. A temperature and history-dependent elasto-viscoplastic internal state variable model of 304L is used. The models are performed with the Sierra finite element code suite. Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

10:50 AM

Simulation of Planar Deposition Polymer Melt Flow and Fiber Orientation in Fused Filament Fabrication: *Blake Heller*[1]; Douglas Smith[1]; [1]Baylor University

Mechanical and thermal properties of a 3D printed part are improved by adding discrete carbon fibers to the Fused Filament Fabrication (FFF) polymer feedstock. The properties of the fiber-filled composite are significantly influenced by the orientation of the carbon fibers within the extruded bead. Fiber orientation in the bead is affected by the flow field which is defined by the melt flow geometry defined by the nozzle, extrudate swell, and the turning flow during the FFF process. In this work, a 2D Stokes flow finite element analysis is performed to evaluate FFF extrusion where special attention is given to the deposition of polymer melt on the moving platform below the nozzle. The shape of the extruded polymer is computed using a free surface normal velocity minimization technique. Once the flow boundary is computed, fiber orientation and the resulting mechanical properties of the composite are computed throughout the melt flow domain.

11:10 AM

Theoretical Investigation of Stiffness Properties of FDM Parts as a Function of Raster Orientation: *Sanchita Sheth*[1]; Robert Taylor[1]; Hari Adluru[2]; [1]University of Texas at Arlington; [2]University of Texas at Arlington Research Institute

This work discusses a theoretical investigation of stiffness properties of parts printed using Fused Deposition Modeling (FDM). Small volumes of different raster orientations were modelled and meshed using SIMULIA TM (Abaqus). These meshes were exported to a damage prediction software BSAM, which uses a regularized extended finite element approach to model interface bond strength between adjacent raster beads. In BSAM, boundary conditions, connectivity, material properties, crack properties, and damage variables have been specified. This BSAM model was then used to specify and predict interface properties for the specimens at various raster angles and compare specimen stiffness properties.

11:30 AM

Computationally Efficient Finite Element (FE) Framework to Simulate Additive Manufacturing Process: Shiyan Jayanath[1]; *Ajit Achuthan*[1]; [1]Clarkson University

Typical Additive Manufacturing (AM) process involves localized heating causing the generation of large thermal gradient and non-uniform cooling during the fabrication process. The thermal gradient and non-uniform cooling depend on thermal boundary conditions as the part is built, which in turn depends on the complexity of the part geometry. The non-uniform heating, cooling and the constraining effect of base plate are the primary factors that influence the evolution of residual stresses. In this work, the development of a multi-scale Finite Element (FE) framework to determine the residual stress evolution and part distortion during the AM process is discussed. The FE framework characterizes various regions of the geometry in to Representative Volume Elements (RVEs) considering thermos-mechanical boundary conditions. Then individual RVEs are used to estimate the overall stress and distortion of the part. The New framework is also equipped with mesh coarsening method to further improve the computational efficiency.

Process Development 8: Process Effects

Wednesday AM
August 9, 2017

Room: 417A-B
Location: Hilton Austin

Session Chair: Guglielmo Vastola, A*STAR Institute of High Performance Computing

8:00 AM

Continuous Laser Scan Strategy for Faster Build Speeds in Laser Powder Bed Fusion System: *Ho Yeung*[1]; Brandon Lane[1]; Felix Kim[1]; Jarred Heigel[1]; Jason Fox[1]; Jorge Neira[1]; [1]National Institute of Standards and Technology

Research has shown significant influence of laser scan strategy on various part qualities in the laser powder bed fusion (LPBF) additive manufacturing (AM) process. The National Institute of Standards and Technology (NIST) developed the Additive Manufacturing Metrology Testbed (AMMT), which provides open architecture for flexible control and monitoring during a laser powder bed fusion (LBPF) AM process. This allows extended control of scan strategies, including intra-vector (within each line) control of laser power and speed. A 'continuous mode' strategy can reduce build times and improve throughput by negating the need to turn the laser off between scan tracks (e.g., sky-writing). Multiple single powder layer experiments are performed utilizing this continuous mode, and optimal mode parameters are selected based on various layer quality metrics. Finally, multi-layer AM parts are built using continuous mode and traditional scan strategies, and comparisons are made between build time and measured part qualities.

8:20 AM

Effect of Printing Speed on Quality of Printed Parts in Binder Jetting Process: *Hadi Miyanaji*[1]; Li Yang[1]; Niknam Momenzadeh[1]; [1]University of Louisville

In binder jetting process, the liquid binder is employed for establishing the initial strength and fabricating the geometry of components. In this process, the delivery of the binding agent is accomplished by deposition of picoliter-sized droplets of the liquid binder through a drop-on-demand (DOD) printhead. The velocity of the droplets impinging the powder bed surface might have significant effect on droplet spreading and absorption dynamics, which can be manifested in quality and integrity of the fabricated parts. In the present study, the effect of the printing speed, which can be translated into droplet horizontal velocity, on dimensional accuracy and equilibrium saturation level of printed samples is experimentally investigated, and the observed trends are discussed in detail.

8:40 AM

Influence of the Ratio between the Translational and Contra-rotating Coating Mechanism on Different Laser Sintering Materials and their Packing Density: *Lars Meyer*[1]; [1]Universität Duisburg-Essen

An initial study about the advanced machine parameters and their impact on the packing density of different laser sintering materials was conducted on a self-developed laser sintering machine. Usually, on commercial machines, the ratio between the translational and contra-rotatory movement of the roller is fixed. The standard ratio is established for polyamide 12, but new materials, such as polyamide 6 or polybutylene terephthalate, need adjustable parameters to find optimized compositions coating results. Other machines do not work with a contra-rotating roller at all, but with a blade to generate a new powder layer. In order to consider this the roller can be replaced by a blade system and allows a comparison between both commercial coating systems from laser sintering machines worldwide.

9:00 AM
Thermal History Correlation with Mechanical Properties for Polymer Selective Laser Sintering: *Samantha Taylor*[1]; Scott Fish[1]; Joseph Beaman[1]; [1]University of Texas at Austin

This study investigates the in-situ monitoring of the Selective Laser Sintering (SLS) process by focusing on finding correlations between tensile strength, elongation to break, and fracture location to the observed thermal history of manufactured parts. It compared the monitoring ability of a stationary reference mid-wave infrared and a bore-sighted mid-wave infrared camera. ZYX tensile bars were built to leverage the high dependence of tensile strength on interlayer bonding, which is generally assumed to be related to layerwise thermal conditions. Various thermal history analysis methods, for example: cold subregion temperature, average layer temperature, and outline average temperature were tested. Additionally, several smoothing techniques that reduced noise over time were assessed for their ability to improve the correlation for each method. Overall, cold subregions observed over four layers in a tensile bar's thermal history had the best correlation with fracture location and mechanical strength.

9:20 AM
A Mobile 3D Printer for Cooperative 3D Printing: Lucas Galvan Marques[1]; Robert Williams[1]; *Wenchao Zhou*[1]; [1]University of Arkansas

Cooperative 3D printing is an emerging technology that aims to provide the scalability to 3D printing by enabling thousands of printhead-carrying mobile robots to cooperate on a single printing job and to integrate pre-manufactured components during the 3D printing process. At the core of the cooperative 3D printing platform is a mobile robot that can carry different printhead or a gripper. In this paper, we present a mobile 3D printer with a filament extrusion printhead that can be controlled over the Internet. First, we designed a compact mobile 3D printer with an extrusion printhead and four omnidirectional wheels. A wireless communication interface is also developed to send commands to and receive information from the mobile 3D printers. Successful prints have been demonstrated with two developed mobile 3D printers cooperatively, which shows the promise of cooperative 3D printing.

9:40 AM Break

10:10 AM
A Floor Power Module for Cooperative 3D Printing: *Jacob Currence*[1]; Rolando Morales-Ortega[1]; Jason Steck[1]; Wenchao Zhou[1]; [1]University of Arkansas

One challenge of 3D printing is that the print size is limited by the size of the printer. Cooperative 3D printing is an emerging technology that addresses this issue by enabling multiple mobile 3D printers to work simultaneously on the same print job. However, powering the mobile printers while to spanning very large print jobs poses an issue. In this paper, we present an electrified floor to power the mobile printers wirelessly. First, we designed a floor module with stainless conductive stripes in a concrete base and a brush that is carried by the robots to make sure contact with the electrified floor is maintained while moving. Then we designed a circuit to sort the polarity of the current from the floor. A prototype of the floor power module was then developed and tested, and results show the developed floor power supply can power the mobile 3D printers effectively.

10:30 AM
Mechanical Properties of 304L Metal Parts made by Laser-foil Printing Process: *Chia-Hung Hung*[1]; Yiyu Shen[1]; Ming Leu[1]; Hai-Lung Tsai[1]; [1]Missouri S&T

Laser-foil-printing (LFP) is a novel laminated object manufacturing process for metal additive manufacturing. It fabricates three-dimensional metal parts by using a dual-laser system to weld and cut metal foils layer by layer. A main advantage of LFP is the higher cooling rate compared to powder-based laser additive manufacturing processes due to the thermal conductivity difference between foil and powder. This study focuses on the mechanical properties of 304L stainless steel parts built by the LFP process. The experimental results indicate that the yield strength and ultimate tensile strength of LFP fabricated 304L SS parts are higher by 20% and 15% in the longitudinal direction, and 99% and 26% in the transverse direction, respectively, in comparison to the parts fabricated by the selective laser melting process. X-ray diffraction and electron backscattered diffraction are used to obtain the lattice structure and the grain size of the fabricated parts.

10:50 AM
The Optimal Variation in Raster Angle Per Layer for the Selective Laser Sintering of Nylon 12: *Bethany King*[1]; [1]Lancaster University

When selective laser sintering, a laser is run across polymer powders to produce cross-sectional infill of a 3D part in a raster pattern. The material properties of a sintered part can be positively influenced by altering the rotational angle of the raster scan each layer. Test samples were manufactured varying the angle of rotation each layer from 0o to 90o then tested for Ultimate Tensile Strength (UTS) and Elongation at Break (EB). The study found that a variation produced a bell curve for both UTS and EB peaking at 45o which produced samples with the greatest improvement when compared to 0o rotation, over a 30% increase in both properties. When scanning parts for strength varying the raster angle does have a considerable impact on the material properties of sintered nylon 12 with an optimal angle of 45o.

11:10 AM
The Effect of Arc-based Direct Metal Energy Deposition on DMLS Maraging Steel: *Bishal Silwal*[1]; Nicholas Shaffer[1]; Christopher Gerdmann[1]; Michael Santangelo[1]; [1]Georgia Southern University

With the growing demand of metal based additive manufacturing it is inevitable that the additively manufactured parts will be used in consolidation with different manufacturing process. Arc based additive manufacturing is a process used to produce three dimensional structure using welding arc. Direct melal laser sintering (DMLS) is an additive manufacturing process using laser power to generate a three dimensional structure. In this paper, the effect of direct energy deposition on the selective laser melting (SLM) has been investigated. The microstructure changes and the melting region are characterized. A computational fluid dynamics model is used to predict the melt region and temperature.

Process Development 9: Metal Powder Processing

Wednesday AM
August 9, 2017

Room: 416A-B
Location: Hilton Austin

Session Chair: Abdalla Nassar, Penn State University

8:00 AM
Ultrasonic Vibration-assisted Direct Laser Deposited TiB Reinforced Ti Composites with a Three-dimensional Quasi-continuous Network Microstructure: *Fuda Ning*[1]; Yingbin Hu[1]; Weilong Cong[1]; [1]Texas Tech University

Ultrasonic vibration has been broadly applied to affect the solidification behavior of liquid melting materials in thermal manufacturing processes such as casting, fusion welding, etc. In this work, direct laser deposition, one of laser additive manufacturing processes, has successfully incorporated ultrasonic vibration to produce TiB reinforced Ti composites with a novel three-dimensional quasi-continuous network (3DQCN) microstructure. Due to the nonlinear effects of acoustic streaming and cavitation induced by ultrasonic vibration, such 3DQCN microstructure is considerably finer than that achieved in the process without ultrasonic vibration. Ultrasonic vibration also results in the formation of thinner and smaller TiB whiskers that distribute along the grain boundaries. The refinement of both 3DQCN microstructural grains and TiB reinforcement further improves the microhardness of TiB reinforced Ti composite parts.

8:20 AM

Development of an Experimental Test Setup for In Situ Strain Evaluation during Selective Laser Melting: Eckart Uhlmann[1]; *Erwin Krohmer*[1]; Felix Hohlstein[2]; Walter Reimers[2]; [1]Institute for Machine Tools and Factory Management (IWF), Technical University Berlin; [2]Institute for Material Science and Technologies, Technical University Berlin

Selective Laser Melting (SLM) is an Additive Manufacturing (AM) process which still underlies a lack of profound process understanding. This becomes noticeable when deformation and crack formation can be observed in SLM parts due to residual stresses. Controlling residual stresses is therefore an important object in recent research in metal AM. In order to minimize residual stresses further knowledge considering their cause and physical correlations of process parameters needs to be generated. In this paper an approach of measuring strains layer by layer during the SLM process by means of in situ X-ray diffraction is presented. For this purpose an experimental test setup is being constructed at the Technical University Berlin. The system requirements and operating principles are discussed in this paper. Furthermore, details of the current progress of the construction and results of preliminary experiments are highlighted.

8:40 AM

In Situ Melt Pool Monitoring and the Correlation to part Density of Inconel® 718 for Quality Assurance in Selective Laser Melting: *Daniel Alberts*[1]; Dieter Schwarze[1]; Gerd Witt[2]; [1]SLM Solutions Group AG; [2]University of Duisburg-Essen

Additive Manufacturing looks back on a history of about two decades and today SLM® technology keeps moving as an integral element in industrial production environments. Sensitive markets such as energy, medical or aerospace have the highest quality standards for complex, safety-related and highly stressed components which are to be met at competitive costs for each build job and single part. In this context process monitoring is necessary for documentation, qualification and at the same time it is expected to be able to detect process anomalies during the process. In addition to surface roughness, part density which mostly depends on volume energy, changing with laser power, scan velocity etc., is a distinctive quality feature of every component. This paper presents a method for a real time melt pool monitoring system based on photodiodes and the correlation between thermal emission and part density of Inconel® 718 with respect to volume energy deviation.

9:00 AM

Influence of Process Time and Geometry on Part Quality in Low Temperature Laser Sintering: *Yuki Yamauchi*[1]; Takashi Kigure[1]; Toshiki Niino[2]; [1]Tokyo Metropolitan Industrial Technology Research Institute; [2]Institute of Industrial Science, the University of Tokyo

The authors are developing a novel laser sintering process that prevents parts being processed from warping by anchoring them to a rigid base plate. Since powder bed temperature of the process is normally lower than in standard process, laser is required to supply more energy in the novel process, namely low temperature process. Resultantly, part quality is more sensitive to laser parameters. Additionally, accumulation and dispersion of energy which is supplied by laser through layers plays important role in consolidation of the powder. Thus, in low temperature process, parameter relating part geometry and time affects the part quality more than in standard, high temperature, process. In this research, influence of part size and process time per layer on density of parts as a primary index of part quality is investigated. Density decreases as the process time per layer increases. With respect to part size, density increases as parts become larger.

9:20 AM

Approve of Porosity for Increasing Process Speed in the Laser Melting Process of Ti6Al4V: *Dominik Ahlers*[1]; Thomas Tröster[1]; [1]Paderborn University / DMRC

Additive Manufacturing of Ti6Al4V is widely used in industry with hot isostatic pressing (HIP) heat treatment afterwards and is used for numerous applications. One of the aims in research is to increase the speed of the AM process. When increasing the process speed through different parameter variations, the porosity increases as well. To close the pores during post processing, the HIP process uses high temperature together with high pressure. The approach here is to use the default process route as described, but consciously increase the process speed and approve a certain value of porosity. The main aim is to identify the parameter set with the highest potential for increasing the process speed, but additionally give the HIP process the possibility to close the pores to get a dense part, in a significantly faster process.

9:40 AM Break

10:10 AM

The Assessment of Residual Stress in Powder Bed Fusion Components Using a Novel Residual Stress Analysis Component, the Three Prong Method: *Stuart Sillars*[1]; Chris Sutcliffe[2]; Adam Philo[1]; Johann Sienz[1]; Stephen Brown[1]; Nick Lavery[1]; [1]College of Engineering, Swansea University; [2]School of Engineering, University of Liverpool

Residual stress is one of the most common reasons for build failures in the laser powder bed fusion process. Residual stresses can be reduced using post-build heat treatment processes; however, residual stress can lead to build failures due to distortion, cracking or baseplate delamination. Accurate measurement of residual stress levels can be difficult due to high equipment set-up costs and long processing times. This paper introduces a simple but novel method of measuring residual stresses in laser-powder bed fusion components, utilising 3 adjoined cantilever beams. Several different cantilever designs have been used to indicate residual stress within additive manufactured components. All of which share the same shortcoming, they indicate stress in one direction. If the principal component of stress is misaligned with the beam, peak stress will be underestimated. The study explores the effect of different scan strategies and energy densities on the residual stress and porosity of the components.

10:30 AM

A Method for Metal AM Support Structure Design to Facilitate Removal: *Niechen Chen*[1]; Matthew Frank[1]; [1]Iowa State University

For powder bed metal additive manufacturing (AM), additional post-processing for support structure removal is required. However, this removal process is not formally considered during the design of support structures. Therefore, when either manual or CNC milling is required, some support structures may not be easily removed due to tool accessibility. In this research, with STL model as input, tool accessibility is calculated and used to map onto the facets to grow supports that are more amenable to machined removal. It provides a way to combine previous analysis on support layout with additional information to guide suitable setups; ones that not only consider critical angles requiring support, but also removability. This work could enable better support designs that will lead to higher throughput of metal AM by reducing effort and expense in post-process machining.

10:50 AM

A Novel Strategy to Build Support-free Overhang Surface below Critical Angle in Direct Metal Laser Sintering Process: *Yaswanth Nuthalapati*[1]; Sagar Sarkar[1]; Cheruvu Siva Kumar[1]; [1]Indian Institute of Technology Kharagpur

The greatest advantage of Direct Metal Laser Sintering process is that it can build geometrically complex parts directly from a CAD model. However, if the design of the part consists of overhang surfaces, support structures need to be built along with the desired part. This auxiliary support structure needs to be removed before the part goes into service. Removal of support structures degrades the surface quality of the part built which requires further post-processing. The minimum support-free overhang angle (critical angle) that can be built is limited by laser beam diameter and powder layer thickness of selected material. In the present study a novel build strategy has been adopted by sub-dividing the geometry of the selected part into different zones and processing it with different laser processing parameters. Results show that with judicious selection of process parameters, it is possible to build support-free overhangs at angles below the critical angle.

11:10 AM

Dilution and Mixing for Functionally Gradient DED Printed Stainless Steel Components with Dissolvable Carbon Steel Supports: Christopher Lefky[1]; Abdalla Nassar[2]; Timothy Simpson[2]; *Owen Hildreth*[1]; [1]Arizona State University; [2]Pennsylvania State University

Additive manufacturing often requires support structures to support overhanging surfaces and provide a pathway for heat to avoid thermally induced strain resulting in distortions. Last year, we introduced dissolvable metal supports for Directed Energy Deposition (DED) printed stainless by printing support structures from low carbon steel that can be selectively electrochemically etched away. This new process enables the facile fabrication of overhanging structures using DED. For this work, we explore the mixing and dilution between the carbon steel support and stainless steel component layers. We found that mixing is extremely inhomogeneous with large variations from layer-to- layer, track-to- track, and even within a single track. The impact of incomplete mixing on microstructure and electrochemical/corrosion properties will be discussed in detail. This work provides important insight into the mixing of functionally gradient materials and the cross-layer corrosion susceptibility of these materials.

11:30 AM

Numerical Study of Cover Gas Flow in Powder Bed-based Additive Manufacturing: *Jan Frederik Hagen*[1]; Stefanie Kohl[1]; Michael Schmidt[1]; [1]Institute of Photonic Techonologies, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU) and Erlangen Graduate School in Advanced Optical Technologies

Part quality in powder bed based laser beam melting depends highly on the location of the build platform. While it has been shown that a regularization of the cover gas flow over the whole build platform is advantageous to the part quality, the exact effects have not been studied extensively. We use a micro-scale melt pool model to investigate and discuss the following effects: What is the influence of turbulence in the cover gas flow on spatter and particle transport? Can the cover gas flow be used to remove the vapor plume and reduce its shielding effects on the laser beam? And what is the thermal influence of the different flow regimes of the cover gas flow on the powder bed? Our simulations allow us to quantitatively assess these effects and thus formulate requirements on the cover gas flow.

Applications 10

Wednesday PM — Room: 406
August 9, 2017 — Location: Hilton Austin

Session Chair: Xuan Song, University of Iowa

1:10 PM

Additive Manufacturing and Mechanical Evaluation of the Stiffness-matched Mandibular Bone Fixation Plates: *Ahmadreza Jahadakbar*[1]; Narges Shayesteh Moghaddam[1]; Amirhesam Amerinatanzi[1]; David Dean[2]; Mohammad Elahinia[1]; [1]The University of Toledo; [2]The Ohio State University

The standard of the care for mandibular reconstruction surgery is the use of Ti-6Al-4V bone fixation plates and screws to immobilize the bone graft and facilitate the bone healing. Although Ti-6Al-4V bone fixation plates provide high immobilization during the healing period, they cause stress shielding due to their high stiffness in comparison with the surrounding cortical bone which may lead to the failure. To address this issue, we have developed a new generation of the patient-specific, bone fixation plates that benefit from stiffness-matching of the surrounding bone. The stiffness-matching feature has been achieved by imposing specific level and type of porosity to the bone fixation plates made of NiTi. After preparing the CAD file of the porous NiTi bone fixation plates, Selective Laser Melting has been utilized for the fabrication. Mechanical tensile and compression tests at body temperature were then used for evaluation of the fabricated bone fixation plates.

1:30 PM

Additive Manufacturing of Porous Materials: *Christopher Jones*[1]; David Robinson[1]; [1]Sandia National Laboratories

Additive manufacturing is heralded by mechanical engineers as a new path to load-bearing structures that use material efficiently. It also has promise in chemical engineering, where there is a ubiquitous reliance on randomly arranged materials. In cases where these have been replaced by deterministically fabricated structures with optimized geometries, major performance improvements have been achieved. Examples include gas chromatography, microfluidic medical devices, and recent “3D battery” structures. High-resolution additive manufacturing methods like stereolithography offer new ways to fabricate optimized structures. We have developed an additively manufactured architecture for chemically reacting flow, and have demonstrated a hydrogen-deuterium separation column that achieves sharply defined separations at a lower pressure drop than a similarly sized packed-powder column. Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.

1:50 PM

A Mobile Robot Gripper for Cooperative 3D Printing: *Jason Steck*[1]; Rolando Morales-Ortega[1]; Jacob Currence[1]; Wenchao Zhou[1]; [1]University of Arkansas

Cooperative 3D printing is a developing technology, which aims to overcome many of the limitations of contemporary 3D printing (e.g., print size, cost, complexity) by allowing multiple mobile 3D printers to work simultaneously on a single print job. In particular, one challenge of 3D printing is the inability to incorporate pre-manufactured components in a structure without human intervention. In this paper, we present a mobile robot gripper that can work with other mobile 3D printers to pick and place components into a 3D printed structure during the printing process. First, we designed a gripper using a rack and pinion actuator that can be driven by a single stepper motor. Next, a mobile robot gripper is developed with the designed mechanism. Finally, we tested the mobile robot gripper for picking and placing objects. Results show the gripper can successfully pick and place pre-manufactured components into a 3D printed structure.

2:10 PM

Biomimetic Anisotropic Reinforcement Architectures by Electrically Assisted Nanocomposite 3D Printing: *Yang Yang*[1]; Zeyu Chen[1]; Xuan Song[1]; Qifa Zhou[1]; Yong Chen[1]; [1]University of Southern California

Many natural structures out-perform conventional synthetic counterparts due to the specially evolved reinforcement architectures. we report an electrically assisted additive manufacturing approach that bio-mimic the Bouligand structure in nature to create highly impact resistant architectures. The alignment of surface modified Multi-walled Carbon Nanotubes (MWCNT-S) was controlled by rotating electric field during printing. The Bouligand-type MWCNT-S leads to enhanced impact resistance compared with random distribution due to the energy dissipation by the rotating anisotropic layers. Furthermore, this approach is used to mimic the Collagen fiber alignment in human meniscus to create reinforced artificial meniscus with circumferential and radial aligned MWCNT-S. The printed meniscus shows enhanced fracture energy compared with native menisci, which shows a potential application as a replica for tissue constructs. The electrically assisted three-dimensional (3D) printing technology enables us to design and evolve reinforced architectures with arbitrary geometries, which shows promising applications in aerospace, mechanical and tissue engineering.

2:30 PM

Technological Challenges for the Automotive Series Production in Laser Beam Melting: *Felix Haeckel*[1]; [1]BMW Group

Compared to traditional production methods Additive Manufacturing enables a tool free production leading to higher flexibility, freedom of design and lightweight potential. For these reasons the BMW Group is proceeding from the production of prototypes to the direct series production of parts. For metal components the process of selective Laser Beam Melting is able to realize these potentials.Besides economic issues also technological challenges have to be met. Among these is the part quality in a production of same parts. To produce compliant to technical specifications in a series production, a defined process stability is needed which can be described throughout machine and process capability indices.These machine capability indices are investigated for the process of selective Laser Beam Melting. Also influences which have the biggest impact on the part quality throughout a simulated series production are being examined. Thus the reproducibility of the process can be quantified.

2:50 PM
Qualification Challenges with Additive Manufacturing in Space Applications: *Christo Dordlofva*[1]; Peter Törlind[1]; [1]Luleå University of Technology

Additive Manufacturing (AM) has the potential to remove boundaries that traditional manufacturing processes impose on engineering design work. The space industry pushes product development and technology to its edge, and there can be a lot to gain by introducing AM. However, the lack of established qualification procedures for AM parts has been highlighted, especially for critical components. While the space industry sees an advantage in AM due to expensive products in low volumes and long lead-times for traditional manufacturing processes (e.g. casting), it also acknowledges the issue of qualifying mission critical parts within its strict regulations. This paper focuses on the challenges with qualification of AM in space applications. A qualitative study is presented where conclusions have been drawn from interviews within the aerospace industry. The results highlight important gaps that need to be understood before AM can be introduced in critical components, and gives insight into conventional component qualification.

Applications 11: Honeycombs and Process Characterization

Wednesday PM | Room: 415A-B
August 9, 2017 | Location: Hilton Austin

Session Chair: Maggie Yuan, Beijing Institute of Technology

1:10 PM
Material Selection on Laser Sintered Stab-resistant Body Armor: *Maggie Yuan*[1]; Yi Liu[1]; Xinming Qian[1]; [1]Beijing Institute of Technology

Stab-resistant body armor (SRBA) is essential defensive equipment to protect the human body from injury due to stabbing. The conventional SRBAs are heavy and inflexible. Therefore a new type of SRBA has been recently developed using Laser Sintering (LS), which has resulted in a substantial improvement to SRBA in terms of structure and material design. In this development, carbon fiber was employed in the polyamide matrix to obtain the optimal stab resistant performances. Four kinds of materials were used and showed that the polyamide/carbon fiber (PA/CF) composite improved stab resistance property compared to pure polyamide (PA). The stab resistance performances of flat plates were weaker than the structured plate. The penetration depth of the PA/CF structured plate was 2 mm less than the pure PA structured plate. SEM observations of the products confirmed experimental conclusions that the addition of the CF largely improved the plate stab resistance. Moreover, using the PA/CF structured plate to produce SRBA would reduce the weight of the product by 30-40% comparing to the conventional SRBA, which would greatly reduce the physical burden to the wearer and largely improve the chance that the armor would be used.

1:30 PM
Controlling Thermal Expansion with Lattice Structures Using Powder Bed Laser Fusion: *Steven Milward*[1]; Nicholas Lavery[1]; Steven Brown[1]; Helen Swygart[2]; Lee Eccles[2]; [1]Swansea University; [2]Qioptiq

Tuning the Co-efficient of Thermal Expansion (CTE) of a component is traditionally limited by material choice. Laser Powder Bed Fusion (LPBF) enables the designer to create complex geometries and lattice structures. When combined with a secondary bonded material, these bi-metallic lattice structures can be designed to exhibit different CTE's whilst retaining stiffness. This allows the designer the freedom to adjust the CTE by changing CAD variables such as lattice angle, and member thicknesses. This paper aims to develop an arrangement for CTE matched components for high precision optical systems. Development pursued using a Static Thermo-Structural Finite Element Analysis model to determine the best arrangements for maximum CTE change. The results are incorporated into a new design prototype of a full cylindrical lens system, which is prepared in both plastic on both a Stratasys Object 1000 and in metal on a Renishaw AM250 system.

1:50 PM
Determination of a Shape and Size Independent Material Modulus for Honeycomb Structures in Additive Manufacturing: *Thao Le*[1]; Dhruv Bhate[2]; John Parsey[1]; Keng Hsu[1]; [1]Arizona State University; [2]Phoenix Analysis & Design Technologies, Inc. (PADT)

Most prior work on modeling cellular structures either assumes a continuum model or homogenizes "effective" cell behavior. The challenge with the former is that bulk properties do not always represent behavior at the scale of the cellular member, while homogenization results in models that are shape specific and offer little insight into practical design matters like transitions between shapes, partial cells or skin junction effects. This paper demonstrates the strong dependence of measured properties on the size of the honeycomb specimen used for experimental purposes and develops a methodology to extract a material modulus in the presence of this dependence for three different honeycomb shapes. The results in this paper show that the extracted modulus for each shape converges as the number of cells in the specimen increase and further, that the converging values of the material modulus derived from the three shapes are within 10% of each other.

2:10 PM
Additively Manufactured Conformal Negative Stiffness Honeycombs: *David Debeau*[1]; Carolyn Seepersad[1]; [1]The University of Texas at Austin

This study presents a novel bistable honeycomb design for use in impact protection applications. The three dimensional nature of the design allows it to conform to complex surfaces and protect against impacts from multiple directions. The honeycombs are also able to tile together, allowing for impact protection across an entire surface. Tests on selective laser sintered nylon 11 prototypes show increased performance over conventional bistable honeycombs. High strain rate drop tests, conducted with direct metal laser sintered prototypes, will also be presented.

2:30 PM
Understanding and Improving Optical Coherence Tomography Imaging Depth in Selectively Laser Sintered Nylon 12 Parts and Powder: *Adam Lewis*[1]; Nitesh Katta[1]; Austin McElroy[1]; Thomas Milner[1]; Scott Fish[1]; Joseph Beaman[1]; [1]University of Texas at Austin

Optical Coherence Tomography (OCT) has shown promise as a new process sensor in selective laser sintering (SLS) which can yield depth resolved data not attainable with conventional sensors. However, OCT images of nylon 12 SLS parts and powder contain artifacts which have not been previously investigated in literature. These artifacts along with the highly scattering nature of the SLS parts and powder limit the imaging depth which decreases the usefulness of OCT imaging. This study seeks to identify the causes of the imaging artifacts and proposes and investigates methods to improve OCT imaging depth in SLS parts and powder.

2:50 PM Break

3:20 PM
Application of Integrated Computational Materials Engineering in Qualification of Additive Manufacturing Parts: *Guofeng Chen*[1]; Zhongjiao Zhou[1]; Changpeng Li[1]; Xu Hua[1]; [1]Siemens Ltd., China

Additive manufacturing (AM) technology has shown its great advantages to produce end-use products with complex design and high-added value. However, the AM-specific characters, such as inherent material anomalies (porosity, lack of fusion defects, or inclusions), anisotropy, location-speci c properties and residual stresses, prevent AM from widely commercial adoption. Therefore, qualification of AM technology is desperately necessary. In this paper, Inconel 718 superalloy manufactured by selective laser melting (SLM) was taken as an example. An Integrated Computational Materials Engineering (ICME) approach was applied to accelerate the qualification process. Experimental and numerical investigation of process parameters, microstructural evolution before and after post heat treatment, the anisotropic fracture mechanics (creep, LCF, HCF, etc) were carried out. Afterwards, the size distribution and frequency of occurrence of material anomalies were taken into consideration for probabilistic fracture mechanics-based assessment. This work is significantly meaningful to improve material quality and speed up the design-to-product transformation of AM parts.

3:40 PM
Powder Bed Fusion Metrology for Additive Manufacturing Design Guidance: *Jared Allison*[1]; Carolyn Seepersad[1]; Conner Sharpe[1]; Steven Kubiak[1]; [1]UT Austin

The benefits afforded by the use of additive manufacturing (AM) are diminished due to limited understanding of the various AM processes. Design for additive manufacturing (DFAM) guidelines can be generated through metrology studies using test parts to characterize specific processes and inform designers. A test part was designed for polymer selective laser sintering (SLS) that incorporates an array of geometric features. The part was then built in multiple materials, build orientations, and locations within the build chamber in a factorial-style study to assess the variation attributed to each processing parameter. Both resolution and accuracy were investigated. Upon measurement of the test cubes, tolerances and design allowables could be established and compiled into a set of design guidelines for SLS. This same characterization strategy can be applied to other AM processes. Two test part options were designed for direct metal laser sintering (DMLS) to be used in a similar metrology study.

4:00 PM
Geometrical Accuracy of Holes and Cylinders Manufactured with Fused Deposition Modeling: *Frederick Knoop*[1]; Volker Schöppner[2]; [1]Paderborn University / DMRC; [2]Kunststofftechnik Paderborn (KTP)

A widespread Additive Manufacturing (AM) technology is Fused Deposition Modeling (FDM) to create prototypes and end-use parts with close-to-production thermoplastics. For the application as a final product, it is important that additively manufactured parts strictly adhere to the geometrical requirements of the technical drawing. In this paper, the cylindrical elements hole and cylinder are investigated in terms of achievable geometrical accuracy. For this purpose, different test specimens were designed, that allow a measurement of inner and outer diameters from 3 to 80 mm (DIN EN ISO 286). Specimens made of ABS M30 were measured with a coordinate measuring machine (CMM) to evaluate deviations from the nominal dimension and form deviations. The measuring method includes a scanning of the surface to record dimensional deviations over the whole diameter. In order to counteract these deviations and to improve the dimensional accuracy, different shrink factors and filling patterns were investigated.

4:20 PM
New Benchmark Part Design for Characterising Accuracy in Binder Jetting Process: Alex Bernard[1]; *Senthilkumaran Kumaraguru*[1]; [1]Indian Institute of Information Technology, Design and Manufacturing, Kancheepuram

Many benchmark parts have been designed in the past to characterise the errors in AM parts but a generic benchmark part may not serve the purpose for all AM processes. For example, in the case of Binder Jetting of polymer materials, unlike many other AM processes, the deviations due to thermal phenomena are absent and it requires a relook into the current benchmark parts to characterise the deviations. In this regard, this work is an attempt to design and develop a benchmark part to capture and study various dimensional and geometrical errors caused during a binder jetting process. The fabricated part is scanned into a point-cloud data and then compared with the original CAD model using cloud-compare software to evaluate geometrical and dimensional deviation. The ability to capture various types of error is evaluated by comparing the performance of the new part with the NIST benchmark part.

Biomedical Applications 2: Scaffolds and Supports

Wednesday PM — Room: Salon J
August 9, 2017 — Location: Hilton Austin

Session Chair: Natalie Rudolph, University of Wisconsin

1:10 PM
A Topological Exploration of Shrinkage in Sintered Bioceramic Parts Fabricated by Vat Photopolymerization: *Donald Aduba*[1]; Keyton Feller[2]; Christopher Williams[1]; [1]Virginia Tech; [2]University of Wisconsin-Platteville

In this work, a vat photopolymerization (VP) additive manufacturing process photocured bioceramic cuboids at different Cartesian build orientations to investigate their effects on post-sintering shrinkage and associated physical properties. A suspension of tri-calcium phosphate (TCP) in Autodesk commercial resin and dimethyl sulfoxide (DMSO) dispersant was used to shape green parts. The shapes were heated and sintered to 1300 °C at 5 °C/min. Part morphology, microstructure, dimensional shrinkage, and mass loss after sintering were evaluated. Part dimensions parallel to the build direction exhibited greater shrinkage compared to the other two dimensions. This paper is the first to investigate the relationship between print topology and post-sintering shrinkage of bioceramic structures shaped by VP. The authors aim to open new research avenues modeling ceramic part shrinkage, accounting for build orientation among other geometric design constraints to tailor part fidelity and performance.

1:30 PM
Additive Manufacturing and Mechanical Testing of Interpenetrating Phase Composites for High-performance Armor Applications: *Zachary Cordero*[1]; Alexander Pawlowski[2]; Matthew French[1]; William Yarberry[1]; J Carver[2]; Amelia Elliott[2]; Derek Splitter[2]; Amit Shyam[2]; [1]Rice University; [2]Oak Ridge National Laboratory

Interpenetrating phase composites were fabricated by infiltrating additively manufactured 316L preforms with molten A356. The mechanical properties of the composites were characterized using quasi-static tension and compression tests. It was found that the stress-strain response could be precisely controlled by adjusting both the volume fraction and the topology of the constituents. Further, the composites exhibited exceptional damage-tolerance when loaded in tension, primarily because the 316L ligaments bridged cracks that developed in the A356. Preliminary hypervelocity impact tests suggest that these composites far outperform monolithic A356 in multiple hit scenarios, making these composites well-suited for lightweight armor applications.

1:50 PM
Understanding and Engineering of Natural Surfaces with Additive Manufacturing: *Ali Khoshkhoo*[1]; Andres Carrano[1]; David Blersch[1]; Hamid Ghaednia[1]; Kamran Kardel[2]; [1]Auburn University; [2]Georgia Southern University

Benthic algae systems that attach to substrata have been shown effective in water pollution remediation and biomass production but yields are limited by attachment preferences in wild cultivars. This work seeks to uncover surface topography preferences for algal attachment by reproducing surface topographies with additive manufacturing. To date, no research effort has taken advantage of using additive manufacturing to reverse engineer the characteristics of the natural surfaces to find the attachment preferences of certain periphyton species towards substrata topography. Natural rocks and surfaces with attached biofilms were retrieved from streams and scanned with optical profilometry for surface parameter extraction and characterization. A material jetting process is used to additively manufacture the reversed surfaces followed by optical profilometry to validate the resultant topography. The results show that certain texture parameters (e.g. areal kurtosis) of surface impacts the biomass adhesion of specific algal communities.

2:10 PM
Additive Fabrication of Polylactic Acid/Ceramic Based Scaffolds for Maxillofacial Regeneration: *Srikanthan Ramesh*[1]; Mohamed Eldakroury[1]; Iris Rivero[1]; Matthew Frank[1]; [1]Iowa State University

The objective of this study is to manufacture polylactic acid (PLA)-based biocomposite 3-D scaffolds through additive fabrication for promoting the regeneration of maxillofacial defects. Additive fabrication has enabled the production of effective scaffolds by overcoming traditional limitations such as suboptimal distribution of cells, and poor control over scaffold architecture. In this study, cryomilled PLA/chitosan/tricalcium phosphate powder biocomposites provided the basis for the generation of hydrogel biocomposites, which were then utilized for the fabrication of scaffolds using a custom-made droplet-based system. Densities and viscosities of hydrogel biocomposite formulations were varied and their effect on printing resolution was studied. Two different scaffold geometries, with the aim of determining a potential platform to stimulate a regenerative response, were designed and fabricated: (i) orthogonal (0°, 90°) and (ii) diagonal (0°, 45°). The influence of biocomposite composition and scaffold design on mechanical, morphological and degradation characteristics of the scaffolds were investigated.

2:30 PM
Binder Jet Additive Manufacturing of Stainless Steel,Tricalcium Phosphate Biocomposite for Bone Scaffold Applications: *Kuldeep Agarwal*[1]; Sairam Vangapally[1]; Alex Sheldon[1]; [1]Minnesota State University, Mankato

Scaffolds are 3D biocompatible structures that mimic the extracellular matrix properties (mechanical support, cellular activity and protein production) of bones and provide place for cell attachment and bone tissue formation. Their performance depends on chemistry, pore size, pore volume and mechanical strength. Recently, additive manufacturing (AM) has been used as a means to produce these scaffolds. This paper explores a new biocomposite manufactured using Binder Jet AM process. Stainless Steel and tricalcium phosphate are combined to form a composite and used in different volume fractions to produce parts with varying densities. Layer Thickness, Sintering time and Sintering temperature are varied to study the effect of process parameters on the microstructure, dimensions and mechanical properties of the resulting structure. It is found that the resulting biocomposite can be tailored by varying the process to change its properties and mimic the properties of scaffolds in bone tissue applications.

2:50 PM Break

3:20 PM
Selective Laser Melting of Novel Titanium-Tantalum Alloy as Orthopedic Biomaterial: *Florencia Edith Wiria*[1]; Swee Leong Sing[2]; Wai Yee Yeong[2]; [1]Singapore Institute of Manufacturing Technology; [2]Nanyang Technological University

Selective laser melting (SLM) is an additive manufacturing technique that is capable of fabricating complex functional 3D metal parts directly from the complete melting and powder fusion. As a powder bed fusion technology, SLM has the potential in expanding its materials library by forming alloys that were previously difficult to achieve by using metal powder mixtures for customization according to the application requirements.Titanium-tantalum (TiTa) is a potential material to use in biomedical applications due to its high strength to modulus ratio. However, it is still not widely used due to the difficulties in obtaining this alloy. SLM is chosen as the method to form this alloy due to its versatility in processing metallic materials and good results obtained from commercially pure titanium. This research aims to develop TiTa as a material to be potentially used in biomedical field by investigating its processing window, resulting microstructure and mechanical properties.

3:40 PM
Development of Patient Specific Surgical Resection Guides Using Medical Imaging 3D Modelling and Additive Manufacturing Processes: *Mazher Mohammed*[1]; Mark Ridgway[1]; Ian Gibson[1]; [1]Deakin University

In this study we will assess the design and fabrication requirements of patient-specific resection guides to augment surgical procedures such as bone grafts and implant placement. Medical imaging data was used to form a 3-dimensional, digital template model of the target anatomy and the resulting surface topography was incorporated into the guide design. The surgical guide was then designed to incorporate slots for bone cutting, holes for drilling of fixation points and an optimised geometry which ensured ease of placement and use. The final device was then manufactured using additive manufacturing to accurately replicate the complex design features. To validate the design, the target patient anatomy was reproduced using additive manufacturing and a 'mock' surgery was performed to assess the device performance. We found our design allowed for efficient placement and use during the mock surgery, confirming the potential of the devised process as a robust methodology for clinical implementation.

4:00 PM
Design Optimisation of a Thermoplastic Splint: *Angus Fitzpatrick*[1]; Mazher Mohammed[1]; Paul Collins[1]; Ian Gibson[1]; [1]Deakin University

Upper limb orthotic devices are generally handmade using laborious and traditional hand-working techniques. Patient 0 is a partial hand amputee that needed a splint post-surgery to hold the remaining ligaments and appendages in a fixed position. This study investigated the use of optical laser scanning to capture the surface topography from Patient 0's current splint. The splint digitised into a 3D CAD model from point cloud data and thus a patient specific digital orthoses was created; then reproduced using additive manufacturing. This approach offers advantages over existing techniques; data collection was rapid and provided accurate information. Utilising rapid iteration both virtually and physically, surface finish, weight reduction, cost minimisation, design and aesthetics optimisation investigated. This approach affords greater flexibility in design and customisation. The final orthosis realised through additive manufacturing using Fused Deposition Modelling (FDM) in ABS. Ultimately, this approach provides an optimized and complete methodology for orthosis production.

4:20 PM
Reverse Engineering a Transhumeral Prosthetic Design for Additive Manufacturing: *Breanna Rhyne*[1]; Brian Post[1]; Phillip Chesser[1]; Alex Roschli[1]; Lonnie Love[1]; Katherine Gaul[1]; [1]Oak Ridge National Laboratory

The customization and time savings additive manufacturing (AM) offers has been applied to construct prosthetics. However, prosthetics produced using AM rarely resemble the original appendage they are intended to replace. This report details the engineering of a transhumeral prosthetic design for AM. A 3D scan of a patient's existing arm, in combination with computer-aided design (CAD), was used to create a mirrored prosthetic, which appeared aesthetically like the existing arm. The process and complexities of integrating mechanical components for basic actuation into a patient-custom prosthetic are discussed. A simple demonstration of the process is provided. The same methodology can be applied to more intricate prosthetics. This work aims to inspire subsequent research into well-functioning, custom prosthetics that can be generated relatively quickly through 3D scanning and AM. Additional research using this technique in other areas is also applicable in the future.

4:40 PM
Augmented Additive Manufacturing for Affordable Prosthetic Socket Printing: *Nicholas Rodriguez*[1]; [1]The University of Texas-Austin

This paper proposes a method to use an off-the-shelf commercial Fused Deposition Modeling (FDM) 3D printer with minimal modifications to manufacture low-cost prosthetic sockets for developing countries. A novel scan pattern designed to increase inter-layer adhesion in FDM parts is modeled and tested to determine its effect on mechanical properties of printed ABS parts. Results from three-point bend testing indicate a significant increase in part strength when using the proposed scan pattern compared to parts manufactured using a traditional scan pattern. The results also indicate these benefits would be seen if the new scan pattern was implemented in printing full prosthetic sockets.

Materials 13: Jetting and Inks

Wednesday PM Room: 615A-B
August 9, 2017 Location: Hilton Austin

Session Chair: Denis Cormier, Rochester Institute of Technology

1:10 PM
Investigating the Impact of Functionally Graded Materials on Fatigue Life of Material Jetted Specimens: *Dorcas Kaweesa*[1]; Daniel Spillane[1]; Nicholas Meisel[1]; [1]The Pennsylvania State University

The capability of Additive Manufacturing (AM) to manufacture multi-materials enables the fabrication of complex and multifunctional parts with varying mechanical properties. Multi-material AM involves the fabrication of 3D printed objects with multiple heterogeneous material compositions. The material jetting AM process specifically has the capacity and capability to manufacture multi-material structures with both rigid and flexible material properties. Existing research has investigated the fatigue properties of 3D printed multi-material specimens and shows that there is a weakness at the multi-material interface. This paper seeks to investigate the effects of gradual material transitions on the fatigue life of 3D printed multi-material specimens. In order to examine the fatigue life at the multi-material interface, discrete digital-material gradient steps are compared against the true functional gradients created via voxel-level design. Results demonstrate whether specific material gradient types improve tensile fatigue life and the predictability of the failure mode at the material interface.

1:30 PM
Guidelines for Developing Binder Jet Printing Parameters for Various Powder Feedstocks: *Derek Siddel*[1]; Peeyush Nandwana[1]; Amy Elliott[1]; [1]Oak Ridge National Laboratory

Binder Jetting is an additive manufacturing process in which a binder is selectively deposited on a powder bed in a layer-wise manner until the desired geometry is produced. Traditionally, this process is optimized for metallic materials with a focus on stainless steel. After rigorous testing, it has been determined that this process also works with a wide range of materials including ceramics and a wide range of powder morphologies as well. When a new powder is procured, there are many factors, such as particle size and shape which determine flow, packing, and saturation values for printing. This paper aims to quantify how these printing parameters are determined for new powders. Particle flow, packing factor, wettability of powder with binder, particle size, drying time and speed, and interrelations between these are analyzed. The compiled results are presented.

1:50 PM
Binderless Jetting: Additive Manufacturing of Metal Parts via Jetting Nanoparticles: *Yun Bai*[1]; Christopher Williams[1]; [1]Virginia Tech

Binder Jetting AM has been used to fabricate metal parts by first jetting a binder into powder bed; the resulting green part is then thermally post-processed wherein the binder is removed and the metal particles are sintered. In this work, the authors replace conventionally-used polymeric binders with nanoparticle suspensions as a means for binding metal powder bed particles together. After being deposited into the powder particles' interstices, the jetted nanoparticles are sintered at a low temperature via a heated powder bed to provide strength to the printed green part. Regions of the powder bed that do not receive the jetted nanoparticle suspension remain as loose powder as the sintering temperature of the nanoparticles is significantly lower than the larger powder bed particles. The concept of printing metal by jetting a nanoparticle binder made of the same material is demonstrated in the context of copper through printing copper parts with satisfactory green strength.

2:10 PM
Electrical and Mechanical Properties of Metal Filled Conductive Material Using Fused Deposition Modeling: *Sagar Navle*[1]; Jitendra Tate[1]; Bahram Asiabanpour[1]; [1]Texas State University

The four different types of metal filled conductive materials supplied by Proto – Pasta was used in this research. These were composite materials which are conductive in nature with different types of metals filled in it, and they were Polishable Stainless Steel, Rustable Magnetic Iron, Conductive Graphite, and Carbon Fiber Reinforced Composite. The matrix material for all these composites was PLA. Lulzbot 3D printer which uses fused deposition modeling (FDM) manufacturing technique was used to print test samples for tensile, compression, and electrical resistivity.

2:30 PM
Fabrication and Characterization of Graphite/Nylon 12 Composite via Binder Jetting Additive Manufacturing Process: *Hadi Miyanaji*[1]; Li Yang[1]; Muhammad Akbar[1]; [1]University of Louisville

Graphite is used in many applications due to its unique combination of physical properties. In the present study, the feasibility of binder jetting additive manufacturing (BJ-AM) process in fabrication of graphite/nylon composites is investigated. The printability of the composite parts with varying graphite amount was experimentally examined through the adjustment of in-process parameters (e.g. saturation level and drying energy) and post-processing curing (e.g. curing time and temperature). The efficiency of nylon as the liquid phase sintering agent was studied via the mechanical property evaluation of the composites. In addition, the electrical properties of the graphite/nylon composites were investigated in order to evaluate the effectiveness of the manufacturing method for graphite-based structures for potential functional applications.

2:50 PM Break

3:20 PM
Fabricating TiC/Ni3Al Hybrid Composite Using Binder Jet Additive Manufacturing: *Peeyush Nandwana*[1]; Derek Siddel[1]; Amy Elliott[1]; [1]Oak Ridge National Laboratory

Binder jet additive manufacturing is a versatile process that utilizes a binder to deposit parts in a powder bed in a layer by layer fashion. The appeal of the process lies in the fact that it can theoretically deposit any material that can be wetted by the binder. This makes it suitable to deposit near net-shaped metal matrix composites (MMCs) unlike other additive manufacturing techniques. The current study focuses on depositing a TiC/Ni3Al MMC for high-temperature tooling applications. To fabricate the composite, a TiC preform was deposited using the binder jet process followed by liquid melt infiltration of Ni3Al. The resulting microstructures and associated challenges will be presented.

3:40 PM
Net Shaping of Steel-tungsten Metal Hybrid via Binder Jet Additive Manufacturing: *Amy Elliott*[1]; Peeyush Nandwana[1]; Derek Siddel[1]; Christopher Shafer[1]; [1]Oak Ridge National Laboratory

Currently in binder jetting, steel is printed and infiltrated with bronze to form fully dense metal parts. In this work, a similar metal matrix composite is created via binder jetting of tungsten powder and infiltration with steel. The combination of tungsten and steel has the potential to be utilized in many high-wear or corrosive applications requiring complex or custom shapes. The microstructure of the tungsten-steel hybrid was imaged, and the material was tested for strength and hardness. The micrographs show high infiltration of the steel into the tungsten and the material property tests show potential for high strength, hardness, and toughness. Overall, since this new material is compatible with binder jetting, it makes possible the creation of high-temperature, complex or custom metal objects with high strength, hardness, and toughness.

4:00 PM
Effect of Contact Angle on Reactive Ink Droplet Evolution: *Avinash Mamidanna*[1]; Owen Hildreth[1]; [1]Arizona State University

Reactive inks are an attractive alternative to traditional particle-based inks. Newer, low-temperature reactive inks are able to print conductive metals with conductivities less than 2 µΩ-cm and without high temperature sintering steps. Recent work has shown that the porosity of metal films printed using these inks can vary from 50% to 94% with just small changes in substrate temperature or solvent selection. In this work, the authors study the impact of contact angles on droplet evolution of these reactive silver ink (RSI) droplets. RSI droplets were printed on substrates with surface energies ranging from hydrophilic to hydrophobic regimes. Using characterization techniques such as scanning electron microscopy, 3D profilometry mapping and imaging with a high speed camera, the impact of contact angle on droplet evolution and its effect on silver morphology was studied. Thus, the effect of contact angles on RSI morphologies was quantified to better understand the reactive silver inks.

4:20 PM
3D Printing of Metal Powder-based Inks via Direct Ink Writing: *Robert Pack*[1]; Brett Compton[1]; [1]University of Tennessee at Knoxville

Direct ink writing (DIW) is a form of additive manufacturing (AM) that utilizes extrusion to deposit viscoelastic feedstock materials to build structural or functional components. A wide variety of powder-based inks can be formulated for DIW using powders, solvents, dispersants, viscosifying agents and polymer binders, and the printing process is material-agnostic, provided the ink formulation exhibits favorable rheological properties. Because of these features, DIW is ideal for fabricating hybrid ceramic/metal architectures that cannot be achieved through powder metallurgy routes or powder bed AM technologies. In this work, we develop nickel and stainless steel inks for use in ceramic/metal composites based on non-toxic carrageenan gels that act as both binder and viscosifyer. Printing characteristics of the inks are evaluated by printing simple tensile bars, and densification behavior and microstructural evolution is monitored as printed samples are dried, debinded, and sintered in argon.

4:40 PM
Electrical Properties of Reactive Silver Inks on Indium Tin Oxide Films: *Avinash Mamidanna*[1]; April Jeffries[1]; Mariana Bertoni[1]; Owen Hildreth[1]; [1]Arizona State University

The formation of high conductivity ohmic contacts is paramount to the performance of optoelectronic devices. Recently, reactive inks have been developed that metallize photovoltaic cells at temperatures below 100 °C, media resistivities below 2 µO-cm, and while consuming 90% less silver than traditional screen printed silver pastes. In this work, we evaluate the electrical interface between printed reactive silver inks (RSI) front contacts and indium tin oxide (ITO). The specific contact resistance of the interface between RSI and ITO which was evaluated by transfer length measurements was ~1 ×10 -4 $O \cdot cm^2$ which is an order of magnitude lower than that of commercially available low-temperature screen printed Ag paste to ITO. Interfacial resistance was also evaluated when a $SnCl_2$ adhesion promoter was used. This novel approach introduces new techniques to deposit front contacts on solar cells and understand their electrical properties with and without using an adhesion promoting layer.

Materials 14: Novel Materials and Processes

Wednesday PM — Room: 410
August 9, 2017 — Location: Hilton Austin

Session Chair: Marlon Cunico, University of São Paulo

1:10 PM
Crack Initiation and Growth in Selective Laser Melted Pure Molybdenum: *Dianzheng Wang*[1]; Zhijian Shen[1]; [1]Tsinghua University

As a brittle material, molybdenum is very hard to be additive manufactured because of its high melting point and high susceptibility to cracks. In this study, selective laser melting was applied to produce dense pure molybdenum (relative density > 99%) and the resultant cracking behavior was analyzed. Grain boundary crack growth behavior was observed by electron backscattering diffraction (EBSD). The nanoscale intergranular impurities like molybdenum carbide were identified and may be responsible for the degradation of grain boundary strength. On the base of local misorientation map, the residual plastic deformation around the cracks were plotted and compared with that of molybdenum alloy.

1:30 PM
Wire + Arc Additive Manufacture of Unalloyed Tantalum: *Gianrocco Marinelli*[1]; Supriyo Ganguly[1]; Filomeno Martina[1]; Stewart Williams[1]; [1]Cranfield University

Wire + Arc Additive Manufacture (WAAM) adopts arc welding technology for the purpose of additive manufacture. The technology is capable of producing metre-scale near net shape metallic components achieving significant cost savings. The present work provides an overview of WAAM of unalloyed tantalum. Results show that tantalum structures can be deposited with high integrity and excellent mechanical properties, superior to those of commercially available tantalum. For example, an ultimate tensile strength of 200 MPa was achieved for the WAAM deposited material compared to the 180 MPa for commercial tantalum, even though the grains in the WAAM material were large and had a high aspect ratio. Interestingly, these grains were refined into an equiaxed microstructure when additional cold-working was implemented, obtaining an average grain size of 650 µm. These findings have significant, practical benefits and may aid industrialisation of the WAAM process for nuclear and other applications requiring tantalum structures.

1:50 PM
Selective Laser Melting of Pure Copper: *Toshi-Taka Ikeshoji*[1]; Kazuya Nakamura[2]; Makiko Yonehara[1]; Ken Imai[1]; Hideki Kyogoku[1]; [1]Kindai University; [2]TRAFAM

Pure copper has the high thermal conductivity and the low emissivity of laser. They are the major obstacle to achieve the higher density by the selective laser melting for pure copper powder. In this research, with the variation in the scanning speed in the range of 300 to 1200 mm/s and the laser power in the rage of 600 to 1000 W, the suitable building condition for the pure copper was searched. The highest relative density of the built material was 99.5%. The building conditions was also searched using the transient heat analysis by FEM. The melt pool depth predicted by the numerical analysis was shallower than the experimentally obtained values, but the tendency to the scanning speed and the laser power met with the experiment.

2:10 PM
Direct Writing of Films from High Speed Aerosol Deposition of Ag: *Jeremiah McCallister*[1]; Michael Becker[1]; John Keto[1]; Desiderio Kovar[1]; [1]The University of Texas at Austin

The Laser Ablation of Microparticle Aerosol (LAMA) process is capable of producing an aerosol of nanoparticles from a microparticle aerosol. The nanoparticles are then accelerated to high velocities (400-1400 m/s) and sprayed onto substrates at room temperature to produce patterned thick films of variable thickness (2 - 150 µm). The process allows for the use of a broad range of inorganic materials to be directly written onto almost any organic or inorganic substrate. Experiments have been conducted by impacting silver particles at a range of velocities. The films were analyzed for their densities, surface finish, and microstructure. Results are compared to molecular dynamics simulations that suggest that the density of films can be increased by increasing impaction velocity of the particles through multiple processes including varying the upstream pressure, increasing the impaction temperature and changing the deposition nozzle size.

2:30 PM
Effect of Bed Temperature on the on the Laser Energy Required to Sinter Copper Nanoparticles: *Nilabh Roy*[1]; Obehi Dibua[1]; Michael Cullinan[1]; [1]The University of Texas at Austin

Copper nanoparticles (NPs) due to their high electrical conductivity, low cost, and easy availability provide an excellent alternative to other metal NPs such as gold, silver and aluminum in applications ranging from direct printing of conductive patterns on metal and flexible substrates for printed electronics applications to making three dimensional freeform structures for interconnect fabrication for chip packaging applications. Lack of research on identification of optimum sintering parameters such as fluence/irradiance requirements for sintering of Cu NPs serves as the primary motivation for this study. This paper focuses on the identification of good sintering irradiance window for Cu NPs on aluminum substrate using Continuous wave (CW) laser. The study also includes the comparison of CW laser sintering irradiance windows obtained with substrates at different initial temperatures. The irradiance requirements for sintering of Cu NPs with substrate at 150-200 °C were found to be 5-17 times smaller than the irradiance requirements for sintering with substrate at room temperature. These findings have also been compared against the results obtained with a nanosecond (ns) laser and a femtosecond (fs) laser.

2:50 PM Break

3:20 PM

Aluminum Matrix Syntactic Foam Fabricated with Additive Manufacturing: *Myranda Spratt*[1]; Joseph Newkirk[1]; K. Chandrashekhara[1]; [1]Missouri University of Science and Technology

Syntactic foams are lightweight structural composites with hollow reinforcing particles embedded in a soft matrix. These materials have applications in transportation, packaging, and armor due to properties such as relatively high specific stiffness, acoustic dampening, and impact absorption. Aluminum matrices are the most widely studied of metal matrix syntactic foams, but there is little to no research in regards to processing the foams with additive manufacturing. It is theorized that the fast cooling rates and limited kinetic energy input of additive could reduce two issues commonly associated with processing syntactic foams: microsphere flotation in the melt and microsphere fracture during processing. In this study, 4047 aluminum blended with glass particles was deposited on a 4047 Al substrate using an additive process. Characterization of the foams include mechanical testing and microstructural analysis.

3:40 PM

Real-Time Layer-by-Layer Ultrasonic Treatment of Additively Manufactured Metallic Materials: *Rasool Mazruee Sebdani*[1]; Joshua Gale[1]; Christopher Rudolf[1]; Wonmo Kang[1]; Ajit Achuthan[1]; [1]Clarkson University

Real-time ultrasonic layer-by-layer treatment (UT) during a direct metal laser sintering (DMLS) process has previously been shown to enhance the mechanical properties of austenitic 316L stainless steel. In the present work, this method is extended to two other metallic materials, Inconel 718, a nickel based super alloy, and 17-4 martensitic stainless steel. While additively manufactured (AM) Inconel 718 typically shows an increase in strength and a decrease in ductility, 17-4 shows the opposite behavior. The primary objective of the present study is to determine the effect of UT on the mechanical properties and the microstructure of these two fundamentally different materials. AM samples were produced with a DMLS process in an EOS M 280 machine. Static stress-strain behavior, variation in hardness through the thickness of the sample, and low-cycle fatigue properties were determined. The variation in microstructure was also studied by obtaining optical and SEM images.

4:00 PM

Fabrication of Metallic Multi-material Components Using Laser Metal Deposition: *Frank Brueckner*[1]; Elena Lopez[1]; Mirko Riede[1]; André Seidel[1]; Robin Willner[1]; Christoph Leyens[1]; [1]Fraunhofer IWS Dresden

Meanwhile, Laser Metal Deposition (LMD) is a well-known Additive Manufacturing technology used in various industrial branches as energy, tooling or aerospace. It can be used for the fabrication of new components but also repair applications. So far, volume build-ups were mostly carried out with one single material only. However, loading conditions may strongly vary and, hence, the use of more than one material in a component would yield major benefits. By means of multi-material build-ups, cost-intensive alloys could be used in highly-loaded areas of the part, whereas the remaining part could be fabricated with cheaper compositions. The selection of combined materials strongly depends on the requested thermo-physical and mechanical properties. Within this contribution, possibilities of material combinations by LMD and selected examples of beneficial multi-material use are presented.

4:20 PM

Design and Fabrication of Hierarchical 3D Architected Metamaterials with Programmable Damage Tolerance and Strength

: *Rayne Zheng*[1]; [1]Virginia Tech

Proliferating nano-structured features into bulk scales remains a daunting task particularly because the lack of fabrication technologies to scale them up to monolithic with controlled features. We report a large area additive manufacturing techniques capable of assembly sub-micron scale features into large area, hierarchical composite bulk materials. The techniques enables assembly functionally graded functionalized nano-structured material into large area bulk materials with programmable modulus and thermal conductivity. We present study on the new type of multi-scale multi-material hierarchical architectures with programmable strength, morphing capabilities as well as high fracture resistance and thermal expansions and shrinkage. We investigated the influence of density and structural size on the fracture toughness of hierarchical 3D stretch-dominated micro-architectures. Through activation of different failure modes multi-scale architected metamaterials, we report simultaneous improvement of fracture toughness and strength at the ultra-low density hierarchical metamaterials.

4:40 PM

Weldability of Additively Manufactured Metal Components: *Jeffrey Rodelas*[1]; Michael Maguire[1]; Dorian Balch[1]; Bradley Jared[1]; [1]Sandia National Laboratories

The design freedom of AM can assist in reducing the number of welding operations; however, not all AM components can entirely avoid welding in higher-level assembly. To date, little emphasis has been placed on understanding the weld behavior on metal AM parts despite metallurgical differences in material composition, microstructure, and defect population compared to conventional non-AM alloys. These differences can result in unexpected weld behavior or in more severe cases, fabrication-related defects e.g., hot cracking. In this study, the solidification behavior of laser welds on AM 304L stainless steel is examined. Quantitative microprobe analysis is used to measure AM microsegregation before and after welding to identify operative solidification mode. Lastly, the effect of surface-active impurity elements on weld geometry will be discussed.*Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Materials 15: 316L and Other Stainless Steels

Wednesday PM — Room: Salon K
August 9, 2017 — Location: Hilton Austin

Session Chair: Christopher Roberts, University of Texas at Austin

1:10 PM

Microstructure Comparison of 316L Parts Produced by Different Additive Manufacturing Processes: *Mihaela Nastac*[1]; Andrew Klein[1]; [1]ExOne

316L is well known for its corrosion resistance and combination of strength and ductility. By using metal additive manufacturing, 316L parts can be produced with volumes and complexity that were previously unachievable. Three of the major metal additive manufacturing technologies – binder jetting, electron beam melting, and selective laser melting – produce 316L parts, but with different material properties and microstructures. This paper will examine the microstructure differences between parts produced by the three methods and discuss recent advances to improve microstructure of metal parts produced by additive manufacturing.

1:30 PM

A Parametric Study on Grain Structure in Selective Laser Melting Process for Stainless Steel 316: Wenda Tan[1]; *Dongwei Sun*[1]; Xuxiao Li[1]; [1]University of Utah

The effect of processing parameters on the grain structure of the stainless steel 316 parts built by selective laser melting (SLM) process is studied. Multi-pass, multi-layer blocks are fabricated with different combinations of processing parameters, including laser power, scanning speed, and scanning patterns. By mapping different combinations of processing parameters to the obtained grain structure, the effects of the processing parameters on the grain shape, size, and orientation are identified, and the mechanisms to determine the grain texture are discussed. The in-process grain coarsening and recrystallization are also analyzed.

1:50 PM

Strength of Micro-Computed Tomography as an Indicator of Process History and Estimator of Mechanical Performance in Additively Manufactured Stainless Steel: *Jonathan Madison*[1]; Laura Swiler[1]; Olivia Underwood[1]; Brad Boyce[1]; Bradley Jared[1]; Jeffrey Rodelas[1]; Bradley Salzbrenner[1]; [1]Sandia National Laboratories

As a portion of a larger effort to relate additively manufactured (AM) microstructure to performance, micro-computed tomography is employed on AM stainless steel tensile samples having resolutions in the range of 10-15 microns per cubic voxel edge. Lack-of-fusion defects are characterized quantitatively for presence, proximity and spatial arrangement utilizing both scalar and distribution quantities. Correlations in observed defect populations will then be presented in relation to mechanical performance, as revealed through high-throughput mechanical testing, as well as in relation to the processing parameters that produced them. Strength of predictivity associated with utilizing micro computed tomography as an insight to processing history or for estimation of mechanical performance will also be discussed in the context of the correlation coefficient and the coefficient of determination.

2:10 PM
Porosity and Mechanical Properties of Selected Laser Melted 316L Stainless Steel: *Trevor Verdonik*[1]; [1]Lehigh University

Metal powder bed laser melting technology is quickly being adopted by industry to produce end-use parts, but porosity continues to be a significant problem. To help address these concerns, we are studying the effects of porosity distribution and morphology on the tensile and fatigue properties of 316L stainless steel. Using a Renishaw AM400 laser melting system, we are testing porosity and mechanical properties at 200, 300, and 400 Watt laser powers and utilizing various combinations of point distance and exposure time; using discrete laser exposures rather than continuous line scanning. By changing these parameters the microstructure and porosity conditions in the sample can be modified substantially. Through comparisons of tensile and fatigue test responses at various parameter sets with corresponding metallography, we are mapping the relationship between printing parameters, porosity, and mechanical properties.

2:30 PM
316L Powder Reuse for Metal Additive Manufacturing: Bryan Sartin[1]; *Tammy Pond*[1]; Brett Griffith[1]; Wes Everhart[1]; Lauren Elder[1]; Ed Wenski[1]; Charlie Cook[1]; David Wieliczka[1]; Wayne King[2]; Alexander Rubenchik[2]; Sheldon Wu[2]; Ben Brown[1]; Curtis Johnson[1]; Joseph Crow[1]; [1]Honeywell FM&T; [2]LLNL

Metal additive manufacturing via laser powder bed fusion is challenged by low powder utilization. The ability to reuse metal powder will improve the process efficiency. 316L powder was reused 12 times during this study, completing thirty-one builds over one year and collecting 380 powder samples. The process, solidified samples, and powder were analyzed to develop an understanding of powder reuse implications. Solidified sample characteristics were affected more by slight process variations than by cycling of the powder. While a small percentage of powder was greatly affected by processing, the bulk powder only observed a slight increase in powder size.This work performed under the auspices of the U.S. Department of Energy by Honeywell Federal Manufacturing and Technology under Contract DE-NA0002839 and Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

2:50 PM Break

3:20 PM
Competing Influence of Porosity and Microstructure on the Fatigue Property of Laser Powder Bed Fusion Stainless Steel 316L: *Meng Zhang*[1]; Chen-Nan Sun[2]; Xiang Zhang[3]; Phoi Chin Goh[4]; Jun Wei[2]; Hua Li[1]; David Hardacre[4]; [1]Nanyang Technological University; [2]Singapore Institute of Manufacturing Technology, A*STAR; [3]Coventry University; [4]Lloyd's Register

Process-induced porosity is commonly believed to be the main cause of fatigue failure for parts made by the selective laser melting process. In this work, stainless steel 316L specimens with different porosity levels were fabricated by varying the powder layer thickness and evaluated in terms of the fatigue S-N curves and fractographic analysis. The results show that when pores are controlled below a critical level, subgrain boundary defects become the weakest link and contribute to low energy intergranular failure. The fatigue strength of all specimens, regardless of porosity level, is inferior to that of conventional austenitic stainless steel. This shows that the presence of the ultrafine grains, despite increasing tensile strength, is the limiting factor for materials under fatigue loading. The finding sheds light on the possibility of fatigue strength improvement through heat treatment to promote high energy transgranular crack initiation.

3:40 PM
Studying Chromium and Nickel Equivalency to Identify Viable Additive Manufacturing Stainless Steel Chemistries: *Zachary Hilton*[1]; Joseph Newkirk[1]; Ronald O'Malley[1]; [1]Missouri University of Science and Technology

Chromium and nickel equivalency modeling has long been used in welding to determine the weldability of steel chemistries. A study was conducted to determine the applicability of Cr-Ni modeling to the additive manufacturing process. Many AM methods involve rapid solidification of small melt pools, similar to welding. Chemistries with varying Cr/Ni ratios were selected for use in a selective laser melting process and modeled using known models. Initial results indicate that the standard "safe welding zone" may not directly apply to additive manufacturing. The capability to build with chemistries outside the weldability "safe zone" could result in improved and varied properties for additively manufactured materials.

4:00 PM
Experimental Analysis on Eradicating Porosity from Additively Manufactured Low Alloy Steels by Using Martensitic Stainless Steel Powder Reinforcement Technique: *Ahmad Farooq*[1]; Chang Tai Chi[1]; Yujiang Xie[1]; [1]Institute of Metal Research, Chinese Academy of Sciences

Due to the inherent quality of possessing low chromium content, porosity of various forms, typically gaseous and lack of fusion pores, can be found abundant within additively manufactured low alloy steels (AMLAS). Oxygen is one of the key reasons behind the formation of these pores that ultimately develops pore induced cracks as well as poor densification of the bulk AMLAS materials. In this paper, low alloy 12CrNi2 steel powder is mixed with martensitic stainless Cr12Ni2 powder and is laser deposited additively using LENS to produce bulk samples. Aim is to introduce increased chromium content within the low alloy samples so as to reduce the erosion of oxygen and gain improved material stability. In order to acquire the optimized powder blend, both the powders were mixed at different ratios and were laser deposited at a power of 900W. Consequent micro structural analysis was performed using SEM and OM.

Materials 16: Thermal Aspects and Porosity Effects

Wednesday PM	Room: 408
August 9, 2017	Location: Hilton Austin

Session Chair: Aref Yadollahi, Mississippi State University

1:10 PM
Using Laser Ultrasonic Testing to Detect Sub-surface Defects in Metal Laser Powder Bed Fusion Components: *Sarah Everton*[1]; Phill Dickens[1]; Chris Tuck[1]; Ben Dutton[2]; [1]University of Nottingham; [2]Manufacturing Technology Centre

Laser powder bed fusion offers many advantages over conventional manufacturing methods, such as the integration of multiple parts which can result in significant weight-savings. The increased design freedom that layer-wise manufacture allows has also been seen to enhance component performance at little or no added cost. However, in order for such benefits to be realised, the material quality must first be assured. Laser ultrasonic testing is a non-contact inspection technique which has been proposed as suitable for in-situ monitoring of metal additive manufacturing processes. This paper explores the current capability of this technique to detect manufactured and seeded sub-surface defects in Ti-6Al-4V samples. The results are compared with x-ray computed tomography reconstructions and validated using destructive testing methods.

1:30 PM

Thermal Property Measurement Methods and Analysis for AM Solids and Powders: *Justin Whiting*[1]; Brandon Lane[1]; Bo Cheng[2]; Kevin Chou[2]; [1]National Institute of Standards and Technology; [2]University of Louisville

Thermal properties of additive manufacturing (AM) solids and precursor materials are important factors for build process and part performance. However, measured thermal properties are not well documented, despite being used extensively in AM modeling and simulation. NIST and the University of Louisville are developing the measurement science for AM material thermal properties. New measurement methods, sample preparation techniques, and results analyses are demonstrated for laser flash (LF) and hot disk (HD) thermal diffusivity and conductivity measurements on metal AM solids and powders. Due to the complexity of these materials, new sample fabrication methods are required and demonstrated, as well as techniques utilizing finite element analysis (FEA) to extract thermal property values from measured LF and HD results. Results from LF and HD measurements are presented and compared. In addition, various models for thermal conductivity in powders are evaluated and compared to the measured results, and discussion provided regarding measurement accuracy.

1:50 PM

Ex situ Determination of Melt Pool Length Through Surface Finish Metrology in Laser Powder Bed Fusion Additive Manufacturing: *Zach Reese*[1]; Jason Fox[2]; Chris Evans[1]; John Taylor[1]; [1]University of North Carolina at Charlotte; [2]National Institute of Standards and Technology

Determination and control of part microstructure is a key concern for laser powder bed fusion additive manufacturing. Existing research from other institutions has determined a relationship between melt pool length/depth and the resultant microstructure exists. Currently, however, no ex situ method exists to determine melt pool length. While in situ techniques for monitoring the melt pool are available, these methods are difficult to enable due to the speed and small size scale of the process. In this work, workpieces from experiments covering a wide range of beam powers and travel velocities are analyzed using a scanning white light interferometer. A variety of characterization techniques are used to isolate the chevron patterns seen on the resultant scan track and relationships to the melt pool length are developed. The results of the analysis show good agreement with results from existing literature, providing a method for ex situ determination of melt pool length.

2:10 PM

Fracture Toughness of Additive Manufactured Composite Metamaterial: *Huachen Cui*[1]; Xiaoyu Zheng[1]; [1]Virginia Tech

Recent studies have shown the excellent performance of metamaterials architected with micron structures, which is conducive in creating lightweight, strong and stiff engineering materials. The development of additive manufacturing technologies, such as large area projection micro-stereolithography, would allow one to fabricate such metamaterials. However, the resistance to fracture, which is quantified by fracture toughness, of metamaterials has not yet been well documented, and is important when it is used in crack-bearing applications. Here, we investigated the fracture toughness of nickel-polymer composites manufactured by a large area micro-stereolithography technique. Both structural size effects and material size effects has been observed. The fracture toughness of the metamaterial has a linear relationship with the square root of the unit cell size, while size-dependent strengthening of nickel shells exploit the possibility to yield a higher fracture toughness of the composite.

2:30 PM

Characterization of Ejected Particles or Spatter during Laser Powder Bed Additive Manufacturing: *Maria Withrow*[1]; Chris Rock[2]; Tim Horn[2]; Harvey West[2]; [1]North Carolina State CAMAL; [2]Center of Additive Manufacturing and Logistics

Recycling powder for AM processes is a critically important factor in the commercialization of AM technologies. Laser powder bed processes are prone to spatter where liquid droplets are ejected from the melt pool during part building and redistributed as powder particles back into the powder bed during reuse. Experiments were performed by spreading a thin layer (20-60 micron) of powder onto customized test blocks and producing beads to study particles ejected from the laser AM process. Ejected particles from the melt pool were collected 1) next to the beads and 2) from particles ejected off the test blocks and collected in the EOS M280 build chamber under various build conditions. The ejected particles were analyzed for morphology, particle size distribution, relative % ejected, magnetic properties and oxygen content and compared under different build conditions.

2:50 PM Break

3:20 PM

A Design of Experiments Approach to Observing the Effect of Primary Process Parameters on Porosity Populations and Fatigue Life in DMLS Inconel 718: *Luke Sheridan*[1]; Joy Gockel[2]; Onome Scott-Emuakpor[1]; Tommy George[1]; [1]Air Force Research Laboratory; [2]Wright State University

Additive manufacturing (AM), a developing approach to component fabrication, offers design flexibility and cost reduction that make it a promising, versatile alternative to traditional manufacturing techniques. In AM components, non-optimal processing may result in lack-of-fusion and gas-induced porosity which are common sites of fatigue crack initiation in aerospace components. Some primary parameters known to influence porosity populations in AM components are beam power, speed, and hatch. Literature has noted that pore size and location have significantly influence fatigue life, but little work has attempted to quantify the pore distributions or draw relationships to component life. This investigation uses a DOE approach to quantify porosity due to varied process parameters. Additionally, porosity within fatigue specimens is observed via multiple methods, and the fatigue life of the components will be obtained. This effort provides insight into the processing-structure-properties-performance relationship for additive materials and makes progress toward qualifying AM components for aerospace applications.

3:40 PM

Critical Defect Signatures and Impacts on Material Performance for Metal Laser Powder Bed Fusion: *Bradley Jared*[1]; Brad Boyce[1]; Jon Madison[1]; Jeff Rodelas[1]; Jakob Ostein[1]; Olivia Underwood[1]; Brad Salzbrenner[1]; David Saiz[1]; Laura Swiler[1]; [1]Sandia National Laboratories

To facilitate adoption in high consequence applications, fundamental questions regarding the intrinsic reliability of additive metals must be answered. Research is characterizing the nature of critical defects in stainless steel alloys, quantifying their impacts on mechanical performance, and correlating their presence with process inputs. High throughput tensile testing is being utilized to efficiently and cost-effectively quantify stochastic material properties. Defect "signatures" are then sought that are descriptive of and/or correlate to quantified material performance distributions. Signatures will be discussed from multiple techniques that span in-situ monitoring, non-destructive post-process evaluation, metallography and high-throughput testing.Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This document has been reviewed and approved for unclassified, unlimited release under SAND2017-3805 A.

4:00 PM

Prediction of Fatigue Lives in Additively Manufactured Alloys based on the Crack-growth Concept: *Aref Yadollahi*[1]; Mohammad J. Mahtabi[1]; Haley Doude[1]; James C. Newman[1]; [1]Mississippi State University

This paper aims to predict the fatigue behavior of additively-manufactured alloys using crack-growth data. Among different sources of damage under cyclic loadings, fatigue due to cracks originated from voids is the most life-limiting failure mechanism in powder-based metal additive manufacturing (AM) parts. Hence, the ability to predict the fatigue behavior of AM materials based on the void features is the first step toward improving AM part reliability. Test results from the literature on AM alloys are analyzed herein to model fatigue behavior based on the semi-circular surface flaws. The fatigue-life variations in the specimens are captured using the distribution of defect size. The results indicate that knowing the statistical distribution of the defect size can provide the opportunity of predicting the scatter in the fatigue-life of the AM materials, using an appropriate fatigue analysis code.

4:20 PM
Classification Based Porosity Prediction Technique Using Melt Pool Signal: *Mojtaba Khanzadeh*[1]; Sudipta Chowdhury[1]; Mohammad Marufuzzaman[1]; Mark Tschopp[2]; Linkan Bian[1]; [1]Mississippi State University; [2]Army Research Lab

The objective of this study is to dichotomize the melt pool types using non-trivial metrics of the melt pool as well as leveraging morphological model of the melt pool in additively manufactured parts. By doing so, an in-situ porosity prediction method is developed. We propose a two-step classification based approach to predict porosity that first utilizes 64% of the data as training and 16% of the data as testing set. Afterwards, using the selected parameters, 80% of the data is used for training and 20% of the data for testing to validate the effectiveness of the methods. Results show that, among the classification approaches used, K-NN (96 %) demonstrate the highest rate of prediction accuracy,followed by DT (95%) and SVM (93%) when non-trivial metrics are used. However, when the same procedure is followed for the morphological model of melt pool, it has resulted in 4-5% more porosity prediction accuracy.

Modeling 2

Wednesday PM — Room: 404
August 9, 2017 — Location: Hilton Austin

Session Chair: Douglas Smith, Baylor University

1:10 PM
Time-Optimal Scan Path Planning Based on Analysis of Sliced Geometry: Yi Xiong[1]; Anke Van Campen[1]; *Anje Van Vlierberghe*[1]; Karolien Kempen[2]; Jean-Pierre Kruth[2]; [1]Flanders Make VZW; [2]KU Leuven

In the powder-bed based layered manufacturing, a focused and high power laser beam is guided to travel through pre-defined trajectories with various process parameters such as the scan speed, laser power, and beam diameter to consolidate powdered materials together. The pre-defined path therefore plays a significant role not only on the build part quality but also on the build time. Current path planning strategies are defined only on the layer level, although contours on one layer can be significantly different in the geometry shape. This paper proposes an adaptive scan path planning method based on the geometric characteristic of contours. With this approach, the user is able to control and optimize the scan path for contours with different geometric types. An algorithm for determining the scanning direction to minimize the build time is discussed in detail. A path planning approach for non-productive paths illustrates the potential time gain applying more intelligent strategies.

1:30 PM
A Slicer and Simulator for Cooperative 3D Printing: *Jace McPherson*[1]; Adam Bliss[1]; Flora Smith[1]; Edmund Harriss[1]; Wenchao Zhou[1]; [1]University of Arkansas

Cooperative 3D printing is an emerging technology that aims to increase the 3D printing speed and to overcome the size limit of the printable object by having multiple mobile 3D printers (or printhead-carrying mobile robots) work together on a single print job on a factory floor. It differs from traditional layer-by-layer 3D printing due to the requirement for multiple mobile printers working simultaneously without interfering with each other. Therefore, a new approach for slicing the CAD model and generating commands for the mobile printers is needed, which has not been discussed in the literature before. We propose a chunk-by-chunk based slicer that divides an object into chunks so that different mobile printers can print different chunks simultaneously without interfering with each other. In this paper, we developed a slicer for cooperative 3D printing with two mobile fused deposition modeling (FDM) printers. In order to validate our slicer and visualize the cooperative 3D printing process, we have also developed a simulator environment, which can be a valuable tool in optimizing cooperative 3D printing strategy. Results show that the developed slicer and simulator are working effectively.

1:50 PM
Study on STL-based Slicing Process for 3d Printing: *Jing Hu*[1]; [1]University of Colorado Denver

This paper presents a framework about layer contour reconstruction algorithms by STL-based slicing process for 3D printing. The experimental results by the traditional uniform slicing show the contour outline of each layer and comparison among the different slicing thickness of the cutting z-plane. We then proposed a simple but effective adaptive slicing method to work on the complicated model. Moreover, we discuss the future work to further study on more slicing approaches.

2:10 PM
ORNL Slicer: A Novel Approach for Additive Manufacturing Tool Path Planning: *Alex Roschli*[1]; Andrew Messing[1]; Michael Borish[1]; Brian Post[1]; Lonnie Love[1]; [1]Oak Ridge National Laboratory

ORNL Slicer is the first software designed to generate machine instructions, or tool paths, from CAD files for large-scale 3D printing of metals and polymers. The software was revolutionary because it allowed for slicing of models reaching 20’ long, generating millions of lines of GCode in seconds. The structure of the first ORNL Slicer had limitations in its framework, which has led to the development of ORNL Slicer 2. In the second version of the slicer, the process is modularized with individual layers being divided into regions, smarter infill patterns and traversals are generated based upon stress, thermal, and other models, and slicing has been structured to allow for slicing and reslicing based on machine feedback during the printing process.

2:30 PM
Novel Approach for Optimizing Infill Density of an Additively Manufactured Structure: *Seokpum Kim*[1]; Gregory Dreifus[2]; Xiang Chen[3]; Kenneth Stephenson[4]; John Bowers[3]; Ahmed Hassen[1]; Mohamed Selim[5]; John Lindahl[1]; David Nuttall[1]; Ralph Dinwiddie[1]; Byron Pipes[6]; Vlastimil Kunc[1]; [1]Oak Ridge National Laboratory; [2]Massachusetts Institute of Technology; [3]James Madison University; [4]University of Tennessee at Knoxville; [5]University of Alabama at Birmingham; [6]Purdue University

We propose a new approach to define infill structures accounting for internal mechanical stress of a 3D printed part. Current commercial slicers use the geometric information of an imported part and generate sparse infill patterns that are uniform in size and shape. The proposed approach utilizes the geometric information and the internal stress field provided by computational structural analysis prior to slicing. The algorithm developed in this study identify the local density of a hexagon infill based on a given stress level and generates an equivalent infill with a variable pattern size. High structural reliability is achieved through vertices shared by edges in the hexagon pattern. A small-scale airplane wing was fabricated as a test case for the developed algorithm. Static load test shows that the infill pattern from the proposed approach has higher mechanical stiffness than the conventional infill pattern.

2:50 PM Break

3:20 PM
Computer Aided High Complex Geometry Generation for Product Optimization with Additive Manufacturing: *Thomas Reiher*[1]; Rainer Koch[2]; [1]Paderborn University / DMRC; [2]Paderborn University / C.I.K.

The demand of saving energy, material and costs is a natural driver in product development. Over years of development products got more complex to achieve these goals. Especially in the area of structural parts and products with comparably simple functions two technologies gained a lot of attention in recent years: additive manufacturing and topology optimization. Unfortunately nowadays the generation of manufacturable geometries that are really taking advantage of the potentials created by TO and AM is very painstaking. Conventional CAD-tools are optimized for the generation of geometries easy to manufacture conventionally. They are based on mainly simple and Boolean operations or on generation of surfaces based on user defined splines. This paper elaborates the underlying hurdles of standard CAD tools and shows potentials of a voxel based approach for computer application in generation of high complex structures for multi-optimized purpose from topology optimization over geometry recapture to 3D printing.

3:40 PM

Multiscale Voxel-Based Design and Additive Manufacture of Composite Components: Narasimha Bodetti[1]; Ding Zhen[1]; Sawako Kaijima[1]; Kurt Maute[2]; *Martin Dunn*[1]; [1]Singapore University of Technology and Design; [2]University of Colorado, Boulder

We develop a multiscale design and manufacturing digital workflow that simultaneously determines the macroscopic topology and the spatially-variable fibrous microstructure of 3D composite components based on a combination of mathematical homogenization, finite element simulation, and multiscale topology optimization. Our approach results in a 3D map of homogenized (anisotropic) composite stiffness, parameterized by three microstructure descriptors: fiber aspect ratio, volume fraction, and orientation. This is input into an algorithm that creates geometric realizations (fibers distributed in a matrix) of optimal designs via an inverse homogenization and generative computational geometry approach and then translates the geometrical realizations into 3D printed multimaterial components via a voxel-based approach with multimaterial inkjet printing of photocured polymers using a Stratasys Connex 3D printer. We demonstrate our approach by designing 2D, 3D, and multilayer plate composite components, realizing them by 3D printing, and experimentally validating their performance.

4:00 PM

Software Tools for Rapid 3D Electronics Fabrication: *Jake Lasley*[1]; David Espalin[1]; Jazmin Munoz[1]; Miguel Licerio[1]; Jose Perez[1]; Ryan Wicker[1]; [1]UTEP - W.M. Keck Center for 3D Innovation

Additive manufacturing allows for rapid fabrication cycles, which is desirable when design changes are anticipated. To make prototypes and end-use parts more functional, electronic components can be embedded into 3D printed parts during the fabrication process. The inclusion of electronic components into 3D printed parts introduces additional functionality, but requires new hardware and software tools to realize the merger. This work discusses software tools developed for collecting electrical schematic data and importing it into a solid CAD modeling environment in which component cavities and traces can be created. The output of the process is a library of files that are processed by a custom slicer to produce a G-code file that contains instructions for depositing plastic and embedding wires that act as interconnect. The software tools allow users to quickly navigate design iterations for 3D printed parts that will include electronic functionality.

Process Development 10: Large Scale and Hybrid Processes

Wednesday PM — Room: 417A-B
August 9, 2017 — Location: Hilton Austin

Session Chair: Chad Duty, University of Tennessee

1:10 PM

Challenges in Making Metal Large-scale Complex Parts for Additive Manufacturing: A Case Study Based on the Additive Manufacturing Excavator (AME): *Andrzej Nycz*[1]; Mark Noakes[1]; Bradley Richardson[1]; Andrew Messing[1]; Brian Post[1]; Jonathan Paul[1]; Jason Flamm[2]; Lonnie Love[1]; [1]Oak Ridge National Laboratory; [2]Wolf Robotics

The AME, printed at The Manufacturing Demonstration Facility of ORNL, was presented at and performed a live demo during the CONEXPO 2017 exhibition. This paper presents challenges in building functional large-scale metal parts based on a case study of the excavator. The excavator's metal arm was 3D printed using a modified Wolf Robotics automated welding cell. Tasks included designing a new type of slicer for the metal AM process, integration of the slicing software with the robotics system, deposition process development, geometric feature characterization, material properties characterization, heat management, mechanical design for metal AM and machining approach to achieve the final part. Two fully functional excavator arms were printed and machined. Integrated hydraulics passageways that also served as structural stiffeners were included in the build for demonstration purposes. As a direct result of this project, the Wolf Robotics ArcZer0+ is now a commercially available metal AM system.

1:30 PM

Changing Print Resolution on BAAM via Selectable Nozzles: *Phillip Chesser*[1]; Brian Post[1]; Randall Lind[1]; Peter Lloyd[1]; Lonnie Love[1]; [1]Oak Ridge National Laboratory

Big Area Additive Manufacturing (BAAM) is an additive manufacturing (AM) technique that rapidly deposits polymer to fabricate large components. However, the increase in deposition rates leads to a decrease in resolution and a consequent decline in part surface finish. A novel technique has been developed where the nozzle diameter can be changed mid-print using a poppet valve. With this technique, a course resolution can be employed to rapidly grow the interior of a part, while a fine resolution can be used on the surface. This allows for an increase in surface quality and resolution without significantly increasing print time. Work is also being done to improve the quality of starts and stops of extrusions, as this is critical when using a small diameter nozzle. This work will explain the development of the dual port nozzle and integration with the BAAM system to produce high resolution parts.

1:50 PM

3D LSP: Tailoring Residual Stresses in Parts by Introducing Laser Shock Peening during Selective Laser Melting: *Nikola Kalentics*[1]; Eric Boillat[1]; Roland Logé[1]; [1]EPFL

One of the biggest limitations of parts made by Selective Laser Melting (SLM) are the high tensile residual stresses (TRS) that accumulate in the near surface region. They are known to have a detrimental effect on the mechanical properties and can even cause SLM process failure. Although a heat treatment can be applied for only a partial stress relieving after the part is made, it cannot introduce beneficial compressive residual stresses (CRS). The 3D LSP process is a novel approach for creating metallic parts with controlled residual stresses by introducing Laser Shock Peening (LSP) during the building phase of SLM. After a certain number of layers are made by SLM, the LSP process is applied and this sequence is repeated until the completion of the part. This approach leads to higher and deeper CRS in the subsurface of the produced part, with expected influence on the improved fatigue properties.

2:10 PM

Examination of Build Orientation and Its Impact on 316 Stainless Steel Dissolvable Supports: Christopher Lefky[1]; Abdalla Nassar[2]; Timothy Simpson[2]; *Owen Hildreth*[1]; [1]Arizona State University; [2]Pennsylvania State University

Support structures are an inconvenient necessity in most Powder Bed Fusion (PBF) printed stainless steel parts. They are used to reduce the effect of thermally induced strain and support overhangs often requiring post-print machining increasing the costs and time of production. Last year, our group introduced dissolvable metal supports for Powder Bed Fusion processed stainless steel. This process requires no change in build parameters and works by sensitizing the component surface during the normal post-print thermal annealing step. For this work, we examine the influences of build orientation on both sensitizing agent diffusion, microstructure evolution, etch rate, and final surface roughness. By studying the impact of building orientation on these important processing outputs, we hope to better control the final microstructure and roughness of parts with dissolvable metal supports.

2:30 PM

Expert Survey to Understand and Optimize Workpiece Orientation in Direct Metal Laser Sintering: *David Hoelzle*[1]; Hao Peng[2]; Morteza Ghasri Khouzani[3]; Shan Gong[3]; Ross Attardo[4]; Peter Ostiguy[4]; Bernice Aboud[4]; Joseph Budzinski[4]; Charles Tomonto[4]; Joel Neidig[2]; Ravi Shankar[3]; Richard Billo[5]; David Go[5]; [1]The Ohio State University; [2]ITAMCO; [3]University in Pittsburgh; [4]Johnson & Johnson□; [5]University of Notre Dame

The additive manufacturing (AM) process Direct Metal Laser Sintering (DMLS) can build complex metal structures. We believe that experts attempt to minimize the design metrics of support volume (V), support-to-part surface area (A), maximal cross-sectional area of the slicing planes (X), parallelism of part faces with the recoater blade (P), and part height (H). This manuscript details an interactive expert survey, the statistical analysis of the survey responses, and the synthesis of an automatic algorithm for part orientation based on survey data. Our analysis shows that the expert attempts to minimize metric V the most, metric X the second most, and metric H the third most; experts put essentially no weight on metrics A and P. The manuscript concludes with two orientation design studies with the automatic algorithm; both optimized parts printed without failure. In comparison, novice users required multiple attempts to print the parts without complete process failure.

2:50 PM Break

3:20 PM

Multi-robot Arc-based Additive Manufacturing for High Material Deposition Rates: *David Espalin*[1]; Philip Morton[1]; Cesar Terrazas[1]; Steven Ambriz[1]; Jose Coronel[1]; Chi Yen Kim[1]; Eric MacDonald[2]; Ryan Wicker[1]; [1]UTEP - W.M. Keck Center for 3D Innovation; [2]Youngstown State University

While the need for complex-shaped metal parts has driven developments in electron beam and laser powder bed fusion, higher material deposition rates and larger build sizes required in production applications are helping drive the development of directed energy deposition (DED) processes such as electron beam and arc-based welding. UTEP's previous experience with robotics and automation, hybrid (multi-process) AM, the LENS DED AM process, and active research in all seven ASTM process categories was leveraged to develop a multi-robot, arc-based AM system. Arc-based AM is the basis for exploring multi-robot, large-scale manufacturing with future plans on incorporating multiple methods such as powder-fed laser DED into the process. Arc-based AM is viewed by the authors as an economic entry point with relatively simple technical challenges due to the well-established industrial application of welding. The design of the system as well as processing parameters and their effect on fabrication results will be discussed.

3:40 PM

Fabrication of 3D Multi-material Parts Using Laser-based Powder Bed Fusion: *Christine Anstaett*[1]; Christian Seidel[1]; Gunther Reinhart[1]; [1]Fraunhofer IGCV

Laser-based powder bed fusion comes in and out of the focus of production technologies in an industrial environment as more and more materials are producible and industry from different branches uses this technology. One big advantage of LBM is the possibility to build very complex parts and therefor minimize the need of raw material. The effects of this aspect, like lightweight-design, resource-efficient production and reducing manufacturing time, can even be increased, if material can be used locally defined in a part so one part does not have to consist out of one material per fabrication-process but at least two. As LBM is a powder-bed-based process a realization of this idea is possible by adopting the conventional delivery device and the manufacturing process itself. In this paper results of a multi-material process are shown and the influences of different material properties on the manufacturing process are derived.

4:00 PM

Multi-process Advanced Manufacturing for 3D-printed Multi-functional Devices: *Jose Coronel*[1]; Steven Ambriz[1]; Chi Yen Kim[1]; Jaime Varela[1]; Angel Martinez[1]; Christopher Minjares[1]; Mireya Perez[1]; David Espalin[1]; Ryan Wicker[1]; [1]UTEP - W.M. Keck Center for 3D Innovation

Multiple manufacturing tools have been developed and incorporated into a five-axis motion system to enable the deposition and embedding of multiple materials including thermoplastics and copper wires/foils. The developed machine has capabilities of using a filament- and pellet-fed extruder for depositing a wide variety of thermoplastics. The inclusion of an automatic tool changer allows the system to quickly switch tools and execute complementary processes between printing steps. In addition to material extrusion tools, the machine contains tools for wire embedding, foil application, machine vision, machining, and robotic component placement. The development of the machine and its printed results will be discussed.

Process Development 11: Wire Processes and Ceramics

Wednesday PM	Room: 416A-B
August 9, 2017	Location: Hilton Austin

Session Chair: Chao Ma, Texas A&M University

1:10 PM

Cost Competitive Wire Arc Additive Manufacturing (WAAM): *Jonathan Hoffmann*[1]; Zachary Farque[1]; [1]Louisiana State University

Wire Arc Additive Manufacturing (WAAM) is an emerging field with strong candidacy for applications requiring near net shape manufacturing, high build rates, and reduced production costs. This study exhibits the capabilities of a WAAM machine that was designed and built for a minimal capital investment. This machine is capable of utilizing multiple arc-based metal transfer methods as well as printing with various wire materials. To demonstrate the machine's capabilities, parts were printed from low carbon steel using Gas Metal Arc Welding (GMAW). Mechanical testing, electron microscopy, and impact energy tests were performed on test coupons taken from each printed part. Finally, a demonstrator pressure vessel will be built and its performance compared to its conventionally manufactured counterparts. Further development of this field lies in exploration of build process optimization aimed at mitigating defects, residual stress, and distortion.

1:30 PM

Design of a Desktop Wire-feed Prototyping Machine: *Yu-Chuen Chang*[1]; Richard Crawford[2]; [1]The University of Texas at Austin ; [2]The University of Texas at Austin

Much additive manufacturing research focuses on systems suitable for industrial applications, especially research on metal processing. Our research aims to design a desktop-scale prototyping machine to process metal wire. Possible applications for this research include various wire structures, such as wire sculptures. The wire joining technology is the most important subsystem of the envisioned layer-based process. In this research, three concepts are proposed and analyzed according to the power required to fully melt the wire. The selected approach uses a wire bender to create the desired geometry of the product, and a pulse TIG welder to join the metal wire to retain the shape. Experiments were conducted to evaluate the joining strength of pulse TIG welds to verify the joining efficiency of the method. The experimental results indicate that filler metal is required to produce acceptable welding strength. A conceptual CAD model of the complete system is presented.

1:50 PM

Visual Sensing and Image Processing for Error Detection in Laser Metal Wire Deposition: *Adeola Adediran*[1]; Andrzej Nycz[1]; Lonnie Love[1]; [1]Oak Ridge National Laboratory

Laser metal deposition with wire (LMD-w) involves feeding metal wire through a nozzle and melting the wire with a high-power laser. With efficient process control, comprising sensing, processing and feedback correction of errors, the technology has a potential of changing the course of manufacturing. However, the limitation most often encountered in LMD is the difficulty in controlling the process. Monitoring and control of metal additive manufacturing processes has been mostly researched on powder-based systems, and has not yet been investigated to much extent on the side of metal wire feed arrangements. This work proposes a method for detecting cavities in a deposited layer in the LMD-w process via optical inspection and processing of images obtained from a high-resolution camera. The aim is to develop an effective sensing module which automatically detects discontinuities in each layer before proceeding to subsequent layers, to reduce part porosity and improve inter-layer bond integrity.

2:10 PM
Multi-sensor Investigations of Optical Emissions and Their Relations to DED Processes and Quality: *Christopher Stutzman*[1]; Abdalla Nassar[1]; Edward Reutzel[1]; [1]Penn State University

In-process monitoring of directed energy deposition (DED) additive manufacturing is a potential means for assessment of build conditions and deposition quality. However, a widely-accepted set of techniques have yet to emerge which link sensor outputs to processing conditions and, more importantly, build quality. This work tests the hypothesis that optical emissions from the laser-interaction zone of DED process, captured by a visible-light spectrometer, imaging camera(s), or selectively-filtered photodiodes, are not correlated with the generation of lack-of-fusion or porosity. Using results from simple DED builds under varying powers, powder flow rates, and hatching patterns, the hypothesis is negated by demonstrating that optical emissions are indeed correlated with both processing conditions and build quality.

2:30 PM
Fiber-fed Laser-melting Process for Printing Transparent Glass: *John Hostetler*[1]; Jonathan Goldstein[2]; Robert Landers[1]; Douglas Bristow[1]; Edward Kinzel[1]; [1]Missouri University of Science and Technology; [2]Air Force Research Labratory

This paper presents the Additive Manufacturing (AM) of glass using a fiber-fed process. Glass fiber with a diameter of 100 µm is fed into a laser generated melt pool. A CO2 laser beam is focused on the intersection between the filament and the work piece which is positioned on a four-axis CNC controlled stage. The laser energy at λ=10.6 µm is directly absorbed by the silica and locally heats the glass above the working point. By carefully controlling the laser power, scan speed, and feed rate, bubble free shapes can be deposited including trusses and basic lenses. Issues unique to the process are discussed, including the thermal breakdown of the glass, buckling of the fiber against an inadequately heated stiff molten region, and dimensional control when depositing viscous material.

2:50 PM Break

3:20 PM
Flash Laser Sintering of Ceramics: *Debbie Hagen*[1]; Joseph Beaman[1]; Desiderio Kovar[1]; [1]The University of Texas at Austin

Selective laser sintering (SLS) of ceramic powders is a difficult challenge due to high sintering temperatures and low fracture toughness inherent to ceramic materials. Use of polymer binders has enabled progress, but at the cost of long pyrolysis times. The recent development of the flash sintering process has shortened furnace sintering times of ceramics from approximately an hour to a few seconds when an electric field is applied to ceramic simultaneously with furnace heating. The hypothesis of this work is that flash sintering combined with laser heating will increase ceramic sintering kinetics and enable the SLS of ceramics. This novel additive manufacturing approach is called Flash Laser Sintering (FLS). The feasibility of sintering ceramic materials with Flash Laser Sintering is evaluated using a flash laser sintering machine designed and constructed at the University of Texas at Austin. The effects of process parameters on sintering quality are presented.

3:40 PM
Process Temperature Monitoring with Physics-based Compressive Sensing: *Yanglong Lu*[1]; Yan Wang[1]; [1]Georgia Institute of Technology

To reduce the number of sensors and costs associated with maintenance and data processing for manufacturing process monitoring, recently a physics-based compressive sensing (PBCS) approach was proposed to monitor temperature distribution in additive manufacturing. PBCS significantly improves the compression ratio from traditional compressive sensing by incorporating the knowledge of physical phenomena in specific applications. The volume of data and the number of sensors needed for monitoring can be significantly reduced. In this study, the PBCS approach is extended to consider the transient process of manufacturing where the dynamics of temperature field needs to be monitored. Three-dimensional thermal distributions in manufacturing processes can be efficiently sampled and reconstructed. The data collection can be reduced in both spatial and temporal domains. This new process monitoring approach is demonstrated with material extrusion processes.

4:00 PM
Alumina-zirconia Ceramics Fabricated by Ultrasonic Vibration-assisted Laser Engineered Net Shaping Process: *Yingbin Hu*[1]; Weilong Cong[1]; Xinlin Wang[1]; Fuda Ning[1]; [1]Texas Tech University

Alumina-zirconia ceramics have attracted a great amount of attentions due to their finer microstructure (such as grain size) and better mechanical properties, as compared with pure alumina and pure zirconia. As a laser additive manufacturing process, laser engineered net shaping (LENS) demonstrates benefits of fine controllability, small substrate deformation, and changeable powder mixture ratio, thus being competitive in direct fabrication of alumina-zirconia ceramics. Despite these advantages, LENS processed ceramics expressed severe problems resulted from inner defects (e.g. cracks, agglomerations, etc.). To reduce these problems, this paper presents a novel ultrasonic vibration (UV)-assisted LENS process for fabrication of bulk alumina-zirconia ceramics. Results show that the introduction of UV lead to the grain refinement of fabricated parts. In addition, the parts fabricated with UV exhibit better qualities than those fabricated without UV.

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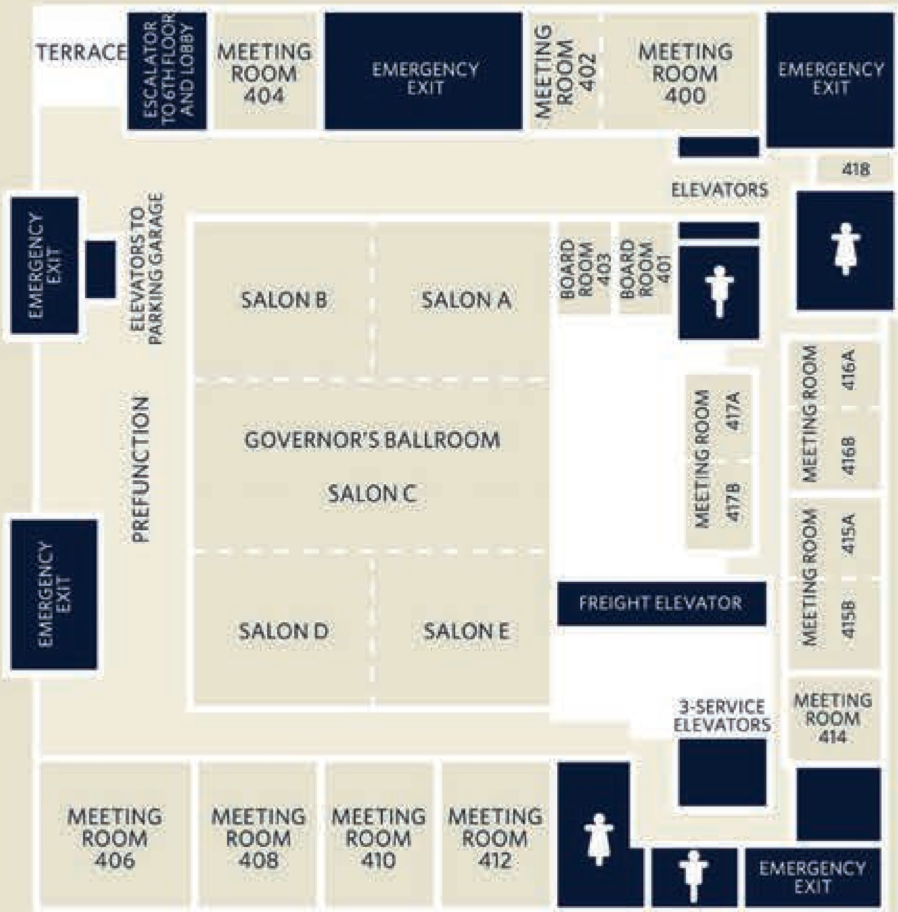

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