THE 32ND ANNUAL INTERNATIONAL VIRTUAL

SOLID FREEFORM FABRICATION SYMPOSIUM

– AN ADDITIVE MANUFACTURING CONFERENCE – 2021

August 2-4, 2021

FINAL PROGRAM

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:

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SCHEDULE AT-A-GLANCE

Wednesday, July 28, 2021		
Virtual platform access opens for registrants Poster presentations available to view on-demand		
Monday, August 2, 2021		
8:00 a.m. to 8:20 a.m.	Introduction	Live
8:20 a.m. to 11:00 a.m.	Plenary Presentations	Live
11:00 a.m. to 12:20 p.m.	FAME Presentations and Awards	Live
1:30 p.m. to 3:30 p.m.	Breakout Sessions	On-Demand
3:45 p.m. to 4:45 p.m.	Live "Zoom-Style" Q&A with Presenters	Live
6:30 p.m. to 8:00 p.m.	Networking Sessions	Live
Tuesday, August 3, 2021		
7:00 a.m. to 8:00 a.m.	Networking Sessions	Live
8:00 a.m. to 10:15 a.m.	Breakout Sessions	On-Demand
10:30 a.m. to 11:30 a.m.	Live "Zoom-Style" Q&A with Presenters	Live
12:00 p.m. to 1:30 p.m.	Student Panel Discussion	Live
1:30 p.m. to 3:30 p.m.	Breakout Sessions	On-Demand
3:45 p.m. to 4:45 p.m.	Live "Zoom-Style" Q&A with Presenters	Live
4:45 p.m. to 6:15 p.m.	Live "Zoom-Style" Q&A with Poster Presenters	Live
Wednesday, August 4, 2021		
8:00 a.m. to 10:15 a.m.	Breakout Sessions	On-Demand
10:30 a.m. to 11:30 a.m.	Live "Zoom-Style" Q&A with Presenters	Live
12:00 p.m. to 1:30 p.m.	Networking Sessions	Live
1:30 p.m. to 3:30 p.m.	Breakout Sessions	On-Demand
3:45 p.m. to 4:45 p.m.	Live "Zoom-Style" Q&A with Presenters	Live
Thursday, August 5 to Tuesday, August 31, 2021		
Virtual platform access continues for registrants		
Tuesday, August 31, 2021		
Virtual platform closes		

All SFF 2021 virtual events will take place in Central Daylight Time (UTC-5:00). Use a tool like the Time Zone Converter to translate event times into your local time zone.

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The symposium registration rate includes access to the virtual event from July 27 to October 31, 2021 and access to the post-conference proceedings in PDF ebook format.

For assistance with your registration, contact mtgserv@tms.org.

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TECHNICAL PROGRAM

TECHNICAL SESSION GRID - MONDAY AM

Time (CDT)	Plenary Session I
8:00 AM	Introductory Comments: David Bourell, University of Texas
8:20 AM	On Corrections of Global Shifts in Metal Additive Manufacturing: Subhrajit Roychowdhury, GE Global Research Center
8:45 AM	Live Q&A with Subhrajit Roychowdhury
8:50 AM	Design for the Additive Manufacturing Process Chain: David Rosen, Georgia Institute of Technology
9:15 AM	Live Q&A with David Rosen
9:20 AM	Reducing Heat Buildup and Regularizing Melt pool Dimensions in Laser Powder Bed Fusion through a “Powder Moat” Scan Strategy: Jack Beuth, Carnegie Mellon University
9:45 AM	Live Q&A with Jack Beuth
9:50 AM	Break
	Plenary Session II
9:55 AM	Mechanics of Additively Manufactured Metals: Effect of Stress State and Microstructural Features: Allison Beese, Pennsylvania State University
	Live Q&A with Allison Beese
10:25 AM	Multi- Material / Modality / Scale / Axis: Realizing Multi-Functional Products with Next-Generation AM Processes: Christopher Williams, Virginia Tech
10:50 AM	Live Q&A with Christopher Williams
10:55 AM	Break
	Plenary Session III: FAME Awards
11:00 AM	FAME Presentation: Understanding the Fatigue Behavior in Additive Manufacturing through Processing-Structure-Properties-Performance Relationships: Joy Gockel, Colorado School of Mines
11:25 AM	Live Q&A with Joy Gockel
11:30 AM	FAME Presentation: Metal Additive Manufacturing, Then and Now: Ola Harrysson, North Carolina State University
11:55 AM	Live Q&A with Ola Harrysson
12:00 PM	FAME Awards Presentation

TECHNICAL SESSION GRID - MONDAY PM

Time (CDT)	Applications -- Lattices and Cellular I	Broad Issues in AM -- I Economics, Emissions and I-DREAM4D	Materials -- Ceramics, Other I - Powder Bed Fusion	Materials -- Metals I - High Entropy Materials	Materials -- Metals II - Titanium Alloys	Modeling -- I Geometries and Supports
Session Chair	Cameron Turner, Clemson University	Shanshan Zhang, University of Texas Rio Grande Valley	Allison Beese, Pennsylvania State University	Frank Liou, Missouri University of Science and Technology	Edward Reutzel, ARL Penn State / CIMP-3D	Tsz Ho Kwok, Concordia University
1:30 PM	Design, Simulation and Experimental Investigation of 3D Printed Mechanical Metamaterials: Sunil Magadum, Central Manufacturing Technology Institute	Enabling Cost-based Support Structure Optimization in Laser Powder Bed Fusion of Metals: Katharina Bartsch, Hamburg University of Technology (TUHH)	Geometry Limitations of Indirect Laser Sintering of Alumina: Doug Sassaman, University of Texas Austin	A High Throughput Additive Manufacturing and Characterization Approach for Evaluating Structure-property Relationships in Multiphase High Entropy Alloys: Jonathan Pegues, Sandia National Laboratories	A Comparative and Experimental Study on the Effect of Heat Treatment Cycles for PBF Ti6Al4V: Evren Yasa, Eskisehir Osmangazi University	Investigation and Modeling of the Residence Time Dependent Material Degradation in the Arburg Plastic Freeforming: Felix Hecker, Paderborn University, Direct Manufacturing Research Center (DMRC)
1:45 PM	Effect of Voronoi Lattice Geometry on the Fatigue Performance of Ti-6Al-4V: Sinéad Uí Mhurchadha, SEAM Research Centre	A Hierarchy of Needs for Implementing Additive Manufacturing Across Industries: Callie Zawaski, Penn State	Selective Laser Flash Sintering: Processing Conditions: Deborah Hagen, University of Texas at Austin	Exploring the Structure-property Relationships of W_xCoCrFeMnNi Graded High Entropy Alloy: Jonathan Pegues, Sandia National Laboratories	Effects of Powder Reuse and Spatial Location Dependency on the Powder Characteristics and Defect Structure of Additively Manufactured Ti-6Al-4V Parts: Arash Soltani-Tehrani, Auburn University	Support Structure Geometry influences on Strength and Removability for LPBF AM: Samantha Welch, Penn State University
2:00 PM	A Comparative Study with the Topology Design of Cellular Mechanical Interface in a Bi-material Structure: Li Yang, University of Louisville	Characterization of Particles and Gases Released from Large-format Additive Manufacturing Machines during Extrusion of Multiple Polymers and Machining: Lauren Bowers, National Institute for Occupational Safety and Health	Characterization of n-type Bismuth Telluride Manufactured via Selective Laser Melting: Ryan Welch, The George Washington University	Exploring the Structure-property Relationships of (Ti, TiAl₆V₄)_xCoCrFeMnNi Graded High Entropy Alloy: Jonathan Pegues, Sandia National Laboratories	Effects of Stripe Width on the Porosity and Tensile Performance of Additively Manufactured Ti-6Al-4V Parts: Arash Soltani-Tehrani, Auburn University	Escaping Tree-support (ET-Sup): Minimizing Contact Points for Tree-like Support Structures in Additive Manufacturing: Tsz Ho Kwok, Concordia University
2:15 PM	Investigation of a Unit Cell Optimization Framework for Lattice Structures Based on Triply Periodic Surfaces: Joseph Fisher, The Pennsylvania State University	Evaluation of Real-time Particle and Chemical Emissions from Large-format Additive Manufacturing Machines: Elizabeth Arnold, National Institute for Occupational Safety and Health	Creating Conformable Lithium Batteries Using Selective Laser Sintering: Timothy Phillips, University of Texas Austin		Generation and Characterization of Parameter- and Process-induced Defects in Powder Bed Fusion Additive Manufacturing, and Impact of Mechanical Properties Thereof: Abdalla R Nassar, The Applied Research Laboratory	Truss-Type Support Structures for SLM: Subodh Subedi, University of Wisconsin Madison
2:30 PM	Dynamic Defect Detection in AM Parts Using FEA Simulation: Kevin Johnson, Michigan Technological University	I-DREAM4D: An Innovation Based Consortium Approach for Talent Preparation for Defense Manufacturing: Joseph Beaman, University of Texas At Austin	Investigating Thermally Induced Phase Separation as a Composite Powder Synthesis Technique for Indirect Selective Laser Sintering: Patrick Snarr, University of Texas at Austin		Evaluating the Efficacy of X-ray Computed Tomography for Flaw Detection in Laser Powder Bed Fusion Additive Manufacturing using Automated Optical Serial Sectioning: Zackary Snow, Pennsylvania State University	Watertight Geometric Modeling for the Additive Manufacturing Digital Thread: Ryan Jennings, Kansas City National Security Campus
2:45 PM	Characterizing and Designing for Geometry-dependent Material Properties in Direct Metal Laser Sintering: Carolyn Seepersad, University of Texas at Austin	Direct Selective Laser Synthesis of CuCrFeTiNiAl High Entropy Alloy from Elemental Powders through Selective Laser Melting: Joni Chandra Dhar, University of Texas Rio Grande Valley	Selective Laser Melting of Metal Cooling Devices onto Silicon: Arad Azizi, Binghamton University		Measurements and Predictions of Residual Distortion in AM Ti-6Al-4V Specimens: James Sobotka, Southwest Research Institute	Manufacturability Analysis of Crumple-formed Geometries Through Reduced Order Models: Olivia Trautschold, Oregon State University
3:00 PM	Characterizing and Designing for Geometry-dependent Material Properties in Direct Metal Laser Sintering: Carolyn Seepersad, University of Texas at Austin				Challenges during laser powder bed fusion of a near-alpha titanium alloy - Ti-6242Si: Sagar Patel, University of Waterloo	
3:15 PM						
3:30 PM	Break					
3:45 AM	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters

TECHNICAL SESSION GRID - MONDAY PM

Time (CDT)	Modeling -- I Melt Pools	Process Development -- I Novel Processes and Advances A	Special Session -- Composite AM I - Metals and Ceramics	Special Session -- Data Analytics in AM I - Optimization of Process, Design and Materials A	Special Session -- Design Methodologies for Tailoring Performance of Additively Manufactured Parts for Naval Applications	Special Session -- Wire-fed AM Processes I
Session Chair	Jack Beuth, Carnegie Mellon University	Christopher Pannier, University of Michigan Dearborn	Amy Elliott, Oak Ridge National Laboratory	Prahalad Rao, University of Nebraska	Ajit Achuthan, Clarkson University	Andrzej Nycz, Oak Ridge National Laboratory
1:30 PM	Controlling Interdependent Meso-nanosecond Dynamics and Defect Generation Using a Digital Twin: Saad Khairallah, Lawrence Livermore National Laboratory	In-situ Meltpool Monitoring and Temperature Estimation via Two-wavelength Pyrometry Using a Single Camera: Xiayun Zhao, University of Pittsburgh	Process Development for the Selective Laser Melting of Tungsten Carbide-nickel Matrix Composites: Edgar Mendoza Jimenez, Carnegie Mellon University	On the Diminishing Returns of Thermal Camera Resolution for PBF Temperature Estimation: Nathaniel Wood, the Ohio State University	A Dislocation Density Based Constitutive Model for the Design of Additively Manufactured (AM) Metals and Alloys: Ajit Achuthan, Clarkson University	Preparation and Characterization of Laser Direct Deposited Spinel Filaments for Wire-fed Additive Manufacturing of Transparent Ceramics: Xiangyang Dong, Missouri University of Science and Technology
1:45 PM	Modeling the Effects of Coordinated Multi-beam Laser Powder Bed Fusion on Melt Pool Geometry and Solidification Microstructure: Rachel Evans, Wright State Universtiy	Effect of Scan Strategy on Melt-pool Geometry, Surface Topology and Internal Porosity of Additively Manufactured Inconel 625 Alloy: Ho Yeung, National Institute of Standards and Technology	Development of Bimetallic Casting for Wear Performance through Infiltration of Additively Manufactured Metal Lattice Structures: James Chandler Liggett, Georgia Southern University	In-situ Thermographic Inspection for Laser Powder Bed Fusion: Tao Liu, Missouri University of Science and Technology	Microstructural Modeling of ß to a Transformation Morphologies in Multi-layered Laser Wire Additively Manufactured Ti-6Al-4V Parts: Andrew (Drew) Huck, Carnegie Mellon University	Recent Advances in Laser-wire Directed Energy Deposition: Novel Modes of Thermal Control and Site-specific Melt Pool Size Control: Brian Gibson, Oak Ridge National Laboratory
2:00 PM	3D Transient Zone in Conduction and Keyhole Mode Melting in Laser Powder Bed Fusion Process: Santosh Rauniyar, University of Louisville	A Numerical Study Showing the Impacts of Dwell Time during the Laser Powder Bed Fusion Process: David Failla, Mississippi State University	Microstructural Evolutions in Jetting Reinforcement Nanoparticles to Metal Matrix in Laser Powder Bed Fusion: Milad Ghayoor, Oregon State University	Towards Online Monitoring and Data-Driven Control: A Study of Segmentation Algorithms for Infrared Images of the Powder Bed: Alexander Nettekoven, University of Texas Austin	Evaluation of Liquid Doping Methods for Use in Laser Powder Bed Fusion: Nathan Crane, Brigham Young University	Development of a Laser Hot Wire Additive Manufacturing Process: Brandon Abranovic, Carnegie Mellon University
2:15 PM	Inference of Metal Additive Manufacturing Process States via Deep Learning Techniques: Mugdha Joshi, Missouri University of Science and Technology	Optical Observation of Sintering State for Large Area Projection Sintering (LAPS): Derek Black, Brigham Young University	Composition-processing-properties Relationships for In Situ Reinforced Ti-B4C-BN Composites via Directed Energy Deposition: Kellen Traxel, Washington State University Student	Droplet Diagnostics in Droplet-on-Demand Liquid Metal Jetting Using Heterogenous Sensing: Aniruddha Gaikwad, University of Nebraska-Lincoln	Influence of the Loading Direction on the Mechanical Properties of Additively Manufactured Metals: Ajit Achuthan, Clarkson University	Preliminary Efforts Using a Fe-10Ni Steel for Wire Arc Additive Manufacturing: Evan Handler, Naval Surface Warfare Center
2:30 PM	Thermomechanical and Geometry Model for Directed Energy Deposition with 2D/3D Toolpaths: Deniz Ertay, University of Waterloo	Improving the 3D Printed Bond Strength at a Discrete Interface Between Dissimilar Materials: Chad Duty, University of Tennessee	Laser Powder Bed Fusion of Highly-reinforced Metal Matrix Composites: Ethan Parsons, Massachusetts Institute of Technology	Deep Learning Assisted Approach to Monitoring Anomalies of 3D-bioprinting Process: Zeqing Jin, University of California, Berkeley	Effect of Composition and Phase Diagram Features on Printability and Microstructure in Laser Powder Bed Fusion: Development and Comparison of Processing Maps Across Alloy Systems: Raiyan Seede, Texas A&M University	In-situ Microstructural Transformations in Wire-arc Additively Manufactured Maraging 250-grade Steel: Sneha Prabha Narra, Carnegie Mellon University
2:45 PM			Study of Printing Parameters in Binder Jet Additive Manufacturing of Cobalt Chrome - Tricalcium Phosphate Biocomposite: John Ruprecht, Minnesota State University Mankato	Bayesian Process Optimization for Additively Manufactured Nitinol: Jiafeng Ye, Auburn University		
3:00 PM			Conformal Multifunctional Composite Fabrication via Conductive Direct Ink-write and Sacrificial Additively Manufactured Tooling: Jacob Viar, Virginia Tech	Multi-modal In-situ Monitoring Data Analysis for Overhang Features Built with Laser Powder Bed Fusion: Ndeye Yande Ndiaye, NIST		
3:15 PM				In-situ Verification of 3D-Printed Electronics Using Deep Convolutional Neural Networks: Daniel Ahlers, Universität Hamburg		
3:30 PM	Break					
3:45 AM	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters

TECHNICAL SESSION GRID - TUESDAY AM

Time (CDT)	Applications -- General I	Applications -- Lattices and Cellular II	Materials -- Ceramics, Other II - Glass, Extrusion and Direct Write	Materials -- Metals III - Novel Innovations	Materials -- Metals IV - Ferrous	Materials -- Polymers I - Overview and Photopolymers
Session Chair	Amy Peterson, University of Massachusetts Lowell	Tim Simpson, Pennsylvania State University	Saniya Leblanc, George Washington University	Christopher Tuck, University of Nottingham	Abdalla Nassar, Applied Research Lab, Pennsylvania State Univ	David Rosen, Georgia Institute of Technology
8:00 AM	Optimization of a Worm Gear Assembly Design for Additive Manufacturing: Detlev Borstell, Koblenz University of Applied Sciences	Machine Learning Derived Graded Lattice Structures: Jier Wang, Imperial College London	Processing of Soda-lime Glass In Laser-based Powder Bed Fusion: Christopher Singer, Fraunhofer Institute for Casting, Composite, and Processing Technology IGCV	Development of Effective Powder Layer Thickness for Different Materials and Process Conditions: Theresa Hanemann, Karlsruhe Institute of Technology	A Combinatorial Approach of Alloy Modification and Heat Treatment Strategies, Towards a Tailored Microstructure with Improved Mechanical Properties of Hot Work Tool Steel: Iris Raffeis, RWTH Aachen University	Evaluating the Effect of Z-pinning parameters on the Mechanical Strength and Toughness of Printed Polymer Composite Structures : Brenin Bales, University of Tennessee
8:15 AM	Laser Sintering Design Guidelines for media transmitting Components: Ivo Kletetzka, Paderborn University (DMRC)	Identification of Defects in Additively Manufactured Microlattices: Jean Baptiste Forien, Lawrence Livermore National Laboratory	Methodology for Determining Design Rules for Helical Channels in Glass Components Produced via Selected Laser Sintering: Desiderio Kovar, The University of Texas at Austin	Towards a Defect-based Process Map: Anthony Rollett, Carnegie Mellon University	Fatigue Properties of 3D Printed Maraging Steel: Nandhini Raju, UCF	Additive Manufacturing of Magneto-active, Shape Programmable Thermoset Composite Laminates via Reactive Extrusion: Oliver Uitz, The University of Texas at Austin
8:30 AM	Utilizing Additive Manufacturing in Thermoacoustic Refrigeration-based Atmospheric Water Generation: Zaid Almusaied, Texas State University	Effect of Material Anisotropy on Static Mechanical Properties of Cellular Structures Fabricated via Electron Beam Powder Bed Fusion Additive Manufacturing: Li Yang, University of Louisville	Adaptive Aperture for Accelerating Extrusion Additive Manufacturing: Concept Design and Toolpath Generation: Maxwell Micali, University of California, Berkeley	Particle-Melt Pool Interactions in Multi-Material Laser Based Directed Energy Deposition: Ronald Sellers, Texas A&M University	Mechanical Properties of 304L Stainless Steel Parts Fabricated by Laser Foil Printing: Chia-Hung Hung,	Fracture Behavior of Amorphous and Semi-crystalline FDM Polymer Materials Under Plane Stress and Plane Strain Conditions: Implications for Material Structure Design: Albert Patterson, University of Illinois at Urbana-Champaign
8:45 AM	Design and Performance of a Novel AlSi10Mg Vapor Chamber Fabricated via Laser Powder Bed Fusion: Christopher M. Bailey, Kansas State University	A Study of Process Parameters and Mechanical Performance of Lattices Using Powder Bed Fusion of Stainless Steel 316L: Scott Jensen, Sandia National Lab	Fabricating Silicon Nitride Parts Using the Ceramic On-Demand Extrusion (CODE) Process and Pressureless Sintering Method: Sachin Choudhary, Missouri University of Science & Technology	Spatial Inhomogeneity of Build Defects Across the Build Plate in Laser Powder Bed Fusion: Terrence Moran, Cornell University	Investigation of Mechanical Properties of Parts Fabricated with Gas- and Water-atomized 304L Stainless Steel Powder in the Laser Powder Bed Fusion Process: M. Hossein Sehhat, University of Missouri, Science and Technology	Feasibility Study on Digital Light Processing of Metamaterials with Nested Structures: Ankit Saxena, Penn State
9:00 AM	Additively Manufactured Inconel 718 Wicking Structures: Adnen Mezghani, Pennsylvania State University	Shock Impact Response and Simulation of Lattice Structures: Bradley Jared, University of Tennessee, Knoxville	Ceramic On-demand Extrusion (CODE) of Zirconium Diboride: Austin Martin, Missouri University of Science and Technology	Analysis of Horizontally Graded Titanium-Tantalum Using Laser Powder Bed Fusion Additive Manufacturing: Cherish Lesko, Wright State University	Strain Energy Approach to Estimating Stress-life and Strain-life Behavior of Additive Manufactured Austenitic Stainless Steels: Jonathan Pegues, Sandia National Laboratories	Improving Vat Photopolymerization Part Performance via Thermally Activated Bond Exchange: Daniel Rau, Virginia Tech
9:15 AM	Robotic Applications of Mechanical Metamaterials Produced Using SLA 3D Printing: Cthulhu-Morphic Grippers: William Yerazunis, Mitsubishi Electric Research Laboratories	Ceramic Chain Lattices for Energy Absorption Under Tensile Loading: Spencer Taylor, Massachusetts Institute of Technology	Dry Aerosol Deposition of Silicate Coatings on Space Relevant Polymeric Substrates: Robert Calvo, New Mexico Institute of Mining and Technology	Pressure Control During Bronze Infiltration of Binder-Jet Printed Stainless-Steel to Create Metal Microchannels: Henry Davis, Brigham Young University	Analysis of Residual Stress Reduction of in situ Annealed LPBF 316L Stainless Steel: William Smith, Lawrence Livermore National Lab	
9:30 AM	Simulation of the Laser-powder Bed Fusion Process for Determining the Effects of Part-to-Substrate Location and Orientation on Distortion in a Connecting Rod: Scott Thompson, Kansas State University	Incorporating Metal Additive Manufacturing-produced Material Properties in Design by Topology Optimization: Yeming Xian, Georgia Institute of Technology	Dry Aerosol Deposition of Barium Neodymium Titanate Dielectric Ceramic: Alex Valdez, New Mexico Institute of Mining and Technology	Investigation of Machinability of Additively Manufactured Metal Alloys: Jay Raval, Texas A&M University	Analysis of Residual Stress Reduction of <I>In Situ</I>-Annealed AM 316L Stainless Steel: William Smith, Lawrence Livermore National Lab	
9:45 AM	Pitch Imperfect: Designing 3D Printed Claves to Mimic the Sound of Their Wooden Counterparts: Emmeline Evans, The Pennsylvania State University	Topology Optimization of a Multi-material, Thin Walled Structure for Wire-arc Additive Manufacturing: Eduardo Miramontes, University of Tennessee, Knoxville		Methods of Automating the Laser-Foil-Printing Additive Manufacturing Process: Tunay Turk, Missouri University of Science and Technology	An Initial Evaluation of Process-property Relations for FDM produced 316L Stainless Steel: Frank Brinkley, Mississippi State University	
10:00 AM				Selective Binder Jetting: Enhancing Part Quality through Fabrication of Shelled Geometries: Kazi Moshiur Rahman, Virginia Tech		
10:15 AM	Break					
10:30 AM	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters

TECHNICAL SESSION GRID - TUESDAY AM

Time (CDT)	Modeling -- II Thermal Aspects A	Modeling -- II Toolpaths and Scanning Strategies	Process Development -- II Melt Pool Imaging	Special Session -- Composite AM II - Polymers A	Special Session -- Data Analytics in AM II - Optimization of Process, Design and Materials B	Special Session -- Wire-fed AM Processes II
Session Chair	Douglas Bristow, Missouri Univ of Science and Technology	Brian Post, Oak Ridge National Laboratory	Jason Fox, National Institute of Standards and Technology	Mehran Tehrani, University of Texas at Austin	Brandon Lane, National Institute of Standards and Technology	Sneha Prabha Narra, Carnegie Mellon University
8:00 AM	Crystal Plasticity Model of Micro-scale Residual Stress in Additive Manufacturing: Daijun Hu, National University of Singapore	A Novel Knowledge-based Toolpath Constructive Approach for Designing High-precision Graded Lattice Structures: Zhiping Wang, Ecole Centrale de Nantes	Pseudo Melt Pool Thermal Feature Construction for In-situ Thermography of Laser Powder Bed Fusion: Cody Lough, Missouri University of Science and Technology	State of the Art and Technology in Additively Manufactured Polymer Composites: Mehran Tehrani, University of Texas at Austin	Physics-informed and Hybrid Machine Learning in Additive Manufacturing: Berkcan Kapusuzoglu, Vanderbilt University	Fused Filament Fabrication on the Moon: Jie Zhang, KU Leuven
8:15 AM	Evaporation Model for Keyhole Dynamics during Additive Manufacturing of Metal: Lu Wang, National University of Singapore	Tool Path Generation and Optimization for Hybrid Additive Manufacturing: Zhen Hong, Ecole Centrale Nantes	Closed-loop Control of Meltpool Temperature in Directed Energy Deposition: Benjamin Bevans, University of Nebraska-Lincoln	Analysis of Fiber Orientation and Concentration in Large Scale Polymer Composite Deposition of Carbon Fiber-reinforced Thermoplastics: Neshat Sayah, Baylor university	Autonomous Multimodal Manufacturing Optimization: Brian Giera, Lawrence Livermore National Laboratory	Wire Arc Additive Manufacturing of Low Carbon Steel for Casting Applications: Eric Weflen, Iowa State University
8:30 AM	High-fidelity Modelling of Thermal Stress for Additive Manufacturing by Linking Thermal-fluid and Mechanical Models: Fan Chen, National University of Singapore	A Roadmap Towards Parallel Printing for Desktop 3D Printers : Chandrakana Nandi, Paul G. Allen School of Computer Science & Engineering	A Novel Non-destructive Testing Method for Powder Bed Fusion Processes in Laser-based Additive Manufacturing: Nicholas S Tomasello, Binghamton University	Correlating Large-scale AM Print Parameters to Fiber Length and Mechanical Performance of Reinforced Polymer Composites: Andrew Rhodes, University of Tennessee	Correlating the Effect of Part Geometry and Support Structure on Thermal History in Laser Powder Bed Fusion: Reza Yavari, University of Nebraska	Printing of Metal Droplet Streams Using Continuous Breakup of a Laser Heated Metal Wire: Kaihao Zhang, Massachusetts Institute of Technology
8:45 AM	Integrated Multi-physics Modeling of Process-structure-property in Additive Manufacturing: Wentao Yan, National University of Singapore	Adaptive Toolpath Planning for Additive Manufacturing through Reduced-order Physical Simulation: Maxwell Micali, University of California, Berkeley	A Data Integration Framework for Additive Manufacturing Big Data Management: Milica Perišic, The University in Belgrade	Characterizing the Internal Morphology of Transition Regions in Large-scale Extrusion Deposition Additive Manufacturing : James Brackett, Univ of Tennessee Knoxville	Data Models for Analytics and Machine Learning in Additive Manufacturing: Paul Witherell, NIST	Data Acquisition in Wire-arc Additive Manufacturing: The Road to Digital Twin: William Carter, Oak Ridge National Laboratory
9:00 AM	Development of a Simulation Model of a Radiation-based Print Heating System for Fused Deposition Modeling: Cameron Turner, Clemson University	Model-based Toolpath Control for Direct Ink Write Additive Manufacturing: Matthew Hildner, University of Michigan	In Situ Synchrotron X-ray Imaging of Directed Energy Deposition of Metals: The Performance Comparisons Between Irregular and Spherical Powders: Hui Wang, Texas A&M University	Modeling Inter-layer Bonding in Additive Manufacturing of Continuous Fiber Reinforced Polymer Composites: Anahita Emami, The University of Texas at Austin	Optimization of Support Geometry for Powder Bed Fusion: A Generative Approach : Mugdha Joshi, Missouri University of Science and Technology	A Multi Robot Coordinated-motion Approach to Large Scale Deposition Systems – MedUSA: Andrzej Nycz, Oak Ridge National Laboratory
9:15 AM	Thermal Modeling of Fiber Optic Embedment in Metal Additive Manufacturing: Elias Snider, Missouri University of Science and Technology	ORNL Slicer 2.0: Towards a New Slicing Paradigm: Michael Borish, Oak Ridge National Laboratory		Understanding Filler Orientation in Material Extrusion Additive Manufacturing of Thermoset Composites: Nadim Hmeidat, University of Tennessee, Knoxville	Quality Assurance in Biomaterial Aerosol Jet Printing Using Machine Learning: Sam Gerdes, University of Nebraska-Lincoln	Defining Robotic Torch Parameters for Non-gravity Aligned (NGA) Metal Additive Manufacturing Using CAD to Part Framework: James McNeil, University of Tennessee-Knoxville
9:30 AM	Thermal Modeling in Additive Manufacturing Using Graph Theory – Validation with In-situ Thermography Measurements for a Large Impeller Part made Using Laser Powder Bed Fusion: Prahalad Rao, University of Nebraska	Expanding Process Space of Laser Powder Bed Additive Manufacturing Using Alternative Scan Strategies: Elizabeth Chang-Davidson, Carnegie Mellon University		A Comparative Study of Extrusion Deposition of Long and Continuous Carbon Fiber Reinforced Composites for Large-scale Additive Manufacturing: Xiangyang Dong, Missouri University of Science and Technology	Analyzing Remelting Conditions Based on In-Situ Melt Pool Data Fusion for Overhang Building in Powder Bed Fusion Process: Zhuo Yang, University of Massachusetts Amherst	Towards a Digital Twin: 4D Data Conditioning for Metal Inert Gas Big Area Additive Manufacturing: Christopher Masuo, Oak Ridge National Laboratory
9:45 AM	Thermal Modeling in Additive Manufacturing Using Graph Theory: Validation with Directed Energy Deposition : Reza Yavari, University of Nebraska	An Efficient Layer Construction Method to Generate Accurate Printing Toolpaths of Periodic Cellular Structures for Selective Laser Melting Process: Shujie Tan, Nanjing University of Aeronautics & Astronautics		Additive Manufacturing of a Carbon Fiber Reinforced Thermoset Resin via Reactive Extrusion Additive Manufacturing (REAM): Pratik Koirala, University of Texas at Austin		
10:00 AM	Thermal Modeling, Bead Parameterization, and Toolpath Analysis of Material Extrusion Additive Manufacturing: Amy Peterson, University of Massachusetts Lowell	Support-free Hollowing for 3+2-Axis Additive Manufacturing: Lufeng Chen, University of Electronic Science and Technology of China		Predictions of the Elastic-plastic Compressive Response of Functionally Graded Polymeric Composite Lattices Manufactured by 3D Printing: Ajit Panesar, Imperial College London		
10:15 AM	Break					
10:30 AM	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters

TECHNICAL SESSION GRID - TUESDAY PM

Time (CDT)	Applications -- General II	Broad Issues in AM -- II Robotics, Security and Digitalization	Materials -- Ceramics, Other III - Jetting and DED	Materials -- Metals V - Precious Metals, Copper, Tungsten, Co-Cr	Modeling -- III Thermal Aspects B	Modeling -- IV Mechanical Properties
Session Chair	David Hoelzle, Ohio State University	Navin Sakthivel, Baker Hughes, A GE Company	Xiangyang Dong, Missouri Univ of Science and Technology	Anthony Rollett, Carnegie Mellon University	Robert Landers, Missouri Univ of Science and Technology	Jeffrey Lipton, University of Washington
1:30 PM	Free Standing 3D Piezoelectric PVDF Sensors via Electrowriting: Kranthi Kumar Reddy Bannuru, Singapore University Of Technology And Design	Impact of 3D Printing in Rapid Evolution of Competitive Robotics Such as World Robotics League: Rajeev Dwivedi, STEM and Robotics Academy	Inkjet Printing Graphene for Devices: From Contacts to Functional Layers: Feiran Wang, University of Nottingham	New Gold Conductive Ink Formulation with Enhanced Cohesion for Material Jetting: Jisun Im, Centre for Additive Manufacturing/University of Nottingham	Non-orthogonal Adiabatic Boundaries in Semi-analytical Laser Powder Bed Fusion Simulations Using Machine Learning: Christian Gobert, Carnegie Mellon University	Coupled Phase-field and Crystal Plasticity Modelling to Investigate the Process-structure-property Relationship of Heat Treatment for Additive Manufactured Alloys.: Yuhui Tu, National University of Ireland, Galway
1:45 PM	A Methodology for the Embedding of Sensors in Components Manufactured Using Metal Laser Powder Bed Fusion: Italo Tomaz, I-Form Advanced Manufacturing Research Centre	Impact of Solid Freeform Fabrication in Enabling Design and Prototyping Capabilities for Competitive Robotics such as World Robotics League, FTC, FRC, WRO etc. : Rajeev Dwivedi, STEM and Robotics Academy	Ceramic Binder Jetting Additive Manufacturing: Effects of Granulation on Properties of Feedstock Powder and Printed and Sintered Parts: Guanxiong Miao, Texas A&M University	Directed Energy Deposition Additive Manufacturing of Nickel Aluminum Bronze: Temperature Dependent Properties for Predicting Distortion: Glenn Hatala, Penn State University	Part-scale Thermal FEA Modeling and Experimental Validation of Laser Powder Bed Fusion: Chao Li, Autodesk Inc.	Multiscale Modeling of Plasticity for Laser Powder Bed Fusion Stainless Steel with Tailored Crystallographic Texture: Xinyu Yang, I-Form, the SFI Research Centre for Advanced Manufacturing
2:00 PM	Additively Manufactured ALSi10Mg Thin Fins via Laser Powder Bed Fusion: A Parametric Analysis: Adnen Mezghani, Pennsylvania State University	Development Testing and Prototyping Varying Robot Architectures Using Solid Freeform Fabrication for World Robotics League: Rajeev Dwivedi, STEM and Robotics Academy	Binder-free Additive Manufacturing of Ceramics Using Hydrothermal-assisted Transient Jet Fusion: Fan Fei, University of Iowa	Laser Powder Bed Fusion Additive Manufacturing of Copper Vapor Chambers: Adnen Mezghani, Pennsylvania State University	Predicting Part Distortion and Recoater Crash in Laser Powder Bed Fusion Using Graph Theory: Humaun Kobir, University of Nebraska-Lincoln	On the Applicability of Internal State Variable Plasticity Models for Metal-based Additive Manufacturing: Matthew Dantin, Mississippi State University
2:15 PM	Electrodeposition on 3D Printed Carbon MEMS: Joshua Tyler, Oak Ridge Associated Universities	Sabotage Attacks in Metal Additive Manufacturing at the Layer Granularity: Patricio Carrion, Auburn University	Direct-writing SiC with Micro-cold Spray: Particle Agglomeration Dependence on Film Density: Derek Davies, Uniiversity of Texas at Austin	Characterization of Copper Coupons Made via Laser Powder Bed Fusion : Pouria Khanbolouki, The University of Texas at Austin	Numerical Prediction of Thermal Histories and Residual Stresses for Directed Energy Deposition (DED) Powder-blown Process: Jakub Mikula, A*STAR	Modified Gibson-Ashby Model for Stiffness Prediction of Defective Lattices: Panwei Jiang, Pennsylvania State University
2:30 PM	Support Structure Reduction Approach by Geometry and Process Parameter Modification Based on AM Ontology and Optimization Procedure: Sang-in Park, Incheon National University	Additive OS: An Open-Source Platform for Additive Manufacturing Data Management & IP Protection: Evan Diewald, Carnegie Mellon University	Direct 3D Printing of Transparent Spinel Ceramics via One-step Laser Direct Deposition: Xiangyang Dong, Missouri University of Science and Technology		Experiment Based Superposition Thermal Modeling of Laser Powder Bed Fusion: Cody Lough, Missouri University of Science and Technology	
2:45 PM		Digital Twin Configuration Management for Additive Manufacturing Supply Chain Workflow: Paul Witherell, NIST			Development of Temperature History Profiles for Production of Ti-6Al-4V Using a 1D Layer Model: Anthony Rollett, Carnegie Mellon University	
3:00 PM						
3:15 PM						
3:30 PM	Break					
3:45 AM	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters

Time (CDT)	Process Development -- III Stereolithography and Jetting	Process Development -- IV Directed Energy Deposition and Laser Powderbed Fusion	Special Session -- Composite AM III - Polymers B	Special Session -- Hybrid AM Processes I - Electronics and Polymers	Special Session -- Volumetric AM
Session Chair	Nathan Crane, Brigham Young University	Denis Corier, Rochester Institute of Technology	Iris Rivero, Rochester Insititute of Technology	Michael Sealy, University of Nebraska Lincoln	Carolyn Seepersad, University of Texas Austin
1:30 PM	Static Liquid Interface to Reduce Support Structure Necessity in Top-down Stereolithography: Nicholas Mulka, Georgia Institute of Technology	Vibration-actuated Powder Dispensing for Directed Energy Deposition Systems: Andrew Greeley, Rochester Institute of Technology	Low Density Mechanical Metamaterial Using DLP-based 3D Printing: Darshil Shah, University of Massachusetts Lowell	Effects of In-Situ Mechanical and Chemical Polishing on Surface Topography of Additively Manufactured Fiber-Reinforced Polymers: Aman Nigam, Texas A&M University	Investigation of Mechanical Properties of Structures Fabricated by Continuous Volumetric Photopolymerization Based 3D Printing: Yizhen Zhu, Arizona State University
1:45 PM	Development of a Variable Tensioning System to Reduce Separation Force in Large-scale Stereolithography: Hongtao Song, The University of Texas at Austin	Thermal History of Pore Formation in Laser Assisted Direct Metal Deposition Using In-situ High Speed X-ray and IR Imaging: Karan Kankaria, Texas A&M University	3D Printing of Structural Battery Composites with Continuous Carbon Fibers: Xiangyang Dong, Missouri University of Science and Technology	Mechanical Behavior of ABS after Interlayer Ultrasonic Peening during Fused Filament Fabrication: Manon Guivier, University of Nebraska-Lincoln	Progress in Photopolymer Resin Development for Volumetric Additive Manufacturing: Maxim Shusteff, Lawrence Livermore National Lab
2:00 PM	Binder/Powder Interaction in Binder Jetting: From Lines to Layers: Nathan Crane, Brigham Young University	Effect of Powder Velocity on Porosity Formation in Directed Energy Deposition: Samantha Webster, Northwestern University	Additive Manufacturing of Neat and Carbon Fiber Reinforced PAEK Polymers: Timothy Yap, The University of Texas at Austin	Integrating a Direct Ink Write and Mask-projection Vat Photopolymerization System to Enable Additive Manufacturing of High Viscosity Photopolymer Resins: Daniel Rau, Virginia Tech	Dopant Patterning for Volumetric Sintering via RF Heating: Jared Allison, The University of Texas at Austin
2:15 PM	Understanding the Effects of Driving Signal for Piezoelectric Inkjet Printing: Chao Sui, University Arkansas	Powder Capture Efficiency Monitoring with In-situ, 3D, Surround Digital Image Correlation in Directed Energy Deposition Additive Manufacturing: James Haley, Oak Ridge National Laboratory	Thermomechanical Properties of a Glass and Carbon Nanofilled Photopolymer Composite Additively Manufactured via Stereolithography: Cameron E. Weeks, Kansas State University	Integrating Digital Light Processing with Direct Ink Writing for Hybrid 3D Printing of Functional Structures and Devices: Xirui Peng, Georgia Institute of Technology	Selective Doping of Composites Using Piezoelectric Printheads: Ali Sohaib, University of Nottingham
2:30 PM	Stress Shielding Effect during Compaction of a Selectively Variant Powder Bed in Hydrothermal-assisted Jet Fusion of Ceramics: Levi Kirby, University of Iowa	Multi-track Geometry Prediction in Laser Additive Manufacturing Using Machine Learning: Lucas Botelho, University of Waterloo	Finite Element Modelling of the Fused Filament Fabrication Additive Manufacturing: Sarah Clark, The University of Texas at Austin	Mechanical Interface for Iterative Hybrid Additive/Subtractive Manufacturing: Eric Weflen, Iowa State University	Adaptive Voxelization for Computed Axial Lithography: Kevin Coulson, University of California, Berkeley
2:45 PM	Use of Wire Grid Polarizers with Liquid Crystal Display for Large Volume Stereolithography: Nicholas Rodriguez, The University of Texas at Austin	Laser Powder Bed Fusion of Stainless Steel 316L Using a Flexible Dual Fiber Laser Array: Tim Lantzsch, Fraunhofer Institute for Laser Technology ILT	Additive Manufacturing of Carbon Fiber Reinforced Polymer Composite via Reactive Extrusion: Pratik Koirala, University of Texas at Austin	High Resolution, High Conductivity Components by Aerosol Jet Printing and Electrodeposition: Lok-kun Tsui, University of New Mexico	
3:00 PM		Laser-material Interactions in LPBF, Visualised through Optical and X-ray High-speed Imaging: Ioannis Bitharas, Heriot-Watt University	Recycling Carbon Fiber Filled Acrylonitrile-Butadiene-Styrene for Large Scale Additive Manufacturing : Roo Walker		
3:15 PM			Design and Manufacture of Continuous Fiber-Reinforced 3D Printed Unmanned Aerial Vehicle Wing: David Rosen, Georgia Institute of Technology		
3:30 PM			Break		
3:45 AM	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters

TECHNICAL SESSION GRID - TUESDAY POSTERS Q&A

	Poster Session on General AM		Poster Session on Materials		Poster Session on Process Development
Eric MacDonald, University of Texas El Paso					
	Live Zoom Q&A with Presenters: 4:45 to 5:15 PM (CDT)		Live Zoom Q&A with Presenters: 5:15 to 5:45 PM (CDT)		Live Zoom Q&A with Presenters: 5:45 to 6:15 PM (CDT)
Available On Demand	Additive Manufacturing of Cu on 316L Stainless Steel via Inconel 718 Intermediate Layers: Xinchang Zhang, Idaho National Laboratory	Available On Demand	Additive Manufacturing of Cu-Ni-Tool Steel Multi-metallic Structures: Xinchang Zhang, Idaho National Laboratory	Available On Demand	Effects of Centrifugal Disc Finishing for Surface Improvements in Additively Manufactured Gears: Foxian Fan, Penn State University
	Voxel-based Damage Reconstruction and Its Application for Component Repair Using Additive Manufacturing: Xinchang Zhang, Idaho National Laboratory		Large Area Projection Sintering of Chocolate: Clinton Abbott, Brigham Young University		Quantification of the Effects of Deposition on Spatter Formation and Dynamics in Laser Powder Bed Fusion via Dynamic X-ray Radiography: Sneha Prabha Narra, Carnegie Mellon University
	Additive Manufacturing of Two-phase Lightweight, Stiff and High Damping Carbon Fiber Reinforced Polymer Microlattices: Zhenpeng Xu,		Rheological Scaling and Modulation to Improve the Extrudability of Metal Filament by Fused Filament Fabrication: AMM HASIB, Arizona State University		Enabling Deposition of Removable Support Structures in Large-format Material Extrusion: Joseph Kubalak, Virginia Tech
	Thermal Modeling in Additive Manufacturing Using Graph Theory: Validation with Laser Powder Bed Fusion for a Large Impeller Part: Reza Yavari, University of Nebraska		Inspection and Detection of Porosity in Additively Manufactured Parts with Different Geometries: Sabrina D'Alesandro, Wright State University		Closed-Loop Control of Meltpool Temperature in Directed Energy Deposition: Benjamin Bevans, University of Nebraska-Lincoln
	Variable Hysteresis of Pantographic Lattices: Zachary Romanick, Clemson University		Influence of Process Conditions on the Thermal Conductivity of Selective Laser Melted AlSi10Mg: Jacob A Goodman, Binghamton University		A Review of Wire-fed AM Process Monitoring and Data Analytics: Matthew Roach, University of Tennessee, Knoxville
	Scan-by-Scan Part-Scale Thermal Modelling for Defect Prediction in Metal Additive Manufacturing: Terrence Moran, Cornell University		Directed Energy Deposition of Stellite 21 Hardfacing Coatings: Ziyad Smoqi, University of Nebraska-Lincoln		On Ultrasound Powder Stream Focusing and Applications to Powder-fed Laser Directed Energy Deposition: Alexander Martinez-Marchese, University of Waterloo
	Towards the Residual Stress Prediction in Wire Arc Additive Manufactured Parts Using a Finite Element Thermomechanical Model: Matthew Register, Center for Advanced Vehicular Systems		Effect of Build Parameters on the Material Properties of Printed Parts Produced by Multi-jet Fusion: Andrew Chen, University of California, Berkeley		Cost Analysis of Metal Additive Manufacturing via FDM Desktop 3D Printers: Jeffery Betts, Mississippi State University
	Aerosol Jet® Printing on Fiber-based Paper Substrates for Smart-packaging: Akash Verma, KU Leuven		Processing of In Situ Titanium Metal Matrix Composites via Directed Energy Deposition and Selective Laser Melting: Kellen Traxel, Washington State University Student		Controlling Powder Bed Cohesion in Binder Jetting (BJ): Colton Inkley, BYU
	Detecting Layerwise Build Defects Using Low-cost Imaging and Machine Learning: Devon Goodspeed, University of Tennessee, Knoxville		Lattice Infill Pattern Design for Increased Green Part Strength and Sintered Density in Metal Binder Jetting: Amanda Wei, Virginia Tech		Origami-inspired Deployable Structures Using Fused Deposition Modeling with Embedded Fabric: Tyler Stevens, Brigham Young University
	Tensile and Fatigue Characteristics of Miniature AlSi10Mg Specimens Fabricated Via Powder Bed Fusion: Susheel Dharmadhikari, The Pennsylvania State University		Enabling Direct Ink Write Edible 3D Printing of Food Purees with Cellulose Nanocrystals: Connor Armstrong, Georgia Institute of Technology		The Effect of Processing Parameters on Melt Pool Geometry and Surface Formation in Laser Powder Bed Fusion: Edwin Glaubitz, Wright State University
	Laser Powder-bed-fusion of Tungsten Materials for Fusion Energy Applications: Alberico Talignani, University of California, Los Angeles		Exploring Variability in Melt Pool Attributes with High-speed Imaging: David Guirguis, Carnegie Mellon University		Microstructural and Mechanical Characterization of Laser Powder Bed Fusion of IN718 Overhangs: Behzad Farhang, University of Texas at Arlington
	Effect of Impact Angle on Deposition of LiNbO3 films by Micro-cold Spray: Stephen Bierschenk, The University of Texas at Austin		Investigation on the Properties of Reinforced IN718 Structures Fabricated Using Laser Powder Bed Fusion: Bharath Bhushan Ravichander, The University of Texas at Arlington		Detecting Hidden Process Anomalies Causing Defects Using In-situ Process Monitoring: Jonathan Ciero, Wright State University
	A Deep Learning Approach to Defect Detection in Additive Manufacturing of Titanium Alloys: Xiao Liu, Dublin City University		Investigating the Effect of Heat Transfer on the Homogenity in Microstructure and Properties of Inconel 718 Alloy Fabricated by Laser Powder Bed Fusion Technique: Behzad Farhang, University of Texas at Arlington		Using Acoustic Sensors to Review Sample Integrity During Selective Laser Flash Sintering of Ceramics: Christina Nissen, The University of Texas at Austin
	Anomaly Segmentation in Thermal Tomography Process Monitoring for Laser Powder Bed Fusion Using Texture Analysis: Alexander Groeger, Wright State University		Study of Spatter Formation and Effect of Anti-spatter Liquid in Laser Powder Bed Fusion Processed Ti-6Al-4V Samples: Bharath Bhushan Ravichander, The University of Texas at Arlington		Evaluating the Extrudability of Common Feedstocks for Fused Filament Fabrication Systems : Zaky Hussein,
	Impact of Porosity Type on Microstructure and Mechanical Properties in Selectively Laser Melted IN718 Lattice Structures: Bharath Bhushan Ravichander, The University of Texas at Arlington				0gon - A Revolutionary New Optical Scanner for Additive Manufacturing : Charles Bibas, Tecnica, Inc.

TECHNICAL SESSION GRID - WEDNESDAY AM

Time (CDT)	Applications -- General III	Applications -- Lattices and Cellular III	Materials -- Metals VI - Aluminum Alloys	Materials -- Metals VII - Stainless Steel and Nickel Alloys	Materials -- Polymers II - Material Extrusion	Modeling -- V Process Modeling
Session Chair	**Scott Thompson, Kansas State University**	**Ajit Panesar, Imperial College London**	**Amrita Basak, Pennsylvania State University**	**Li Yang, University of Louisville**	**Chad Duty, University of Tennesee**	**Matthew Priddy, Mississippi State University**
8:00 AM	Material Extrusion Based Additive Manufacturing of Metal Foam Materials with Tailorable Properties: Dayue Jiang, State University of New York at Binghamton	Additively Manufactured Heterogeneously Porous Metallic Bone: Pan Wang, Singapore Inst of Manufacturing Tech (SIMTech)	Investigation of Defects Formation Mechanism and Its Reduction in Selective Laser Melting Fabricated Al7075 Alloy: Mayank Patel, Indian Institute of Technology Kanpur	The Selective Laser Melting Process Development of 17-4 PH Stainless Steels with Pulsed-wave Lasers: Evren Yasa, Eskisehir Osmangazi University	Comparison of Component Properties and Economic Efficiency of the Arburg Plastic Freeforming and Fused Deposition Modeling: Felix Hecker, Paderborn University, Direct Manufacturing Research Center (DMRC)	Numerical predictions of bottom layer stability in material extrusion additive manufacturing: Md Tusher Mollah, Technical University of Denmark
8:15 AM	Distortion Control in LPBF Fabricated Inconel 718 Thin Walls for Application in Nuclear Spacer Grids: Syed Zia Uddin, Carnegie Mellon University	A Numerical and Experimental Approach to Understand the Fatigue Performance of Additively Manufactured Lattices: Valerio Carollo, TWI	Operando Diffraction of Phase Evolution in Selective Laser Melting of Elemental Blends of Al-Sc and Al-Sc-Zr: Jennifer Glerum, MSE, Northwestern University	Linear elastic finite element calculations of short cracks initiated from the defects: effect of defect shape and size: Arun Poudel, Auburn University	Effect of process parameters on the vibration properties of PLA structure fabricated by additive manufacturing: Fangkai Xue, Université de lorraine, CNRS, Arts et Métiers ParisTech, LEM3	Using Medial Surfaces to Produce Graded Voronoi Cell Infill Structures for 3D Printed Objects: Tyler Williams, University of Washginton Mechanical Engineering Department
8:30 AM	Binder Jet Additive Manufacturing for Low CTE Washout Tooling: Dustin Gilmer, University of Tennessee Knoxville/Oak Ridge National Laboratory Bredesen Center	Finite Element Modelling of Defects In Additively Manufactured Strut-based Lattice Structures: Ifeanyi Echeta, University of Nottingham	Metal Additive Manufacturing with Bessel Beams: Thej Tumkur, Lawrence Livermore National Lab	Effect of powder characteristics on tensile properties of additively manufactured 17-4 PH stainless steel : Arun Poudel, Auburn University	Exploring Polymer Healing Theory to Predict Adhesive Strength during Repair of Thermoplastic Parts Using Fused Deposition Modeling: Charul Chadha, University of Illinois at Urbana-Champaign	Laser Spot Size and Scaling Laws for Laser Beam Additive Manufacturing: Jordan Weaver, National Institute of Standards and Technology
8:45 AM	Additive Manufacturing of Si-SiC Cermets for Combustion Device Applications: Patryk Radyjowski, The University of Texas at Austin	Comparison between Ti-6Al-4V and 316L Stainless Steel Micro Lattice Structures Produced by Additive Manufacturing: Mark Hartnett, Irish Manufacturing Research	Mapping the Process Window for Reliable Metal Droplet-on-demand Manufacturing: Nicholas Watkins, Lawrence Livermore National Laboratory	Use of Powder with Non-spherical Morphology in a Laser Powder Bed Fusion Additive Manufacturing Process: Mahya Shahabi, Worcester Polytechnic Institute	The Effect of Fused Filament Fabrication Thermal Post-Processing Conditions on the Mechanical Strength and Dimensional Accuracy on ULTEM® 1010: Callie Zawaski, Penn State	Discrete Element Modeling of Fused Deposition Modeling Process: Cameron Turner, Clemson University
9:00 AM	Thermofluid Optimisation of AM High Heat Flux Components for Fusion: Daniel Padrao, University of Nottingham	On Comparative Computational Fluid Dynamics Analysis of Additively Manufactured Triply Periodic Minimal Surface Radially Gyroidal for Heat Sink Application: Willem Groeneveld-Meijer, Pennsylvania State University	Powder Spreadability Measurements to Predict Performance in SLM Printers: Aurelien Neveu, GranuTools	Sintering and Material Properties of 17-4PH Stainless Steel Fabricated by Atomic Diffusion Additive Manufacturing (ADAM): Nandhini Raju, UCF	Characterizing Internal Porosity of 3D-printed Fiber Reinforced Materials: Frye Mattingly, University of Tennessee, Knoxville	
9:15 AM		The Anisotropic Yield Surface of Cellular Materials: Kaitlynn Conway, Clemson University		Effect of Heat Treatment on the Tensile Behavior of 17-4 PH Stainless Steel Additively Manufactured by Metal Binder Jetting: P.D. Nezhadfar, Auburn University	The Effect of Stress Intensity Factor on Fatigue Life of Additive Manufactured Parts Made from Polymer: Hayat EL Fazani, Carleton University	
9:30 AM		Apparent Mechanical Properties of Sinusoid-based Lattice Structure: Numerical Analysis and Experimental Validation: Mariela Gomez-Castaneda, Cinvestav		A Comparative Study on the Microstructure and Texture Evolution of L-PBF and LP-DED 17-4 PH Stainless Steel during Heat Treatment: P.D. Nezhadfar, Auburn University	The Material Testing of Nanoparticle Doped 3D Printed ABS to Decrease Resistance and Create a Conductive Pathway: Sara Damas, Clemson University	
9:45 AM		Applied Viscous Thread Instability for Manufacturing 3D Printed Foams : Brett Emery, University of Washington		Additively Manufactured Hastelloy-X: Effect of Post-process Heat Treatment on Microstructure and Mechanical Properties: Muztahid Muhammad, Auburn University	Mechanical Properties of High-performance Plastic Polyether-ether-ketone (PEEK) Printed by Fused Deposition Modeling: Zezheng Wang, Georgia Southern University	
10:00 AM				Process Optimization and Mechanical Properties of Laser Powder Bed Fusion Built Haynes 230: Ziheng Wu, Carnegie Mellon University		
10:15 AM	Break			Electron Beam Selective Melting of IN738LC Alloy; Defects Control, Microstructural Characterization and Mechanical Properties: Yang Li, Tsinghua University	Break	
10:30 AM	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters

Time (CDT)	Modeling -- VI Material Modeling A	Process Development -- V Extrusion	Process Development -- VI Novel Processes and Advances B	Special Session -- Data Analytics in AM III: Process Monitoring and Flaw Detection A	Special Session -- Dimensional and Surface Characterization for Additive Manufacturing I	Special Session -- Hybrid AM Processes II - Process Planning and Characterization
Session Chair	Fransciso Medina, University of Texas El Paso	Rajeev Dwivedi, STEM and Robotics Academy	Xiayun Zhao, University of Pittsburgh	Subhrajit Roychowdhury, GE Global Research Center	Joy Glockel, Colorado School of Mines	Judith Lavin, Sandia National Laboratories
8:00 AM	Exploring Transient Printing Processes and Defects of Various Builds during Additive Manufacturing: Huiliang Wei, Nanjing University of Science and Technology	Insertion and Air-gapped Retrieval of Part Quality Information in Additive Manufacturing Toolpaths for Cyber-Secure In-situ Process Monitoring: Nathan Raeker-Jordan, Virginia Tech	Combining Technologies: In-situ Direct-write Techniques for Hybrid Injection Molded Electronics: Joshua Krantz, University of Massachusetts Lowell	In-situ Flaw Detection in Wire Arc Additive Manufacturing Using an Acoustic Sensor: Benjamin Bevans, University of Nebraska-Lincoln	Geometrical Deviations in Additive Manufacturing – Influences on the Manufacturing Accuracy: Tobias Lieneke, Paderborn University / Direct Manufacturing Research Center	Abrasive Flow Machining of Additively Manufactured Titanium: Thin Walls and Internal Channels: Sagar Jalui, The Pennsylvania State University
8:15 AM	Finite Element Simulation of Direct Deposition Additive Manufacturing for Fiber Reinforced Thermoplastics: Zhaogui Wang, Dalian Maritime University	Feasibility Study of Large-format, Freeform 3D Printing for On-orbit Additive Manufacturing: Aditya Thakur, Institute of Space System (IRAS)	Multiple-material powder bed fusion machine development: reducing cross-contamination between materials: Scott Snarr, Univ of Texas At Austin	Unsupervised Defect Classification of 2D SEM and 3D X-Ray CT Images from Laser Powder Bed Fusion: Andrew Lang, The Boeing Company	Empirical and simulated x-ray computed tomography probability of detection analysis for additive manufacturing and calibrated defect artifact development: Felix Kim, National Institute of Standards and Technology	Mapping Energy Consumption during Milling of Interlayer Ultrasonic Peened 316 Stainless Steel: Kossi Loic Avegnon, University of Nebraska-Lincoln
8:30 AM	A Multi-grid Cellular Automaton Model for Simulating Dendrite Growth and Its Application in Additive Manufacturing: Yefeng Yu, The Department of Mechanical Engineering	Variable Extrusion Width and Height for Interlocking Features in Fused Filament Fabrication 3D Printing: Osama Habbal, University of Michigan Dearborn	Geometrical Analysis of Single- and Multi-layer Objects Printed by a 3D Printing Hexacopter: Alexander Nettekoven, University of Texas Austin	Acoustic Signatures in Metal Laser-powder Bed Fusion: Elaine Rhoades, Georgia Institute of Technology	An Investigation on the Definition and Qualification of Form on Lattice Structures: Maxwell Praniewicz, National Institute of Standards and Technology	Ultrasonic Characterization of Frequency Dependence from Interlayer Milling and Peening 316 Stainless Steel during Additive Manufacturing: Jazmin Ley, University of Nebraska-Lincoln
8:45 AM	A Periodic Homogenization Model Including Porosity to Predict Elastic Properties of 3d-printed Continuous Carbon Fiber-reinforced Composites: Valentin Marchal, Université de Technologie de Belfort-Montbéliard	A TRIZ-Based Analysis of the Fundamental Limits of Fused Filament Fabrication: Jason Weaver, Brigham Young University	Material Pressure Sensing at the Nozzle in Direct-write Additive Manufacturing Enables the Precise Fabrication of Complex Parts: Ali Asghari Adib, Ohio State University	Detecting Defects Caused by Optical Lens and Focus-related Aberrations in Laser Powder Bed Fusion: Aniruddha Gaikwad, University of Nebraska-Lincoln	Effective Registration of Engineered Lattice Geometry: A Comparative Study of Measurement Methodologies: Scott Jensen, Sandia National Lab	Residual Stress Measurement (RSM) in Hybrid Additive Manufacturing: Gurucharan Madireddy, University of Nebraska-Lincoln
9:00 AM	Effects of Local Fiber Orientation State on Thermal-mechanical Behaviors of Composite Parts Made by Large Area Polymer Deposition Additive Manufacturing: Zhaogui Wang, Dalian Maritime University	Mechanical Evaluation of Topology and Toolpath Optimized Composite Structures Manufactured via Multi-axis Material Extrusion: Joseph Kubalak, Virginia Tech	A Modular Lightweight Additive Manufacturing System for Cementitious Materials with Diverse Aggregate Sizes: Mehrab Nodehi, Texas State University	Machine Learning Enabled Laser Spatter and Flaw Detection in Laser Powder Bed Fusion Processes: Jack Beuth, Carnegie Mellon University	Surface Improvement of Additively Manufactured Polypropylene Parts: Luis Folgar, AMT Inc.	Automated Process Planning for a 5-axis Hybrid Manufacturing System: Xinyi Xiao, Miami University
9:15 AM	Simulation of Micro-void Development within Large Scale Polymer Composite Deposition Beads: Aigbe Awenlimobor, Baylor University	Mechanical Characterization of Epoxy Components Manufactured via Reactive Extrusion: Oliver Uitz, The University of Texas at Austin	Fabrication of Bioinspired Optical Material with Self-sensing Capability via Thermal Field Assisted 3D Printing: Tengteng Tang, Arizona State University	Autoencoder-based Anomaly Detection for Laser Powder Bed Fusion: Bumsoo Park, Rensselaer Polytechnic Institute		Collision-free Solution for Multi-axis Hybrid Additive Manufacturing: Xinyi Xiao, Miami University
9:30 AM	High-fidelity Modeling of Binder-powder Interactions in Binder Jetting: Zeshi Yang, National University of Singapore	Concrete Metering and Extrusion System for Infastructure-scale Printing: Celeste Atkins, Oak Ridge National Laboratory	Robot Trajectory Planning for Large Scale Additive Manufacturing: Ademola Oridate, The University of Texas at Austin	Automated Anomaly Detection of Laser-based Additive Manufacturing Using Melt Pool Sparse Representation and Unsupervised Learning: Farhad Imani, University of Connecticut		New Robotic Work-cell for Hybrid Large-scale Metals Additive and Subtractive Manufacturing: Joshua Penney, University of Tennessee
9:45 AM	Modeling Collapse Behavior in Large-scale Thermoset Additive Manufacturing: Stian Romberg, University of Tennessee, Knoxville		Review of Current Problems and Developments in Large Area Additive Manufacturing (LAAM): Tyler Crisp,	In-situ Detection and Prediction of Porosity in Laser Powder Bed Fusion Using Dual-wavelength Pyrometry: Ziyad Smoqi, University of Nebraska-Lincoln		Hybrid Laser Powder Bed Fusion of Aluminum Alloy Radio Frequency Resonators: Alexander Riensche,
10:00 AM						The Role of Interface in Additively Manufactured Interpenetrating Composites: Jason Allen, Oak Ridge National Laboratory
10:15 AM	Break					
10:30 AM	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters

TECHNICAL SESSION GRID - WEDNESDAY PM

Time (CDT)	Applications -- Biomedical	Applications -- General IV	Materials -- Metals IX - AlSi10Mg	Materials -- Metals VIII - Nickel Alloys	Materials -- Polymers III - Powder Bed Fusion and Direct Write
Session Chair	John Obielodan, University of Wisconsin-Platteville	Matt Frank, Iowa State University	Saad Khairallah, Lawrence Livermore National Laboratory	Edward Kinzel, University of Notre Dame	Douglas Smith, Baylor University
1:30 PM	Fabrication of Stretchable Sensors for Biomedical Applications: Srikanthan Ramesh, Rochester Institute of Technology	Development of a Method to Derive Design Guidelines for Production-suitable Support Structures in Metal Laser Powder Bed Fusion: Stefan Lammers, Paderborn University	Investigation Towards AlSi10Mg Powder Recycling Behavior in the LPBF Process and Its Influences on Mechanical Properties: Christian Weiss, Fraunhofer Institute for Laser Technology (ILT)	Energy Density Effect on the Keyhole and Lack of Fusion Porosity during Laser Powder Bed Fusion Process: Subin Shrestha, University of Louisville	Flowability Measurements of Different SLS Materials at Elevated Temperatures with a Modified Schulze Ring Shear Tester: Moritz Rüther, University of Paderborn
1:45 PM	In-situ Sensing of Construct Quality in Biological Additive Manufacturing: Sam Gerdes, University of Nebraska-Lincoln	Design-for-fracture of FDM Mesostructure for Thermoplastic Materials Under Manufacturability Constraints: Albert Patterson, University of Illinois at Urbana-Champaign	Evaluation of Early Fatigue Damage Detection in Additively Manufactured AlSi10Mg: Susheel Dharmadhikari, The Pennsylvania State University	Effects of Build Orientation and Heat Treatment on Neutron Irradiation Hardening in Inconel 625 Fabricated via Laser Powder Bed Fusion: Mohanish Andurkar, Kansas State University	Low Temperature Laser Sintering on a Standard System: First Attempts and Results with PA12: Dennis Menge, Paderborn University
2:00 PM	3D Bioprinting of Cell-laden Scaffolds for Skin Substitutes : Fateme Fayyazbakhsh, Missouri University of Science and Technology	Conformal Cooling: An Analysis of Additive Cooling Channels: Luke Meyer, Oak Ridge National Laboratory	Increasing Productivity in Laser Powder Bed Fusion Additive Manufacturing of AlSi10Mg: Joy Gockel, Colorado School of Mines	Effects of Heat Treatment and Fast Neutron Irradiation on the Microstructure and Microhardness of Inconel 625 Fabricated via Laser-Powder Bed Fusion: Tahmina Keya, Auburn University	The Influence of Grain Size Distribution of PA12 on Key Steps of the Polymer Laser Sintering Process: Jens Sesseg, EOS GmbH
2:15 PM	Biomass-dependent Mechanical Properties of 3D-printed PLA/Organosolv Lignin Composites: John Obielodan, University of Wisconsin-Platteville	Design and Hybrid Additive Manufacturing for Electronic Components that Can Withstand Shock Loading: Connor Gunsbury, The University of Texas at Austin	Influence of Process Conditions on the Thermal Conductivity of Selective Laser Melted AlSi10Mg: Arad Azizi, Binghamton University	Residual Stress Measurements via X-ray Diffraction Cos-\\945; Method on Various Heat-Treated Inconel 625 Specimens Fabricated via Laser-Powder Bed Fusion: Mohanish Andurkar, Kansas State University	A Control of Surface Quality in Selective Laser Sintering Additive Manufacturing with Reclaimed Polyamide Materials: Feifei Yang, University of Washington
2:30 PM	Finite Element Modeling of Failure Modes during 3D Printed Polymeric Bioresorbable Vascular Scaffold Crimping: Caralyn Collins,	Multimaterial AM-aware Design of Asymmetric Acoustic Absorbers: Tyler Wiest, The University of Texas at Austin	Powder Bed Fusion Additive Manufacturing of Curved-surface AlSi10Mg Parts: Surface Finish, Geometrical Deviation, and Microstructure: Yue Zhou, Binghamton University	Additively Manufactured Haynes 230 by Laser Powder Direct Energy Deposition (LP-DED): Effect of Heat Treatments on Microstructure and Tensile Properties: Muztahid Muhammad, Auburn University	Correlation of Density with Microstructure and Mechanical Properties in Polymer Powder Bed Fusion Processes: Clinton Abbott, Brigham Young University
2:45 PM	Rotational Digital Light Processing for Edible Scaffold Fabrication: Alexis Garrett, University of Nebraska-Lincoln	Pushing the Limits of Printed RF: Advancing Towards Free-form Antennas, Waveguides, and Interconnects for X-band Applications: Katherine L. Berry, University of Massachusetts Lowell		(LATE REG) Microstructure Pore-stress Interactions and Their Influence on Scatter in AM Fatigue Life Data: Luke Sheridan, Air Force Research Laboratory	Investigation into Laser Sintering of PEEK Using Commercially Available Low Powder Bed Temperature Machine: Takashi Kigure, Tokyo Metropolitan Industrial Technology Research Institute
3:00 PM	Accelerated Corrosion Behavior of Additive Manufactured WE43 Magnesium Alloy: Rakeshkumar Karunakaran, University of Nebraska-Lincoln			Microhardness and Mechanical Properties in Additively Manufactured Inconel 718: Cherish Lesko, Wright State University	Printability Assessment of Cellulose-Based Polymer Structures Using Direct Ink Writing: Amrita Basak, Pennsylvania State University
3:15 PM	Aerosol Jet® Printing of 3D Micropillars Using Multiple Materials: Miriam Seiti, KU LEUVEN			Powder Reuse Effects on the Tensile Behavior of Additively Manufactured Inconel 718 Parts: Arash Soltani-Tehrani, Auburn University	Effects of Fiber Length Evolution in Carbon Fiber-reinforced Epoxy Composites for Direct Ink Writing: Nadim Hmeidat, University of Tennessee, Knoxville
3:30 PM	Post-processing of Additively Manufactured Covid-19 Nasopharyngeal Swabs at Scale: Konstantin Rybalcenko, Additive Manufacturing Technologies	Break			
3:45 AM	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters

Time (CDT)	Modeling -- VII Material Modeling B	Process Development -- VII In-situ Monitoring	Special Session -- Data Analytics in AM IV - Process Monitoring and Flaw Detection B	Special Session -- Dimensional and Surface Characterization for Additive Manufacturing II
Session Chair	Jason Allen, Oak Ridge National Laboratory	Joseph Newkirk, Missouri University of Science and Technology	Bradley Jared, Sandia National Laboratories	Hui Wang, Texas A&M University
1:30 PM	Influence of Oxygen Content on Melt Pool Dynamics in Powder Bed Fusion Processes: Hou Yi Chia, National University of Singapore	Powder Spread Process Monitoring in Polymer Laser Sintering and Its Influences on Part Properties: Helge Klippstein, Paderborn University	Microstructure and Tensile Test Data Alignment for Additive Manufacturing Data Registration: Shaw Feng, NIST	Influence of Measurement and Sampling Strategy on Analysis of Surface Finish in Laser Powder Bed Fusion Additive Manufacturing of Nickel Superalloy 625: Jason Fox, National Institute of Standards and Technology
1:45 PM	Particle Segregation by Size during Powder Spreading Process of Powder Bed Based Additive Manufacturing: Hui Chen,	In-situ Detection of Laser Powder Bed Fusion Process Signatures Based on Sensor Fusion Approach: Ivan Zhirnov, Karlstad University	Powder Features Affecting Structural and Mechanical Properties of Additively Manufactured Inconel 718: A Machine Learning Analysis: Mohammad Shahadath Hossain, Auburn University	Surface Roughness Variation in Laser Powder Bed Fusion Additive Manufacturing: Rachel Evans, Wright State Universtiy
2:00 PM	A Method of Predicting Powder Flowability for SLS: Doug Sassaman, University of Texas Austin	Design and Implementation of Laser Powder Bed Fusion Additive Manufacturing Testbed Control Software : Keely Hutchinson, Kansas State University	Automated Detection of Part Quality during Two Photon Lithography via Deep Learning: Xian Lee, Iowa State University	Predicting Surface Geometry for Steady-state FFF Printing: Christopher Pannier, University of Michigan - Dearborn
2:15 PM	Modeling Light Scattering Vat Photopolymerization Resins with Monte Carlo Ray Tracing: Keyton Feller, Virginia Tech	Image Registration and Matching Error in 2D and 3D for Laser Powder Bed Fusion: Andrew Lang, The Boeing Company	Heterogenous Sensing and Scientific Machine Learning for In-process Anomaly Detection in Laser Powder Bed Fusion – A Single-track Study: Aniruddha Gaikwad, University of Nebraska-Lincoln	Investigations for the Optimization of Visual and Geometrical Properties of Arburg Plastic Freeforming Components: Felix Hecker, Paderborn University, Direct Manufacturing Research Center (DMRC)
2:30 PM	Multi-physics & Multi-materials Modeling of Steel/Inconel Functionally Gradient Material Fabricated with Laser-based Directed Energy Deposition: Wei Li, The University of Texas at Dallas	Investigations on Optical Emissions and Their Relation to Processing Parameters and Processing Regimes in the Laser Powder Bed Fusion Process: Christopher Stutzman, Penn State University	Predictive Control of Porosity in Laser Powder Bed Fusion: Paromita Nath, Vanderbilt University	Real-time Geometry Quality Management During Directed Energy Deposition Using Laser Line Scanner: Liu Yang, Korea Advanced Institute of Science and Technology
2:45 PM	Cellular Automata Modeling of Layer-wise Microstructure Convergence as Functions of Material and Processing Variables: Matthew Rolchigo, Oak Ridge National Laboratory	Optical Emission Sensing for Laser-based Additive Manufacturing – What Are We Actually Measuring?: Christopher Stutzman, Penn State University	Using Deep Convolutional Neural Networks for Process Shift Detection, Root Cause Isolation and Defect Prediction in Metal Additive Process: Subhrajit Roychowdhury, GE Global Research Center	Location and Orientation Dependency in Surface Roughness of Nickel Super Alloy 625 Parts: Statistical and Distributional Analysis: Saina Abolmaali, Auburn University
3:00 PM			Porosity Analysis of Laser Powder Bed Fusion Parts Using the Statistics of Extremes: Mahya Shahabi, Worcester Polytechnic Institute	Locational Dependency of Additively Manufactured Parts: Effects of Surface Roughness on Fatigue Behaviors: Seungjong Lee, Auburn University
3:15 PM			Layer-wise Certification for Direct Energy Deposition Processes based on Melt Pool Morphology Dynamic Analysis: Wenmeng Tian, Mississippi State University	Effect of Surface Texture on Deformation Behavior during Shot Peening of Electron Beam Melted (EBM) Ti-6Al-4V: Mustafa Rifat, Pennsylvania State Unversity
3:30 PM	Break			
3:45 AM	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters	Live "Zoom-Style" Q&A with Presenters

Plenary I

Monday AM August 2, 2021

Session Chair: D. Bourell, University of Texas

8:00 AM
Introductory Comments: *David Bourell*[1]; [1]University of Texas Austin

8:20 AM Plenary
On Corrections of Global Shifts in Metal Additive Manufacturing: *Subhrajit Roychowdhury*[1]; Sharath Aramanekoppa[1]; Rajesh Bollapragada[1]; Brion Sarachan[1]; Bakshi Kaivalya[1]; Rogier Blom[1]; [1]GE Global Research Center

In the current paradigm of metal additive manufacturing, the process runs open loop with pre-specified process parameters. It is therefore important to ensure that the machine is delivering the commanded parameters under all conditions. However, due to various factors, viz., variations in ambient temperature, thermal lensing, optics misalignment, optics degradation, laser degradation etc., the process parameters at the powder bed may drift from the commanded ones. To maintain process compliance, we developed a machine learning based algorithm that can estimate the deviations between commanded and delivered power and spot-size based on the photodiode data from a witness coupon on a layer wise basis. To compensate for the drifts that typically acts over a slow time scale (hour to days), we implemented a layer-wise compensation mechanism based on the estimates to ensure desired power and spot-size is delivered to the process.

8:45 AM Question and Answer Period

8:50 AM Plenary
Design for the Additive Manufacturing Process Chain: *David Rosen*[1]; [1]Georgia Institute of Technology

Post-processing operations are required for most additive manufacturing (AM) processes. For production parts, consideration of these post-processing operations during design is critical to achieve design requirements. For metal parts, heat treatment, support structure removal, and finish machining are frequently required to convert the AM-fabricated part to its final state. Also, polymer parts usually require some post-processing operations, including support removal and finishing. A design framework called the Process Chain Map (PCM) is introduced in this paper that explicitly relates design requirements for the part to each step in the AM process chain. This PCM visually shows the role of each step in the process chain and facilitates communication among design and manufacturing personnel. Software implementation of the PCM enables generation of system-level problem formulations of multidisciplinary design optimization problems. An example of a metal AM part demonstrates the PCM and the formulation of such a design problem.

9:15 AM Question and Answer Period

9:20 AM Plenary
Reducing Heat Buildup and Regularizing Melt pool Dimensions in Laser Powder Bed Fusion through a "Powder Moat" Scan Strategy: Evan Diewald[1]; Christian Gobert[1]; Nicholas Jones[1]; *Jack Beuth*[1]; [1]Carnegie Mellon University

The stochastic nature of the laser powder bed fusion (LPBF) process results in undesired defects such as porosity, residual stress, and inconsistent microstructure. Many flaws are related to erratic thermal conditions caused, in part, by suboptimal infill scanning strategies. This article presents an approach for reducing heat buildup in metals additive manufacturing (AM) that can be implemented within the bounds of most commercial machines. The "Powder Moat" strategy, where a thin wall is built outside the boundaries of the intended part, eliminates in-plane hotspots by inducing a predictable delay after each raster. A semi-analytical model is used to generate process maps of delay times and moat thicknesses as a function of laser power and velocity, and the approach is validated through high speed imaging. By standardizing melt pool dimensions and thermal distributions, the strategy serves the broad goal of process qualification and is a practical step toward increasing AM's reliability.

9:45 AM Question and Answer Period

9:50 AM Break

Plenary II

Monday AM August 2, 2021

Session Chair: D. Bourell, University of Texas

9:55 AM Plenary
Mechanics of Additively Manufactured Metals: Effect of Stress State and Microstructural Features: *Allison Beese*[1]; [1]Pennsylvania State University

The unique thermal histories seen in additive manufacturing (AM) of metal alloys results in microstructures with phases, grain morphologies, or internal pores that differ from those in their conventionally processed counterparts. These microstructures dictate the resulting mechanical properties of the alloys; thus, to enable the adoption of AM for structural applications, an understanding of the links between microstructure and deformation and/or fracture is required in order to safely and reliably design against failure. In this talk, I will present our work on experimentally and computationally investigating the impact of these microstructural features on the stress-state dependent deformation and failure behavior of additively manufactured alloys. Additionally, I will describe our work on designing, fabricating, and characterizing functionally graded materials in which the chemistry is intentionally changed as a function of position to impart disparate properties as a function of position within a 3D component.

10:20 AM Question and Answer Period

10:25 AM Plenary
Multi- Material / Modality / Scale / Axis: Realizing Multi-Functional Products with Next-Generation AM Processes: *Christopher Williams*[1]; [1]Virginia Tech

Additive Manufacturing's layer-wise fabrication approach empowers engineers to selectively place (multiple-) materials to realize products that satisfy multiple functions and design objectives. However, to fully realize this potential, AM processes are in need of further advancements in material selection and process capability. To address this need, it is necessary to tailor both materials for the unique constraints imposed by AM processes, and the processes for the unique properties of the materials. The aim of this talk is to highlight research in which materials and AM processes are concurrently designed to realize direct printing of multi-functional products. Specifically, AM of (i) fully-aromatic polyimides (via multi-scale vat photopolymerization), (ii) composite metal lattices (via multi-material binder jetting of foundry sand), (iii) fiber reinforced composites with embedded actuation and sensing (via multi-modal AM), and (iv) composite structures featuring optimized topology and toolpathing (via multi-axis robotic deposition) will be presented.

10:50 AM Question and Answer Period

10:55 AM Break

Plenary III

Monday AM August 2, 2021

Session Chair: D. Bourell, University of Texas

11:00 AM Plenary
FAME Presentation: Understanding the Fatigue Behavior in Additive Manufacturing through Processing-Structure-Properties-Performance Relationships: *Joy Gockel*[1]; [1]Colorado School of Mines

In additive manufacturing (AM), the material is created at the same time as the component. Therefore, the properties must be related back to the processing conditions. In laser powder bed fusion, the processing parameters (laser power, speed, etc.) influence the formation of material features (surface roughness, porosity, microstructure, etc.) that affect component performance. A critical challenge impacting the qualification of AM parts is an understanding of the fatigue behavior. This presentation will discuss the influence of processing and material structure on the fatigue performance of nickel-based superalloy 718 through a series of investigations using targeted processing modifications, comprehensive characterization, predictive modeling, innovative test coupon geometries, and novel test methods. The inclusion of in-situ process monitoring techniques provides valuable insights to detect the formation of defects and accelerate processing parameter development for new materials. Implementation of AM in critical applications can be achieved through a fundamental understanding of the processing-structure-properties-performance relationships.

11:25 AM Question and Answer Period

11:30 AM Plenary
FAME Presentation: Metal Additive Manufacturing, Then and Now: *Ola Harrysson*[1]; [1]North Carolina State University

Metal Additive Manufacturing has been around for over two decades, but my journey in this area started in August of 2002 at SFF in Austin, Texas. NC State University acquired the very first Electron Beam Melting machine from Arcam AB in 2003, which has shaped the rest of my research career. The first EBM machine was very primitive compared to the current systems and only one material (H13) was available. For the past 18 years, our research group has focused on new material development for powder bed fusion processes as well as finishing of metal AM components and custom designed medical implants. The future research at NC State University will focus on new alloy development for metal AM processes.

11:55 AM Question and Answer Period

12:00 PM FAME Awards Presentation

Applications: Lattices and Cellular I

Monday PM August 2, 2021

Session Chair: C. Turner, Clemson University

1:30 PM
Design, Simulation and Experimental Investigation of 3D Printed Mechanical Metamaterials: *Sunil Magadum*[1]; Amol Gilorkar[2]; Deepak M[2]; Rakshith B S[2]; Navaharsha P[2]; Nagahanumaiah[1]; Somashekara M Adinarayanappa[2]; [1]Central Manufacturing Technology Institute, Bengaluru; [2]Indian Institute of Technology, Dharwad

Mechanical metamaterials have generated special interest recently due to their tailorable structure, exceptional mechanical properties, and advancements in 3D printing processes that allow the fabrication of intricately structured components. Designing innovative structures of metamaterials will lead to the development of advanced materials with special properties. The experimental investigation presented in this paper involves the design, simulation, fabrication, and testing of three different mechanical metamaterial models i.e. Chiral, Re-entrant, and Hybrid printed in acrylonitrile styrene acrylate (ASA) using fused deposition modeling (FDM). Subsequently, a uniaxial compression test and ex-situ characterization was performed for studying the mechanical properties, the types of fracture and crack propagation of the printed metamaterial models which may lead to the development of metamaterials with tunable compressive/bending stiffness.

1:45 PM
Effect of Voronoi Lattice Geometry on the Fatigue Performance of Ti-6Al-4V: *Sinéad Uí Mhurchadha*[1]; Sabrina Marques[1]; Lola Givet[1]; Ramesh Raghavendra[1]; [1]SEAM Research Centre

This paper investigates the effect of strut thickness and number of pores on the fatigue performance of Ti-6Al-4V voronoi lattice structures designed with the same part density. The aim of this study is to establish the variation in high cycle fatigue parameters for constant volume lattice structures designed with various lattice parameters. Voronoi geometries were designed with varying strut thicknesses and number of pores varied to maintain a constant specimen volume. The geometries were tested under compressive fatigue conditions at a reversal ratio, R, of 0.1. It was found that the strut thickness has a significant influence on the fatigue life of the lattice. An increase in the strut thickness by 100 µm can result in a reduction in fatigue life by up to a factor of 10. The results from this research can influence the design of lattice structures for osteointegration in load-bearing biomedical implant applications.

2:00 PM
A Comparative Study with the Topology Design of Cellular Mechanical Interface in a Bi-material Structure: Antonio Coriano[1]; *Li Yang*[1]; [1]University of Louisville

Many structure and component designs require the use of multiple materials, which is currently a challenge for many additive manufacturing (AM) processes. One of the often noted issues with multi-material AM processes is the lack of interfacial strength with the structures caused by material incompatibility. In this work, the concept of mechanical interface design utilizing 3D cellular structures was explored for the design of interfaces for a simple bi-material beam structure. Various cellular unit cell topologies that represent different design rules were designed and evaluated. From the perspective of structure design, the effectiveness of different cellular topology designs for such purpose was investigated, which include criteria such as maximum failure strength, interface efficiency, ductility and toughness. The results aim to provide both feasibility and structural design guideline information for this interesting concept.

2:15 PM
Investigation of a Unit Cell Optimization Framework for Lattice Structures Based on Triply Periodic Surfaces: *Joseph Fisher*[1]; Timothy Simpson[1]; Simon Miller[1]; [1]The Pennsylvania State University

Triply Periodic Minimal Surfaces (TPMS) have been identified as good candidates for the generation of lattice structures produced with additive manufacturing. TPMS based lattice structures avoid sharp features characteristic of strut-based lattice structures because of their constant zero mean curvature. Although studies have explored part-scale optimization of TPMS based lattice structures, they have only varied the volume fraction by changing the level set in the approximate surface equations. By defining new parameterizations in the approximate surface equation, we can redistribute volume within the lattice structure at any volume fraction. In this paper, we introduce a framework for optimization of this new parameterization of TPMS equations. We curve fit the coefficients as a function of the level set to generate new equations that are solely dependent on the level set, allowing for replacement of standard equations. We demonstrate this framework on the IWP endo-skeletal TPMS lattice under compression and shear loading.

2:30 PM

Dynamic Defect Detection in AM Parts Using FEA Simulation: *Kevin Johnson*[1]; Gita Deonarain[1]; Jason Blough[1]; Andrew Barnard[1]; David Labyak[1]; Troy Hartwig[2]; Tristan Cullom[3]; Edward Kinzel[4]; Douglas Bristow[4]; Robert Landers[4]; Ben Brown[2]; [1]Michigan Technological University; [2]Kansas City National Security Campus managed by Honeywell; [3]Missouri S&T; [4]University of Notre Dame

The goal of this paper is to evaluate the affects of build support material on the ability to find internal defects in AM parts dynamically. The different resonant frequencies of parts are determined by the stiffness and mass involved in the mode shape at each resonant frequency. Voids or defects in AM parts will change the stiffness and mass therefore shift the resonant frequencies. The mass and stiffness of the entire system including the build support material will determine these resonant frequencies. This paper will investigate the use of FEA dynamic simulation to determine how different build support structures will affect the ability to find the resonant frequency shifts of AM parts due to voids and defects.This work was funded by the Department of Energy's Kansas City National Security Campus which is operated and managed by Honeywell Federal Manufacturing Technologies, LLC under contract number DE-NA0002839.

2:45 PM

Characterizing and Designing for Geometry-dependent Material Properties in Direct Metal Laser Sintering: Conner Sharpe[1]; Andrew Allan[1]; *Carolyn Seepersad*[1]; Bradley Jared[2]; [1]University of Texas at Austin; [2]Sandia National Laboratories

Layer-based AM techniques such as direct metal laser sintering (DMLS) frequently result in anisotropic material properties that depend on geometric design factors such as feature orientation relative to the build platform. These issues can be exacerbated in lattice structures, where the use of small struts can cause degradation in part quality and significant deviations from the expected mechanical properties of the bulk constituent material. These issues are commonly ignored during the design process due to insufficient data or implementation difficulties. This work tests strut tensile specimens that are built at a variety of diameters and overhang angles. The parts are analyzed with digital image correlation (DIC) to investigate the effect of these factors on effective stiffness and strength. The stiffness results are then incorporated into a process-aware design optimization framework that illustrates the potential for significant improvements in the performance of additively manufactured lattice structures.

Broad Issues in AM: I Economics, Emissions and I-DREAM4D

Monday PM August 2, 2021

Session Chair: S. Zhang, University Of Texas Rio Grande Valley

1:30 PM

Enabling Cost-based Support Structure Optimization in Laser Powder Bed Fusion of Metals: *Katharina Bartsch*[1]; Claus Emmelmann[1]; [1]Hamburg University of Technology (TUHH)

Support structures are essential to laser powder bed fusion (PBF-LB/M). They sustain overhangs, prevent distortion, and dissipate process-induced heat. Their removal after manufacturing is required, though, increasing the overall costs. Therefore, optimization is important to increase the economic efficiency of PBF-LB/M. To enable optimization focused on the support structures' costs, a cost model is developed. The whole production process including the design, manufacturing, and post-processing of a part is considered by deriving formulas for the individual costs. The cost model is applied to a benchmark procedure previously developed. Additionally, a case study investigating different support layout strategies is conducted.

1:45 PM

A Hierarchy of Needs for Implementing Additive Manufacturing Across Industries: *Callie Zawaski*[1]; Viswanath Meenakshisundaram[1]; Camden Chatham[1]; Christopher Williams[1]; [1]Virginia Tech

While the incorporation of additive manufacturing (AM) has been growing in numerous industries including automotive, aerospace, medical, and defense, its deployment is still limited due to gaps in the processes, materials, and resulting products. To better understand the needs of AM users the authors interviewed >100 people across multiple industries as part of the NSF I-Corps program. Interviewees were asked about their use of AM, their perceived limitations of the technologies, and their critical needs for further implementation. Through synthesis of the data collected, a "hierarchy of needs" was created to reflect the articulated stages for industrial AM, consisting of 1) machine reliability, 2) part reliability, 3) material selection, 4) qualification, and 5) production in (both mass production and customized part production). This hierarchy can be used to better understand market needs and to guide further development and research of AM systems for further growth and adoption of the processes.

2:00 PM

Characterization of Particles and Gases Released from Large-format Additive Manufacturing Machines during Extrusion of Multiple Polymers and Machining: *Lauren Bowers*[1]; Stephen Martin[1]; Alycia Knepp[1]; Austin Schmidt[2]; Andrew Bader[2]; Aleksandr Stefaniak[1]; [1]National Institute for Occupational Safety and Health; [2]Additive Engineering Solutions

Polymer extrusion on Large-Format Additive Manufacturing (LFAM) machines releases particles and gases; however, the characterization of these emissions has not been studied. Emissions during the extrusion of six different polymers on two LFAM machines were collected and characterized on filters and substance-specific media. Wipe samples of work surfaces and printed parts were collected and analyzed for bisphenol A and S (BPA, BPS). Filter samples showed low concentrations of metals detected during printing with all polymers (maximum = 1.6 mg/m^3 for iron). Low levels of gases were detected, including respiratory irritants (phenol), asthmagens (caprolactam), and carcinogens (formaldehyde) in air. Work surfaces and printed parts were contaminated with low levels of BPA (<8-587 ng/100 cm^2) and BPS (<0.22-2.5 ng/100 cm^2). All extruded polymers released varying levels of chemicals that could influence air quality and surface contamination, which emphasizes the importance of health and safety practices to minimize exposures and risks.

2:15 PM

Evaluation of Real-time Particle and Chemical Emissions from Large-format Additive Manufacturing Machines: *Elizabeth Arnold*[1]; Aleksandr Stefaniak[1]; Lauren Bowers[1]; Alycia Knepp[1]; Austin Schmidt[2]; Andrew Bader[3]; [1]National Institute for Occupational Safety and Health; [2]Additive Engineering Solutions ; [3]Additive Engineering Solutions

As use of large-format additive manufacturing (LFAM) machines becomes more prevalent, there is an increased need for information regarding emissions during LFAM material extrusion. Particle number and total volatile organic compound (TVOC) concentrations were monitored during extrusion of six different polymers from two LFAM machines. The polymers were acrylonitrile butadiene styrene (ABS); polycarbonate (PC); and high-melt-temperature polymers including polysulfone (PSU), poly(ether sulfone) (PESU), polyphenylene sulfide (PPS), and Ultem (poly(ether imide)), for which little data exists. Particle emission rates (no./min) ranged from 1.1×10^{12} (ABS) to 9.7×10^{12} (PC). TVOC emission yields for print jobs ranged from 0.005 mg/g extruded (PESU) to 0.7 mg/g extruded (ABS). The use of wall-mounted exhaust ventilation fans had no significant impact on particle emission levels ($p < 0.05$). Engineering controls such as local exhaust ventilation could be implemented to reduce particle and chemical emissions from LFAM machines.

2:30 PM
I-DREAM4D: An Innovation Based Consortium Approach for Talent Preparation for Defense Manufacturing: James Li[1]; *Joseph Beaman*; [1]University of Texas Rio Grande Valley

Recent development in additive manufacturing promoted tremendous innovation opportunities in defense sectors, supporting development of new materials and structures that withhold extreme conditions, and fabrication of autonomous systems embedded with 3D printed sensors and lightweight and smart materials, powered by advance AI algorithms. Fully capturing these innovation opportunities calls for a collaborative effort to expose, educate and engage next generations learners at different levels. This talk introduces I-DREAM4D, a DoD Consortium for Innovation Driven Research/Education Ecosystem for Advanced Manufacturing for the Defense, which is created with a goal to prepare young people who are ready to lead the innovation process for US military and defense manufacturing operations. With participation of 5 universities, more than 10 defense manufacturing industry members, 2 defense labs, and one national research center, this consortium provides a platform to solve the talent gap deemed as one of the most challenging issues for US Manufacturing.

2:45 PM
Direct Selective Laser Synthesis of CuCrFeTiNiAl High Entropy Alloy from Elemental Powders through Selective Laser Melting: *Joni Chandra Dhar*[1]; Lazaro Lopez Mendez[1]; Shanshan Zhang[1]; Ben Xu[2]; Jasim Uddin[1]; Jianzhi Li[1]; [1]University of Texas Rio Grande Valley; [2]Mississippi State University

This study investigated synthesis of CuCrFeNiTiAl high entropy alloy (HEA) from pure elements using selective laser melting (SLM). The objectives are to validate the feasibility of the HEA fabrication from elemental powder materials, and to examine the effect of different laser energy inputs on the microstructures formed. The as-built samples under high, medium and low energy densities were characterized by X-ray diffraction (XRD), and the microstructures were observed using scanning electron microscopy (SEM). The XRD results showed that five major crystal structure phases (hexagonal, monoclinic, orthorhombic, body-centered cubic and rhombohedral) were present in all samples. Fine-grained phases were noticed on the formed surface with non-uniform microstructural distribution. Such phases in high and low energy density samples were observed polygonal while round-shaped microstructures were observed for samples prepared under medium energy density conditions. Also, the grain size was proportional to energy levels of the fabrication process.

Materials: Ceramics, Other I - Powder Bed Fusion

Monday PM August 2, 2021

Session Chair: A. Beese, Pennsylvania State University

1:30 PM
Geometry Limitations of Indirect Laser Sintering of Alumina: *Doug Sassaman*[1]; Joseph Beaman[1]; Desiderio Kovar[1]; Matthew Ide[2]; Carolyn Seepersad[1]; [1]University of Texas Austin; [2]ExxonMobil Research and Development Company

Complex ceramic architectures, such as honeycombs, are of great interest in the world of Additive Manufacturing (AM). However, design limitations and guidelines for manufacturing these with AM have not yet been established. In this work, we compare previously proposed geometry limitations for polymer Selective Laser Sintering (SLS) to ceramic geometries produced using indirect SLS. We focus on a small subset of shapes which are simple to produce and measure. We study the previously proposed geometry limitations for polymer SLS, and show that the these limitations for polymer SLS provide a good starting place for the design and manufacture of ceramic geometries using indirect SLS.

1:45 PM
Selective Laser Flash Sintering: Processing Conditions: *Deborah Hagen*[1]; Desiderio Kovar[1]; Joseph Beaman[1]; [1]University of Texas at Austin

Selective Laser Flash Sintering (SLFS) is an innovation in ceramic additive manufacturing. SLFS combines selective laser heating with simultaneous application of an electric field. The electric current that flows through the laser-heated ceramic powder bed during SLFS greatly enhances the sintering rate and lowers sintering onset temperature, making SLFS a promising path to polymer-free direct laser-sintering of ceramic powder. This work evaluates the effects of various SLFS processing conditions, such as laser scanning variables, applied energy density, and electric field.

2:00 PM
Characterization of n-type Bismuth Telluride Manufactured via Selective Laser Melting: *Ryan Welch*[1]; Dean Hobbis[2]; George Nolas[2]; Saniya LeBlanc[1]; [1]George Washington University; [2]University of South Florida

Thermoelectric modules are devices that use the Seebeck or Peltier effect to generate power or pump heat. A thermoelectric module consists of n- and p-type legs connected thermally in parallel and electrically in series. Thermoelectric materials usually have high electrical conductivity and low thermal conductivity. The structure of the material — porosity, grain structure, and dislocations — influence the material transport properties. In this work, we manufactured ingots of n-type bismuth telluride from dry powder via selective laser melting. The structure and composition of the laser melted samples were compared to a traditionally manufactured, melt grown sample. The results indicated a high porosity, high aspect-ratio grain structure, and bismuth and tellurium rich areas throughout the sample. We concluded that the powder morphology and build direction influenced the porosity and the grain structure, respectively, while oxidation caused variations in constituent elements within the samples.

2:15 PM
Creating Conformable Lithium Batteries Using Selective Laser Sintering: *Timothy Phillips*[1]; Craig Milroy[2]; Joseph Beaman[1]; [1]University of Texas Austin; [2]Texas Research Institute

Selective laser sintering is an additive manufacturing technique that consists of using a laser to consolidate powdered material to create complex three dimensional parts. Typically, SLS utilizes thermoplastic polymer media to create dense plastic components (direct SLS). It is also possible, however, to use composite powders with non-melting additives paired with a suitable binder to create highly functional materials (indirect SLS). This paper will describe the creation of composite materials using conductive and electroactive material additives to create lithium-ion battery components (i.e. anodes, cathodes, separators, and cases). Selective laser sintering adds to the geometric flexibility of the lithium battery components and enables batteries that conform to their surroundings, effectively reducing their footprint. Preliminary galvanostatic charge/discharge and capacity numbers will be presented for the functional Li-ion half cells created using SLS, as well as next steps to improve capacity and reliability.

2:30 PM
Investigating Thermally Induced Phase Separation as a Composite Powder Synthesis Technique for Indirect Selective Laser Sintering: *Patrick Snarr*[1]; Joseph Beaman[1]; Derek Haas[1]; [1]University of Texas at Austin

The nuclear energy and nuclear defense industries have long relied on traditional manufacturing techniques for fabrication of reactor and weapon components. With the recent growth of additive manufacturing (AM), the nuclear industry is now asking the question of how AM could be used to manufacture components found in the nuclear fuel cycle. Many important components in the nuclear fuel cycle are made from ceramics, including the popular fuel, uranium oxide. This research investigates an indirect selective laser sintering technique (SLS) that can be used to fabricate complex ceramic components. Thermally induced phase separation (TIPS) was explored as a technique to coat ceramic particles with a polymer, which can then be employed in an indirect SLS method. The process variables of TIPS were studied, and the resulting powder characterized. Parts were fabricated using the composite powder to show initial feasibility of TIPS as a composite powder synthesis technique for indirect SLS.

2:45 PM
Selective Laser Melting of Metal Cooling Devices onto Silicon: *Arad Azizi*[1]; Fatemeh Hejripour[1]; Matthew Heitner[1]; Nasim Anjum[1]; Vahideh Radmard[1]; Najmeh Fallahtafti[1]; Srikanth Rangarajan[1]; Changhong Ke[1]; Bahgat Sammakia[1]; Scott Schiffres[1]; [1]Binghamton University

A process for selective laser melting of metal onto silicon is demonstrated. Freeform structures on silicon devices can serve as single or two-phase heat sinks, or vapor chambers. This process will remove the thermal bottleneck of the thermal interface material that bridges the gap between silicon chips and heat sinks. This work overcomes the relatively weak bonding of metals onto silicon. By introducing an interlayer alloy (Sn3Ag4Ti), the wettability and bonding properties of these substrates with metals improves considerably without the need for any metallization. Furthermore, the low melting point of Sn3Ag4Ti reduces the thermal stresses at the interface during solidification. The developed process overcomes several key challenges relating to the speed of bonding and preventing thermal-stress damage. Simulations of the melting process will be related to the process parameters and the experimentally measured bond strength. Potential benefits of this technology to cooling in high performance computing will be discussed.

Materials: Metals I - High Entropy Materials

Monday PM August 2, 2021

Session Chair: F. Liou, Missouri University of Science and Technology

1:30 PM
A High Throughput Additive Manufacturing and Characterization Approach for Evaluating Structure-property Relationships in Multiphase High Entropy Alloys: *Jonathan Pegues*[1]; Michael Melia[1]; Raymond Puckett[1]; Shaun Whetten[1]; Nicolas Argibay[1]; Andrew Kustas[1]; [1]Sandia National Laboratories

High entropy alloys (HEA) exhibit unique physical/mechanical properties that often exceed those of conventional materials. Navigating the phase/property space presents significant challenges, particularly for conventional fabrication and characterization methods. Thus, a new approach is required to rapidly evaluate the phase-property space over large composition ranges. Powder based directed energy deposition provides an opportunity to synthesize a broad range of compositions in a single metallurgical sample via in situ alloying. This screening approach is utilized to investigate the phase-property space afforded by compositionally grading a transition metal-based HEA with several refractory metals. A high throughput microstructural-mechanical analysis method was also utilized to rapidly assess the associated phases-strength characteristics as a function of local composition. Compositions promoting solid solutions, multiple phases, intermetallics, high hardness, and brittleness were identified and discussed in the context of alloy-specific microstructural characteristics and configurational entropy.SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

1:45 PM
Exploring the Structure-property Relationships of W_xCoCrFeMnNi Graded High Entropy Alloy: *Jonathan Pegues*[1]; Michael Melia[1]; Benjamin Gould[2]; Raymond Puckett[1]; Shaun Whetten[1]; Nicolas Argibay[1]; Tomas Babuska[3]; [1]Sandia National Laboratories; [2]Argonne National Laboratory; [3]Lehigh University

Tungsten has been identified as a promising shielding material for high-temperature applications such as those involving plasma-material interactions. Utilizing an additive manufacturing enabled high throughput materials discovery framework, a tungsten graded high entropy alloy is screened to establish first order structure-property relationships. Compact metallurgical W_xCoCrFeMnNi specimens spanning x = 0 – 20% at. fractions were fabricated utilizing in-situ alloying enabled by powder based directed energy deposition. Microstructure evolution as a function of specific W_xCoCrFeMnNi compositions were identified through a combination of XRD/XRF and SEM-EDS/EBSD. Microhardness measurements were also performed to rapidly establish baseline structure-property relationships. Functional composition maps identifying compositions that promote solid solutions, multiple phases, intermetallics, high hardness, and brittleness are discussed in relation to the alloy-specific microstructural characteristics and configurational entropy. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

2:00 PM

Exploring the Structure-property Relationships of (Ti, $TiAl_6V_4$)$_x$CoCrFeMnNi Graded High Entropy Alloy: *Jonathan Pegues*[1]; Michael Melia[1]; Mark Rodriguez[1]; Raymond Puckett[1]; Shaun Whetten[1]; Nicolas Argibay[1]; Andrew Kustas[1]; [1]Sandia National Laboratories

High entropy alloys are a promising group of materials with seemingly limitless and unexplored composition spaces capable of producing physical/mechanical properties that exceed those of conventional materials. Utilizing an additive manufacturing enabled high throughput materials discovery framework, titanium graded high entropy alloys are screened to establish first order structure-property relationships. Compact metallurgical (Ti, $TiAl_6V_4$)$_x$CoCrFeMnNi specimens spanning x = 0 – 100% at. fractions were fabricated using in-situ alloying enabled by powder based directed energy deposition. Microstructure evolution as a function of specific (Ti, $TiAl_6V_4$)$_x$CoCrFeMnNi compositions were identified through a combination of XRD/XRF and SEM-EDS/EBSD. Microhardness measurements were also performed to rapidly establish baseline structure-property relationships. Functional composition maps identifying compositions that promote solid solutions, multiple phases, intermetallics, high hardness, and brittleness are discussed in relation to the alloy-specific microstructural characteristics and configurational entropy. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

Materials: Metals II - Titanium Alloys

Monday PM August 2, 2021

Session Chair: E. Reutzel, ARL Penn State / CIMP-3D

1:30 PM

A Comparative and Experimental Study on the Effect of Heat Treatment Cycles for PBF Ti6Al4V: Mutlu Karasoglu[1]; *Evren Yasa*[2]; Evren Tan[3]; Aydin Yagmur[4]; [1]Eskisehir Technical University; [2]Eskisehir Osmangazi University; [3]ASELSAN Inc.; [4]EOS GmbH

Powder bed fusion (PBF) presents the highest level of technology maturity and industrialization level for metallic materials among other Additive Manufacturing technologies. The advantages of high geometrical complexity, ability to produce internal cavities, reduced lead time and buy-to-fly ratio enables a wide range of application areas from aerospace to biomedical. Laser-PBF and Electron-PBF present different limitations and opportunities while they can both utilize Ti6Al4V. The performance of the E-PBF and L-PBF parts highly depends on the resulting microstructures and differs significantly due to various mechanisms such as preheating temperatures and processing environment. Moreover, the obtained material properties generally necessiate heat treatments for reducing residual stresses, enhancing mechanical properties and changing the microstructure. This study aims to investigate the effect of the same heat treatment cycles on the E-PBF and L-PBF microstructure evolution and microhardness by a comparative experimental work with several combinations of exposure durations, temperatures and cooling rates.

1:45 PM

Effects of Powder Reuse and Spatial Location Dependency on the Powder Characteristics and Defect Structure of Additively Manufactured Ti-6Al-4V Parts: *Arash Soltani-Tehrani*[1]; Mohammad Salman Yasin[1]; Shuai Shao[1]; Nima Shamsaei[1]; [1]Auburn University

In laser powder bed fusion (L-PBF), different powder characteristics including powder size and morphology may yield different packing states and thus different defect content in the resulting parts. As the powder is spread by the recoater, the packing state may not be uniform on the powder bed, giving rise to location-dependent part performance. In addition, as the powder is reused (a common practice in AM industry), its characteristics continuously evolve, causing the defect content to change from build to build. This study aims to investigate the effects of powder reuse and part location on powder characteristics as well as the defect structure of the parts. Results indicate powder reuse in an L-PBF system can reduce the defect content in the as-fabricated parts due to the superior flowability and packing state of reused powder. Part density was also found to be location-dependent, with more defects near the gas outlet.

2:00 PM

Effects of Stripe Width on the Porosity and Tensile Performance of Additively Manufactured Ti-6Al-4V Parts: *Arash Soltani-Tehrani*[1]; Mohammad Salman Yasin[1]; Shuai Shao[1]; Nima Shamsaei[1]; [1]Auburn University

In laser powder bed fusion (LB-PBF) additive manufacturing, parts are manufactured in a layer-by-layer pattern. In each layer, the laser scans the cross-section according to the hatch track size, which can be sufficiently long to cover up the whole cross-section or be partitioned into multiple segments. In the case of partitioning, the thermal history experienced by the part can be considerably different. Accordingly, defect distribution, as well as mechanical properties, might be affected. In this study, two sets of specimens were fabricated using LB-PBF from Ti-6Al-4V; in one set, the tracks were partitioned in 5-mm sections, while in the other set, they were separated at 100 mm resulting in no segments in the cross-sections. It was found that altering the stripe width can considerably affect the defect content as well as laser penetration depth. However, tensile strength was found not to be much sensitive to changing the stripe width.

2:15 PM

Generation and Characterization of Parameter- and Process-induced Defects in Powder Bed Fusion Additive Manufacturing, and Impact of Mechanical Properties Thereof: *Abdalla Nassar*[1]; Brett Diehl[1]; David Corbin[1]; Anil Chaudhary[2]; Jared Blecher[3]; Ryan Overdorff[4]; Peter Lee[5]; [1]The Applied Research Laboratory; [2]Applied Optimization; [3]3D Systems ; [4]3D Systems; [5]Northrup Grumman

Prevention, in-situ sensing, and post-build detection of defects in powder bed fusion additive manufacturing (PBFAM) are of significant interest to both researchers and end-users of the technology. The goal of much of this work is to quickly detect, then quantify the impact of defect characteristics on mechanical properties as part of a rapid certification/qualification strategies for PBFAM. Unfortunately, such efforts are impeded by a limited ability to controllably reproduce flaws, representative of natural ones. Here, controls methods are developed and implemented to produce lack of fusion, keyholing-induced porosity, and entrained spatter in Ti–6Al–4V samples produced using otherwise optimized (default) processing parameters. The developed methods do not rely on CAD or build file modifications, but rather in-situ parameter perturbations. The size, distribution, and morphology of defects are confirmed with high-resolution X-ray computed tomography, demonstrating the ability to produce defects of known size and morphology at known locations.

2:30 PM

Evaluating the Efficacy of X-ray Computed Tomography for Flaw Detection in Laser Powder Bed Fusion Additive Manufacturing using Automated Optical Serial Sectioning: *Zackary Snow*[1]; Edward Reutzel[1]; Abdalla Nassar[1]; Griffin Jones[1]; Rachel Reed[2]; Veeraraghavan Sundar[2]; Jayme Keist[3]; [1]Applied Research Lab at the Pennsylvania State University; [2]UES Inc.; [3]Applied Research Laboratory at the Pennsylvania State University

Flaws in additively manufactured (AM) components contribute to variability in fatigue properties. X-ray computed tomography (XCT) is often used to quantify flaw populations in AM material. However, we show that XCT flaw detectability can be as low as 3.3%. A custom, automated defect recognition algorithm was used to identify flaws in XCT and automated optical serial sectioning (AOSS) data of a 0.63 mm thick, cylindrical section of AM Ti-6Al-4V built on a commercial laser powder bed fusion system. Over 1000 flaws ranging from 8.5-65.2 µm in diameter were identified in the AOSS data. Only 33 flaws were identified in the corresponding region of the XCT data. Our results show that flaws absent from the XCT data do not only correspond to flaws below the XCT resolution. We conclude that the voxel size alone is not sufficient for determining XCT flaw detectability and recommend standardized XCT image quality metrics.

2:45 PM
Measurements and Predictions of Residual Distortion in AM Ti-6Al-4V Specimens: *James Sobotka*[1]; Matthew Kirby[1]; Shengyen Li[1]; [1]Southwest Research Institute

In 2018, the National Institute of Standards and Technology (NIST) presented additive manufacturing (AM) benchmark specimens. These specimens provide a challenge problem for the modeling and simulation community to evaluate predictive models of the AM build process. These tests included a residual stress/ distortion challenge problem for Inconel 625 and 15-5PH stainless steel using laser powder-bed fusion machines.. In 2019, we followed NIST specifications to produce the same geometry using Ti-6Al-4V in a Renishaw AM250 machine. This presentation describes the build process, shows 3D micro-CT scans pre/ post-sectioning, and presents distortion measurements following sectioning of the specimen from the build plate. Furthermore, this presentation describes a process-modeling framework to predict residual stresses using a sequential thermo-mechanical approach driven by laser scan strategy. This presentation closes with results from sensitivity studies and validation predictions that highlight predictive capabilities of the residual stress capability by predicting/ measuring residual distortion for an aerospace component.

3:00 PM
Challenges during Laser Powder Bed Fusion of a Near-alpha Titanium Alloy - Ti-6242Si: *Sagar Patel*[1]; Mohsen Keshavarz[1]; Mihaela Vlasea[1]; [1]University of Waterloo

Ti-6Al-2Sn-4Zr-2Mo-Si (Ti-6242Si) is a near-a phase titanium alloy that has a greater strength up to 565 °C compared to the workhorse Ti-6Al-4V alloy with a typical service temperature of up to 400 °C. While there is a wealth of literature to help understand the laser powder bed fusion (LPBF) of Ti-6Al-4V, only a few research articles about LPBF of Ti-6242Si are available in the open literature. In this work, LPBF processing diagrams and temperature prediction models were used to investigate the impact of process parameters such as laser power, scan speed, and beam spot radius on macroscale characteristics of the builds such as density and surface roughness. The use of processing diagrams allowed for exploration of density ranges between 99.55-99.98 %, and surface roughness, Sa, ranges between 8-16 µm in Ti-6242Si processed by LPBF. Cracking in Ti-6242Si manufactured by LPBF is reported for the first time. Cracking during LPBF of Ti-6242Si was observed to strongly depend upon the predicted melting mode (conduction, transition, and keyhole) for a given set of LPBF process parameters.

Modeling: I Geometries and Supports

Monday PM August 2, 2021

Session Chair: T. Kwok, Concordia University

1:30 PM
Investigation and Modeling of the Residence Time Dependent Material Degradation in the Arburg Plastic Freeforming: *Felix Hecker*[1]; Elmar Moritzer[2]; [1]Paderborn University, Direct Manufacturing Research Center (DMRC); [2]Paderborn University, Kunststofftechnik Paderborn (KTP)

The Arburg Plastic Freeforming (APF) is an additive manufacturing process with which three-dimensional, thermoplastic components can be produced layer by layer. One disadvantage of the APF is the long residence time of the molten material in the plasticizing unit compared to conventional injection moulding. The dosing volume is emptied very slowly due to only discharging fine plastic droplets. As a result, long residence times can be expected, which can lead to thermal degradation of the material.The aim of this study was to develop a model for calculating the residence time of the material in the APF. The residence time of the material in the thermally critical dosing volume is predicted using software developed in-house. The accuracy of the model could be verified by experimental investigations. Finally, the thermal degradation of the material was investigated by analyzing the molecular chain length distribution and considered in correlation to the mechanical properties.

1:45 PM
Support Structure Geometry influences on Strength and Removability for LPBF AM: *Samantha Welch*[1]; [1]Penn State University

Support structures are necessary when additively manufacturing a wider range of geometry in metal laser powder bed fusion. These scaffold-like structures perform multiple roles providing a structural and thermal interface to build part geometry, and are removed from the part post-build. While many variables exist for generating support geometry, few quantitative comparisons exist to show the influence of these variables in application. This study investigates the influences of support geometry changes on supported area strength and removability using tensile coupons fabricated in multiple material/parameter combinations. The results show that a larger tooth sizing is beneficial to both support strength and removability while decreased grid spacing aids in strength but not removability. A relationship between part parameters and z-offset settings is also observed. The quantitative results and settings recommendations for support structures from this study can be used to improve the success rate of builds and part geometry requiring support structures.

2:00 PM
Escaping Tree-support (ET-Sup): Minimizing Contact Points for Tree-like Support Structures in Additive Manufacturing: *Tsz Ho Kwok*[1]; [1]Concordia University

Support structures are often needed in additive manufacturing (AM) to print overhangs. However, they are the extra materials that must be removed afterwards. When the supports have many contacts to the model or are even enclosed inside some concavities, removing them is very challenging and has a risk of damaging the part. Therefore, the purpose of this research is to develop a new type of tree-support, named escaping tree-support (ET-Sup), which tries to build all the supports onto the build plate to minimize the number of contact points. All the operations are performed efficiently with the help of a ray representation. The method is tested on different overhang features, including a lattice ball and a mushroom shape with a concave cap. All the supports generated for the examples can find their way to the build plate. The computation time is around one second for these cases.

2:15 PM
Truss-Type Support Structures for SLM: *Subodh Subedi*[1]; Dan Thoma[1]; Krishnan Suresh[1]; [1]University of Wisconsin Madison

Support structures are critical in selective laser melting (SLM) of 3D metal additively manufactured components. Besides providing structural support, they serve as conduits for efficient heat dissipation. Support structures heavily influence the printability of a part as well as its physical and mechanical properties. Commonly used thin walled surface support structures are reliable, but are difficult to optimize, post-process, and often entrap a significant amount of powder. This paper presents the concept of truss-type surface support structures for SLM to address these challenges. The proposed structures are easy to optimize, provide better anchorage and part printability; further, they do not entrap powder, and are easy to remove. Experimental results demonstrate the effectiveness of these designs over commonly used support structures, paving a path towards optimal support structure design for SLM.

2:30 PM
Watertight Geometric Modeling for the Additive Manufacturing Digital Thread: *Ryan Jennings*[1]; Brian Ferguson[1]; John McCann[1]; Benjamin Urick[2]; Richard Crawford[2]; Dan Keller[2]; [1]Kansas City National Security Campus; [2]nVariate, Inc.

The standard digital workflow for generating input data for additive manufacturing (AM) processes consists of an ad hoc and pragmatic approach of modeling representations. Typical downstream representations employed are the result of the CAD model not being directly suitable for use. Derivative models are generated to fill this need and to solve critical issues with flaws in the CAD data, but as a result introduce many other problems affecting both the digital process as well as the precision of the final AM print.The Kansas City National Security Campus (KCNSC) is working towards a solution to eliminate these problems by investigating the value provided by a smooth, accurate, and watertight geometric definition within the native CAD platform. To do so, KCNSC is partnering with nVariate, Inc. to utilize their patented technology to create natively watertight models, and explore directly slicing the watertight CAD models for use on the AM machine. The Department of Energy's Kansas City National Security Campus is operated and managed by Honeywell Federal Manufacturing & Technologies, LLC under contract number DE-NA0002839.

2:45 PM
Manufacturability Analysis of Crumple-formed Geometries Through Reduced Order Models: *Olivia Trautschold*[1]; Andy Dong[1]; [1]Oregon State University

Crumple-formed structures have irregular, multiscale geometric complexity. Similar to periodic lattices, crumpled geometries may be tailored to applications requiring a high strength-to-weight ratio. Their inherently irregular geometries decrease the sensitivity of the relationship between macroscale properties and microscale manufacturing defects but also pose a unique challenge for the analysis of manufacturability using additive processes. This paper presents a preliminary study into the manufacturability of crumple-formed structures using a model reduction technique that preserves the robust bulk statistical properties of crumpled structures. Current approaches to manufacturability analysis lack dimensionality reduction techniques suitable for approximating the multiscale geometric complexity and irregularity of crumpled structures. Manufacturability predicted by the reduced order model is experimentally assessed by comparison between the simulated and manufactured crumpled geometries using image analysis techniques. As an alternative to conventional confinement-based crumple forming, additive manufacturing allows for increased geometric control and structural reproducibility.

Physical Modeling: I Melt Pools

Monday PM August 2, 2021

Session Chair: J. Beuth, Carnegie Mellon University

1:30 PM
Controlling Interdependent Meso-nanosecond Dynamics and Defect Generation Using a Digital Twin: *Saad Khairallah*[1]; Aiden Martin[1]; Jonathan Lee[1]; Gabe Guss[1]; Nicholas Calta[1]; Joshua Hammons[1]; Michael Nielsen[1]; Kevin Chaput[2]; Edwin Schwalbach[2]; Megna Shah[2]; Michael Chapman[2]; Trevor Willey[1]; Alexander Rubenchik[1]; Andrew Anderson[1]; Y. Morris Wang[3]; Manyalibo Matthews[1]; Wayne King[4]; [1]Lawrence Livermore National Laboratory; [2]Air Force Research Laboratory; [3]U. California Los Angeles; [4]The Barnes Group Advisors

We used ALE3D high-fidelity multi-physics model, which was verified with in-situ X-ray and other diagnostics experiments, to study laser-powder and laser-melt pool interactions at short time scales. We captured different modes of laser powder interactions that involve laser expulsion of spatter and laser shadowing (spatter blocking the laser rays). We report on self-replicating spatter, that once formed, become hard to get rid of due to a self-replication mechanism that involves loose particles in the powder layer. We explain how pre-sintering the powder could be a strategy to mitigate this effect. Spatter beyond a size threshold can cause pores due to laser shadowing. We identified the laser scan strategy as one source of these large spatter sizes and derived a stability criterion to prevent them. Work performed under the auspices of U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE- AC52-07NA27344. Lawrence Livermore National Security, LLC. Release LLNL-ABS-799067.

1:45 PM
Modeling the Effects of Coordinated Multi-beam Laser Powder Bed Fusion on Melt Pool Geometry and Solidification Microstructure: *Rachel Evans*[1]; Joy Gockel[1]; [1]Wright State University

The laser powder bed fusion (LPBF) additive manufacturing (AM) process is beneficial for many reasons; however, it is limited by the solidification thermal conditions achievable in the available processing parameter ranges for single-beam processing methods. The addition of multiple heat sources has the potential to provide better control over the thermal conditions, thus providing better control of the microstructure of AM parts. This work investigates the effects of adding multiple, coordinated heat sources to the LPBF process. To do this, existing thermal models of LPBF have been modified to predict the thermal effects of two coordinated heat sources. These computational models are used to calculate melt pool dimensions and thermal conditions due to the coordinated multi-beam scan strategy. The predictive method used in this research provides insight into the effects of using multiple coordinated beams in LPBF, which is a necessary step in increasing the capabilities of the AM process.

2:00 PM
3D Transient Zone in Conduction and Keyhole Mode Melting in Laser Powder Bed Fusion Process: *Santosh Rauniyar*[1]; Kevin Chou[1]; [1]University of Louisville

In the laser powder bed fusion (LPBF) process, laser travels in predefined scan paths in each layer of the layer by layer building process. There exists a transient regime at the start and at the end of the individual scans for any given value of power and scan speed. The melt pool geometry in the transient regime is different compared to the quasi-steady state in the middle region of the scans. The transient zone is prominent in the smaller scan lengths (e.g. 2 mm or less) since the track length may not be enough for the melt track to reach a quasi-steady state. In this study, the melt pool geometry in the transient zone of short scan lengths is analyzed for conduction and keyhole mode of melting. Discrete element method is used to generate a powder bed of Ti-6Al-4V particles and thermo-fluid simulation is performed in commercial software.

2:15 PM
Inference of Metal Additive Manufacturing Process States via Deep Learning Techniques: Richard Anarfi[1]; Benjamin Kwapong[1]; Kenneth Fletcher[1]; Aaron Flood[2]; Todd Sparks[2]; *Mugdha Joshi*[3]; [1]University of Massachusetts Boston; [2]Product Innovation and Engineering; [3]Missouri University of Science and Technology

Numerical simulation of metal additive processes are computationally intensive tasks. Iterative solution techniques for physics-based methods can lead to lengthy solution times and convergence problems, particularly if fluid dynamics of the melt pool are considered. Deep learning (DL) techniques offer an opportunity to infer solution results quickly. This paper proposes a DL method based on long short-term memory (LSTM) network trained on rendered images from metal additive process simulation and CAM data. We first obtain vector representations of the images by training on an autoencoder. LSTM is a memory-based recurrent neural network (RNN) that is capable of processing long sequences of data while combating temporal stability problems encountered with conventional RNNs. The LSTM model is used to predict images of the process given scan path and process information. This could later be used to compare with process monitoring systems as part of a quality assurance or process control schema.

2:30 PM
Thermomechanical and Geometry Model for Directed Energy Deposition with 2D/3D Toolpaths: *Deniz Ertay*[1]; Mihaela Vlasea[1]; Kaan Erkorkmaz[1]; [1]University of Waterloo

Directed energy deposition (DED) is a metal additive manufacturing (AM) technology, where achieving tight dimensional tolerances is more challenging compared to conventional manufacturing processes. Process modeling and monitoring are common approaches to improve process accuracy and repeatability. So far, analytical modeling efforts have been limited to simple scan paths in literature. In this study, a voxel-based modeling approach is presented, capable of simulating a complex deposition path and predict the melt pool temperature, thermal history, and deposition geometry. A dual-wavelength pyrometer is used coaxially with the laser beam to validate the melt pool temperature predictions by sampling the calibrated intensity field in the melt pool and the actual position along the deposition path. Two different sets of processing parameters are used in the experiments to validate the model predictions, along complex beam paths. The differences in measured and predicted melt pool temperature and deposition geometry are observed.

Process Development: I Novel Processes and Advances A

Monday PM August 2, 2021

Session Chair: C. Pannier, University of Michigan-Dearborn

1:30 PM
In-situ Meltpool Monitoring and Temperature Estimation via Two-wavelength Pyrometry Using a Single Camera: Chaitanya Vallabh[1]; Dian Li[1]; Yubo Xiong[1]; *Xiayun Zhao*[1]; [1]University of Pittsburgh

In laser powder bed fusion processes, meltpool dynamics monitoring can help predict the process behavior and part condition. In this work, we present an in-situ meltpool monitoring approach built on the principles of two-wavelength pyrometry using a single high-speed camera as opposed to the typical utilization of multiple cameras. The camera and the optics system are coaxially aligned to the source laser and the reflected meltpool. The camera can continuously monitor the meltpool sufficiently fast (>100,000 fps) with a spatial resolution of 20 µm. The intensities of the meltpool at two wavelengths are analyzed for obtaining the temperature profile. The changes in meltpool morphology, laser scan speed and path are also monitored. Preliminary data shows a great potential of the developed method for continuously estimating meltpool temperature profile, and monitoring meltpool morphology and motion. Experimental data corresponding to these parameters can help correlate the process parameters to the part defects.

1:45 PM
Effect of Scan Strategy on Melt-pool Geometry, Surface Topology and Internal Porosity of Additively Manufactured Inconel 625 Alloy: *Ho Yeung*[1]; Felix Kim[1]; Jorge Neira[1]; [1]National Institute of Standards and Technology

The effect of the scanning strategy on melt-pool geometry, surface topology, and internal porosity is investigated on a custom-built laser powder bed fusion additive manufacturing (AM) testbed. The testbed adapted an open platform design with all the control parameters accessible, and is driven by an in-house developed simple AM (SAM) control software. The software allows the scan strategy to be created from a combination of different infill patterns/paths and laser power/velocity controls. Nine Inconel 625 cubic parts were built with different scan strategies, some of which are not available on commercial systems. The build process was in-situ monitored with a high-speed camera aligned with the heating laser. The parts built were ex-situ measured with X-ray computed tomography-imaging for porosity, and laser profiler for surface topology. The in-situ and ex-situ measurements are compared, and the characteristics of different scan strategies are highlighted.

2:00 PM
A Numerical Study Showing the Impacts of Dwell Time during the Laser Powder Bed Fusion Process: *David Failla*[1]; Matthew Priddy[1]; [1]Mississippi State University

Laser powder bed fusion (L-PBF) is an additive manufacturing technique often used for producing metallic components with small tolerances. To leverage this precision, process parameters such as scan speed and laser power require calibration via experimental trial and error. Numerical methods, such as sequentially-coupled thermomechanical simulations, can be leveraged to predict part defects and residual stresses. However, the dwell time that occurs during the powder layer deposition of the L-PBF process is often neglected within these frameworks. This work demonstrates the impact of dwell time by simulating the fabrication of 316L stainless steel cubes from 10 mm to 75 mm side lengths. This is to determine the impacts of dwell time on the predicted thermal history and residual stresses in the L-PBF part as a function of cross-sectional area. Validation will be derived by contrasting predicted part deformations and estimated residual stresses with L-PBF printed 316L stainless steel cubes.

2:15 PM
Optical Observation of Sintering State for Large Area Projection Sintering (LAPS): *Derek Black*[1]; Landon Shumway[1]; Jacob Henderson[1]; Nathan Crane[1]; [1]Brigham Young University

Additive manufacturing (AM) is commonly implemented in the areas of prototyping and modelling. However, there are still significant obstacles to broader adoption, including poor repeatability and mechanical properties when compared to traditional manufacturing processes. While many methods for evaluating AM part quality exist, most are difficult or impossible to implement in real time and use for feedback control. In Large Area Projection Sintering (LAPS), extended sintering times make it possible to observe prints in real time. This study investigates the capabilities of optical imaging to assess sintering state in real time. While illuminating the build area, the reflection from the build surface was measured via an optical camera and correlated to different stages of melting which is referred to as sintering state. The measured sintering state was then compared to measured material properties. The properties of most interest include degree particle melt, ultimate tensile strength, and elongation at break.

2:30 PM
Improving the 3D Printed Bond Strength at a Discrete Interface Between Dissimilar Materials: *Chad Duty*[1]; Justin Condon[2]; Tyler Smith[2]; Alexander Lambert[2]; Seokpum Kim[2]; Vlastimil Kunc[2]; [1]University of Tennessee; [2]Oak Ridge National Laboratory

The majority of extrusion-based 3D printing technologies make use of a single material. However, more complex applications require the deposition of multiple materials that often have different processing conditions or material properties. The bond between these materials typically occurs at a discrete interface between adjacent rows or successive layers in a 3D printed structure. A z-pinning approach has previously demonstrated improved mechanical properties for a single material system by extruding material into an existing void that spans multiple layers in a printed structure. The current research extends this concept to the printing of multi-material structures, where a material with a lower processing temperature is deposited on previous layers of a higher melt polymer. The geometry and spacing of the z-pins that cross the interface are varied to improve the bonding strength between the two materials by more than an order of magnitude.

Special Session: Composite AM I - Metals and Ceramics

Monday PM August 2, 2021

Session Chair: A. Elliott, Oak Ridge National Laboratory

1:30 PM

Process Development for the Selective Laser Melting of Tungsten Carbide-nickel Matrix Composites: *Edgar Mendoza Jimenez*[1]; Baby Reeja-Jayan[1]; Jack Beuth[1]; [1]Carnegie Mellon University

In this work, laser powder bed fusion (LPBF) is used for the additive manufacturing of composite samples consisting of tungsten carbide particles with a nickel binder. Such process can become a viable low-energy alternative to the conventional production of ceramic-metal composites for applications including tooling, electronics, and wear components. Single track experiments are used to evaluate the melting behavior of the composite material. Samples are then printed with of process parameters that adequately melted the material. The density, microstructure, and functional properties of these samples are measured. Highly dense (>98%) samples are successfully manufactured and analyzed as a function of LPBF parameters. Macro- and microdefects resulting from the laser processing are also discussed. A methodical approach to evaluate an acceptable processing region is presented and used to investigate the feasibility of additively manufacturing tungsten carbide-nickel composites via LPBF.

1:45 PM

Development of Bimetallic Casting for Wear Performance through Infiltration of Additively Manufactured Metal Lattice Structures: *James Liggett*[1]; Dean Snelling[1]; Mingzhi Xu[1]; Oliver Myers[2]; Scott Thompson[3]; [1]Georgia Southern University; [2]Clemson University; [3]Kansas State University

High chromium white iron is an alloy frequently employed in the production of abrasion resistive wear components. Although this alloy demonstrates excellent wear performance from the formation of chromium carbides, it is brittle and lacks toughness. Impact resistance is often of great importance for ground engaging wear components, and for this reason a method is proposed by which high chromium white iron wear components may be reinforced by the formation of a bimetallic composite. In this research, an additively manufactured lattice structure of 316L stainless steel is infiltrated with high chromium white iron via the metal casting process. This procedure results in a bimetallic casting of reinforced white iron. Through complete infiltration, partial metallurgical diffusion bonding was observed between the two alloys. Furthermore, mechanical and metallurgical testing results validated this method as a means of reinforcing high chromium white iron castings for applications requiring high abrasion and impact resistance.

2:00 PM

Microstructural Evolutions in Jetting Reinforcement Nanoparticles to Metal Matrix in Laser Powder Bed Fusion: *Milad Ghayoor*[1]; Omid Sadeghi[1]; Ryan Doyle[1]; Bryce Cox[1]; Joshua Gess[1]; Somayeh Pasebani[1]; [1]Oregon State University

Oxide dispersion strengthened (ODS) alloys are metal-matrix composites in which nano-oxides suppress grain boundary mobility at elevated temperature and enhance creep resistance. Conventional manufacturing of ODS alloy includes numerous steps such as mechanical alloying and hot consolidation, making it costly and time-consuming. The laser powder bed fusion (LPBF) process was utilized to produce 316L ODS alloy. This study investigates the microstructure of 316L ODS alloy developed via two different additive approaches. First, 316L powder and alumina particles were mixed and used as feedstock for producing 316L ODS. Second, ink-jetting in LPBF process was utilized to manufacture 316L ODS. The ink, containing nanoparticles of alumina, was selectively deposited into powder bed, and then laser consolidated powder and nanoparticles into nanocomposite. Detailed microstructure characterization revealed that the alumina was melted, precipitated, and homogenously dispersed in the matrix during solidification; thus, eliminating ball-milling and further machining to make a component from ODS alloys.

2:15 PM

Composition-processing-properties Relationships for In Situ Reinforced Ti-B4C-BN Composites via Directed Energy Deposition: *Kellen Traxel*[1]; Amit Bandyopadhyay[1]; [1]Washington State University

Composite material development via laser-based additive manufacturing offers many exciting advantages to manufacturers; however, a significant challenge exists in our understanding of process-property relationships for these novel materials. Herein we present our work on the effects of input processing parameters on a highly oxidation-resistant titanium matrix composite towards influencing the microstructure and properties for high-temperature applications. By adjusting the linear input energy density, a composite feedstock of titanium-boron carbide-boron nitride (5wt% overall reinforcement) resulted in a highly reinforced microstructure composed of borides, carbides, and nitrides, with variable properties and oxidation performance depending on the overall input energy. Single-tracks and bulk samples were fabricated to understand the processing characteristics better and in situ reactions that occur during processing. Our results indicate that input processing parameters can play a significant role in microstructure formation and oxidation resistance of titanium matrix composites and can be exploited by manufacturers for improving component performance.

2:30 PM

Laser Powder Bed Fusion of Highly-reinforced Metal Matrix Composites: *Ethan Parsons*[1]; [1]MIT Lincoln Laboratory

Aluminum metal matrix composites (MMCs) are highly desirable materials for precision aerospace applications, where stiffness and low mass are critical, but they are rarely used because of their cost and machining difficulty. In these applications, components typically have complex geometries and are produced in small numbers. Therefore, processing metal matrix composites additively would be the ideal solution, but MMCs with high ceramic content are not commercially available for AM. Here, using purely mechanical methods and readily available constituent powders, we fabricate composite feedstock powders optimized for laser powder bed fusion in a cost-effective, scalable manner. We demonstrate that these powders can be laser consolidated to nearly 100% relative density, providing a potential pathway for the broader adoption of these high-performance yet underused materials.

2:45 PM

Study of Printing Parameters in Binder Jet Additive Manufacturing of Cobalt Chrome - Tricalcium Phosphate Biocomposite: Kuldeep Agarwal[1]; *John Ruprecht*[1]; [1]Minnesota State University

Traditional metals such as stainless steel, titanium and cobalt chrome are used in biomedical applications (implants, scaffolds etc.) but suffer from issues such as osseointegration and compatibility with existing bone. One way to improve traditional biomaterials is to incorporate ceramics with these metals so that their mechanical properties can be similar to cortical bones. Tricalcium phosphate is such a ceramic with properties so that it can be used in human body. This research explores the use of binder jetting based additive manufacturing process to create a novel biocomposite made of cobalt chrome and tricalcium phosphate. Experiments were conducted and processing parameters were varied to study their effect on the printing of this biocomposite. This effect is important to understand so that the material can be optimized for use in specific applications. This study is an extension of the work presented in 2019 to include more material and analysis with SEM.

3:00 PM
Conformal Multifunctional Composite Fabrication via Conductive Direct Ink-write and Sacrificial Additively Manufactured Tooling: *Jacob Viar*[1]; Joseph Kubalak[1]; Christopher Williams[1]; Bradley Davis[2]; [1]Design, Research, and Education for Additive Manufacturing Systems (DREAMS) Lab; Department of Mechanical Engineering; [2]Hume Center for National Security and Technology at Virginia Tech; Bradley Department of Electrical & Computer Engineering

Mulitfunctional composites have gained significant interest as they enable the integration of sensing and communication capabilities into structural, lightweight composites. Researchers have explored additive manufacturing processes for creating these structures through selective patterning of electrically conductive materials onto composites. Thus far, work in this area has been limited to fabricating simple, planar geometries due to an inability to adequately deposit conductive material over concave geometries. Proposed methods of integrating functional devices within composites have been shown to negatively affect their mechanical performance. In this work, we present a novel method for integrating electronic passives onto the interior surfaces of closed, complex continuous fiber composite structures via direct ink writing of conductive inks onto additively manufactured sacrificial tooling. Additionally, characterization of a complex composite surface featuring a patch antenna operating in the Ku band. The process is demonstrated as creating multifunctional composites without negatively affecting the mechanical performance of the structure.

Special Session: Data Analytics in AM I - Optimization of Process, Design and Materials A

Monday PM August 2, 2021

Session Chair: P. Rao, University of Nebraska

1:30 PM
On the Diminishing Returns of Thermal Camera Resolution for PBF Temperature Estimation: *Nathaniel Wood*[1]; Edwin Schwalbach[2]; Andrew Gillman[2]; David Hoelzle[1]; [1]The Ohio State University; [2]Air Force Research Laboratory

Powder Bed Fusion (PBF) faces ongoing challenges in the areas of process monitoring and control. Standard methods for alleviating these issues rely on machine learning, which requires costly and time-consuming training data. Expense is compounded by the perceived necessity of using sensors with extremely high resolutions. This research avoids this cost by employing an Ensemble Kalman Filter (EnKF), which uses measured data to correct physics-based model predictions of the process, to monitor part internal temperature fields during building. This work tests EnKF performance, in simulation, for two model architectures, using simulated cameras of varying resolution as our measuring instruments. Crucially, we show that increasing camera resolution produces diminishing returns in EnKF accuracy, relative to the model predictions, with up to 81% error reduction. This result shows that current AM quality control practices with expensive sensors may be inefficient. With appropriate algorithms, cheaper setups may be used with little additional error.

1:45 PM
In-situ Thermographic Inspection for Laser Powder Bed Fusion: *Tao Liu*[1]; Cody Lough[1]; Hossein Sehhat[1]; Jie Huang[1]; Edward Kinzel[2]; Ming Leu[1]; [1]Missouri University of Science and Technology; [2]University of Notre Dame

Laser powder bed fusion is strongly influenced by the quality of the powder layer including the powder properties as well as the layer thickness. In particular, thermal stresses can produce sufficient part deformation to the point that a part interferes with the wiper. This paper investigates the use of long-wave infrared thermography to monitor the surface temperature of the build. When cold powder is spread by the recoater, heat diffuses from the underlying part through the powder. The surface temperature history is a strong function of the thermal transport properties of the powder as well as the thickness. This correlation is explored and measured experimentally. It is then used to estimate the powder layer thickness above overhanging parts. This approach is shown to capture the part distortion and predicts wiper state prior to catastrophic interaction with the part.

2:00 PM
Towards Online Monitoring and Data-Driven Control: A Study of Segmentation Algorithms for Infrared Images of the Powder Bed: *Alexander Nettekoven*[1]; Scott Fish[1]; Joseph Beaman[1]; Ufuk Topcu[1]; [1]University of Texas Austin

An increasing number of selective laser sintering and selective laser melting machines use off-axis infrared cameras to improve online monitoring and data-driven control capabilities. However, there is still a severe lack of algorithmic solutions to properly process the infrared images from these cameras that has led to several key limitations: a lack of online monitoring capabilities for the laser tracks, insufficient pre-processing of the infrared images for data-driven methods, and large memory requirements for storing the infrared images. To address these limitations, we study over 30 segmentation algorithms that segment each infrared image into a foreground and background. By evaluating each algorithm based on its segmentation accuracy, computational speed, and robustness against spatter detection, we identify promising algorithmic solutions. The identified algorithms can be readily applied to the selective laser sintering and selective laser melting machines to address each of the above limitations and thus, significantly improve process control.

2:15 PM
Droplet Diagnostics in Droplet-on-Demand Liquid Metal Jetting Using Heterogenous Sensing: *Aniruddha Gaikwad*[1]; Tammy Chang[2]; Nicholas Watkins[2]; Brian Giera[2]; Saptarshi Mukherjee[2]; David Stobbe[2]; Andrew Pascall[2]; Prahalada Rao[1]; [1]University of Nebraska-Lincoln; [2]Lawrence Livermore National Laboratory

The goal of this work is to monitor the characteristics of jetted liquid metal droplets in a droplet-on-demand liquid metal jetting (DoD-LMJ) additive manufacturing process. A millimeter-wave near-field sensor and high-speed video camera were deployed in a custom tin liquid metal jetting system. Experiments were conducted to capture the effect of processing parameters on the droplet characteristics, viz., size, velocity, and shape of droplets. Subsequently, predictive models were developed to monitor these droplet characteristics using the multimodal sensor data, and then predict droplet parameters from the millimeter-wave signals alone, to achieve a major reduction in processing requirements. We present a multilayer perceptron-based non-linear autoregression with exogenous inputs model to predict droplet size and velocity. Additionally, we developed an ensemble machine learning model to monitor the shape of droplets. Our models predict/classify with a statistical fidelity exceeding 0.9 (R2 and F1-score), demonstrating the potential of heterogeneous sensing in LMJ systems.

2:30 PM
Deep Learning Assisted Approach to Monitoring Anomalies of 3D-bioprinting Process: *Zeqing Jin*[1]; Grace Gu[1]; [1]University of California, Berkeley

Advances in additive manufacturing (AM) have enabled the fabrication of parts with complex designs and multiple functionalities. Recent 3D-bioprinting technology is now able to create biocompatible materials and structures for functional living cells. Meanwhile, the success of long-term biological applications is dependent on creating a high-quality bioprinted part identical to the desired design. However, challenges exist in detecting the anomalies within transparent bioprinted parts with complex features accurately and efficiently. In this study, an anomaly detection system based on layer-by-layer camera images and machine learning algorithms is developed to distinguish and classify imperfections for transparent hydrogel-based bio-printed materials. High accuracy is obtained by utilizing convolutional neural network methods as well as image processing techniques. It is envisioned that this work will provide effective information on the layer-wise printing conditions as well as potential applications in autonomous correction of bioprinters without human interaction.

2:45 PM
Bayesian Process Optimization for Additively Manufactured Nitinol: *Jiafeng Ye*[1]; Mohammad Salman Yasin[1]; Jia Liu[1]; Aleksandr Vinel[1]; Daniel Silva Izquierdo[1]; Nima Shamsaei[1]; Shuai Shao[1]; [1]Auburn University

Nitinol, a popular shape memory alloy, has various applications in automotive, telecommunication, and medical. Additive manufacturing can further unleash its potential with great flexibility and cost-effectiveness in design and rapid prototyping. In this work, we utilize a Gaussian process-based Bayesian optimization method to efficiently optimize process parameters of the laser beam-powder bed fusion (LB-PBF) process to achieve high-density fabrication with nitinol shape memory alloy. Specifically, Gaussian process regression is applied to formulate a surrogate model between the critical process parameters (i.e., laser power, scanning speed) and the porosity of the nitinol samples. Then Bayesian optimization is integrated to successively explore the design space to find the optimal process parameters. Compared with the traditional trial-and-error methods, this method can quickly find the optimal process parameter for the high-quality nitinol products and accelerate the product innovation with nitinol in additive manufacturing.

3:00 PM
Multi-modal In-situ Monitoring Data Analysis for Overhang Features Built with Laser Powder Bed Fusion: *Ndeye Yande Ndiaye*[1]; Zhuo Yang[2]; Simin Li[3]; Jennifer Li[4]; Yan Lu[1]; Brandon Lane[1]; Ho[1]; [1]National Institute of Standards and Technology; [2]UMass Amherst; [3]University of Maryland; [4]Blair High School

Part geometry in the powder bed fusion process decides the cross-section of layer slices which impact the mechanism of the support structure. The overhang down-skin surface receives support purely from powders showing poor geometric accuracy and surface roughness. This study collects in-situ coaxial melt pool and layerwise overview images to investigate the dimensional deviations in overhang regions based on a part designed with several overhang features. Statistical analysis within crossed layers and modalities is conducted to retrieve common features and find correlations between multi-modal observations. Both the layerwise pixel (LWP) index and melt pool monitoring (MPM) index strongly correlate to the overhang features of different gradients. The LWP index at the overhang down-skin region is noticeably higher than in the regular region, similar to the MPM index on microscale regional analysis. The results match the observations from XCT scan and provide a way to do fast anomaly detection in real-time.

3:15 PM
In-situ Verification of 3D-Printed Electronics Using Deep Convolutional Neural Networks: *Daniel Ahlers*[1]; [1]Universität Hamburg

Printed electronics processes are becoming more stable and evolve into first industrial applications. These industrial applications require proper quality assurance to get a mostly autonomous production process. In this work, we present a new approach to inspect printed electronics and ensure their quality. Our hardware setup extends a fused filament fabrication (FFF) printer with an extruder for direct dispensing of conductive paste, a pick and place unit, and two cameras. The cameras take multiple images during printing. A trained neural network analyzes these pictures to separate the electronic wires from the plastic background. All separated images of a layer are combined to get a full view of the layer. Our algorithms then examine the detected wires to identify printing flaws. The algorithms currently detect connection breaks, shorts, find points that have not been reached, and evaluate the width of the printed wires.

Special Session: Design Methodologies for Tailoring Performance of Additively Manufactured Parts for Naval Applications

Monday PM August 2, 2021

Session Chair: A. Achuthan, Clarkson University

1:30 PM
A Dislocation Density Based Constitutive Model for the Design of Additively Manufactured (AM) Metals and Alloys: Chamara Herath[1]; Janith Wanniarachchi[1]; *Ajit Achuthan*[1]; [1]Clarkson University

Classical crystal plasticity based constitutive models are inept at capturing the effects of complex hierarchical microstructures of additively manufactured (AM) components. Therefore, microstructure informed constitutive models which apprehend the sub grain level features are important for the design and development of components for advanced applications. In this presentation, the development of a microstructure informed crystal plasticity based constitutive model that accounts for the geometric and mechanistic effects of the grains and other sub grain features will be discussed. The size and shape effect of individual grains are accounted by considering the grains as ellipsoids, containing a core and mantle with different shear strain parameters. The effect of cellular structure is accounted following a dislocation density based approach, treating the cellular structure as tubular structures with hexagonal cross sections. Model is validated experimentally by testing coupon 316L samples manufactured by laser engineered net shaping (LENS).

1:45 PM
Microstructural Modeling of ß to a Transformation Morphologies in Multi-layered Laser Wire Additively Manufactured Ti-6Al-4V Parts: *Andrew (Drew) Huck*[1]; Anthony Rollett[1]; Amit Verma[1]; Brandon Abranovich[1]; Jack Beuth[1]; Ali Guzel[1]; Lonnie Smith[1]; P.C. Pistorius[1]; Amaranth Karra[1]; [1]Carnegie Mellon University

This work is supported by the Quality Made program from the Office of Naval Research. The room temperature microstructure of Ti-6Al-4V in multi-bead laser weld deposited builds is characterized by predominantly lamellar a phase growth with interlamellar ß. This microstructure is the result of a complex position dependent thermal history from subsequent layer depositions. Several a morphologies and different lamellar sizes appear depending on local ß character and cooling rates, which can affect the bulk mechanical properties of the material by causing local changes. This work attempts to model location referenced microstructural evolution in laser-wire deposited parts using a classical nucleation and growth model. Additive isothermal time steps in a JMAK type transformation with impingement correction are taken to approximate the cooling curves. Predicted values include area fractions of grain boundary, colony, basketweave, and martensitic a phase, as well as average lamella thickness. Results were compared to actual built structures.

2:00 PM
Evaluation of Liquid Doping Methods for Use in Laser Powder Bed Fusion: *Taylor Davis*[1]; Tracy Nelson[1]; Nathan Crane[1]; [1]Brigham Young University

Laser powder bed fusion (LBPF) is one of the most widely-preferred additive manufacturing (AM) techniques, but it has not yet achieved its potential to spatially vary mechanical properties by spatially tuning the composition in three dimensions. Such control would allow for greater design flexibility and enable optimization of single parts for performance of various functions. Most efforts to achieve composition control have required extensive modifications of the powder delivery system that significantly reduce the build rate. The current study is a preliminary feasibility test for spatial composition control while maintaining standard powder delivery methods. The effects of small amounts of alumina dopant on a 316L stainless steel plate using single-track tests are reported. Size and dispersion of alumina particles in the melt pool, melt pool size and geometry, and the size and structure of resulting grains are compared for a range of process parameters.

2:15 PM
Influence of the Loading Direction on the Mechanical Properties of Additively Manufactured Metals: Janith Wanniarachchi[1]; Chamara Herath[1]; *Ajit Achuthan*[1]; [1]Clarkson University

Unlike the classical grain structure in conventional stainless steel, the growth direction of the epitaxial grain structure in additively manufactured (AM) stainless steel (SS 316L) is highly correlated with the thermal gradient. The thermal gradient also influences the formation of the tubular dislocation network, typically found in AM material due to the high solidification rate. In this study, the role of the direction of the tubular subgrain features on mechanical properties is investigated. Samples manufactured using laser engineered net shaping (LENS) were tested using in-situ micron-scale tensile testing. The mechanical performance of specimens loaded in the direction parallel and perpendicular to the build directions of the wall were compared. Differences in the slip band formation between the two testing directions were studied. An empirical model based on dislocation theory to predict the yield strength and ductility of the material by taking the aspect ratio of the tubular microstructure is proposed.

2:30 PM
Effect of Composition and Phase Diagram Features on Printability and Microstructure in Laser Powder Bed Fusion: Development and Comparison of Processing Maps Across Alloy Systems: *Raiyan Seede*[1]; Jiahui Ye[1]; Austin Whitt[1]; William Trehern[1]; Alaa Elwany[1]; Raymoundo Arroyave[1]; Ibrahim Karaman[1]; [1]Texas A&M University

Additive manufacturing (AM) has gained considerable interest due to its ability to produce parts with complex geometries with the potential for local microstructural control. However, there is a fundamental gap in understanding how changes in process variables and alloy composition affect additively manufactured parts. This systematic study sheds light on the effects of alloying composition and corresponding phase diagram features on the printability and solidification microstructures of four binary nickel-based alloys representing isomorphous, weak solute partitioning, strong solute partitioning, and eutectic alloying conditions. A simple framework for developing processing maps detailing porosity and microsegregation across the laser power – scan speed parameter space is established and validated for each of these alloys to determine how material properties affect printability and microstructure in L-PBF. This knowledge is vital in optimizing alloy chemistry and process parameters to design alloys specifically for additive manufacturing and will provide a path toward local microstructure control.

Special Session: Wire-fed AM Processes I

Monday PM August 2, 2021

Session Chairs: A. Nycz, Oak Ridge National Laboratory; B. Jared, University of Tennessee, Knoxville

1:30 PM
Preparation and Characterization of Laser Direct Deposited Spinel Filaments for Wire-fed Additive Manufacturing of Transparent Ceramics: John Pappas[1]; *Xiangyang Dong*[1]; [1]Missouri University of Science and Technology

A new approach for direct fabrication of spinel filaments is proposed for wire-fed additive manufacturing (AM) of transparent ceramics in this study. Cylindrical magnesium aluminate spinel filaments were prepared by a laser direct deposition process. With a laser melt-grown process, the need for powder binders and post-processing procedures was eliminated. The morphology, microstructure, and phase composition of the obtained spinel filaments were characterized in terms of processing conditions and powder composition. The cross-sections of the as-fabricated filaments were also analyzed to characterize porosity, grain size, and cracking obtained from the proposed method. The insights gained allowed for production of high-purity ceramic filaments with an easy control of residual porosity as further tailored for wire-fed AM of ceramics. This is particularly important for AM of transparent ceramics, where even a small amount of residual pores greatly hindered optical properties and yielded parts with a transition from transparency to opaqueness.

1:45 PM
Recent Advances in Laser-wire Directed Energy Deposition: Novel Modes of Thermal Control and Site-specific Melt Pool Size Control: *Brian Gibson*[1]; Paritosh Mhatre[1]; Bradley Richardson[1]; Lonnie Love[1]; [1]Oak Ridge National Laboratory

This presentation will highlight recent advances in techniques for the control of thermal properties and the deposition of dynamic bead geometries in a laser hot-wire directed energy deposition process being developed by Oak Ridge National Laboratory in partnership with GKN Aerospace. First, issues related to real-time closed loop melt pool size control will be presented, followed by the development novel control variants that stemmed from the use of this form of control. One such variant is average power control via manipulation of print speed and deposition rate, which when performed on a layer-wise basis in tandem with real-time melt pool size control, has been shown to prevent laser power reductions and increase process efficiency as heat accumulates in the object under construction. Secondly, site-specific melt pool size control will be presented with two primary use cases highlighted: surface modification (embossing of secondary geometries) and mitigation of volumetric defects.

2:00 PM
Development of a Laser Hot Wire Additive Manufacturing Process: Elizabeth Chang-Davidson[1]; *Brandon Abranovic*[1]; Jack Beuth[1]; [1]Carnegie Mellon University

This work focuses on parameter development for a large-scale laser hot wire process, consisting of a moving melt pool formed by a laser source and a heated wire fed into the melt pool. Parameter development for a large-scale hot wire feed additive manufacturing process was carried out with the use of semi-analytical welding models and finite element analysis. Initial work consisted of mapping key melt pool dimensions from single bead geometries across process space, then proceeded to stacking single beads into thin walls. Semi-analytical modeling was used to correct flaws in these walls, including selecting interlayer dwell times. Simulation of thin walls was undertaken via a custom FEA model utilizing element birth and death, resulting in temperature histories used for microstructure prediction. Finally, parameter development was extended to complex geometries such pads, cubes, thin walled T junctions, and curved surfaces. The work culminated in the fabrication of a specialized component.

2:15 PM
Preliminary Efforts Using a Fe-10Ni Steel for Wire Arc Additive Manufacturing: *Evan Handler*[1]; Daniel Bechetti[1]; Sam Pratt[1]; [1]Naval Surface Warfare Center Carderock Division

The Fe-10 wt% Ni (Fe-10Ni) metallurgical system maintains excellent low temperature impact toughness while achieving yield strength in excess of 100 ksi (690 MPa). These properties have been achieved in both arc weld and laser powder bed fusion additive manufacturing (AM). Repeated thermal cycling and low oxygen content in Fe-10Ni deposits have been shown to induce the microstructural refinement and phase transformations that lead to the excellent mechanical properties. This presentation will highlight efforts to assess the suitability of Fe-10Ni for Wire Arc Additive Manufacturing (WAAM) for large scale AM builds. The WAAM mechanical properties will be compared to those achieved by traditional arc welding. Specific elements examined include microstructure characterization, hardness, tension, and impact testing. The manufacturing process changes that led to differences between WAAM and traditional welding will be examined.

2:30 PM
In-situ Microstructural Transformations in Wire-arc Additively Manufactured Maraging 250-grade Steel: Yao Xu[1]; Brajendra Mishra[1]; *Sneha Prabha Narra*[2]; [1]Worcester Polytechnic Institute; [2]Carnegie Mellon University

Wire arc additive manufacturing has recently garnered interest due to near-net-shaped manufacturing of large-scale components because of higher deposition rates and lower feedstock costs. Meanwhile, there is also temperature build-up during layer-by-layer fabrication that can result in defects and microstructural transformations. Hence, it is critical to assess the impact of thermal cycles and heat accumulation on the as-fabricated microstructure and properties. In this work, microstructure characterization of Maraging Steel 250 thin-wall parts was performed to explain the change in hardness with wall height. The influence of processing parameters, such as interlayer dwell time, on grain/martensite block size, tempered martensite, and precipitation was compared. In addition, the thermal history of each layer was estimated using a conduction-based heat transfer model to explain the observed microstructure. This work establishes a comprehensive understanding of the effect of thermal cycles and heat accumulation on microstructure evolution in wire arc additively manufactured Maraging Steel 250.

Applications: General I

Tuesday AM August 3, 2021

Session Chair: A. Peterson, University of Massachusetts Lowell

8:00 AM
Optimization of a Worm Gear Assembly Design for Additive Manufacturing: *Detlev Borstell*[1]; Marie-Christine Georg[1]; [1]Koblenz University of Applied Sciences

Worm gears are widely used to transmit power at predominantly low speeds and high-speed ratios. Their self-locking characteristic makes them unique to many drive applications. Industrial power requirements are causing forces and tensions mostly prohibiting thermoplastic materials in worm gear drive trains. Double basses are tuned using a worm gear assembly made from machined steel, brass or cast bronze. Neglectable power requirements and hours of operation, esthetic expectations and the classic luthier's approach to making such an instrument by hand have excluded the double basses' tuning assembly from all engineering approaches regarding optimal design and costs.Manufacturing the traditionally designed double bass worm gear assembly using Additive Manufacturing Processes requires the application of general design rules and the rules of Design for Additive Manufacturing (DFAM) resulting in an optimized gear assembly regarding weight, costs and design properties.

8:15 AM
Laser Sintering Design Guidelines for media transmitting Components: *Ivo Kletetzka*[1]; Christina Kummert[2]; Hans-Joachim Schmid[2]; [1]Direct Manufacturing Research Center (DMRC) and Particle Technology Group, Paderborn University ; [2]Direct Manufacturing Research Center (DMRC) and Particle Technology Group, Paderborn University

In automotive and other fields of application media-carrying components often have complex, flow-optimized geometries and are made of plastics for reasons of weight and cost. Therefore, the laser sintering technology is predestinated to manufacture these components as it offers a very high degree of design freedom and good mechanical properties.For industrial applications the long-term properties of the SLS material in contact with liquid media are important and were therefore investigated for PA12, PP and PA613. Hereby, different media such as motor oil or Glysantin based coolant were tested with different temperatures and immersion times of up to 26 weeks. The mechanical properties were tested after immersion and compared to injection molded samples. Furthermore, laser sintering design guidelines for media-carrying components were developed. These guidelines for instance include the minimum wall thickness to ensure media tightness and the removal of powder from channels with a high length to diameter ratio.

8:30 AM
Utilizing Additive Manufacturing in Thermoacoustic Refrigeration-based Atmospheric Water Generation: *Zaid Almusaied*[1]; Bahram Asiabanpour[1]; [1]Texas State University

Atmospheric water generators are devices that generate water by condensation. The water vapor in the air is cooled, by a refrigeration system, below the dew point and thus forces a phase transfer from gaseous to liquid. Thermoacoustic refrigeration (TAR) was used as the refrigeration technology. The TAR is an innovative clean technology that utilizes an acoustic wave passing through a gas to create a temperature gradient in a specially designed porous material. The main components of such a system are resonator tube, stack, acoustic driver, gas, and heat exchangers. An additive manufacturing process was utilized to develop different configurations and interchangeable components of the TAR system. Results of the experiments including geometry and resonance variations are presented in this article.

8:45 AM
Design and Performance of a Novel AlSi10Mg Vapor Chamber Fabricated via Laser Powder Bed Fusion: *Christopher Bailey*[1]; Cameron Weeks[1]; Scott Thompson[1]; [1]Kansas State University

As more stringent size, weight, and power (SWaP) constraints are imposed on thermal management solutions, the necessity for more efficient passive cooling systems becomes more urgent. Passive two-phase heat spreaders, such as vapor chambers, which utilize several thin geometries that act as wicking structures to create an overall phase-changing slug flow, are very effective at dissipating high heat fluxes; however, their geometries are often extremely difficult to manufacture due to their small and complex size within a hermetically sealed chamber. The use of additive manufacturing allows for the creation of vapor chambers with more complex internal geometries and space-efficient/conformal form factors. This study will provide the several design steps for additive manufacturing taken to ensure the successful fabrication and de-powdering of a state-of-the-art AlSi10Mg vapor chamber produced via laser powder bed fusion (L-PBF). The vapor chamber thermal performance as measured through controlled experiments will also be provided.

9:00 AM
Additively Manufactured Inconel 718 Wicking Structures: *Adnen Mezghani*[1]; Abdalla Nassar[2]; Douglas Wolfe[2]; [1]Pennsylvania State University; [2]Applied Research Laboratory

An integral component in two-phase thermal management systems, namely heat pipes (HP) and vapor chambers (VC), is a porous wicking structure. Traditional methods for manufacturing wicking structures for HPs and VCs involve secondary manufacturing processes and are generally limited to simple geometries. More complex geometries and part consolidation may, however, be possible with laser powder bed fusion (LPBF) additive manufacturing (AM). This work explores the manufacturability of Inconel 718 wicking structures for implementation into high-temperature Inconel HP/VC. Several Inconel 718 wicking structures were successfully fabricated with promising capillary performance. An anticipated future outcome is fabrication of a complete assembly of an Inconel 718 HP/VC with sodium metal as a working fluid.

9:15 AM
Robotic Applications of Mechanical Metamaterials Produced Using SLA 3D Printing: Cthulhu-Morphic Grippers: *William Yerazunis*[1]; Erin Solomon[1]; [1]Mitsubishi Electric Research Laboratories

A multi-tentacular 3D-printed soft robotic gripper with 12 independently actuated degrees of freedom (DoF) is developed and tested. The gripper achieves both broad flexibility of each tentacle and high overall strength of the gripper by creating each tentacle from a SLA printed mechanical metamaterial. This additive manufacturing method was paramount to the success of this design because key features of the chosen architecture could not have been easily manufactured any other way. With the exception of the steel-cable tendons, 100% of the actual tentacles are 3D printed. The gripper uses RC servos and tension cables to provide +/- 120° of flex range per tentacle section, with centralized control. The gripper is quantitatively evaluated for grip strength for multiple objects, grip modes and pull directions. With an axial lift strength well in excess of 100 N (lifting > 10 kg) the gripper is strong enough to be useful in industrial applications.

9:30 AM

Simulation of the Laser-powder Bed Fusion Process for Determining the Effects of Part-to-Substrate Location and Orientation on Distortion in a Connecting Rod: Benjamin Weinhold[1]; Emmanuel Adeniji[1]; Ashton Albright[1]; Jon-Michael Grote[1]; Blake Heck[1]; Keran Wang[1]; Mohammad Masoomi[2]; *Scott Thompson*[1]; [1]Kansas State University; [2]Ansys

The use of computer simulation for designing parts and ensuring their effective additive manufacture can result in reduced product development times which would otherwise require costly trial-and-error manufacturing and testing experiments. The goal of this project was to determine the effect of part-to-substrate location on final part quality as measured via distortion. A connecting rod from an engine was selected for re-design for mass reduction and additive manufacturing. The rod was modeled and optimized using the topology optimization features of Ansys Workbench. After topology optimization, the laser-powder bed fusion process was simulated using the Ansys Workbench Additive Wizard while having the optimized rod in three separate orientations at two different substrate locations. In all cases investigated, orientation had a more significant impact on distortion than location. The effect of over supporting the part for distortion control can be investigated further to circumvent location/orientation dependencies.

9:45 AM

Pitch Imperfect: Designing 3D Printed Claves to Mimic the Sound of Their Wooden Counterparts: *Emmeline Evans*[1]; Christopher McComb[1]; [1]The Pennsylvania State University

Despite the benefits afforded students by music education, public schools operating on insufficient budgets often cut music programs to reduce expenses. Students deserve access to high quality instruments, regardless of socioeconomic status or district funding. Therefore, the goal of this research is to develop 3D printed, PLA claves that reproduce the sound of wooden claves. This study examined clave vibration by approximating claves as damped, simply supported, thin beams. The frequency predictions obtained from that model are compared to experimental results obtained by recording clave prototypes and analyzing the resulting frequency spectra. Results indicate that while it is technically feasible to 3D print a correctly pitched PLA clave, the design would not be suitable for an education instrument.

Applications: Lattices and Cellular II

Tuesday AM August 3, 2021

Session Chair: T. Simpson, Penn State University

8:00 AM

Machine Learning Derived Graded Lattice Structures: *Jier Wang*[1]; Ajit Panesar[1]; [1]Imperial College London

Herein, we propose a new lattice generation strategy that is computationally cheaper and produces high quality geometric definition based on Machine Learning (ML) when compared to traditional methods. To achieve the design of high-performance unit cells, firstly, the optimal mechanical property for each cell region is derived according to the loading condition and the reference density obtained utilising a conventional topology optimisation result. Next, a Neural Network (NN) is employed as an inverse generator which is responsible for predicting the cell pattern for the optimal mechanical property. Training data (~ 500) were collected from Finite Element (FE) analysis with varied cell parameters and then fed to the NN. With the help of ML, the time spent in building the inverse generator is significantly reduced. Furthermore, the ML-based inverse generator can handle different cell types rather than one specific type which facilitates the diversity and optimality of lattices.

8:15 AM

Identification of Defects in Additively Manufactured Microlattices: Nicholas Calta[1]; *Jean Baptiste Forien*[1]; Gabe Guss[1]; Philip Depond[1]; Manyalibo Matthews[1]; [1]Lawrence Livermore National Laboratory

Effective process monitoring for defect detection remains a significant challenge in laser powder bed fusion (LPBF) additive manufacturing. This is a particularly important goal during the fabrication of highly complex parts that LPBF is uniquely suited to produce, because the post-build inspection of such parts is extremely challenging. Here, we use high speed pyrometry to measure thermal emission from the melt to identify defects in microlattice builds. We illustrate that specific thermal signatures can be successfully used to identify engineered defects in microlattices build, and discuss the uncertainties associated with this approach. The applicability of this approach to identifying process error-derived defects will also be discussed. Prepared by LLNL under Contract DE-AC52-07NA27344.

8:30 AM

Effect of Material Anisotropy on Static Mechanical Properties of Cellular Structures Fabricated via Electron Beam Powder Bed Fusion Additive Manufacturing: Yan Wu[1]; *Li Yang*[1]; [1]University of Louisville

This work presents an attempt to employ analytical modeling-based approach for the estimation of the effect of anisotropic material properties on cellular structures of multiple unit cell topology designs. Three different unit cell designs that represent different design rules, including re-entrant auxetic, BCC and octahedral, were investigated in this study in order to identify generic characteristics. A direct stiffness matrix-based model was employed for the adequate capturing of the finite-size effect of the cellular patterns. The anisotropic material property baseline was conveniently established experimentally via tensile testing of strut coupons fabricated via electron beam powder bed fusion (EB-PBF). Subsequently, cellular structure samples were fabricated also using EB-PBF and subjected to static compressive mechanical testing in order to verify the model. The results suggested good modeling accuracy, and provided additional insights into the different material anisotropy effects with different cellular structure topology designs.

8:45 AM

A Study of Process Parameters and Mechanical Performance of Lattices Using Powder Bed Fusion of Stainless Steel 316L: *Scott Jensen*[1]; Benjamin White[1]; Anthony Garland[1]; Michael Heiden[1]; David Saiz[1]; Brad Boyce[1]; Bradley Jared[1]; [1]Sandia National Laboratory

Few structures demonstrate the unique capabilities of laser powder bed fusion (LPBF) better than lattices. Yet, obtaining as-modeled geometries can be surprisingly difficult and can lead to a range of mechanical properties. In this study, we generated 3x3x3 unit cells of FCC lattices under a wide range of laser power and scan speeds. We then identify changes in as-printed strut diameters measured from top and side lattice surfaces. Compression tests identified process dependent mechanical properties, where trends were evaluated as a function of strut diameter and part density. Results revealed which mechanical properties were straightforward to predict using simple feature-based quality metrics while others remain more challenging to capture. The various lattice failure mechanisms encountered will also be discussed. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

9:00 AM

Shock Impact Response and Simulation of Lattice Structures: *Bradley Jared*[1]; David Damm[1]; Shawn Stacy[1]; David Saiz[1]; David Moore[1]; John Carpenter[2]; David Jones[2]; Manyilibo Matthews[3]; Jonathan Lind[3]; Jenny Wang[3]; [1]Sandia National Laboratories; [2]Los Alamos National Laboratory; [3]Lawrence Livermore National Laboratory

Engineered lattice structures represent a compelling, complex geometrical hierarchy enabled through additive manufacturing. While researchers have extensively explored these structures for quasi-static and elastic load environments, the presented work is focused on material and mechanical performance under dynamic compression. Structures were designed using octet and pyramidal cell architectures and then fabricated from stainless steel and titanium alloys using laser-powder bed fusion. Forward ballistic plate-impact experiments were performed using a light gas gun at impact velocities from 0.25 to 1 km/s, generating pressures from 4.6 to 19.5 GPa. Computed tomography was performed on the lattice samples both before and after shock impact to quantify material and structural defects. Using the exact impact conditions, multiple shock physics hydrocodes were used to simulate the experiments. Experimental and simulation results, and their agreement, will be discussed and provide motivation for future research. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

9:15 AM

Ceramic Chain Lattices for Energy Absorption Under Tensile Loading: *Spencer Taylor*[1]; Abdel Moustafa[2]; Zachary Cordero[1]; [1]Massachusetts Institute of Technology; [2]Rice University

Although ceramics exhibit good high-temperature strength, their usefulness in structural applications is limited due to their damage intolerance and flaw sensitivity. This paper introduces the chain lattice, a novel material construction which can utilize ceramic additive manufacturing processes to transform monolithic, 3D-printable ceramics from a brittle, flaw-sensitive material into a damage-tolerant, notch-insensitive material with a specific energy absorption several orders of magnitude greater than that of fully dense ceramics. Chain lattices consist of two interpenetrating lattices, where one lattice toughens the material and prevents catastrophic localized failure, while the other lattice serves as a porous matrix that densifies to absorb energy during tensile loading. A model is developed to predict the effect of chain lattice geometry on strength and energy absorption, and finite element analysis is used to validate the model and examine the fracture behavior of chain lattices.

9:30 AM

Incorporating Metal Additive Manufacturing-produced Material Properties in Design by Topology Optimization: *Yeming Xian*[1]; David Rosen[1]; [1]Georgia Institute of Technology

During metal powder bed fusion processes, properties of the raw material will change after consolidation and cooling in a manner that is controlled by the local thermal history. Our objective is find out how material properties change during metal printing, and incorporate them in the design by topology optimization, such that the topology optimized design represents the true mechanical performance of the fabricated part. Literature review tells us that during fabrication of metal and alloy products, the formation of grain structure and texture indicates an inherent anisotropy of properties and heterogeneities in local geometry.In an effort to produce 3D anisotropic lattice-like structures with local heterogeneities, we propose a multi-microstructure, density-based, topology optimization formulation. The formulation indirectly addresses the effect of local temperature history on local material properties. Rather than being treated as a global property, realistic AM-induced material anisotropy will be investigated on a microstructure level.

9:45 AM

Topology Optimization of a Multi-material, Thin Walled Structure for Wire-arc Additive Manufacturing: Bradley Jared[1]; *Eduardo Miramontes*[1]; Joshua Penney[1]; William Hamel[1]; Joshua Robbins[2]; [1]University of Tennessee, Knoxville; [2]Sandia National Laboratories

Recent advances in additive manufacturing have ignited interest in topology optimization (TO) due to opportunities provided to harness its design flexibility. The potential of this technological pairing is explored by addressing the problem of minimizing part mass while maximizing part stiffness, which is of interest to a wide range of industries. Multi-material, thin-walled optimized structures are being developed utilizing a TO software platform developed by Sandia National Laboratories called Plato. The design workflow will be discussed, as optimized structures will be developed for a variety of geometries from simple shapes to complex free-from geometries. The designs are targeted for demonstration using wire-arc additive manufacturing and the possibility of harnessing TO to reduce material use and build time will be discussed.

Materials: Ceramics, Other II - Glass, Extrusion and Direct Write

Tuesday AM August 3, 2021

Session Chair: S. Leblanc, George Washington University

8:00 AM

Processing of Soda-lime Glass In Laser-based Powder Bed Fusion: *Christopher Singer*[1]; Sebastian Platt[2]; Max Horn[1]; Markus Piechotta[2]; Jan Wegner[2]; Stefan Kleszczynski[2]; Christian Seidel[3]; Gerd Witt[2]; Johannes Schilp[4]; [1]Fraunhofer Institute for Casting, Composite, and Processing Technology IGCV; [2]University of Duisburg-Essen; [3]University of Applied Sciences Munich; [4]University of Augsburg

Processing of electrically insulating materials with high temperature resistance is a major challenge in laser-based powder bed fusion (PBF-LB). Glasses are promising material class, which also offer the potential for manufacturing optical or electronic components while having high chemical resistance. Therefore, this paper investigates the processability of soda-lime glass in conventional PBF-LB machines using Yb:YAG- and CO2-lasers. Firstly, the flow properties and particle shape of the glass powder were inspected. Secondly, the influence of laser power, scan velocity, layer height and hatch distance as well as exposure pattern on the manufacturing of single tracks, single layers and finally 3-D-parts were investigated. Furthermore, the platform heating was varied in the temperature range between 250 to 590 °C resulting in increasing relative density for higher temperatures. The geometrical shape and the relative densities of the manufactured parts were analyzed using optical methods.

8:15 AM

Methodology for Determining Design Rules for Helical Channels in Glass Components Produced via Selected Laser Sintering: Joseph Nissen[1]; Joseph Beaman[1]; *Desiderio Kovar*[1]; [1]University of Texas at Austin

Glass components with complex features such as internal helical channels can achieve interesting optical properties for use in fiber optics and other photonic applications, but they are historically expensive and difficult to manufacture. A methodology is proposed to predict the successful resolution of internal helical channels in selectively laser sintered parts through the use of dimensionless parameters. Theses parameters are derived from the part dimensions of channel diameter, part length, helix diameter, and helix pitch. A demonstration of this methodology is used in the production of glass parts via indirect selective laser sintering for optical applications, and the success or failure of features is analyzed for both green parts and the debinded and sintered resultant glass components.

8:30 AM
Adaptive Aperture for Accelerating Extrusion Additive Manufacturing: Concept Design and Toolpath Generation: *Maxwell Micali*[1]; Charles Friesen[1]; Tarek Zohdi[1]; [1]University of California, Berkeley

As additive manufacturing becomes more applicable in prototyping and production workflows, it is important to minimize build time while maintaining appropriate resolution of geometric features throughout the part. A nozzle with an adaptive and dynamic aperture is able to accomplish this by changing the extrusion diameter in the midst of printing, allowing precision to be exchanged for higher throughput when precision is not required. This work presents a design concept for such an adaptive and dynamic aperture which has been tested on a ceramic extrusion printer. The design features the use of an iris mechanism to continuously vary the nozzle aperture diameter from fully closed to 20mm, maintaining a circular cross section while printing. In order to dynamically control the aperture size, this work also presents methods for computing process plans during which the diameter changes throughout the process, enabling seamless integration into standard and familiar user workflows.

8:45 AM
Fabricating Silicon Nitride Parts Using the Ceramic On-Demand Extrusion (
CODE) Process and Pressureless Sintering Method: *Sachin Choudhary*[1]; Ming Leu[1]; Austin Martin[1]; Jeremy Watts[1]; Gregory Hilmas[1]; Tieshu Huang[2]; [1]Missouri University of Science and Technology; [2]Kansas City National Security Campus, Department of Energy

Aqueous paste of silicon nitride was freeform fabricated using the CODE (Ceramic On-Demand Extrusion) process. The process utilizes solids loading of 40 Vol% in the pastes,while using a small amount of binder (~1 wt%) and 1 wt% organics in the form of dispersants. Several competing dispersant candidates were characterized using zeta- potential measurements to select the most effective dispersant. The combined effects of dispersant, pH, and solids loading were optimized to produce pastes with a shear thinning rheology suitable for the CODE process. Through the layer-wise process, silicon nitride ceramic parts were fabricated without any compaction and subsequently fired to 92% of theoretical density using pressureless sintering method.Future efforts outlining the strategy to achieve higher density sintered parts in pressureless sintering are discussed.

9:00 AM
Ceramic On-demand Extrusion (CODE) of Zirconium Diboride: *Austin Martin*[1]; Sachin Choudhary[1]; Jeremy Watts[1]; Gregory Hilmas[1]; Ming Leu[1]; Tieshu Huang[2]; [1]Missouri University of Science & Technology; [2]NNSA's Kansas City National Security Campus

Ultra-high temperature ceramics (UHTC) are of great interest for applications involving extreme environments due to their reliable high temperature structural performance. Ceramic On-Demand Extrusion (CODE) is a direct-write additive manufacturing process which allows for the creation of near theoretically (>99%) dense parts with large cross-sections. Direct-write additive manufacturing processes allow for the integration of sub-structures and graded chemistries. The processing and properties of CODE additively manufactured zirconium diboride (ZrB_2) was investigated. Processing optimization including feedstock rheology, pressureless sintering, and print fidelity were explored. Finally, mechanical and thermal properties were also examined and will be discussed.

9:15 AM
Dry Aerosol Deposition of Silicate Coatings on Space Relevant Polymeric Substrates: *Robert Calvo*[1]; Paul Fuierer[1]; [1]New Mexico Institute of Mining and Technology

Polymer surfaces in low earth orbit (e.g. solar array substrates, thermal blankets), are attacked by reactive atomic oxygen and vacuum ultraviolet radiation. Till now, sputtered amorphous silica has been used by NASA to mitigate attack, however; rough machined surfaces preclude the use of these thin films, and adhesion and abrasion cause failures. Dry aerosol deposition (DAD) offers the possibility of a more robust nanocrystalline barrier coating of greater thickness. Recent experimental work on quartz, amorphous silica, and mixed silicates aerosol-deposited on Kapton will be presented. The dependence of film thickness and surface roughness on process parameters will be discussed. Phase and microstructural analysis will be shown. Preliminary mechanical behavior of coating and composite structure will be presented.

9:30 AM
Dry Aerosol Deposition of Barium Neodymium Titanate Dielectric Ceramic: *Alex Valdez*[1]; Paul Fuierer[1]; [1]New Mexico Institute of Mining and Technology

For modern microwave and millimeter wave communication technologies and miniaturized designs, the production of dielectric ceramics with tunable dielectric constant (K) and high quality factor (Q) is critical. Hybrid and additive manufacturing (AM) techniques are needed for ceramics in order to build custom-design dielectric resonators, antennas, etc. Dry aerosol deposition (DAD) is a novel kinetic AM process which can produce thick film and low profile 3D ceramic structures at room temperature. BaNd2Ti4O12 (BNT) is a complex perovskite microwave dielectric with high K, high Q, and low thermal coefficient of resonant frequency. Preliminary work from our lab on DAD BNT will be presented, including powder preparation, optimized process parameters, microstructural analysis and (RF) dielectric properties of films. Comparison to sintered, bulk BNT will be made.

Materials: Metals III - Novel Innovations

Tuesday AM August 3, 2021

Session Chair: C. Tuck, University of Nottingham

8:00 AM
Development of Effective Powder Layer Thickness for Different Materials and Process Conditions: *Theresa Hanemann*[1]; Deniz Jansen[2]; Markus Radek[3]; Astrid Rota[3]; Jörg Schröpfer[2]; Martin Heilmaier[1]; [1]Karlsruhe Institute of Technology; [2]University of Applied Sciences Munich; [3]EOS Electro Optical Systems GmbH

A realistic assumption of the effective powder layer thickness (EPLT) is of great importance when simulating the laser powder bed fusion process as well as for single layer experiments relating process parameters to multilayer builds. Due to densification of the powder material when melting the EPLT can be calculated theoretically as the quotient of nominal layer thickness and powder bed density. However, this theoretical assumption greatly underestimates the EPLT which is influenced by spatter and denudation. In this study we investigated the development of EPLT with nominal layer thickness for different powders and process parameters. The ratio of effective to nominal layer thickness, which can also be a measure of powder waste, was found to increase with decreasing nominal layer thickness. Additionally, the effective layer thickness was changed significantly with changing laser parameters and material.

8:15 AM
Towards a Defect-based Process Map: *Anthony Rollett*[1]; [1]Carnegie Mellon University

Although the outlines of a defect-based process map for powder bed fusion additive manufacturing (AM) have been in place for some time, many of the details remain to be defined. At low speeds, keyholes become unstable and shed pores. Computer vision helps to quantify this transition in terms of keyhole depth and aspect ratio based on high speed synchrotron x-ray visualization. Lack of fusion porosity is dominated by (lack of) melt pool overlap which is seemingly straightforward but subtly dependent on melt pool shape. For the latter, direct visualization provides unique insight into the laser penetration such that the effective absorptivity varies with power density. At high speed and power, fluid flow behind the heat source often causes pile-ups that become frozen in place, resulting in severe variability in melt pool dimensions. Tomography or sectioning reveals defect structures and machine learning again provides new tools for analysis of defect structures.

8:30 AM
Particle-Melt Pool Interactions in Multi-Material Laser Based Directed Energy Deposition: *Ronald Sellers*[1]; Benjamin Gould[2]; Sarah Wolff[1]; [1]Texas A&M University; [2]Argonne National Laboratory

Laser based metal directed energy deposition (DED) is an additive manufacturing process that is currently on the rise in the industry. However, there is still a knowledge gap in the understanding of fundamental interactions between particles and the melt pool in the DED process and how to change the parameters to alter microstructure. This work utilized synchronized in-situ thermal and X-ray imaging to understand the anomalous behavior of molybdenum powder binding onto a Ti-6Al-4V substrate as fundamental understanding for layer-by-layer processing. Using these visual techniques, particle velocity, mass, surface energy, kinetic energy, contact area, and temperature were observed and calculated. The correlation is shown and recorded to understand the wettability of particles and why some will bounce off of the substrate while others enter the melt pool. This work will allow for the manipulation of particle-melt pool interactions in DED which will help reproduce and build better parts more efficiently.

8:45 AM
Spatial Inhomogeneity of Build Defects Across the Build Plate in Laser Powder Bed Fusion: *Terrence Moran*[1]; Derek Warner[1]; Arash Soltani-Tehrani[2]; Nam Phan[3]; Nima Shamsaei[4]; [1]Cornell University; [2]Auburn University ; [3]Naval Air Systems Command; [4]Auburn University

The population of build defects as a function of position on the build plate was examined in Ti-6Al-4V specimens fabricated on two common commercial laser powder bed fusion (LPBF) systems. Using standard build parameters, X-ray computed tomography revealed that spatial heterogeneity of the defect population can be substantial, relative to the variations in defect population that can occur due to other parameters, e.g. part geometry, build orientation, and laser power schedule. To understand the potential importance of such variability, its impact on fatigue performance is considered. Systemic asymmetries inherent to LPBF fabrication are investigated as potential sources of the spatial heterogeneity. Shielding gas flow simulations are shown to correlate well with the observed build quality heterogeneity.

9:00 AM
Analysis of Horizontally Graded Titanium-Tantalum Using Laser Powder Bed Fusion Additive Manufacturing: *Cherish Lesko*[1]; Joseph Walker[2]; John Middendorf[2]; Joy Gockel[1]; [1]Wright State University; [2]Open Additive, LLC

Fine spatial resolution in complex additively manufactured (AM) objects requires the use of laser powder bed fusion (LPBF). New LPBF technology allows the fabrication of multi-directional compositional gradients into a single build. A sample with compositional grades perpendicular to the build direction was produced. Compositional regions ranging from 100% titanium to 100% tantalum were built with different process parameters for each region. Scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and X-ray diffraction were used to observe both the bulk and interface regions. SEM images demonstrate that cellular morphology is present because of non-equilibrium solidification and elemental segregation. EDS line and area scans indicate diffusional segregation of tantalum away from the interface regions and localized differences in cooling rates. The ability to include compositional gradients in three dimensions along with the fine spatial resolution of LPBF will lead to the capability to design and fabricate complex geometries with tailored properties.

9:15 AM
Pressure Control During Bronze Infiltration of Binder-Jet Printed Stainless-Steel to Create Metal Microchannels: *Henry Davis*[1]; James Harkness[1]; Isa Kohls[1]; Nathan Crane[1]; Brian Jensen[1]; Richard Vanfleet[1]; Robert Davis[1]; [1]Brigham Young University

Additive manufacturing (AM) of metal microfluidic channels could enable applications requiring higher temperature and higher thermal conductivity materials. Combining these thermal properties with AM's ability to form small-scale complex flow paths could create functional structures like microscale gas chromatography columns or heat exchangers. We are developing processes to fabricate sealed metal microchannels using bronze infiltration of binder-jet printed stainless-steel parts. These processes will require the bronze infiltrant to fill the porous printed material and to seal small gaps between separately printed structures without filling the printed microchannels. We demonstrate that using a sacrificial powder to control infiltrant pressure can selectively fill small pores between printed particles while leaving microchannels free of infiltrant. This approach relies on the infiltrant approaching pressure equilibrium in the part. We observed deviations from pressure equilibrium and discuss necessary design tolerances based on these observations.

9:30 AM
Investigation of Machinability of Additively Manufactured Metal Alloys: *Jay Raval*[1]; Aamer Kazi[1]; Xiangyu Guo[1]; Ryan Zvanut[2]; Chabum Lee[1]; Bruce Tai[1]; [1]Texas A&M University; [2]Honeywell FM&T

Additively manufactured metals differ from their conventionally produced counterparts due to the inherent material inhomogeneity, porosity, and thermal stress induced by the process. These differences make the machining of additively manufactured metals more difficult and cause premature tool failure or unexpected surface finish at certain conditions. This study takes the first step to investigate and identify the causes of these issues, particularly for Ti-6Al-4V. Printed and wrought samples, as well as heat treatment effect, are compared in a dry cutting condition at a cutting speed of 90 m/min in terms of cutting power, vibration, temperature, and produced surface finish. The results show a lower cutting power and more vibration for as-printed Ti samples, indicating a less ductile microstructure and inclusion of pores. Heat treatment can eliminate these phenomena. There is no significant difference found in the produced surface finish at the current cutting condition.

9:45 AM
Methods of Automating the Laser-Foil-Printing Additive Manufacturing Process: *Tunay Turk*[1]; Chia-Hung Hung[1]; M. Hossein Sehhat[1]; Ming C. Leu[1]; [1]Missouri University of Science and Technology

Laser Foil Printing (LFP) is a laser-based metal Additive Manufacturing (AM) method recently developed at Missouri University of Science and Technology. This study investigates and compares two different methods of automating fabrication of parts for the LFP process. Specifically, the edge elevation issue due to laser cutting is investigated. Edge elevation occurs after the foil cutting operation, which is an essential step of the LFP process. Previously, mechanical polishing was done onto the fabricated layer to remove the elevated edges. However, as mechanical polishing is very time-consuming, the current study focuses on two other methods to get rid of the elevated edges. One of them uses laser polishing to remove the elevated edges. Another method is changing the order of the fabrication steps between pattern welding and cutting in the LFP process. Comparisons are made to observe the differences in part quality, properties, and building time between these two methods.

10:00 AM
Selective Binder Jetting: Enhancing Part Quality through Fabrication of Shelled Geometries: *Kazi Moshiur Rahman*[1]; Amanda Wei[1]; Hadi Miyanaji[2]; Christopher Williams[1]; [1]Virginia Tech; [2]Kennametal Co.

In binder jetting, liquid binder is selectively jetted onto a powder bed to fabricate parts in a layer-wise fashion. Following printing, the binder is cured to increase green part strength and then pyrolyzed during sintering. While the binder defines part geometry and provides green part strength, its presence can also hinder sintering densification due to the entrapment of residual char. In this study, the authors explore the tradeoff of the role of binder by investigating the effects of printing "shelled" parts (i.e., only the "shell" of the part geometry features bound powders, and the interior contains unbound powders) on final part quality. To investigate the effect of selective binder deposition on part quality, parts with varying shell thickness were printed; their relative density, dimensional shrinkage, pore morphology and distribution, microstructure, and mechanical strength were evaluated. Shelled parts demonstrate an increase in final density of ~5% over traditional binder jetted counterparts.

Materials: Metals IV - Ferrous

Tuesday AM August 3, 2021

Session Chair: A. Nassar, Applied Research Lab At Penn State

8:00 AM

A Combinatorial Approach of Alloy Modification and Heat Treatment Strategies, Towards a Tailored Microstructure with Improved Mechanical Properties of Hot Work Tool Steel: *Iris Raffeis*[1]; Frank Adjei-Kyeremeh[1]; Simon Ewald[1]; Uwe Vroomen[1]; Johannes Schleifenbaum[1]; Andreas Bührig-Polaczek[1]; [1]RWTH Aachen University

Hot Work Tool steels (HWTS) are of huge industrial significance because of their tooling applications owing to among others their high toughness properties and resistance to soft hardening. Due to the inherent benefits of the Additive Manufacturing (AM) process-route, particularly the Laser Powder Bed Fusion (LPBF) process, AM processability of these alloys have received keen interest. However, recent advances in that regard have either fallen short of comprehensive microstructure characterisation or to improve reported poor ductility, adopted several heat treatments steps. This investigation takes the approach of combining both alloy modification and heat treatment strategies to present a methodology for achieving tailored microstructure with enhanced mechanical properties of an H11 (1.2343) LPBF processed HWTS. A standard H11 HWTS and its modification (H11-M) are both LPBF processed in as-built, pre-heat and post heat-treated conditions with comparative mechanical testing and microstructure characterisation.

8:15 AM

Fatigue Properties of 3D Printed Maraging Steel: *Nandhini Raju*[1]; David Rosen[2]; [1]UCF; [2]Singapore University of Technology and Design

The objective of this paper is to investigate fatigue properties of maraging steel, in the fabricated, machined, and heat-treated conditions, printed by powder bed fusion. Samples were manufactured in an EOS M280 machine in the X and Z build directions. Manufactured samples were tested under four different conditions: as fabricated, machined, heat-treated, and machined and heat treated. Each condition was expected to have different fatigue properties. The maximum stress and number of cycles to failure results were compared to understand the influence of the different build orientations and conditions on fatigue properties and limits. Results showed that machining and heat treatment, individually and together, had significant effects on fatigue properties. Additionally, the selection of standards, selection of sample counts, and statistical analysis of results will be discussed along with the maraging steel fatigue properties.

8:30 AM

Mechanical Properties of 304L Stainless Steel Parts Fabricated by Laser Foil Printing: *Chia-Hung Hung*[1]; Ming C. Leu[1]; [1]Missouri University of Science and Technology

In this study, two laser welding modes (conduction mode and keyhole mode) have been used to fabricate 304L stainless steel parts by the laser-foil-printing (LFP) process. Their tensile properties, fracture surface, microstructure, and porosity are measured and compared in the laser scanning (X) direction and the layer building (Z) directions. The parts fabricated by both modes are near fully dense, while the conduction-mode part has a slightly higher density than the keyhole-mode part. With this slightly deference in density, the yield strength (YS) and ultimate tensile strength (UTS) are statistically consistent in the ANOVA analysis. However, the elongations of conduction-mode parts are 9% and 32% higher than the keyhole-mode parts in the X and Z directions, respectively. The electron backscattered diffraction (EBSD) patterns show their distinct grain growth orientations, which explains their elongation disparity.

8:45 AM

Investigation of Mechanical Properties of Parts Fabricated with Gas- and Water-atomized 304L Stainless Steel Powder in the Laser Powder Bed Fusion Process: *M. Hossein Sehhat*[1]; Austin Sutton[1]; Ming Leu[1]; Joseph Newkirk[1]; [1]University of Missouri, Science and Technology

The use of gas-atomized powder as the feedstock material for the Laser Powder Bed Fusion (L-PBF) process is common in the Additive Manufacturing (AM) community. Although gas-atomization produces powder with high sphericity, its expensive production cost has become a downside for its application in AM processes. Water-atomization may overcome this limitation due to its low-cost relative to the gas-atomization process. In this work, gas and water-atomized 304L stainless steel powders were morphologically characterized through scanning electron microscopy. The water-atomized powder had a wider particle size distribution and exhibited less sphericity. Measuring powder densities to obtain the Hausner ratio indicated that the water-atomized powder was less flowable than the gas-atomized powder. Through examining the mechanical part properties of L-PBF fabricated parts through tensile testing, gas-atomized powder shows higher tensile strength and elongation than those of water-atomized powder.

9:00 AM

Strain Energy Approach to Estimating Stress-life and Strain-life Behavior of Additive Manufactured Austenitic Stainless Steels: *Jonathan Pegues*[1]; Seungjong Lee[2]; Nima Shamsaei[2]; [1]Sandia National Laboratories; [2]Auburn University

The unpredictable fatigue behavior of additive manufactured (AM) metals has limited their widespread adoption for use in fatigue critical applications. To overcome this challenge, predictive models capable of capturing the fatigue performance of AM metals under a variety of material and loading conditions are needed. This work explores a cyclic strain energy method to correlate the fatigue performance of laser beam powder bed fused austenitic stainless steel subjected to several heat treatments and loading conditions. Results indicate that the strain energy per cycle could be reasonably estimated for each condition utilizing classical cyclic deformation approaches. Despite the complex deformation behavior of the metastable stainless steel, the average strain energy approach successfully correlated the fatigue data for all heat treatment and loading conditions.SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

9:15 AM

Analysis of Residual Stress Reduction of in situ Annealed LPBF 316L Stainless Steel: William Smith[1]; *William Smith*[1]; John Roehling[1]; Bey Vrancken[1]; Maria Strantza[1]; Ava Ashby[1]; Rishi Ganeriwala[1]; Bjorn Clausen[2]; Gabriel Guss[1]; Joseph McKeown[1]; Michael Hill[3]; Manyalibo Matthews[1]; [1]Lawrence Livermore National Laboratory; [2]Los Alamos National Laboratory; [3]University of California, Davis

High residual stresses are typical within parts built using laser powder bed fusion (LPBF), which is due to the rapid heating and cooling cycles inherent to the process. Such high stresses can lead to warping and potential deviation from original design specifications. With the growing interest in metal 3D printing within commercial industries it is imperative that methods of efficient residual stress reduction are found. In this work, an in situ method of reducing residual stress during LPBF is explored. By selectively illuminating the print surface with homogenously intense light from an array of laser diodes, we directly apply a heat source to the print surface and control the thermal history of the part. We study the effects of temperature history on the residual stress state in stainless steel 316L parts made using LPBF. Prepared by LLNL under Contract DE-AC52-07NA27344. LLNL-ABS-808072

9:45 AM

An Initial Evaluation of Process-property Relations for FDM produced 316L Stainless Steel: *Frank Brinkley*[1]; J. Betts[1]; Adam Vitale[1]; Matthew Priddy[1]; [1]Mississippi State University

A large focus in the additive manufacturing (AM) community has been on printing metals; however, this technology presents a large start-up cost and is prohibitive for smaller research institutions. Recently, advances in technology have enabled the use of a traditional fused deposition modeling (FDM) system for manufacturing metal components. These processes use a metal powder incorporated into a polymer binder which is de-bound and sintered after printing to produce a nearly fully dense metal part. This technology greatly reduces entry cost, but the mechanical properties and the impact of process parameters on these properties are still not fully understood. This study investigates the relationship between three primary process parameters (hot-end temperature, layer height, and print speed) and the resulting mechanical properties. This investigation specifically focuses on these relationships for a Creality Ender3 printer with Ultrafuse 316L filament.

Materials: Polymers I - Overview and Photopolymers

Tuesday AM August 3, 2021

Session Chair: D. Rosen, Georgia Institute of Technology

8:00 AM

Evaluating the Effect of Z-pinning parameters on the Mechanical Strength and Toughness of Printed Polymer Composite Structures: *Brenin Bales*[1]; Tyler Smith[2]; Seokpum Kim[2]; Vlastimil Kunc[2]; Chad Duty[1]; [1]University of Tennessee; [2]Oak Ridge National Laboratory

Traditional Fused Filament Fabrication methods create a mechanically anisotropic structure that is stronger in the deposition plane than across successive layers. A recently developed Z-Pinning process deposits continuous pins in the structure that are orientated in the build direction across multiple layers. Initial studies of this technique have demonstrated the ability to increase inter-layer strength and toughness. The current study evaluated various z-pinning parameters for carbon fiber reinforced polylactic acid (CF-PLA) structures, including infill percentage, pin length, and deposition pattern. Each of these was found to affect the ability of the z-pin to mechanically bond with the existing lattice structure and had a resulting impact on the mechanical strength and toughness. Relationships between mechanical performance and various print parameters will be presented, with the intent of identifying a printed structure and process parameters that can achieve a mechanically isotropic data set.

8:15 AM

Additive Manufacturing of Magneto-active, Shape Programmable Thermoset Composite Laminates via Reactive Extrusion: *Oliver Uitz*[1]; Ademola Oridate[1]; Rui Leng[2]; Tan Pan[2]; Carolyn Seepersad[1]; Zoubeida Ounaies[2]; Mary Frecker[2]; [1]The University of Texas at Austin; [2]Pennsylvania State University

Reactive extrusion additive manufacturing (REAM) systems create parts by mixing and depositing thermosetting polymer feedstocks with a robotically guided extrusion nozzle. The resulting structures cure in situ, ideally in ambient conditions. The resin and hardener feedstocks exist in liquid form prior to deposition by the REAM system, allowing active additives to be mixed into them prior to deposition. In this application, iron oxide particles are mixed with an elastomeric precursor to produce a magneto-active elastomer (MAE). By pairing a shape memory polymer (SMP) with the MAE, a laminated unimorph structure is REAM fabricated in which the SMP is actuated with the MAE. The laminates are then "shape programmed" in a hands free manner by heating the SMP above its glass transition temperature, applying an external magnetic field to induce deformation in the unimorph, and then cooling the SMP below its glass transition temperature to 'lock' the deformation in place.

8:30 AM

Fracture Behavior of FDM Polymer Materials: Impact of Sample Size, Notch, and Element Layout: *Albert Patterson*[1]; Charul Chadha[1]; Iwona Jasiuk[1]; James Allison[1]; [1]University of Illinois at Urbana-Champaign

Fracture behavior of additively manufactured (AM) thermoplastic materials is an emerging topic of interest. AM fabrication produces a structured material, one that can be designed to produce metamaterials and other structured materials. Material produced using fused deposition modeling (FDM) is especially known for this effect; it has 3-D anisotropy and defined material elements which can be modeled as regions of isotropic material arranged in a tight lattice. This study experimentally examined four FDM-fabricated materials (two amorphous (ABS and polycarbonate) and one semi-crystalline (slow-cooled PLA)). A series of physical experiments were performed using compact tension (CT) tests. The results were examined and used to generate guidelines for design of FDM material structures for design under various fracture conditions.

8:45 AM

Feasibility Study on Digital Light Processing of Metamaterials with Nested Structures: *Ankit Saxena*[1]; Guha Manograhan[1]; [1]Penn State

Additive manufacturing (AM) has enabled the design and development of advanced metamaterials with complex micro/nano structures. Mimicking the nested strengthening mechanisms found in bio-materials can lead to the development of advanced adaptive metamaterials that exhibit high strength under high strain conditions, a property that is not feasible via traditional structural materials and AM methods such as material extrusion and powder bed fusion. This paper studies the feasibility of using Digital Light Processing (DLP) to rapidly manufacture tailored metamaterial lattices with nested strengthening elements. Novel meta-material lattices were printed at different resolutions with minimum feature size varying from 10µ to 100µ. Tensile tests using Digital Image Correlation (DIC) were performed on the lattice structure to understand this new mechanical response by engaging the strengthening elements. Findings from this study presents both design guidelines and mechanical strength of nested metamaterial structures.

9:00 AM

Improving Vat Photopolymerization Part Performance via Thermally Activated Bond Exchange: *Daniel Rau*[1]; Leslie Hamachi[2]; Clay Arrington[1]; Daylan Sheppard[3]; David Fortman[4]; Timothy Long[5]; Christopher Williams[1]; William Dichtel[3]; [1]Virginia Tech; [2]California Polytechnic State University San Luis Obispo; [3]Northwestern University; [4]Cornell University ; [5]Arizona State University

Vat photopolymerization (VP) offers designers excellent surface finish, feature resolution, and throughput, but layer interfaces in the printed materials can limit their tensile properties. To improve interlayer network formation via self-healing, we demonstrate the development and VP printing of a novel urethane acrylate resin containing carbamate bonds. In the presence of a dibutyltin dilaurate (DBTDL) catalyst and heat, the carbamate bonds undergo dissociative exchange resulting in rapid stress relaxation. ZX tensile samples with layers perpendicular to tensile load demonstrate an increase in elongation at break after thermal annealing, indicative of self-healing. The strain at break for samples containing catalyst increase from 33.9% to 56.0% after annealing, compared to a decrease from 48.1% to 32.1% in control samples without catalyst. This thermally activated bond exchange process improves the performance of VP-printed materials via self-healing at layer interfaces and provides a means to change the Young's modulus after printing.

Modeling: II Toolpaths and Scanning Strategies

Tuesday AM August 3, 2021

Session Chair: B. Post, Oak Ridge National Laboratory

8:00 AM
A Novel Knowledge-based Toolpath Constructive Approach for Designing High-precision Graded Lattice Structures: *Zhiping Wang*[1]; Yicha Zhang[2]; Alain Bernard[1]; [1]Ecole Centrale de Nantes; [2]Université de Technologie Belfort-Montbéliard

Current part-scale lattice design methods cause accuracy loss and manufacturability uncertainty in AM preparation stages. STL model conversion and slicing can lead to loss of shape accuracy and surface quality, while unqualified toolpaths may cause printing failures, e.g. pores or re-melting in powder-bed fusion process. Moreover, all these steps are time-consuming due to large size of model file. To solve these challenges, this paper proposes a novel toolpath-based constructive design method to generate high-precision graded lattice unit cells with manufacturability. It integrates implicit modeling, direct slicing, gradient bidirectional-offsetting and fine toolpath configuration to construct qualified toolpaths without any intermediate steps. To save computation time in part-scale lattice design, predefined different types or sizes of graded lattice unit cells are populated and assembled into a given design space directly. Hence, it has big potential to improve industrial application of part-scale porous structures with fine and gradient porous features.

8:15 AM
Tool Path Generation and Optimization for Hybrid Additive Manufacturing: *Zhen Hong*[1]; Zhiping Wang[1]; Sihao Deng[2]; Yicha Zhang[2]; Alain Bernard[1]; [1]Centrale Nantes; [2]Université de Technologie Belfort-Montbéliard

Tool path is very important for tooling in CNC and deposition nozzle for AM. A new method of hybrid tool path generation and optimization is proposed. The tool path is generated based on sweeping deposition profile and optimized by Genetic Algorithm based method considering the path lengths as the criterion. For the sweeping method, the profile is based on a three-dimensional geometric model of Gaussian distribution and the trajectory is the combination of common-used tool path types like contour and rastering, etc… At last, three cases are introduced in Grasshopper/ rhino to verify the proposed method.

8:30 AM
A Roadmap Towards Parallel Printing for Desktop 3D Printers: *Chandrakana Nandi*[1]; Molly Carton[1]; Adam Anderson[1]; Haisen Zhao[1]; Eva Darulova[2]; Adriana Schulz[1]; Dan Grossman[1]; Zachary Tatlock[1]; [1]University of Washington; [2]Max Planck Institute for Software Systems (MPI-SWS)

3D printers with multiple extruders (or multi-head printers) are common in the desktop fabrication community. These printers are primarily used for multi-color and multi-material printing. Most of them do not exploit the multi-headedness to parallelize the printing process and lower the printing time. This work presents a simple toolpath algorithm that generates parallel infill for fixed-width dual-extruder printers given the 3D mesh of a model. We have implemented a prototype of the algorithm, and developed both hardware and firmware extensions to support parallel 3D printing on a specific dual-extruder printer. We present an early evaluation comparing the printing times of sequential toolpath and the parallel toolpath generated by our algorithm on several models.

8:45 AM
Adaptive Toolpath Planning for Additive Manufacturing through Reduced-order Physical Simulation: *Maxwell Micali*[1]; Tarek Zohdi[1]; [1]University of California, Berkeley

The high thermal gradients and cyclic heating involved in metal additive manufacturing processes result in parts which are susceptible to high residual stresses, deformation, in-process crack formation, and anisotropic material properties. While some of these effects can be partially remediated through post-processing techniques such as heat treatment and hot isostatic pressing (HIP), part quality is difficult or impossible to fully restore. By properly specifying and optimizing process parameters a priori, process-induced defects can be mitigated or eliminated. Efficient physical process simulation techniques employed in concert with evolutionary optimization methods can yield process plans tailored for a specific part's geometry, orientation, and material composition, with the goal of reducing or eliminating the need for post-processing steps. Using a reduced-order model for efficient part-scale additive manufacturing simulation, physical insight can be fed back into an adaptive process planning and toolpath optimization framework.

9:00 AM
Model-based Toolpath Control for Direct Ink Write Additive Manufacturing: *Matthew Hildner*[1]; Albert Shih[1]; [1]University of Michigan

This presentation covers a model-based approach for toolpath control of Direct Ink Write (DIW) Additive Manufacturing (AM). The model uses the continuity and momentum equations to describe the transient flow of viscous fluid during DIW. The transient flow behavior is found using the Characteristic Method (CM) solver and tested on a flow-controlled Positive Displacement Pump (PDP) DIW system. The two tests performed are system response to the step input and rectangular infill toolpath. Simulations of the PDP LMEX for open-loop and a corrected open-loop control are studied.

9:15 AM
ORNL Slicer 2.0: Towards a New Slicing Paradigm: *Michael Borish*[1]; Alex Roschli[1]; [1]Oak Ridge National Laboratory

One fundamental step of additive manufacturing is slicing. Slicing is the conversion of a 3D mesh to a set of layers containing all the necessary pathing to construct the object. The slicing process is typically viewed as one step in a sequential additive manufacturing workflow: an object is designed in CAD, sliced, and subsequent G-code is sent to the additive manufacturing system for construction. While successful, this workflow has limitations such as the utilization of sensor feedback for pathing alteration. To address limitations and better take advantage of opportunities resulting from the Industry 4.0 revolution, researchers at Oak Ridge National Laboratory developed a new slicer, ORNL Slicer 2.0. Slicer 2.0 was developed with the concept of "on-demand" slicing whereby the slicer takes a more active role in object construction. In this paper, we describe the fundamental design philosophy of this new approach as well as the Slicer 2.0 framework.

9:30 AM
Expanding Process Space of Laser Powder Bed Additive Manufacturing Using Alternative Scan Strategies: *Elizabeth Chang-Davidson*[1]; Nicholas Jones[1]; Jack Beuth[1]; [1]Carnegie Mellon University

Metals additive manufacturing is an emerging field in manufacturing, in which one commonly used technology is laser powder bed fusion (L-PBF). Melt pool sizes in L-PBF are closely tied to printed part material properties, but are currently limited by keyholing porosity flaws or by machine limits on laser power and velocity. For carefully selected process parameters, much larger than typical melt pools were created by rapidly scanning the laser back and forth across a constant width. A systematic way to apply this technique was mapped across laser power and velocity using semi-analytical simulation software. Sample single stripes and cubes were printed using parameters selected to span process space in power and velocity. These experimental results were used to calibrate the simulations and demonstrate viability of the technique. This systematically applicable technique increases the range of melt pool sizes and therefore range of material properties possible to print using L-PBF machines.

9:45 AM

An Efficient Layer Construction Method to Generate Accurate Printing Toolpaths of Periodic Cellular Structures for Selective Laser Melting Process: *Shujie Tan*[1]; Xi Zhang[1]; Liping Ding[1]; Yicha Zhang[2]; [1]Nanjing University of Aeronautics and Astronautics; [2]ICB-COMM, UMR 6303, CNRS, Univ. Bourgogne Franche-Comté, UTBM

Limited by stereolithography file format, current data processing in additive manufacturing (AM) chain is time-consuming and has a loss of model precision in data transformation. However, both the CAD software and AM machine accept the input of more convenient and high-precision mathematical curve expressions. A predefined curved scanning pattern can be achieved in a galvanometer scanning system of selective laser melting (SLM) process, which can improve the scanning accuracy and efficiency for the shapes that can be represented by mathematical functions, e.g. circle. Therefore, this study proposes a layer construction-based method to generate the toolpaths for cellular structure. To demonstrate the proposed method, a case study on the toolpath generation for a flame arrestor element with a large quantity of curved fine channels, is presented. Compared with the conventional printing preparation methods, the proposed method reduces up to 90% of the total preparation and achieves higher quality toolpaths.

10:00 AM

Support-free Hollowing for 3+2-Axis Additive Manufacturing: *Lufeng Chen*[1]; Ruosong Liu[1]; [1]University of Electronic Science and Technology of China

Additive manufacturing (AM), also known as 3d printing, has become a hot topic in academia and industry in the past decades. For a typical layer-based additive manufacturing where the object is printed in a layer-by-layer fashion, the battle to reduce or even eradicate the support structure is always faced by researchers and industrial practitioners. The newly emerging multi-axis printing platform inspired by the five-axis machine tool opens new directions, such as surface quality improvement, support-free printing, etc. In this paper, we have presented a framework for the support-free hollowing of 3+2-axis printing. A suite of algorithms including curved skeleton extraction, print sequence optimization, hollowing generation, and print path planning is introduced. It is expected that the print efficiency will improve while the residue artifacts caused by the support structure on the contact surface can ultimately be eradicated.

Phyiscal Modeling: II Thermal Aspects A

Tuesday AM August 3, 2021

Session Chair: D. Bristow, Missouri Univ of Science & Technology

8:00 AM

Crystal Plasticity Model of Micro-scale Residual Stress in Additive Manufacturing: *Daijun Hu*[1]; Wentao Yan[1]; [1]National University of Singapore

Metal additive manufacturing has great potential in industries, but residual stress that arise in the additively manufactured parts has become a critical bottleneck for applications, due to its detrimental effect on mechanical properties. In this work, a crystal plasticity model which predicts the micro-scale residual stress of additively manufactured parts is developed, where both the temperature profiles from the thermal-fluid flow simulation and the grain structure from the phase-field grain growth simulation are incorporated. Residual stiffness method is applied in this model to simulate the melting and solidification phenomena in additive manufacturing process. The simulation results for 316L stainless steel by selective laser melting are compared with recently published experimental results for validation. This model provides new insights into the formation and evolution of residual stress, and specifically presents the correlation between plastic deformation, grain structure and residual stress.

8:15 AM

Evaporation Model for Keyhole Dynamics during Additive Manufacturing of Metal: *Lu Wang*[1]; Yanming Zhang[1]; Wentao Yan[1]; [1]National University of SIngapore

The molten pool flow, particularly the keyhole effect, in the selective laser melting process, plays a key role in the defects which are difficult to be observed through experiments. In this study, we derived a new formulation of evaporation for metal alloys from thermodynamics considering the chemical compositions, and the formation of the keyhole was simulated using the Finite Volume Method (FVM) with the Volume of Fraction method to track the gas-liquid interface, where the multi-reflection of the laser within the keyhole and powder bed was incorporated using a ray-tracing algorithm. The geometry features of the simulated keyhole and melting pool showed a good agreement with the experimental observation by ultrahigh-speed X-ray imaging in Argonne National Lab. To understand the physical mechanisms of keyhole, the laser energy distribution on the keyhole surface, and the driving forces (e.g. Marangoni force, recoil pressure) on the keyhole surface were further analyzed

8:30 AM

High-fidelity Modelling of Thermal Stress for Additive Manufacturing by Linking Thermal-fluid and Mechanical Models: *Fan Chen*[1]; Wentao Yan[1]; [1]National University of Singapore

The widely applied thermo-mechanical model using the finite element method (FEM) leaves much to be improved due to their oversimplifications on material deposition, molten pool flow, etc. In this study, a high-fidelity modelling approach by linking the thermal-fluid and mechanical models is developed to predict the thermal stress for AM taking into account the influences of thermal-fluid flow. Profiting from the precise temperature profiles and melt track geometry extracted from the thermal-fluid model, this work aims at simulating the thermal stress distribution by involving physical changes in the AM process, e.g., melting and solidification of powder particles, molten pool evolution and inter-track inter-layer re-melting. The thermal stress evolution in the AM process of single track, multiple tracks and multiple layers are simulated, where the rough surfaces and internal voids can be well incorporated. With the application of the data-driven prognostic model, the computational cost can be greatly reduced.

8:45 AM

Integrated Multi-physics Modeling of Process-structure-property in Additive Manufacturing: *Wentao Yan*[1]; [1]National University of Singapore

Aimed at predicting the mechanical properties from process parameters, we have developed and integrated a variety of Process-Structure-Property models. To comprehensively understand the manufacturing process, we have developed powder dynamics models to simulate the powder spreading procedure and the powder spattering and denudation phenomena, and a powder melting model incorporating the physically-informed heat source models, i.e., tracing ray deflections for laser and beam penetration for electron beam. A comprehensive phase field model has been developed to reproduce the grain evolutions, from nucleation, growth, to coarsening. A crystal plasticity model has been developed to predict the mechanical properties based on the microstructure. Moreover, the temperature profile from the powder melting model has been implemented into the crystal plasticity model to simulate the thermal stress evolution in micro-scale. These models have been validated against experimental observations showing good agreement and unique advantages in revealing the physical mechanisms.

9:00 AM

Development of a Simulation Model of a Radiation-based Print Heating System for Fused Deposition Modeling: Daniel Collins[1]; *Cameron Turner*[1]; [1]Clemson University

Fused Deposition Modeling (FDM) has become a standard 3D printing process for thermoplastics. However, the process results in different strength characteristics along each cardinal direction of a part attributed to different bonding times between filaments. The resulting anisotropic characteristics are an obstacle when considering FDM printed parts for mechanical purposes. Work at Arizona State University has demonstrated a method using laser-based heating to achieve improved polymer bonding without loss of dimensional accuracy. In this research we consider the possibilities of reheating the filament via radiative heat transfer to achieve the same outcome. By exploring the approach in simulation and conducting confirmation experiments, we evaluate the ability to increase strength in FDM components by post-deposition controlled radiative heat-transfer.

9:15 AM

Thermal Modeling of Fiber Optic Embedment in Metal Additive Manufacturing: *Elias Snider*[1]; Douglas Bristow[1]; Michelle Gegel[1]; [1]Missouri University of Science and Technology

Embedded Optical Fibers (OFs) are useful as strain sensors in many applications (e.g., electromagnetic interference, distributed strain measurements). Embedding OFs using additive manufacturing equipment allows utilization in high-value parts. Adhering OFs to metal parts using additive manufacturing, however, requires processing temperatures dangerous to the fiber, posing challenges for fiber survival. Embedment-capable OFs are costly to manufacture, and embedment processes are expensive and time-consuming. Thermal models of embedment processes will help users efficiently determine embedment parameters. This work employs transient thermal models of embedment processes to identify and simulate significant design parameters like coating thickness, embedment geometry, and cooling time. Trends in peak fiber core temperatures and their significance in embedment process are discussed. Experiments using a Laser Engineered Net Shaping (LENS®) machine (direct energy deposition) with 316L 53-150 µm stainless steel powder to embed single mode, nickel-coated fibers with 300-900 µm diameter are presented. Resulting embedded OF transmissions are discussed.

9:30 AM

Thermal Modeling in Additive Manufacturing Using Graph Theory – Validation with In-situ Thermography Measurements for a Large Impeller Part made Using Laser Powder Bed Fusion: Reza Yavari[1]; Paul Hooper[1]; Kevin Cole[1]; *Prahalad Rao*[1]; [1]University of Nebraska

This work is a continuation of the graph theory approach to predict the thermal history of an additively manufactured part previously presented in the symposia. The objective of this paper is to use the graph theory approach to predict the thermal history of large-volume parts made using the laser powder bed fusion (LPBF) process. To realize the foregoing objective, we build a 316L stainless steel part of outside diameter 155 mm and height 40 mm resembling an impeller-like shape on a Renishaw AM250 LPBF system; the build time for this part is approximately 16 hours. Surface temperature measurements were obtained using a calibrated long wave infrared thermal camera. Using the graph theory-based thermal simulation strategy, we predict the surface temperature distribution trends with mean absolute error of approximately 10% of experimental temperature measurements and in less than 85 minutes (1/10thof the build time).

9:45 AM

Thermal Modeling in Additive Manufacturing Using Graph Theory: Validation with Directed Energy Deposition: Prahalad Rao[1]; Jordan Severson[1]; *Reza Yavari*[1]; Kevin Cole[1]; [1]University of Nebraska

The objective of this work is to validate the graph theory approach for thermal modeling in the context of the directed energy deposition (DED) of titanium alloy (Ti-6Al-4V) parts. The data for this work is sourced from the published work of a different research group. Single track thin wall parts were deposited and temperature trends were tracked by embedding thermocouples in the substrate on which the material is deposited. The DED process was simulated using the graph theory approach, and the predicted temperature trends were validated versus the temperature trends measured by the thermocouples. As an example, the temperature trends predicted by the graph theory approach have mean absolute percentage error ~11% (MAPE) and root mean square error 23 °C (RMSE) when compared to the experimental data.

10:00 AM

Thermal Modeling, Bead Parameterization, and Toolpath Analysis of Material Extrusion Additive Manufacturing: *Amy Peterson*[1]; Tone D'Amico[2]; Masoumeh Pourali[1]; [1]University of Massachusetts Lowell; [2]Worcester Polytechnic Institute

We have developed a finite element model to simulate heat transfer and generate temperature profiles during material extrusion AM (MatEx) of amorphous polymers. At benchtop (fused filament fabrication, FFF) scales, short times over Tg were reported, indicating limited opportunity for interlayer diffusion. At larger (big area additive manufacturing, BAAM) scales, much longer times above Tg were observed, which can lead to continued flow of extruded material and warping of the printed structure. The effects of material and processing parameters were investigated at both scales, and different trends were observed at the small and large scales. We have also investigated the importance of geometry and toolpath design. Finally, we have begun efforts to predict properties of FFF-printed semi-crystalline polymers. Combined, these results indicate that designing MatEx materials and processes in concert will lead to improved structure performance, and give preliminary guidance in development of design rules.

Physical Modelling: II Melt Pool Imaging

Tuesday AM August 3, 2021

Session Chair: J. Fox, National Institute of Standards and Technology

8:00 AM

Pseudo Melt Pool Thermal Feature Construction for In-situ Thermography of Laser Powder Bed Fusion: *Cody Lough*[1]; Robert Landers[1]; Douglas Bristow[1]; James Drallmeier[1]; Edward Kinzel[2]; [1]Missouri University of Science and Technology; [2]University of Notre Dame

Manufacturing parts layer-by-layer with Laser Powder Bed Fusion (LPBF) permits non-contact spatiotemporal measurement of each layer's thermal history. The thermographic measurements produce voxel-based temperature history data for a part's volume that has applications in process validation and part qualification. Thermal feature extraction is a common post-processing technique that compresses this data to single value per voxel (e.g. maximum temperature and time above threshold). This compression potentially reduces the ability to flag a part's defects. This paper presents a framework to retain all significant heating and cooling data for a voxel. The framework arranges a voxel's time series temperature data into a pseudo melt pool (PMP) image. The PMP is a thermal feature that can leverage image classification algorithms and reveals obscured secondary features (i.e. PMP length, width, and aspect ratio). An experimental study compares the PMP's part porosity correlation strength with the compressed thermal features' correlation strengths.

8:15 AM

Closed-loop Control of Meltpool Temperature in Directed Energy Deposition: *Benjamin Bevans*[1]; Ziyad Smoqi[1]; James Craig[2]; Alan Abul-Haj[3]; Brent Roeder[4]; Bill Macy[5]; Jeffrey Shield[1]; Prahalada Rao[1]; [1]University of Nebraska-Lincoln; [2]Stratonics, Inc.; [3]ARA Engineering; [4]R3 Digital Sciences; [5]Macy Consulting

This work concerns the laser directed energy deposition (DED) additive manufacturing of stainless-steel parts. In this work, we achieved closed-loop control of the meltpool temperature. We demonstrate that maintaining the meltpool temperature at a steady state through closed-loop control of laser power leads to the following outcomes: (1) mitigation of microstructure heterogeneity, and (2) reduction in porosity of parts.

8:30 AM
A Novel Non-destructive Testing Method for Powder Bed Fusion Processes in Laser-based Additive Manufacturing: *Nicholas Tomasello*[1]; Arad Azizi[1]; Fatemeh Hejripour[1]; Scott Schiffres[1]; [1]Binghamton University

A novel technique to measure thermal properties during selective laser melting that modulates the energy source periodically and measures the periodic temperature response to detect defects will be presented. This technique has the benefit of providing thermal conductivity information that can be related to microstructure. The measurement heating frequency can limit the thermal interrogation depth, and so is relatively insensitive to geometry compared to conventional thermography. To demonstrate this work, we built a benchtop printer that uses a blue laser as a melting and thermal interrogation source. The temperature oscillations are measured by a photodiode connected to a lock-in amplifier. By altering the frequency range, different depths into the part can be assessed, and microstructure can be determined. Applications to powder properties, melt pool, and post-printed sensing will also be discussed.

8:45 AM
A Data Integration Framework for Additive Manufacturing Big Data Management: Milica Perišic[1]; Dimitrije Milenkovic[1]; *Yan Lu*[2]; Albert Jones[2]; Nenad Ivezic[2]; Boonserm Kulvatunyou,[2]; [1]The University in Belgrade; [2]National Institute of Standards and Technology

Large amounts of data are generated through the entire, AM part development lifecycle. Data include those produced for process monitoring, material-property characterization, and part qualification. Hence, data integration and management are critical in streamlining, accelerating, certifying, and deploying AM components. However, achieving that integration and management have several challenges because AM data embodies the four characteristics of Big Data - volume, velocity, variety, and veracity. This paper proposes an AM framework as a foundation for addressing those challenges. In the framework, AM data are streamed, curated, and configured automatically, which increases the effectiveness associated with archiving and querying. The framework also includes a description of the big data, named AM metadata. Metadata helps to link various types of big data and to improve browsing, discovering, and analyzing that data. Finally, the framework can be used to derive requirements for standards that enable interoperability for data sharing.

9:00 AM
High-speed synchrotron X-ray imaging of directed energy deposition of metals: the comparison of powder delivering performance, effects of processing parameters on the pore formation, and pore formation mechanisms: *Hui Wang*[1]; Sarah Wolff[1]; Benjamin Gould[2]; Ziheng Wu[3]; [1]Texas A&M University; [2]Argonne National Laboratory; [3]Carnegie Mellon University

Laser-based powder-blown directed energy deposition (DED) receives more and more attention in both academia and industry because it is a competitive method for repairing and remanufacturing. State-of-art DED additive manufacturing processes use both irregular and spherical powders since each of these two types of powders shows its advantages. Nowadays, most investigations focus on the comparisons of these two types of powders through the analysis of mechanical and microstructural properties. However, why the differences exist is still unknown. High-speed X-ray imaging has been proven to be a competitive method to reveal the fundamental physics of phenomena in laser additive manufacturing (AM) processes. Therefore, in situ synchrotron X-ray imaging is used to provide the fundamental understanding of powder delivering performance in the DED AM. Based on the results, high-speed X-ray imaging is extended to investigate the effects of processing parameters on pore formation and pore formation mechanisms in the DED AM process.

Special Session: Composite AM II - Polymers A

Tuesday AM August 3, 2021

Session Chair: M. Tehrani, University of Texas at Austin

8:00 AM
State of the Art and Technology in Additively Manufactured Polymer Composites: *Mehran Tehrani*[1]; [1]University of Texas at Austin

While polymer additive manufacturing (AM) has advanced significantly over the past few decades, the limitations in material properties, speed of manufacture, and part size have relegated this technology mostly to the space of rapid prototyping rather than the legitimate production of end-use parts. Polymer composites have been identified as a potential solution to these limitations, as they offer improved properties, reduce the time required to manufacture functional parts over traditional subtractive technology, and reduce warping to lead to a larger build envelop. In this presentation, the most promising technologies for composites AM as well as the state-of-the-art and technology in this field will be reviewed. As such, mechanics, design, materials science, and processing of polymer composite AM will be discussed in the light of experiments, theory, and numerical simulations.

8:30 AM
Analysis of Fiber Orientation and Concentration in Large Scale Polymer Composite Deposition of Carbon Fiber-reinforced Thermoplastics: *Neshat Sayah*[1]; Douglas Smith[1]; [1]Baylor University

Materials produced with Large Area Additive Manufacturing (LAAM) are significantly enhanced through the addition of short carbon fibers to the polymer matrix. Carbon fiber reinforced composites are used in LAAM due to their lightweight, favorable mechanical properties, multifunctional application, and low manufacturing costs. The thermomechanical, mechanical, and electrical properties of the 3D printed composite are highly dependent on the distribution and orientation of the suspended carbon fibers which are defined by the polymer deposition manufacturing process. This study aims to gain a better understanding of fiber orientation and fiber concentration within the microstructure of a LAAM bead. High-resolution-3D micro-computed tomography (CT) is used to evaluate porosity, fiber migration, and fiber orientation. Measured results are used to validate predictions of the same for simple LAAM extrusion flows. Preliminary results will focus on the microstructure within a single bead and during the flow process upstream of the polymer composite deposition event.

8:45 AM
Correlating Large-scale AM Print Parameters to Fiber Length and Mechanical Performance of Reinforced Polymer Composites: *Andrew Rhodes*[1]; Roo Walker[1]; John Lindahl[2]; Chad Duty[1]; [1]University of Tennessee; [2]Oak Ridge National Laboratory

The development of large-scale polymer Additive Manufacturing (AM) has progressed quickly as a leading energy efficient AM process, but the understanding of the unique microstructure within large-scale AM fiber-reinforced polymer composites has not kept pace. This leaves significant opportunities to improve the mechanical performance of printed structures through understanding the micro-structure of AM composites. Specifically, this work examines mechanical performance relative to fiber length, and effect of processing parameters on the fiber length of AM composites. Fiber length distributions from raw stock were compared against those of printed materials, and stock extruded under different processing conditions, which were then correlated to the respective part strengths to better understand the relationship between fiber length, processing conditions, and printed composite strength. This research will guide future modifications to hardware design and print parameters to maintain fiber length and maximize mechanical performance.

9:00 AM

Characterizing the Internal Morphology of Transition Regions in Large-scale Extrusion Deposition Additive Manufacturing: *James Brackett*[1]; Zaky Hussein[1]; Elijah Charles[1]; Tyler Smith[1]; Ahmed Hassen[2]; Seokpum Kim[2]; Vlastimil Kunc[2]; Chad Duty[1]; [1]University of Tennessee Knoxville; [2]Oak Ridge National Laboratory

A dual-hopper feed system that was developed for the Big Area Additive Manufacturing (BAAM) system allows for transitioning between different materials while maintaining continuous deposition. This technique creates a step-change in material feedstock by rocking the pellet feeding system to alternate which hopper is currently supplying material, allowing for multi-material construction. The step-change in feedstock material produces a transition region that is characterized by a compositional gradient and blended internal morphology. Initial cross-sectional imaging of the transition region revealed a non-homogenous blend of materials with distinct domains of each material, likely due to incomplete mixing within the screw. This study used a carbon fiber reinforced acrylonitrile butadiene styrene (CF-ABS) and an unfilled ABS to characterize the internal structure and to correlate it to mechanical performance by tracking microhardness across cross-sections of the transition region. Blending capability of the conventional printing hardware was also compared to that of a static-mixing nozzle.

9:15 AM

Modeling Inter-layer Bonding in Additive Manufacturing of Continuous Fiber Reinforced Polymer Composites: *Anahita Emami*[1]; Mehran Tehrani[1]; [1]The University of Texas at Austin

Recent advancements in Additive Manufacturing (AM) of continuous fiber composites through Fused Filament Fabrication (FFF) have enabled the development of customized high-performance composite structures. One of the key challenges in FFF is estimating the effects of process parameters on mechanical properties of the manufactured products. In this study, a coupled thermo-mechanical finite element method (FEM) is used to simulate the FFF process, and a theoretical bonding model is implemented to estimate the degree of bonding between printed layers. The model is utilized as a basis to establish the relation between processing conditions and inter-layer properties. The processing parameters such as nozzle temperature, bed temperature, layer height, and printing speed are considered as the inputs of the model while the degree of bonding between printed layers and the residual stresses are the outputs. Finally, the optimal processing parameters are determined to achieve the highest performance of the FFF method.

9:30 AM

Understanding Filler Orientation in Material Extrusion Additive Manufacturing of Thermoset Composites: *Nadim Hmeidat*[1]; Edward Trigg[2]; Louisa Smieska[3]; Arthur Woll[3]; Hilmar Koerner[2]; Brett Compton[1]; [1]The University of Tennessee; [2]Air Force Research Laboratory; [3]Cornell University

Direct ink writing (DIW) enables the deposition of a broad range of composite materials and imposes preferential orientation on high-aspect-ratio filler materials, including nano-platelets, whiskers, and fibers. This alignment of filler materials is controlled via the shear stresses in the deposition nozzle. These shear stresses are highly non-uniform during printing, leading to spatial variation of orientation of filler materials within the printed road. Because adjacent printed roads usually overlap one another by a certain percentage, an interfacial boundary and deformed region between the roads exist, which influences the final arrangement of filler materials. This talk will focus on recent efforts in understanding filler orientation within printed composite inks as characterized by polarized light microscopy, nanoindentation mapping, and micro-beam small-angle X-ray scattering. Results establish relationships between the composition of the printed material, overlap of printed roads, optical birefringence patterns, local and bulk mechanical properties, and filler orientation within a printed component.

9:45 AM

A Comparative Study of Extrusion Deposition of Long and Continuous Carbon Fiber Reinforced Composites for Large-scale Additive Manufacturing: Aditya Thakur[1]; John Pappas[1]; Ming Leu[1]; *Xiangyang Dong*[1]; [1]Missouri University of Science and Technology

Large-scale additive manufacturing (LSAM) of carbon fiber reinforced composites (CFRC) has recently gained much interest in fabricating large-format components with good mechanical strength. A comparative investigation of extrusion deposition of long- and continuous-CFRC was performed due to their potentials in further improvement of mechanical properties. Thermoplastic pellets and continuous carbon fiber tows were directly used as feedstock materials in the proposed method. The printability and microstructure including fiber length, distribution and orientation as well as porosity were characterized and compared. Mechanical properties were also measured for all printed samples. With an average fiber length of 20.1 mm, larger than critical fiber length, and highly oriented fiber distribution, long-CFRC exhibited a flexural modulus value nearly comparable to that of continuous-CFRC while its flexural strength was slightly lower than that of continuous-CFRC. The feasibility of the proposed method for LSAM was further demonstrated in fabrication of large-format CFRC components with complex geometries.

10:00 AM

Additive Manufacturing of a Carbon Fiber Reinforced Thermoset Resin via Reactive Extrusion Additive Manufacturing (REAM): *Pratik Koirala*[1]; Oliver Liam Utiz[1]; Ademola A Oridate[1]; Carolyn Conner Seepersad[1]; Mehran Tehrani[1]; [1]University of Texas at Austin

This project investigates a novel additive manufacturing (AM) technique, reactive extrusion AM, for carbon fiber reinforced thermosetting resins. The process utilizes highly exothermic resin/catalyst systems with fast curing cycles, eliminating the need for an external energy source. Chemical cross-linking occurs between the printed layers, resulting in parts with strong interlayer properties. Carbon fibers are added to the thermosetting resin for mechanical reinforcement with fumed silica as a rheology modifier. Inter- and intra-layer tensile properties of REAM neat polymer and composites reinforced with 20wt.% of milled fibers are measured. These properties are correlated, using a mechanics model, to the fiber length/orientation distributions data attained from X-ray-micro computed tomography(uCT). Degree of curing is also characterized using Differential Scanning calorimetry (DSC)and correlated to thermal images captured during parts' AM.

10:15 AM

Predictions of the Elastic-plastic Compressive Response of Functionally Graded Polymeric Composite Lattices Manufactured by 3D Printing: Janos Plocher[1]; Vito Tagarielli[1]; *Ajit Panesar*[1]; [1]Imperial College London

We use 3D printing to manufacture lattices with uniform and graded relative density, made from a composite parent material comprising a nylon matrix reinforced by short carbon fibres. The elastic-plastic compressive response of these solids is measured up to their densification regime. Data from experiments on the lattices with uniform relative density is used to deduce the dependence of their homogenised constitutive response on their relative density, in the range 0.2-0.8. This data is used to calibrate Finite Element (FE) simulations of the compressive response of Functionally Graded Lattices (FGLs), which are found in good agreement with the corresponding measurements. This exercise is repeated for two lattice topologies (body-centred cubic and Schwarz-P) and provides a dataset that can be used in topology optimisation to maximise the performance of 3D printed FGLs components in terms of stiffness, strength or energy absorption.

Special Session: Data Analytics in AM II - Optimization of Process, Design and Materials B

Tuesday AM August 3, 2021

Session Chair: B. Lane, National Institute of Standards and Technology

8:00 AM
Physics-informed and Hybrid Machine Learning in Additive Manufacturing: *Berkcan Kapusuzoglu*[1]; Sankaran Mahadevan[1]; [1]Vanderbilt University

This work investigates several physics-informed and hybrid machine learning strategies that incorporate physics knowledge in experimental data-driven deep learning models for predicting the bond quality and porosity of fused filament fabrication parts. A physics-based sintering model is developed to predict the neck diameter and porosity of FFF parts. Three types of strategies and their combinations are explored to incorporate physics information into a deep neural network (DNN), thus ensuring consistency with physical laws: (1) incorporate physics constraints within the loss function of the DNN, (2) use physics model outputs as additional inputs to the DNN model, and (3) pre-train a DNN model with physics model input-output and then update it with experimental data. These strategies help to enforce a physically consistent relationship between bond quality and tensile strength, thus making porosity predictions physically meaningful. The results show how the combination these strategies produces accurate results even with limited experimental data.

8:15 AM
Autonomous Multimodal Manufacturing Optimization: *Brian Giera*[1]; Kyle Devlugt[1]; Adam Jaycox[1]; [1]Lawrence Livermore National Laboratory

Characterization of additively-manufactured parts is often serial, where different processing steps and measurements are executed in a non-colocated and non-automated fashion. Furthermore, these activities require sustained manual oversight and intervention. Thus, the development cycle (e.g. part specification, fabrication, and qualification) is subject to bottlenecks, making part repeatability difficult and costly to achieve, quantify, and optimize. To address these issues, our team is standing up hardware and software to achieve “Autonomous Multimodal Manufacturing Optimization,” as demonstrated in a modular manufacturing cell wherein cradle-to-grave data is collected from sensing, simulation, and inspection. We present some of our early stage modules, in terms of data archiving, digital twins of fabrication and inspection of fused deposition modeling parts, and analyzing part files to leverage experiential knowledge in a formulaic and process general way.This work was performed under the auspices of the U.S. Department of Energy by LLNL under Contract DE-AC52-07NA27344.

8:30 AM
Correlating the Effect of Part Geometry and Support Structure on Thermal History in Laser Powder Bed Fusion: *Reza Yavari*[1]; Prahalad Rao[1]; Heimdall Mendoza[2]; [1]University of Nebraska; [2]Edison Welding Institute

The objective of this work is to quantify the effect of part geometry and support structure in the thermal history of laser powder bed fusion processed-parts. In this work, a variety of parts with differing geometry and support structures were produced on the open architecture laser powder bed fusion platform at Edison Welding Institute (EWI). During the printing process surface temperature measurements were acquired using a thermal camera. In this work we correlate the build quality as a function of the temperature and part design.

8:45 AM
Data Models for Analytics and Machine Learning in Additive Manufacturing: *Paul Witherell*[1]; Yung-Tsun Lee[1]; Hyunseop Park[2]; Hyunwoong Ko[3]; Junhyuk Choi[4]; [1]National Institute of Standards and Technology; [2]Pohang University of Science and Technology; [3]Nanyang Technological University; [4]Pohang University of Science and Technology

As additive manufacturing (AM) matures as a production technology new data sets have emerged from all aspects of a part’s development, from design iterations to process monitoring to testing and certification. These data sets have created many new challenges in data curation and many new opportunities with data analytics and machine learning. These challenges and opportunities are not mutually exclusive. This paper investigates the use of data standards to provide structure to AM analytics, including the representation of objectives, parameters, constraints, and algorithms. By aligning analytics-based data structures with AM data models, we develop requirements for sets of re-usable analytical metamodels across the design and fabrication of an AM part. These requirements characterize AM-specific data types and analyses opportunities within the context of machine learning and data analytics techniques. We develop an example metamodel and demonstrate its application within an in situ decision-making environment.

9:00 AM
Optimization of Support Geometry for Powder Bed Fusion: A Generative Approach: *Mugdha Joshi*[1]; Todd Sparks[2]; Aaron Flood[1]; FueWen Liou[1]; [1]Missouri University of Science and Technology; [2]Product Innovation and Engineering LLC

A key issue in powder bed fusion additive manufacturing system is the optimization of support geometry. Correct selection of support strategy can reduce build time, improve surface finish, reduce support removal time, and maximize build success. Strategies used to design support structure are time consuming and need skilled personnel. In this research, we have deployed a deep generative model to minimize human intervention in support design. Conventional shape synthesis algorithms synthesize new objects by retrieving and combining shapes and parts from a database. Presented in this paper is a model mapping the object space to a probabilistic latent space. Arithmetic is performed on the object vectors in the latent space to perform morphological operations on the geometry. The dimensionally reduced latent space unlocks computationally tenable generation of variations in part geometry by learning features such as overhangs, holes, or internal voids.

9:15 AM
Quality Assurance in Biomaterial Aerosol Jet Printing Using Machine Learning: *Sam Gerdes*[1]; Srikanthan Ramesh[2]; Aniruddha Gaikwad[1]; Iris Rivero[2]; Ali Tamayol[3]; Prahalada Rao[1]; [1]University of Nebraska-Lincoln; [2]Rochester Institute of Technology; [3]University of Connecticut

Aerosol jet printing centers on the deposition of atomized materials. The process can fabricate high-resolution features, for the creation of microelectronics, flexible electronics, and biomimetic surfaces, among others. However, deposit quality is a complex function of the process parameters (sheath gas flow, carrier gas flow, and print speed). Improper selection of process parameters or process drifts often leads to suboptimal print quality and the potential to alter the print’s functionality. Accordingly, the objective of this work is to ensure flaw-free deposition. To realize this objective, we use machine learning strategies to classify and predict the characteristics of the deposit as a function of the process parameters and theoretical model results. Once trained for a machine setup and material, the resulting machine learning network can identify the deposit quality as a function of the process parameter combination, prior to printing, saving operator time on failed prints.

9:30 AM
Analyzing Remelting Conditions Based on In-Situ Melt Pool Data Fusion for Overhang Building in Powder Bed Fusion Process: *Zhuo Yang*[1]; Yan Lu[2]; Jaehyuk Kim[2]; Brandon Lane[2]; Yande Ndiaye[2]; Sundar Krishnamurty[1]; [1]University of Massachusetts Amherst; [2]National Institute of Standards and Technology

Coaxial melt pool monitoring (MPM) images provide in-depth insights into the building process of laser powder bed fusion additive manufacturing. An in-situ MPM image captures the independent melting condition at a specific scanning position. However, it is challenging to identify material defects such as horizontal lack-of-fusion using individual, discontinuous MPM images. This paper builds upon the authors' previous work on data registration and data fusion, to analyze material remelting conditions based on melt pool images. MPM data are fused to formulate layerwise remelting maps to evaluate printing quality. A 3D part with various overhang features was built to verify the method. A regular layer with solid support from the previous layers has around 30% remelting ratio for the given laser scan conditions. In contrast, overhang regions remelted at about 10% with the same process setting, which are too narrow to provide sufficient material fusion, resulting in lack-of-fusion between melting tracks. The negative impact in remelting would not immediately disappear in subsequent layers following the overhang regions. Results shows three additional layers are required to fully recover the remelting condition back to normal. The remelting results from MPM are also visible within layerwise optical images of the same surface.

Special Session: Wire-fed AM Processes II

Tuesday AM August 3, 2021

Session Chairs: S. Narra, Carnegie Mellon University; B. Silwal, Georgia Southern Univ

8:00 AM
Fused Filament Fabrication on the Moon: *Jie Zhang*[1]; Brecht Van Hooreweder[1]; Eleonora Ferraris[1]; [1]KU Leuven

Additive manufacturing (AM) techniques possess the capabilities to rapidly produce low-volume and highly-customised parts with minimal material waste. These attributes magnify their indispensability especially when traditional manufacturing techniques are limited or not available. It can be such a case for off-earth manufacturing, e.g. in manned lunar explorations, when both materials and manufacturing techniques will be limited. This paper presents a preliminary discussion on the possibility of performing fused filament fabrication (FFF) on the Moon from the perspective of heat transfer in the printed parts. It makes use of experimental data and simulations to quantify the significance of each heat transfer mechanisms taking place during printing. The quantification then enables us to investigate how the lunar environment affects the cooling in the printed parts. Finally, FFF on the Moon is predicted to be feasible. Yet, apparent differences are pointed out as compared with the counterpart printing activities on the Earth.

8:15 AM
Wire Arc Additive Manufacturing of Low Carbon Steel for Casting Applications: *Eric Weflen*[1]; Mitchell Black[1]; Matthew Frank[1]; Frank Peters[1]; [1]Iowa State University

While metal AM research often focuses on high-cost materials, lower-cost alloys such as low carbon steel are used at higher volumes in the casting industry. Welding is a standard process step in casting production, but robotic automation has been limited due to this industry's low-volume and high-mix. However, advances in flexible automation show their potential. This research presents the application of WAAM using a 6-axis robot arm with low carbon steel castings. Process parameters, including travel speed, cooling time, and step over distance, are evaluated for their effect on the resulting geometry. Demonstration parts assess the ability to produce objects with varying geometries without defects. A method is discussed for depositing material on non-planar surfaces, such as the filling of a concave feature. These findings broaden the scope of applications in which wire arc additive manufacturing can be applied in industrial applications and develops parameters for depositing within non-planar cavities.

8:30 AM
Printing of Metal Droplet Streams Using Continuous Breakup of a Laser Heated Metal Wire: *Kaihao Zhang*[1]; Justin Beroz[1]; Henry Merrow[1]; Caroline Jordan[1]; Ulrich Muecke[1]; A. John Hart[1]; [1]Massachusetts Institute of Technology

We present a novel wire-fed AM technique that achieves direct printing of metal microdroplets from a fine wire feedstock. The process involves a wire feed mechanism that advances a wire at a controlled speed and a desired trajectory, and the modulated laser heating applied near the wire tip to liquefy the moving wire and generate a stream of molten droplets. We demonstrate the stable feeding of a F 50 µm 304L stainless steel wire at a controlled speed ranging from 0.5 to 1.5 m/s, and continuous breakup into molten droplets with a corresponding diameter of 120-180 µm, at a frequency of ~1 kHz. Via experiments and numerical modeling, we analyze the mechanism of breakup and the factors influencing the stability of the droplet stream. Further, we investigate how to direct the droplet trajectory, and present preliminary results where the droplets are printed onto moving substrates.

8:45 AM
Data Acquisition in Wire-arc Additive Manufacturing: The Road to Digital Twin: *William Carter*[1]; David Marsh[1]; Luke Meyer[1]; Andrzej Nycz[1]; Mark Noakes[1]; [1]Oak Ridge National Laboratory

One of the issues facing additively manufactured parts is the inability to guarantee a lack of defects and certify parts as ready for use in real-world applications. While this can be justified by things like lower cost and shorter lead times in areas such as tooling, in higher-risk applications like aerospace better certification methods are needed. One of the most promising proposals for part certification is a digital representation of a part known as a digital twin. A digital twin is an electronic representation of a part and can be created using data collected during the build process. A data acquisition system capable of collecting the necessary data for a digital twin of a wire-arc part will be presented along with a sample of data collected using this system.

9:00 AM
A Multi Robot Coordinated-motion Approach to Large Scale Deposition Systems – MedUSA: *Andrzej Nycz*[1]; Steven Patrick[1]; Peter Wang[1]; Mark Noakes[1]; Lonnie Love[1]; Jonathan Paul[2]; Jason Flamm[2]; Randy Lind[1]; [1]Oak Ridge National Laboratory; [2]Lincoln Electric

Single deposition heads and gantry systems are the most common 3D printer kinematic arrangements. The recent advances in Direct Energy Deposition systems led to a more frequent use of classical robotic manipulators. This work presents the next step in the evolution of large-scale deposition systems. One of the major challenges of 3D printing is scaling up to be able to manufacture truly significant sizes, reaching far beyond the workspace provided by the standard 2m arms, while keeping high productivity and quality. While the typical way of increasing available workspace is to introduce a larger kinematic system or robot, a more optimal way of increasing the productivity and scale is by intelligently sharing the workload between several smaller subsystems working as one united collective. This work explores the potential, challenges and current capabilities of multi-robot coordinated large scale systems, based on the development of a four-robot wire-arc-based printer named MedUSA.

9:15 AM
Defining Robotic Torch Parameters for Non-gravity Aligned (NGA) Metal Additive Manufacturing Using CAD to Part Framework: *James McNeil*[1]; William Hamel[1]; Joshua Penney[1]; [1]University of Tennessee-Knoxville

The research described from this work focuses on the steps necessary to define welding robot parameters necessary to complete NGA segments of Large Scale Additive Metals Manufacturing (LSAMM) builds. A novel framework for slicing and building parts out of gravity alignment has been developed and demonstrations of the NGA capability have allowed overhangs of up to 105 degrees. The presented research focuses on the virtual CAD to Part and the necessary steps from slicing to generation of robot end position. New software developed at the University of Tennessee have allowed a variety of demonstration parts to be completed with an understanding on fundamental heuristics of torch angle and shift for the success of NGA segments.

9:30 AM
Towards a Digital Twin: 4D Data Conditioning for Metal Inert Gas Big Area Additive Manufacturing: David Marsh[1]; William Carter[1]; Andrzej Nycz[1]; Mark Noakes[1]; *Christopher Masuo*[1]; [1]Oak Ridge National Laboratory

Recent efforts to extend additive process monitoring and improve part quality have focused on the creation and verification of digital twins. The implementation of digital twins in additive manufacturing is complex, because many process variables of interest, such as internal part temperatures, are not directly observable. The first step in the creation of a comprehensive digital twin for metal inert gas additive manufacturing is the tuning and certification of thermal and geometric models using measured print data. The presented 4D data processing approach (x,y,z, and time) allows collected process data from temperature, geometry, energy input, energy output, and material deposition sensors to be applied to any unknown model without the need to rerun experiments. Example data was collected and processed, and unexpected benefits and challenges for the data collection methods are discussed.

Applications: General II

Tuesday PM August 3, 2021

Session Chair: D. Hoelzle, Ohio State University

1:30 PM
Free Standing 3D Piezoelectric PVDF Sensors via Electrowriting: *Kranthi Kumar Reddy Bannuru*[1]; Hong Yee Low[1]; [1]Singapore University of Technology And Design

Piezoelectric micro-architectures using soft materials are sought for applications in robotic sensors and actuators, wearable electronics, and energy harvesting. The sensitivity of piezoelectric PVDF sensors is attributed primarily to ß-crystalline phase with oriented dipoles. The 3D electrowriting process combines mechanical stretching and electric field assisted poling of PVDF in a single step extrusion process that are known to improve electroactive crystalline phases in PVDF. In this work, we demonstrate the fabrication of free-standing 3D PVDF structures with an average individual layer height as small as 30 µm and continuous prints up to >20 layers for multiple designs. The extent of ß-phase transformation of PVDF during the process is compared to pvdf in powder form and film using a FT-IR and XRD techniques. Furthermore, the sensors fabricated using 3D PVDF structures is sensitive to various load profiles at varying frequencies with the piezoelectric voltage coefficient (g33) between 1.72E-4 to 4.08E-4 V.m/N.

1:45 PM
A Methodology for the Embedding of Sensors in Components Manufactured Using Metal Laser Powder Bed Fusion: Sinéad Uí Mhurchadha[1]; Minh Phuoc Huynh[2]; *Italo Tomaz*[2]; Paul Quinn[1]; Ramesh Raghavendra[1]; [1]SEAM Research Centre; [2]I-Form Advanced Manufacturing Research Centre

This paper presents a methodology for the embedding of a sensor in a 316L stainless steel component during LPBF. The aim of this study is to overcome the drawbacks of traditional sensor attachment to the surface of components by embedding sensors into a part during the manufacturing process. A methodology for the embedding process that ensures the functionality of the sensor within the component is presented and an investigation into the effect of the embedding process on the part quality is reported. An off-the-shelf accelerometer was embedded into a turbine and tested under rotational loading conditions. The interface where the print was paused is also studied to investigate the effect of the embedding methodology on material properties. The embedded sensor is capable of detecting off-axis rotation and over-speed of the turbine; however, some tolerance issues are observed. Finally, based on the initial results, a more robust embedding methodology is proposed.

2:00 PM
Electrodeposition on 3D Printed Carbon MEMS: *Joshua Tyler*[1]; Gabriel Smith[2]; John Cumings[3]; Nathan Lazarus[2]; [1]Oak Ridge Associated Universities; University of Maryland; [2]US Army Research Laboratory; [3]University of Maryland

Many polymer-based 3D printing processes such as two-photon polymerization (2PP) most easily print non-conducting materials. Pyrolysis, thermal decomposition to carbon at elevated temperatures, of 2PP parts has recently enabled the additive manufacturing of conductive carbon structures at the microscale for use in sensors and electrical passives, but carbon remains substantially less conductive than bulk metals. In this work, an electroplating process was developed to conformally coat additively manufactured pyrolytic carbon with copper and nickel. The use of pyrolyzed carbon as an electroplating seed layer allows for the increased electrical and mechanical properties of copper and nickel to be integrated with microfabricated pyrolyzed carbon, allowing more complex metal MEMS to be rapidly fabricated in three dimensions. The resistance of metal/carbon devices was significantly lower than the bare pyrolyzed carbon material and the hybrid devices showed an increase in the success of soldering to the plated surface.

2:15 PM
Support Structure Reduction Approach by Geometry and Process Parameter Modification Based on AM Ontology and Optimization Procedure: *Sang-in Park*[1]; [1]Incheon National University

This research proposes a support structure reduction methodology to improve surface quality and manufacturing cost. To eliminate or reduce the structure, we locally modify geometries of a CAD model and/or find optimum process parameters to minimize geometrical accuracy and to maximize surface quality. The proposed method consists of three steps. Firstly, we select parameters related to support generation, surface quality and build-fail. To do this, an additive manufacturing ontology for a material extrusion process is constructed. Secondly, we develop geometry-process-property libraries to study relationship among parameters. Finally, we develop an optimization process for preventing build-fail without support-structures to modify the geometries and process parameters. The proposed approach successfully searches for high-impact parameters related to support reduction, and the geometry and process parameter modification results in improvement in surface quality without support structures.

Broad Issues in AM: II Robotics, Security and Digitalization

Tuesday PM August 3, 2021

Session Chair: N. Sakthivel, Baker Hughes, a GE company

1:30 PM

Impact of 3D Printing in Rapid Evolution of Competitive Robotics Such as World Robotics League: *Rajeev Dwivedi*[1]; [1]STEM and Robotics Academy

Competitive Robotics such as World Robotics League (WRL), World Robotics Olympiad (WRO), FIRST programs such as FTC and FRC etc. have recently evolved as an avenue for learning, innovation and providing real life perspective to classroom learning. Given the short duration for Robot Development and diverse range of challenges, innovation and product development has to happen at fast pace. Typical challenges include stow, configure, launch, travere 3D environment, sorting, assembe etc. Many challenges include underwater and aerial spaces. Participants typically use reconfigurable "Robotics Kits". However, "Robotics Kits" are limited in many ways and do not go beyond mobile platform and simple mechanisms. Many participants are turning to quicker alternatives such as 3D printing. This paper provides a current state of the Competitive Robotics, the existing solutions and examples of how 3D printing is accelerating innovation in competitive robotics.

1:45 PM

Impact of Solid Freeform Fabrication in Enabling Design and Prototyping Capabilities for Competitive Robotics such as World Robotics League, FTC, FRC, WRO etc.

: *Rajeev Dwivedi*[1]; [1]STEM and Robotics Academy

Competitive Robotics such as World Robotics League (WRL), World Robotics Olympiad (WRO), FIRST programs such as FTC and FRC etc. have recently evolved as an avenue for learning, innovation and providing real life perspective to classroom learning. Given the short duration for Robot Development and diverse range of challenges, innovation and product development has to happen at fast pace. Typical challenges include stow, configure, launch, travere 3D environment, sorting, assembe etc. Many challenges include underwater and aerial spaces. Participants typically use reconfigurable "Robotics Kits". However, "Robotics Kits" are limited in many ways and do not go beyond mobile platform and simple mechanisms. Many participants are turning to quicker alternatives such as Solid Freeform Fabrication. This paper provides a current state of the Competitive Robotics, the existing solutions and examples of how Solid Freeform Fabrication is accelerating innovation in competitive robotics.

2:00 PM

Development Testing and Prototyping Varying Robot Architectures Using Solid Freeform Fabrication for World Robotics League: *Rajeev Dwivedi*[1]; [1]STEM and Robotics Academy

Educational and competitive robotics provide avenue for hands on experimentation and hence effective tools for STEM education. Most of the the leagues are limited in providing a systematic approach to learning, evaluation and skill building. The manufacturer provided kits are extremely limited in their abilities and are limited to 2D environments with tasks limited to push, pull launching and sorting items. World Robotics League (WRL) is a platform for systematic learning with challenges offered in growing order of complexity. Additionally, WRL league provides avenues for experimentation in 3D space, Aerial and Underwater Robotics. With emphasis on experimentation and limitations of off the shelf kits, Solid Freeform Fabrication (SFF) becomes a most viable technology to build special end effectors, actuators, propellers, compliable and and streamlined body of Robots. This paper provides a survey of various leagues, kits available in the market and many avenues that could be possible due to SFF.

2:15 PM

Sabotage Attacks in Metal Additive Manufacturing at the Layer Granularity: *Patricio Carrion*[1]; Lynne Graves[2]; Mark Yampolskiy[1]; Nima Shamsaei[1]; [1]Auburn University; [2]University of South Alabama

Additive Manufacturing (AM) is dependent on a number of precise manufacturing parameters, such as layer thickness, to produce functional parts. Layer thickness misconfiguration during normal manufacturing is generally detectable as it impacts the entire build. In this paper, however, we demonstrate that targeted misconfigurations, as might be contemplated by a cyber-physical attacker, can be executed without hacking into the firmware, impacting part quality and avoiding detection. Using a modified build file with a Powder Bed Fusion (PBF) machine, we create fusion defects, mimicking selective layer thickness flaws through disabled laser beam exposure, while maintaining geometrical and visual part integrity. We then confirm part functionality degradation, demonstrating metal AM susceptibility to cyber-physical attacks and thereby illustrating the necessity for security investments with regards to this increasingly adopted manufacturing process.

2:30 PM

Additive OS: An Open-Source Platform for Additive Manufacturing Data Management & IP Protection: *Evan Diewald*[1]; Jack Beuth[1]; [1]Carnegie Mellon University

The additive manufacturing (AM) digital thread presents unique challenges for data management and security. While proprietary software packages solve many issues, they can be expensive and lacking in customization. Additive OS is an open-source platform for importing, sharing, organizing, and querying AM data. Man-in-the-middle attacks, secure print licensing, and IP theft are addressed using custom smart contracts, ontology is preserved with a NoSQL database and directed acyclic graph (DAG) representations, and peer-to-peer content delivery facilitates low-latency file transfer. The application includes a browser-based graphical user interface, but developers can access the underlying API to invoke sophisticated queries, add functionality, or run the lightweight client on low-resource hardware.

2:45 PM

Digital Twin Configuration Management for Additive Manufacturing Supply Chain Workflow: *Paul Witherell*[1]; Hyunwoong Ko[1]; Duncan Gibbons[2]; [1]National Institute of Standards and Technology; [2]Stellenbosch University

The additive manufacturing (AM) workflow is a ductile entity, often varying depending on the design, the product, the process, the material, and the application. Information models and schemas have been developed that can provide structure to data and information throughout the workflow. The result has been a well-characterized outline of an AM digital thread. However, implementation-specific details are often missing from these characterizations, creating challenges in establishing part-specific workflows, or digital twins, necessary for product configuration management. While software vendors are increasingly filling this gap, a software-agnostic workflow has yet to be defined. This paper investigates the workflow of an AM part and establishes the fundamentals of a standardized configuration management approach to establishing a digital twin, including suitable formats; interoperability; versioning; digital rights and ownership. The result is a comprehensive outline for establishing a digital twin of an AM part.

Materials: Ceramics, Other III - Jetting and DED

Tuesday PM August 3, 2021

Session Chair: X. Dong, Missouri University of Science and Technology

1:30 PM
Inkjet Printing Graphene for Devices: From Contacts to Functional Layers: *Feiran Wang*[1]; Gustavo Trindade[1]; Jonathan Gosling[2]; Graham Rance[3]; Oleg Makarovsky[2]; Nathan Cottam[2]; Zakhar Kudrynsky[2]; Lyudmila Turyanska[1]; Mark Fromhold[2]; Christopher Tuck[1]; [1]Centre for Additive Manufacturing, Faculty of Engineering, University of Nottingham; [2]School of Physics and Astronomy University of Nottingham; [3]Nano and Micro-Research Centre, nmRC University of Nottingham

Inkjet printing provides a powerful approach of fabricating graphene devices, especially for large area, customised formats and co-deposition ability with low cost and good quality. Using graphene-polymer ink produced by liquid exfoliation of graphite in ethyl cellulose, we demonstrate various functionalities of inkjet printed graphene composite film with satisfied conductivity and precise geometry. Thermal gravimetric analysis and Raman spectroscopy revealed the preferable thermal anneal at 250oC to improve the intralayer ordering of the few-layer graphene structure for a minimum resistivity of 0.003 O.cm. A fully inkjet-printed Graphene/hexagonal Boron Nitride transistor was fabricated and attained signature graphene transfer behaviour with different electron and hole mobilities, which is consistent with the theoretical modelling. A prototype of a photodetector has also been fabricated by inkjet printing graphene contacts to an InSe flake, which outperformed traditional metal contacts with a good linear ohmic due to the band alignment.

1:45 PM
Ceramic Binder Jetting Additive Manufacturing: Effects of Granulation on Properties of Feedstock Powder and Printed and Sintered Parts: *Guanxiong Miao*[1]; Wenchao Du[1]; Mohammadamin Moghadasi[1]; zhijian Pei[1]; Chao Ma[1]; [1]Texas A&M University

Nanopowder could be beneficial for ceramic binder jetting additive manufacturing to achieve a high density on printed and sintered parts because of its high sinterability. However, the flowability of the nanopowder is poor because of the large interparticle cohesion. This poor flowability prohibits the application of nanopowder in ceramic binder jetting. In this study, to improve the flowability of nanopowder, alumina nanoparticles (300 nm) are granulated into micron-sized granules (53–90 µm) through spray freeze drying. The raw nanopowder and granulated powder are compared by characterizing their flowability, sinterability, and printability. Results show that the granulated powder has a much better flowability than the raw nanopowder while the superior sinterability of the nanopowder is maintained after granulation. The higher density and smaller surface roughness of the part printed with granulated powder indicate that the granulation improves the printability of the nanopowder.

2:00 PM
Binder-free Additive Manufacturing of Ceramics Using Hydrothermal-assisted Transient Jet Fusion: *Fan Fei*[1]; Levi Kirby[1]; Xuan Song[1]; [1]University of Iowa

Major ceramic additive manufacturing (AM) processes require a high concentration of organic binder to selectively bond ceramic particles into green parts, which leads to issues such as low density and unreliable properties in resulting components. In this work, a new ceramic AM process named hydrothermal-assisted transient jet fusion (HTJF) is introduced, which fuses particles through selectively depositing a volatile dissolving ink, such as deionized water, into a pressurized / heated powder bed, triggering hydrothermal-assisted mass transfer between particles and interparticle pores. A prototype system is presented to demonstrate the binder-free fabrication of ceramics. The effects of process parameters on macroscopic properties of printed parts and particle-scale mass transfer in the HTJF process are studied using experimental and computational techniques.

2:15 PM
Direct-writing SiC with Micro-cold Spray: Particle Agglomeration Dependence on Film Density: *Derek Davies*[1]; Michael Gammage[2]; Michael Becker[1]; John Keto[1]; Desiderio Kovar[1]; [1]University of Texas at Austin; [2]CCDC DEVCOM Army Research Laboratory

Micro-cold spray produces thick films by accelerating aerosolized nano- and micro-particles through a nozzle from near atmospheric pressure to medium vacuum (1-3 Torr). By impacting these accelerated particles on a substrate that is translated orthogonal to the aerosol jet, patterned films are deposited. As compared to cold spray which is capable of depositing metallic or metal-matrix composite films, micro-cold spray has demonstrated the unique capability of depositing high quality ceramic films at room temperature. Particle agglomeration occurs ubiquitously for the particles used in micro-cold spray and is believed to significantly affect the density and microstructure of the deposit. We perform molecular dynamics simulations of multi-particle agglomerate impact, varying parameters such as agglomerate size and shape, to determine the effect of agglomeration on film density. These simulation results are compared to experimental results from SiC films with the aim of understanding how agglomerate size and morphology influences deformation and bonding mechanisms.

2:30 PM
Direct 3D Printing of Transparent Spinel Ceramics via One-step Laser Direct Deposition: John Pappas[1]; Edward Kinzel[1]; *Xiangyang Dong*[1]; [1]Missouri University of Science and Technology

This study investigated the additively manufactured transparent spinel ceramics by one-step laser direct deposition. Dense transparent magnesium aluminate spinel samples were directly fabricated from micron-size powders with greatly lowered manufacturing costs and simplified processing procedures. A highest optical transmittance of 82% was achieved at a wavelength of 632.8 nm, nearly comparable to that of sintered counterparts. Porosity and cracking were found to be main factors limiting the obtained transparency. The effects of laser processing conditions and powder compositions were systematically investigated. The morphology, optical transmittance, microstructure, and phase composition of the printed spinel samples were characterized. A single spinel phase was obtained from the proposed deposition method. Powder flow rate and laser power most significantly affected residual porosity. While cracking remained the most challenging issue for laser additively manufactured ceramics, doping showed promising results in effectively controlling crack formation during deposition attributed to grain refinement and introduced toughening mechanisms.

Materials: Metals V - Precious Metals, Copper, Tungsten, Co-Cr

Tuesday PM August 3, 2021

Session Chair: A. Rollett, Carnegie Mellon University

1:30 PM
New Gold Conductive Ink Formulation with Enhanced Cohesion for Material Jetting: *Jisun Im*[1]; Feiran Wang[1]; Gustavo Trindade[2]; Christopher Tuck[1]; [1]Centre for Additive Manufacturing/University of Nottingham; [2]University of Nottingham

Gold nanoparticles are one of the promising conductive materials for printed electronics since they have high electrical conductivity, good chemical resistance and biocompatibility compared to other metals. They therefore form an interesting material for multifunctional Additive Manufacturing. The drawbacks of inks containing nanoparticles include the short shelf-life due to agglomeration and the formation of microcracks or voids during post-processing, leading to reduced electrical conductivity and mechanical properties. In order to overcome those problems, we employed the ligand-stabilized gold nanoparticles with an average diameter of 2.3nm for better ink stability and lower sintering temperature for various substrates. In addition, we employed two different thiol-terminated types of cohesion enhancers in order to have a continuous and uniform printed pattern for high electrical conductivity in 2D and 3D. The gold ink can be sintered at as low as 120^{o}C and the electrical conductivity of 2x10^{6} S/m can be achieved after printing 5 layers.

1:45 PM
Directed Energy Deposition Additive Manufacturing of Nickel Aluminum Bronze: Temperature Dependent Properties for Predicting Distortion: *Glenn Hatala*[1]; Qian Wang[1]; Edward Reutzel[1]; Charles Fisher[2]; Jennifer Semple[2]; [1]Pennsylvania State University; [2]Naval Surface Warfare Center – Carderock Division

There is increased interest in using nickel aluminum bronze (NAB) alloys in large-scale directed energy deposition additive manufacturing (DEDAM) processes, but excessive distortion is of concern during fabrication. High-fidelity simulations can improve distortion prediction and enable use of distortion mitigation techniques, however open literature and public databases lack the required temperature-dependent NAB properties necessary for accurate predictions. The first contribution of this paper lies in acquiring temperature-dependent properties of alloy C95800 test specimens obtained from multiple wire-fed additive processes. The second contribution involves thermal-mechanical simulation and analysis of a DEDAM NAB build. Finite-element simulations using temperature-dependent material properties are compared to those using temperature-independent material properties, i.e. constant at room temperature. Significantly greater distortion is predicted in simulations using temperature-dependent properties. These results show that use of temperature-independent properties in distortion prediction could lead to inaccurate DEDAM NAB parts that require significant post-processing or are completely unusable.

2:00 PM
Laser Powder Bed Fusion Additive Manufacturing of Copper Vapor Chambers: *Adnen Mezghani*[1]; Abdalla Nassar[1]; Corey Dickman[1]; Eduardo Valdes[2]; Raul Alvarado[2]; [1]Pennsylvania State University; [2]SET Group, LLC.

An integral component in two-phase thermal management systems, namely heat pipes (HP) and vapor chambers (VC), is a porous wicking structure. Traditional methods for manufacturing wicking structures for HPs and VCs involve secondary manufacturing processes and are generally limited to simple geometries. More complex geometries and part consolidation may, however, be possible with laser powder bed fusion (LPBF) additive manufacturing (AM). This work aims to leverage the unprecedented level of customization and design freedom of LPBF AM to produce HPs and VCs with integrated wicking structures. Several copper wicking structures were successfully fabricated with capillary performance, K/r_{eff}, ranging from 0.186 µm to 1.74 µm. Several VCs, with integrated wicking structures, were then fabricated and tested to validate the printability of complete and functional assemblies of copper HPs and VCs

2:15 PM
Characterization of Copper Coupons Made via Laser Powder Bed Fusion: *Pouria Khanbolouki*[1]; Raju Ghimire[1]; Mehran Tehrani[1]; [1]The University of Texas at Austin

Additive manufacturing (AM) of copper brings the potential to optimize various thermal and electrical components in microelectronics, aerospace vehicles, and thermal/power systems. Advances in AM have recently enabled laser-based powder bed fusion (L-PBF) of copper. This work investigates the electrical, thermal, and mechanical properties of additively manufactured copper coupons made via L-PBF. These properties are correlated to the microstructure of copper samples. Our results can guide the design of AM copper parts for different applications and be used to improve the properties of L-PBF copper.

Physical Modeling: III Thermal Aspects B

Tuesday PM August 3, 2021

Session Chair: R. Landers, Missouri S&T University

1:30 PM
Non-orthogonal Adiabatic Boundaries in Semi-analytical Laser Powder Bed Fusion Simulations Using Machine Learning: *Christian Gobert*[1]; Evan Diewald[1]; Nicholas Jones[1]; Jack Beuth[1]; [1]Carnegie Mellon University

Simulating temperature fields for laser powder bed fusion (L-PBF) additive manufacturing (AM) processes through Finite Element Analysis (FEA) is computationally expensive. Semi-analytical approaches for simulating L-PBF can achieve drastic decreases in computation time compared to FEA, however lack the ability to incorporate complex adiabatic boundaries. Identical simulations were run in semi-analytical and FEA environments across multiple process conditions including variation in laser power, laser speed, scan strategy and geometry. A convolutional neural network was then trained to perform heat diffusion on adiabatic boundaries in the semi-analytical environment, using FEA simulations as ground truth.

1:45 PM
Part-scale Thermal FEA Modeling and Experimental Validation of Laser Powder Bed Fusion: *Chao Li*[1]; Erik Denlinger[1]; Michael Gouge[1]; Jeff Irwin[1]; Pan Michaleris[1]; Abdalla Nassar[2]; Qian Wang[2]; Zhuoer Chen[3]; Chris Davies[3]; [1]Autodesk Inc.; [2]Penn State University; [3]Monash University

Thermal modeling of laser powder bed fusion (PBF) could calculate the thermal history of a build, which can in turn be used as an input to predict temperature related characteristics such as residual stress, distortion, microstructure, lack of fusion, and hot spots. To estimate the heat loss to the powder bed during the process, convective heat transfer is widely used as thermal boundary condition. However, this convection coefficient is usually selected based on empirical estimation. Autodesk Netfabb Simulation offers three thermal BCs options: universal convective, trapped powder, and material dependent convective. In this work, thermocouple measurements of the substrate and parts during the build are used to validate our thermal FEA models.

2:00 PM

Predicting Part Distortion and Recoater Crash in Laser Powder Bed Fusion Using Graph Theory: *Humaun Kobir*[1]; Reza Yavari[1]; Alex Riensche[1]; Leandro Castro[1]; Ben Bevans[1]; Kevin Cole[1]; Prahalada Rao[1]; [1]University of Nebraska-Lincoln

The laser powder bed fusion (LPBF) process tends to create flaws, such as part distortion, which limits its use for making mission-critical components. Flaw formation in LPBF parts is influenced by the temperature distribution (thermal history) during the process. To preclude flaw formation, such as distortion (deformation) and subsequent recoater crash, a key need is to develop fast and accurate models to predict the thermal history. Accordingly, we developed a graph theory-based thermal model that predicts the thermal history of the LPBF in less than 20% of the time taken by finite element-based models (FEM). Subsequently, the thermal history from the graph theory was coupled with FEM to predict distortion. This hybrid model is verified with FEM and Netfabb. it is also validated with the experimental data in the context of recoater crash prediction. The approach correctly predicted recoater crashes and distortion within 5% of FEM predictions.

2:15 PM

Numerical Prediction of Thermal Histories and Residual Stresses for Directed Energy Deposition (DED) Powder-blown Process: *Jakub Mikula*[1]; Athanasius L. Commillus[1]; Guglielmo Vastola[1]; Zhang Yong Wei[1]; [1]A*STAR

In this work, we have developed a thermal and mechanical solver as part of a in-house C++ code in order to predict thermal histories and residual stresses in 3D components printed by Directed Energy deposition (DED) powder-blown technology. In contrast to the conventional powder-bed process where the part is built in a layer-by-layer fashion, here the component is progressively built up by a continuous deposition (of molten material) controlled by the g-code (machine's code for the tool path). Efficient predictions of thermal histories on the component scale are of utmost importance providing guidance to g-code optimization to tailor the mechanical properties and the residual stress. Starting with CAD data, we discuss the numerical implementation of the heat source following the g-code path and demonstrate the results on a printed aerofoil component. This work is a prerequisite for other meso-scale simulations aiming to model the manufacturing process with sufficient fidelity.

2:30 PM

Experiment Based Superposition Thermal Modeling of Laser Powder Bed Fusion: *Cody Lough*[1]; Robert Landers[1]; Douglas Bristow[1]; James Drallmeier[1]; Edward Kinzel[2]; [1]Missouri University of Science and Technology; [2]University of Notre Dame

The complicated laser scan pathing required to manufacture geometrically intricate parts by Laser Powder Bed Fusion (LPBF) produces significant thermal variance within layers. This thermal variance can locally cause detrimental engineering property inhomogeneity and defects (e.g. porosity) in mission critical parts. Modeling layers' temperature histories reveals the manufacturing scenarios that could produce those serious defects. Superposition thermal models make this task feasible by quickly simulating a layer's temperature history. This paper establishes a superposition model based on in-situ thermal camera measurements for pulsed laser LPBF. The model simulates LPBF by superimposing a basis function (i.e. powder bed's single laser pulse temperature response) inverted from spatiotemporal Short-Wave Infrared (SWIR) data along the laser's scan path. Case studies of simple and complex layers demonstrate the superposition model's prediction capabilities and limitations. The model has applications in feed-forward decision making and establishes a baseline for in-situ diagnostics.

2:45 PM

Development of Temperature History Profiles for Production of Ti-6Al-4V Using a 1D Layer Model: Lonnie Smith[1]; Amit K Verma[1]; Andrew (Drew) Huck[1]; P. Chris Pistorius[1]; *Anthony Rollett*; [1]Carnegie Mellon University

Directed energy deposition (DED) is an additive process that uses a laser beam to melt a feed of hot wire, which creates a melt pool on the surface of a metallic substrate. The work here seeks to generate temperature history profiles for layer-wise development of parts built using Ti-6Al-4V (Ti64). By utilizing an explicit transient finite-difference method, a simple, 1D layer model that incorporates system parameters and multiple modes of heat transfer, including convective heat loss, is used to produce plausible temperature history profiles. The results achieved with this model are obtained quickly (in comparison to finite element based solutions) and will be used to develop predictions of the fraction of phases that form in the creation of Ti64 parts via DED. Validation of the simulations is achieved by calibrating the model against metallographic information obtained from etching the cross sections of fabricated samples.

Physical Modeling: IV Mechanical Properties

Tuesday PM August 3, 2021

Session Chair: J. Lipton, University of washington

1:30 PM

Coupled Phase-field and Crystal Plasticity Modelling to Investigate the Process-structure-property Relationship of Heat Treatment for Additive Manufactured Alloys.: *Yuhui Tu*[1]; Seán Leen[1]; Noel Harrison[1]; [1]National University of Ireland, Galway

Additive manufacturing (AM) generated microstructures are usually more complex than conventionally manufactured counterparts. One example is AM Ti-6Al-4V alloys, which display lamellar morphologies within prior ß-grains. While AM microstructures are highly dependent on temperature profiles, these features, in turn, influence the mechanical behaviour. This paper aims at introducing an approach that integrates phase-field modelling (PFM) with crystal plasticity finite element (CPFE) modelling, to investigate the process-structure-property relationships for post-processing heat treatment.In particular, quantitative PFM is implemented to simulate grain growth during annealing, which is necessary to eliminate initial defects. The evolved microstructure predicted is firstly compared to measurements from electron backscatter diffraction analysis, and is then imported into a CPFE model for prediction of mechanical response. Finally, the predicted results of the CPFE model are validated against mechanical test data. Prediction of microstructure and associated properties is key to fulfilling the potential benefits of producing tailored AM components.

1:45 PM

Multiscale Modeling of Plasticity for Laser Powder Bed Fusion Stainless Steel with Tailored Crystallographic Texture: *Xinyu Yang*[1]; Xianglong Wang[2]; Mathieu Brochu[2]; Javier Segurado[3]; Noel Harrison[1]; Seán Leen[1]; [1]I-Form, the SFI Research Centre for Advanced Manufacturing; [2]McGill University; [3]IMDEA Materials Institute

This paper presents multi-scale modeling of plastic deformation of stainless steel 316L (SS316L) with tailored single-crystalline-like structure fabricated by laser beam powder bed fusion (PBF-LB). A polycrystal model, based on the visco-plastic self-consistent (VPSC) formulation, implemented in the finite element (FE) software Abaqus, was adapted to provide a multi-scale elasto-visco-plastic response at each integration point with consideration of crystallographic texture effect and the resultant different deformation mechanisms. Tensile responses along the <100>, <110> and <111> crystallographic directions were studied, and the contributions of slip and twinning deformation modes were quantified to rationalize the superior strength-ductility synergy of PBF-LB SS316L comparing with samples manufactured by conventional technology.

2:00 PM
On the Applicability of Internal State Variable Plasticity Models for Metal-based Additive Manufacturing: *Matthew Dantin*[1]; Matthew Priddy[1]; [1]Mississippi State University

The thermomechanical modeling of metal-based additive manufacturing (MBAM) often focuses on the prediction of thermally induced distortion and residual stresses. Mechanical models in literature range in fidelity from inherent strain, J2 plasticity, rate-dependent plasticity, to temperature- and rate-dependent internal state variable (ISV) models. The objective of this work is to discuss the advantages and disadvantages of using ISV models for the prediction of residual stresses and distortion in MBAM parts with a focus on the implementation and motivation of using ISV models. Furthermore, results using a J2 plasticity and an ISV model are compared for a thin wall Ti-6Al-4V directed energy deposition (DED) build. The ISV model used in this work is the Evolving Microstructural Model of Inelasticity, which is a rate- and temperature-dependent dislocation mechanics-based ISV plasticity model that has been used to predict residual stresses and distortion in DED parts along with weld solidification cracking.

2:15 PM
Modified Gibson-Ashby Model for Stiffness Prediction of Defective Lattices: *Panwei Jiang*[1]; Saurabh Basu[1]; [1]Penn State University

Additively manufactured lattice structures often exhibit porosity and surface roughness defects in the as-received state. These defects degrade the stiffness of the parent structure whose quantification is important for their systematic design and post-processing. Here, we argue that this is not possible using traditional macro-scale models such as the Gibson-Ashby (GA) law which only takes the relative density of the lattice into account. This is because these defects manifest fluctuations in mechanical behavior at a smaller scale, which is not encapsulated by a macro-scale model. This concept is demonstrated by simulation and analysis of the full field elastic response of 2.5D body centered cubic lattices with artificially implanted porosity and surface roughness. The complex degradation caused by defects is captured in multiplicative alterations to the GA law. A method based on principal component analysis of strain fields in the struts of the lattice structure is calibrated to delineate these effects.

Process Development: III Stereolithography and Jetting

Tuesday PM August 3, 2021

Session Chair: N. Crane, Brigham Young University

1:30 PM
Static Liquid Interface to Reduce Support Structure Necessity in Top-down Stereolithography: *Nicholas Mulka*[1]; Tarun Goyal[1]; Amit Jariwala[1]; David Rosen[1]; [1]Georgia Institute of Technology

Stereolithography (SLA) is a vat photopolymerization additive manufacturing process that utilizes photocurable resin, which requires sacrificial supporting structures on many part overhangs. This study details a novel process for conducting top-down SLA from a thin resin layer located above a static immiscible supporting fluid. The thin resin layer defines the thickness of the cured layer, preventing overcuring. The support fluid prevents deflection from buoyant and gravitational forces on thin overhangs from anchored parts due to minute density differences between the supporting fluid and cured resin. This has two primary advantages: most support structures are not needed, and the volume of resin necessary to print is greatly reduced compared to traditional top-down SLA. Using this process, we have experimentally demonstrated printed geometry with overhangs of up to 90 degrees. Additionally, material properties of both fluids and process parameters of the system have been identified for the system's feasibility and broader adaptation.

1:45 PM
Development of a Variable Tensioning System to Reduce Separation Force in Large-scale Stereolithography: *Hongtao Song*[1]; Nicholas Rodriguez[1]; Morgan Chen[1]; Carolyn Seepersad[1]; Richard Crawford[1]; Eric Duoss[2]; [1]University of Texas at Austin; [2]Lawrence Livermore National Laboratory

Projection micro stereolithography (PμSL) is a powerful additive manufacturing tool, offering unparalleled resolution and throughput, but the ability to print high viscosity resin on a large-scale is limited. One of the key challenges in PμSL is to separate a newly polymerized layer from the vat floor without damaging the part. Since the separation force scales up with the printing area, the risk of damaging the part increases significantly with larger-scale systems and must be addressed. In this paper, a novel roll-to-roll, variable tensioning system is proposed to reduce the separation force during printing. A mathematical model is proposed to predict the separation force for different 2D geometries, and a set of experiments is conducted on an experimental prototype to validate the model. The effect of different separation parameters including peel rate and peel angle is discussed in detail. The results showed that the proposed system reduces the separation force significantly.

2:00 PM
Binder/Powder Interaction in Binder Jetting: From Lines to Layers: Trenton Colton[1]; *Nathan Crane*[1]; [1]Brigham Young University

Print quality and print speed limit the increased use of Binder Jetting in industry. Further understanding of binder/powder interactions will dramatically improve the quality and speed of the development process. With increased understanding, simple procedures or tests could predict print saturation levels, optimize green part strength, decrease print time, and improve dimensional accuracy. Current methods of characterization of the interaction overlook the crucial interactions between printing parameters including drop velocity, droplet spacing, line spacing, and inter-arrival time. Previous work shows the impact of droplet velocity, spacing, and inter arrival times on single printed lines. This presentation will compare these results to studies on single and multi-layer parts. Printed parts are characterized by their mass and optical inspection. The relationships between parameters that form single printed lines are compared to limits to create single and multi-layer parts.

2:15 PM
Understanding the Effects of Driving Signal for Piezoelectric Inkjet Printing: *Chao Sui*[1]; Lucas Marques[1]; Wenchao Zhou[1]; [1]University Arkansas

Piezo inkjet has been widely used in a wide variety of industrial applications due to its robustness and insensitivity to ink chemistry. The driving signal plays a major role in droplet generation, such as droplet size, velocity, pinch-off time, satellites, and ultimately printing speed and quality. This paper aims to establish a model and provide a fundamental understanding of the effects of the driving signal on the printing speed. In this paper, we developed an analytical model of how ejection velocity changes with time during the jetting process, and derived the effects of the driving signal parameters on the droplet volume and pinch-off time, which are two main factors of printing speed. The model is calibrated and validated with a custom experimental setup, which is equipped with a high-speed camera to capture the droplet formation dynamics for the study. Results show that the model prediction agrees well with experimental results.

2:30 PM

Stress Shielding Effect during Compaction of a Selectively Variant Powder Bed in Hydrothermal-assisted Jet Fusion of Ceramics: *Levi Kirby*[1]; Fan Fei[1]; Xuan Song[1]; [1]University of Iowa

Traditional binder jetting processes use organic binders in forming green parts, which can lead to residual ash and structural defects in final parts. Our recently developed hydrothermal-assisted transient jet fusion process eliminates the need for organic binders through substitution of the organic binder with a volatile dissolving ink. To enable the selective fusion of particles, a uniaxial pressure and a mild temperature were simultaneously applied to a selectively ink-jetted powder bed which induced a stress shielding effect, i.e., unbalanced stresses between the printed region and the surrounding loose powder. This work is intended to better understand the stress shielding effect during the compaction of the powder bed as functions of printing parameters, e.g., applied pressure, printing pattern, etc. Results showed the stress in the ink-saturated region was significantly reduced compared to the surrounding loose powder, due to a difference between compaction properties (e.g., elasticity, cap) of the two regions.

2:45 PM

Use of Wire Grid Polarizers with Liquid Crystal Display for Large Volume Stereolithography: *Nicholas Rodriguez*[1]; [1]The University of Texas at Austin

Spatial light modulators that use liquid crystal devices (LCDs) to pattern ultraviolet light for vat polymerization suffer from a few limitations: limited range of wavelengths that can be patterned, low damage threshold for incoming light, and low efficiency of light transmission. A monochrome LCD can more efficiently transmit useful wavelengths of light for stereolithography (365-405nm) than a color LCD, but it still contains two absorptive film polarizers that suffer from previously mentioned limitations. Wire grid polarizers reflect rather than absorb the blocked polarizations of light, resulting in a higher intensity damage threshold. They can also polarize lower wavelength light that is only limited by the wire pitch. This research studies the effects of replacing an LCD's film polarizers with wire grid polarizers to allow for the polarization and patterning of high intensity UV light, resulting in shorter curing times and the ability to print a wider range of stereolithography feedstocks.

Process Development: IV Directed Energy Deposition and Laser Powderbed Fusion

Tuesday PM August 3, 2021

Session Chair: D. Cormier, Rochester Institute of Technology

1:30 PM

Vibration-actuated Powder Dispensing for Directed Energy Deposition Systems: *Andrew Greeley*[1]; Denis Cormier[1]; [1]Rochester Institute of Technology

Directed energy deposition system users often face several challenges associated with conventional powder delivery systems. In addition to high cost of wasted powder, it can be difficult to determine the amount of material being deposited, as some dispensed powder is not captured in the melt pool. This work studies the effectiveness of a vibration-actuated powder dispensing system using a small capillary opening. With proper design, contact forces prevent the powder from being dispensed when no vibration is applied. Conversely, when vibration is applied, the contact forces are overcome and the powder is dispensed into the melt pool. This work combines discrete element modeling simulations with experimental results to investigate the effects of vibration parameters and capillary size on the mean and variance of output mass flow rate for 316L stainless steel powder.

1:45 PM

Pore Coalescence in Directed Energy Deposition Using in-situ X-ray imaging and Infrared Thermography: *Karan Kankaria*[1]; Niranjan Parab[2]; Benjamin Gould[2]; Aaron Greco[2]; Tao Sun[2]; Sarah Wolff[1]; [1]Texas A&M University; [2]Argonne National Laboratory

Directed Energy Deposition has exceptional potential as a metal additive manufacturing process due to its capability to build multi-material parts with controlled microstructure. However, control of porosity remains a major challenge for part qualification and certification. In-situ high speed X-ray imaging combined with thermal imaging gives a clear insight into the evolution of this porosity. Depending on the local density of pores, some pores coalesce to form larger spherical pores whereas some slowly shrink to give flattened pores and the remaining pores either burst or reach the surface. This work can help control porosity by laser parameters and thermal history of the melt pool.

2:00 PM

Effect of Powder Velocity on Porosity Formation in Directed Energy Deposition: *Samantha Webster*[1]; Kornel Ehmann[1]; Jian Cao[1]; [1]Northwestern University

Inherent process defects such as porosity currently limit the use of additive manufacturing (AM) fabricated components in industry due to shorter fatigue life, potential for catastrophic failure, and lower strength. The conditions under which these defects form, and their corresponding mechanisms, are still not fully understood across laser-based AM platforms. While high-speed synchrotron imaging has been used for ¬in situ observation of melt-pool dynamics, powder entrainment, and defect formation in laser powder bed fusion (LPBF), phenomena in powder-blown processes such as directed energy deposition (DED) will be very different due to much more stochastic and violent powder delivery. This study addresses those differences by using the X-ray imaging technique at the Advanced Photon Source and a high through-put DED set-up to observe types of pore formation. An analytical model adapted from hydrophobic solid particle entrance into a liquid is presented, and the importance of powder velocity will be discussed.

2:15 PM

Powder Capture Efficiency Monitoring with In-situ, 3D, Surround Digital Image Correlation in Directed Energy Deposition Additive Manufacturing: *James Haley*[1]; Samuel Leach[1]; Brian Jordan[1]; Thomas Feldhausen[1]; Ryan Dehoff[1]; Vincent Paquit[1]; [1]Oak Ridge National Laboratory

In powder-based Laser Directed Energy Deposition (L-DED) Additive Manufacturing (AM), powder capture efficiency strongly effects part quality and deposition stability. In order to better quantify and monitor powder capture efficiency, an in-situ, 360° array of high resolution visible cameras and long wave infrared cameras were installed in a DED machine. This camera array is capable of triangulating surface roughness features to generate 3D dimensional metrology and mapping thermographic measurements during deposition. These measurements are leveraged to dimensionally assess powder capture efficiency as a function of part temperature, and better understand the interplay between toolpath geometry and deposition performance. Capabilities and limitations are discussed as well as the extensibility of the technique to control applications.

2:30 PM

Multi-track Geometry Prediction in Laser Additive Manufacturing Using Machine Learning: *Lucas Botelho*[1]; Richard van Blitterswijk[1]; Amir Khajepour[1]; [1]University of Waterloo

Laser additive manufacturing (LAM) allows for complex geometries to be fabricated without the limitations of conventional manufacturing. However, LAM is highly sensitive to small disturbances, resulting in variation in the geometry of the produced layer (clad). Therefore, in this research a monitoring algorithm is discussed with the capability of predicting the geometry of multiple tracks of added material. Though imaging can be used to measure the geometry of the melt pool during LAM, the appearance of the melt pool changes in multi-track processes due to the previous layers. Hence, a machine learning algorithm may be able to accommodate for the changing melt pool appearance with sufficient data. Images can be captured during LAM with visible-light and infrared sensors which may provide sufficient information for the geometry to be predicted. A convolutional neural network (CNN) can then use these images to estimate the geometry (height and width) during LAM processes.

2:45 PM
Laser Powder Bed Fusion of Stainless Steel 316L Using a Flexible Dual Fiber Laser Array: *Tim Lantzsch*[1]; Thomas Westphalen[1]; Christian Tenbrock[1]; Martin Traub[1]; Constantin Haefner[1]; [1]Fraunhofer Institute for Laser Technology ILT

In recent years, Laser Powder Bed Fusion (LPBF) has become an industrially established manufacturing technique. State-of-the-art LPBF machines feature a combination of fiber lasers and galvanometer scanners due to their high dynamic and excellent focusability. To increase the productivity of LPBF machines the number of laser scanner systems (LSS) is multiplied, which causes an almost linear increase of machine costs. In this study a flexible optical system which allows the combination of two fiber lasers with a single galvanometer scanner is developed and integrated into a LPBF lab machine to scale the productivity within one scan field. The resulting machine is characterized and used for the manufacturing of test specimen out of stainless steel AISI 316L. The manufactured specimens using this approach are analyzed in terms of melt pool formation via high-speed videography as well as resulting part density and build-up rate. The obtained results are compared with state-of-the-art LPBF-machines.

3:00 PM
Laser-material Interactions in LPBF, Visualised through Optical and X-ray High-speed Imaging: *Ioannis Bitharas*[1]; Niranjan Parab[2]; Cang Zhao[2]; Tao Sun[2]; Anthony Rolett[3]; Andrew Moore[1]; [1]Heriot-Watt University; [2]Argonne National Laboratory; [3]Carnegie Mellon University

We present results from our latest visualisation studies of atmospheric effects during LPBF. The interactions between the laser, metallic vapour, particles, and gas cross-flow during multilayer builds are analysed both experimentally and through multiphysics modelling. We examine the production of process by-products, characterise their extraction and highlight the most important factors. Simultaneous synchrotron x-ray and schlieren imaging experiments give insight into the joint behaviour of the melt pool, laser plume, and powder particles. The interconnected dynamics of the vapour and liquid phases are explored under varying energy input. Image processing and analysis aid in relating our observations to process stability.

Special Session: Composite AM III - Polymers B

Tuesday PM August 3, 2021

Session Chair: I. Rivero, Rochester Institute Of Technology

1:30 PM
Low Density Mechanical Metamaterial Using DLP-based 3D Printing: *Darshil Shah*[1]; Joshua Morris[1]; Alireza Amirkhizi[1]; Christopher Hansen[1]; [1]University of Massachusetts Lowell

The rise of readily available high-resolution additive manufacturing (AM) technologies, such as digital light processing (DLP), in the past decade has led to increasing research interest in fabrication and performance characterization of mechanical metamaterials, which typically contain mesoscale features. Based on the preliminary metamaterial performance maps, the vector of resin development points toward developing low-density, high modulus material system which is not commercially available. Here, we aim to develop these resin systems and characterize their properties to enable metamaterial and other applications. The resin is demonstrated to fabricate 26 × 26 × 26 mm complex mechanical metamaterial structure with over 34% density reduction and increased modulus by over 10%. The thinnest negative and positive feature was 500 and 400 µm, respectively. The structures are further characterized for performance validation and dimensional fidelity. Also, initial efforts to fabricate multi-material structures, which modeling indicates could result in substantial performance enhancement, are presented.

1:45 PM
3D Printing of Structural Battery Composites with Continuous Carbon Fibers: Aditya Thakur[1]; *Xiangyang Dong*[1]; [1]Missouri University of Science and Technology

The rapidly increasing demand in mobile electric technologies makes it necessary to develop multifunctional composite materials to achieve high volumetric energy storage. A new coextrusion-based 3D printing method was proposed in this study to fabricate structural battery composites with continuous carbon fibers, which can simultaneously carry mechanical loading and achieve electrical energy storage. Solid polymer electrolyte (SPE) coated continuous carbon fibers were coextruded and deposited layer-by-layer with functional polymer matrix materials doped with active and conductive materials. A novel functional, full lithium-ion structural battery was successfully printed with each coated carbon fiber acting as a micro-battery cell. A comparative study of thermoset and thermoplastic materials as binders was performed. The printability, microstructure, mechanical and electrochemical performance was directly compared. The bonding between SPE-coated carbon fibers and doped polymer matrix materials was shown to govern the performance of the printed structural battery composites.

2:00 PM
Additive Manufacturing of Neat and Carbon Fiber Reinforced PAEK Polymers: *Timothy Yap*[1]; Nathaniel Heathman[1]; Tim Phillips[1]; Joseph Beaman[1]; Mehran Tehrani[1]; [1]The University of Texas at Austin

High-performance polymers, such as the polyaryletherketone (PAEK) family, have the potential to replace metals in several applications. A study of the tensile properties of two members of the PAEK family is conducted using two different additive manufacturing (AM) methods. Polyetherketoneketone, both neat (PEKK) and reinforced with 10 wt.% milled carbon fibers (CFPEKK), was manufactured with fused filament fabrication (FFF), and polyetherketone, both neat (PEK) and reinforced 10 wt.% milled carbon fibers (CFPEK), was manufactured with selective laser sintering (SLS). The degree of crystallinity of specimens at various stages was measured by differential scanning calorimetry (DSC) to learn how printing and annealing affect their crystallinity. Tensile fracture surfaces were examined using laser confocal microscopy to determine the fracture mechanisms. Results of this study provide a new understanding of the performance of AM PAEK parts.

2:15 PM
Thermomechanical Properties of a Glass and Carbon Nanofilled Photopolymer Composite Additively Manufactured via Stereolithography: *Cameron Weeks*[1]; Christopher Bailey[1]; Gurpreet Singh[1]; Scott Thompson[1]; [1]Kansas State University

The objective of this study was to investigate the topology, morphology, and thermomechanical properties of a glass filled photopolymer with the introduction of a carbon nanotube filler that was additively manufactured using stereolithography (SLA). These material properties were sought for assessing the feasibility of 3D printing complex-designed heat pipes (or vapor chambers) for low heat flux applications. These applications include human wearables, low heat producing electronics, and more. Typically, heat pipes are produced from metal which is expensive and dense; however, the use of polymers can lead to inexpensive and lightweight heat pipes for unique applications. This study will provide measurements for thermal conductivity, geometric variation, microstructure, and tensile strength. Several observations along with the performance of the specimens will be discussed and shown. Future investigations will include new applications of this technology and further studies of nano-additive polymer-composite in 3D printing.

2:30 PM
Finite Element Modelling of the Fused Filament Fabrication Additive Manufacturing: *Sarah Clark*[1]; Timothy Yap[1]; Mehran Tehrani[1]; [1]The University of Texas at Austin

Fused filament fabrication (FFF) is a material extrusion additive manufacturing (AM) process that works well with thermoplastic polymers and is inexpensive compared to other AM processes, leading to its increasing popularity for industrial applications. With an accurate Finite element analysis (FEA) model, the FFF process can be simulated with various printing parameters, so the part can be manufactured under optimal conditions for improved mechanical performance. FEA is used here to simulate the thermal histories, among other properties, involved in FFF to estimate the extent of interlaminar bonding, or degree of fusion between two subsequent layers. Several simulation cases of increasing complexity are presented within MSC Digimat-AM, and both a thermocouple and an infrared thermal imaging system are used to validate the results from Digimat-AM. Validations results along with several insights into the FFF process are discussed.

2:45 PM
Additive Manufacturing of Carbon Fiber Reinforced Polymer Composite via Reactive Extrusion: *Pratik Koirala*[1]; Oliver Liam Uitz[1]; Carolyn Conner Seepersad[1]; Mehran Tehrani[1]; [1]University of Texas at Austin

This project investigates a novel additive manufacturing (AM) technique, liquid reactive extrusion, for carbon fiber reinforced polymer composites. The process utilizes highly exothermic resin/catalyst systems with fast curing cycles, eliminating the need for an external energy source. Chemical cross-linking occurs between the printed layers, resulting in parts with nearly isotropic properties. Carbon fibers are added to the thermosetting resin for mechanical reinforcement. An ANSYS simulation is utilized to optimize the AM processing parameters. Inter- and intra-layer tensile properties of the neat polymer and composites reinforced with both milled and chopped fibers are measured. These properties are correlated to the fiber length/orientation distributions and fiber-matrix adhesion in each sample using a theoretical mechanics model. The degree of curing is also characterized and correlated to thermal images captured during reactive extrusion AM.

3:00 PM
Recycling Carbon Fiber Filled Acrylonitrile-Butadiene-Styrene for Large Scale Additive Manufacturing
: *Roo Walker*[1]; Tyler Smith[2]; John Lindahl[2]; Christopher Hershey[2]; Vlastimil Kunc[2]; Chad Duty[1]; [1]University of Tennessee - Knoxville; [2]Oak Ridge National Lab

The recovery, recycling, and reuse of this scrap material as a secondary feedstock material is essential for the feasibility of large-scale AM (LSAM) sustainability. Carbon fiber reinforced acrylonitrile butadiene styrene (CF-ABS) was recycled and used as a secondary LSAM feedstock material to compare printability and mechanical properties against that of virgin feedstock materials. Virgin CF-ABS, or primary feedstock, was melt blended with secondary feedstock to create multiple recycled blends. Each material was printed on the Big Area AM system. Material and mechanical properties were evaluated using a series of tensile, dynamic mechanical analysis, and rheological analysis. Based on injection molded data, the mechanical properties were expected to decrease in proportion to the increase in recycled content, but it was found that some properties improved. By successfully characterizing the impact of incorporating secondary feedstocks in large-scale AM, a pathway can be defined for further reducing material waste and improving AM sustainability.

3:15 PM
Design and Manufacture of Continuous Fiber-Reinforced 3D Printed Unmanned Aerial Vehicle Wing: Aarthi Devarajan; Dhileep Kumar Jayashankar; Guoying Dong[1]; *David Rosen*[2]; [1]Singapore University of Technology and Design; [2]Georgia Institute of Technology

The Markforged Mark Two 3D printer is capable of printing various orientations of continuous fiber reinforcement. An initial study of how the orientation of the fiber influences the strength characteristics (tensile and flexural properties) was conducted. Four combinations of carbon fiber reinforcement orientations were tested, specifically unidirectional, isotropic, concentric and a combination of isotropic and concentric, with onyx as the matrix material. The results will aid in designing a wing with the optimum fiber configuration, that will give the desired mechanical properties based on the forces acting on the wing. Design for Additive Manufacturing (DfAM) concepts and tools will be used to design and manufacture a large UAV wing. The design methodology will be a product-process co-design optimization method. A structural optimization technique will be used to determine the optimum layout of the carbon fiber material, and design for multiscale structures will be considered for the remaining interior regions.

Special Session: Hybrid AM Processes I - Electronics and Polymers

Tuesday PM August 3, 2021

Session Chair: M. Sealy, University of Nebraska-Lincoln

1:30 PM
Effects of In-Situ Mechanical and Chemical Polishing on Surface Topography of Additively Manufactured Fiber-Reinforced Polymers: *Aman Nigam*[1]; Bruce Tai[1]; [1]Texas A&M University

Additive manufacturing of fiber-reinforced polymers (FRPs) has revolutionized fused filament fabrication (FFF) by producing polymeric parts with enhanced mechanical properties. However, FFF suffers from poor surface quality and dimensional accuracy, particularly for FRPs, due to their abrasive and rheological nature. This study examines an in-situ polishing scheme for FRPs in the FFF configuration. Glass-fiber-reinforced Nylon was used as the study material. Three polishing schemes, mechanical, chemical, and a combined thereof, were adopted along with various parameters in each case. The results show significant surface improvements in all cases, and the combined process can further reduce the Ra value to around 2 µm and the dimensional error to 0.2 mm and less. The combined process also enhances surface uniformity (i.e., similar Ra in all directions). In particular, with the combined approach, the in-situ polishing scheme is expected to improve the quality of 3D printed FRPs significantly.

1:45 PM
Mechanical Behavior of ABS after Interlayer Ultrasonic Peening during Fused Filament Fabrication: *Manon Guivier*[1]; Trevor Swanson[2]; Jesse Kuebler[2]; Christopher Lawson[2]; Lucia Fernandez-Ballester[2]; Mehrdad Negahban[2]; Michael Sealy[2]; [1]AgroParisTech; [2]University of Nebraska-Lincoln

Hybrid additive manufacturing brought new opportunities to improve the mechanical properties of materials by secondary processing of individual layers during printing. Previous work demonstrated interlayer shot peening during printing by fused filament fabrication (FFF) affected mechanical behavior while inadvertently imparting debris contamination from pulverized beads. The encouraging results motivated a study on the use of contamination free ultrasonic peening (UP) as an alternative interlayer surface treatment. Ultrasonic peening of FFF printed acrylonitrile Butadiene Styrene (ABS) was studied in order to compare the effects on mechanical properties between ultrasonic peening and previously studied shot peening, different print orientations, and different interlayer peening frequencies. Two different layer peening frequencies (L4 and L8) were compared to an as-printed control (L0). Two orientations for each layer peening frequency were chosen for comparison. Tensile tests were conducted in order to observe the influence of interlayer UP on tensile strength of ABS parts.

2:00 PM
Integrating a Direct Ink Write and Mask-projection Vat Photopolymerization System to Enable Additive Manufacturing of High Viscosity Photopolymer Resins: *Daniel Rau*[1]; Mattia Forgiarini[1]; Christopher Williams[1]; [1]Virginia Tech

Vat Photopolymerization (VP) enables the fabrication of parts with high-resolution features and sharp edges through its selective patterning of UV irradiation on a resin surface. However, its recoating procedure limits the process to low viscosity photoresins, which limits both the available processable materials and the mechanical properties of the final parts. To enable layered processing of high viscosity photoresins, and thus high-performance materials, a Direct Ink Write (DIW) and a VP system are integrated into a single additive manufacturing platform. The hybrid process uses the DIW system to first extrude an unpatterned layer of photoresin that is then selectively cured into the desired layer shape by the Mask-Projection VP system. The relaxation of viscosity constraints due to material deposition via DIW allows for the high-resolution printing of new high-performance photoresins with novel chemistries, high molecular weight monomers, or high solids loading that ultimately result in improved performance over traditional resins.

2:15 PM
Integrating Digital Light Processing with Direct Ink Writing for Hybrid 3D Printing of Functional Structures and Devices: *Xirui Peng*[1]; Xiao Kuang[1]; Devin Roach[1]; Yaoqing Wang[1]; Craig Hamel[1]; Chunliang Lu[2]; H. Jerry Qi[1]; [1]Georgia Institute of Technology; [2]Xerox Corporation

As a branch of additive manufacturing (AM), multi-material 3D printing has drawn tremendous attention as it offers more design flexibility that can combine materials with various properties. However, low cost, high-speed, high-resolution, and versatile multi-material 3D printing methods are still lacking. In this presentation, we present a new hybrid multi-material 3D printing system that consists of top-down digital light processing (DLP) printing and direct ink writing (DIW) printing to fabricate composite structures and unique devices in a single printing job. The DLP part allows for high-speed and high-resolution printing of a material matrix with complex geometry, while the DIW part enables the printing of functional materials, including liquid crystal elastomers (LCEs) and conductive silver inks. With this hybrid 3D printing system, composites prototype, active soft robots, circuit-embedding architectures, and strain sensors can be successfully printed, showing a great prospect in soft robotics, electronics, active metamaterials, and biomedical devices.

2:30 PM
Mechanical Interface for Iterative Hybrid Additive/Subtractive Manufacturing: *Eric Weflen*[1]; Michael Ginther[1]; Mohamed Eldakroury[1]; Matthew Frank[1]; [1]Iowa State University

Additive and subtractive manufacturing systems for in-envelope production of large objects face challenges in the areas of tool reach and access. One approach to overcoming this is iteratively alternate between AM and subtractive machining. However, polymer objects require cooling before machining, resulting in poor thermal welding when the subsequent polymer layer is deposited. This paper describes a method for iterative AM and machining for in-envelope hybrid manufacturing that uses a mechanical bond to transition back to AM after machining. This is accomplished using an AMBIT screw-extrusion head to additively manufacture a section of the object in a 5-axis machining center. After the object is machined, a dovetail cutting tool forms undercut geometry in the interface where AM will resume. Upon polymer solidification, a mechanical interlock is formed. This work evaluates several undercut geometries for mechanical performance. This iterative approach to hybrid additive/subtractive manufacturing reduces machining complexity while maintaining structural integrity.

2:45 PM
High Resolution, High Conductivity Components by Aerosol Jet Printing and Electrodeposition: *Lok-kun Tsui*[1]; Ste-Ven Kayser[2]; Judith Lavin[2]; [1]University of New Mexico; [2]Sandia National Laboratories

Aerosol jet printing (AJP) can be used to print high resolution features with linewidths as low as 10 um. However, Ag nanoparticle inks used in AJP have low conductivity (~14%) when compared to bulk metal. Thicker layers may be printed to compensate for this low conductivity, but at the cost of print time and resolution. We have used electrodeposition to plate a highly conductive dense film using an aerosol jet printed component as a seed layer. An acid CuSO4 plating bath was used in a 2-electrode configuration with a Cu anode to deposit a dense layer of Cu onto printed Ag. This allowed for a decreased trace resistance of over 100-fold for transformer components and multi-level interconnects. This hybrid electrodeposition/AJP process offers the best of both processes: high resolution patterning and high conductivity. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

Special Session: Volumetric AM

Tuesday PM August 3, 2021

Session Chair: C. Seepersad, University of Texas at Austin

1:30 PM
Investigation of Mechanical Properties of Structures Fabricated by Continuous Volumetric Photopolymerization Based 3D Printing: *Yizhen Zhu*[1]; Shengyinghao Chen[1]; Xiangjia Li[1]; [1]Arizona State University

Material is stacked in a layered manner to build objects with complex three-dimensional (3D)geometry shapes using most additive manufacturing processes. However, the way of material is deposited to create parts has a significant impact on the mechanical performance of printed 3D structures. In specific, 3D printed materials show anisotropic mechanical properties, which are determined by printing orientations. To overcome this bottleneck, a novel structural beam-based ultra-fast volumetric 3D printing, inspired by the plant growth in nature, was thereby developed. Such process features constructing desired geometry continuously by direct manipulation of the optical field in 3D space, where the photopolymerization occurs consistently in all directions. The mechanical properties of printed parts were fully investigated and further modulated by adjusting printing parameters. The proposed technology enables the construction of 3D structures with isotropic mechanical properties and opens intriguing perspectives for mass production using advanced printing technology.

1:45 PM
Progress in Photopolymer Resin Development for Volumetric Additive Manufacturing: *Maxim Shusteff*[1]; Johanna Schwartz[1]; Caitlyn Cook[1]; Erika Fong[1]; James Oakdale[1]; Bryan Moran[1]; Dominique Porcincula[1]; Kyle Champley[1]; Hossein Heidari[2]; Joseph Toombs[2]; Charles Rackson[3]; Robert McLeod[3]; Hayden Taylor[2]; [1]Lawrence Livermore National Laboratory; [2]University of California, Berkeley; [3]University of Colorado, Boulder

The emergence of volumetric additive manufacturing (VAM) offers fertile opportunities for photopolymer materials development. The support-free layerless 3D printing VAM process presents a different set of constraints for the parameter space of compatible materials, compared to traditional layered photopolymer AM. Along with the breadth of material possibilities available to this process comes the necessity to control resin curing dynamics at all points within the build volume. To do this requires delving in great detail into the curing kinetics, evolution of mechanical properties, and their interplay with total energy delivered to the resin, and the energy dosing rate. We discuss what we have learned about these parameters, and present differences in how major classes of resins such as acrylates and thiol-enes behave from this perspective. We also relate these results to standard layered 3D printing, and discuss how the volumetric AM perspective can also benefit resin development for traditional stereolithography.

2:00 PM
Dopant Patterning for Volumetric Sintering via RF Heating: *Jared Allison*[1]; Carolyn Seepersad[1]; John Pearce[1]; Joseph Beaman[1]; Ali Sohaib[2]; Christopher Tuck[2]; Richard Hague[2]; [1]University of Texas at Austin; [2]University of Nottingham

Radio frequency (RF) radiation is a potential energy source for volumetric sintering of selectively doped polymer powder beds. Owing to the large difference in their electrical properties, mixtures of nylon and graphite powders generate sufficient heat in the presence of RF radiation to cause local fusion of the powders, whereas undoped nylon powder remains transparent to RF radiation. By selectively doping regions of the powder bed that correspond to the part geometry and exposing the entire powder bed to RF radiation, it is possible to volumetrically sinter parts. However, the doped geometry causes distortions in the applied electric field that result in non-uniform heating within the part. The geometric effects are mitigated through computational strategies to functionally grade the dopant concentration throughout the part volume. The design of a mechanism for patterning the dopant is presented, and the heating uniformity improvements from functional grading are demonstrated for various geometries.

2:15 PM
Selective Doping of Composites Using Piezoelectric Printheads: *Ali Sohaib*[1]; Jared Allison[2]; Hongtao Song[2]; Carolyn Seepersad[2]; Christopher Tuck[1]; Richard Hague[1]; Joseph Beaman[2]; [1]University of Nottingham; [2]University of Texas at Austin

The use of Radio frequencies (RF) for heating and manufacturing of composite materials has been extensively used and studied. However, leveraging its use in AM is relatively new as it requires control and understanding of numerous factors that affect conversion of EM energy to thermal energy inside the composite. Among them, the electrical conductivity of particles, particle size and distribution are important as they determine the temperature range and gradients once the composite is subjected to RF. Use of piezoelectric printheads for selective deposition of conductive nanoparticles in a composite allows control over temperature gradients while maintaining high production speeds compared to other AM methods. However, the limited particle loading in the inks and the inhibition of heating due to solvents makes the standard layer-by-layer fabrication non-viable. This study looks at overcoming the issues inherent to piezoelectric jetting and evaluates new processes for fabrication of composites suitable for RF heating.

2:30 PM
Adaptive Voxelization for Computed Axial Lithography: *Kevin Coulson*[1]; Joseph Toombs[1]; Magnus Gu[1]; Hayden Taylor[1]; [1]DFN Lab University of California, Berkeley

Computed axial lithography (CAL) is a tomographic additive manufacturing technology that offers exceptionally fast printing in a wide range of materials. CAL involves pre-computing a sequence of light patterns to be projected into a photopolymer. For a uniform spatial discretization of the target geometry, computational time scales inversely with the cube of the discretization pitch, which makes it challenging to exploit the full space-bandwidth product of available spatial light modulators. This work introduces an adaptive voxelization approach to reduce computational expense. Using one of several proposed mesh-based complexity analyses, a CAD model is recursively subdivided into stacked sub-meshes of varying voxel resolution. These complexity methods can be tailored to emphasize complexity in particular regions. Each sub-mesh is then independently voxelized before projections are generated and optimized in parallel. On a four-core CPU, this method results in a 2-3x speedup with applications in high-precision CAL and other voxel-based additive manufacturing computations.

Applications: General III

Wednesday AM August 4, 2021

Session Chair: S. Thompson, Kansas State University

8:00 AM
Material Extrusion Based Additive Manufacturing of Metal Foam Materials with Tailorable Properties: *Dayue Jiang*[1]; Fuda Ning[1]; [1]State University of New York at Binghamton

Metal foam has attracted worldwide attention because of its lightweight and unprecedented functional properties. Traditional manufacturing approaches can only fabricate metal foam with inhomogeneous distributions and shapes of pores, causing difficulties in tailoring the properties. In this study, we leveraged the innovative printing-debinding-sintering process to fabricate the metal form materials with tailorable properties using the commercially affordable filament. Specifically, the filament comprised of 316L stainless steel powders and a binder system was printed at 200°C to achieve the green builds, followed by catalytic and thermal debinding processes to produce the brown parts. Final metal parts were obtained after being sintered with temperature up to 1380 °C . After that, the dimensional shrinkage, porosity, microstructure, and compressive properties of the samples would be characterized to elucidate the process-structure-property relationship. This study will provide great insights into structural design and fabrication of metal form materials using the high-efficiency and low-cost processes.

8:15 AM
Distortion Control in LPBF Fabricated Inconel 718 Thin Walls for Application in Nuclear Spacer Grids: *Syed Zia Uddin*[1]; Qu He[1]; Jack Beuth[1]; [1]Carnegie Mellon University

Nuclear spacer grids, an intricate consumable part of a nuclear fuel assembly, currently require lead time of more than two years from order placement to delivery using conventional fabrication methods. Laser Powder Bed Fusion (LPBF) type Additive Manufacturing (AM) process could reduce the lead time and cost significantly by printing out the structure in one major step. However, one of the main challenges in LPBF fabrication is the buckling type deformation of the tall thin walls that are abundant in the current spacer grid design. In this research, LPBF fabrication and finite element simulation of the simplified spacer grid structures with a wall thickness of 300µm and height of 47mm (~1.5inch) were performed. To eliminate the observed buckling deformation, different stiffening modifications were introduced to the thin walled cross section of the spacer grid structure. Findings in the current research would facilitate successful LPBF fabrication of tall thin wall structures.

8:30 AM
Binder Jet Additive Manufacturing for Low CTE Washout Tooling: *Dustin Gilmer*[1]; Lu Han[2]; Michelle Lehmann[1]; Amelia Elliott[2]; Tomonori Saito[2]; [1]University of Tennessee Knoxville/Oak Ridge National Laboratory Bredesen Center; [2]Oak Ridge National Laboratory

Tooling is one of the emerging industrial uses for Additive Manufacturing (AM). One promising AM technique for creating tools is Binder jet AM which can create tools from virtually any powdered materials utilizing selective ink-jetting of a binding fluid (binder) into layers of powder. This produces a composite of particles bound with the binder and by utilizing a low CTE ceramic material as the powder in this process and hyperbranched polyethyleneimine (PEI) as the binder enables the creation of composite ceramic tooling. This composite ceramic tooling exhibits strength up to 6.25 MPa at a 5.5 wt% binder content in the parts. The strength can be further increased utilizing post-processing such as customized coating and infiltration with a secondary component to 50 MPa or more. This ceramic tooling also has functional water solubility while maintaining a low CTE, making it ideal for washout mandrel for composite tooling.

8:45 AM
Additive Manufacturing of Si-SiC Cermets for Combustion Device Applications: *Patryk Radyjowski*[1]; David Bourell[1]; Desiderio Kovar[1]; Janet Ellzey[1]; [1]The University of Texas at Austin

Traditional manufacturing methods for high-temperature devices are time intensive and limited to simple shapes. Additive manufacturing (AM) reduces lead times and opens the design space to more complex geometries. Indirect laser sintering of siliconized silicon carbide (Si-SiC) cermet was evaluated for creating devices compatible with combustion environments. Heat recirculating combustors especially benefit from geometric flexibility. Si-SiC process improvements are presented for the prodution of ceramic combustors. The effect of flame on the material was studied by direct exposure of samples to hot combustion products at 1000°C and 1260°C for 10 hours. Subsequently, three experimental Si-SiC combustors were manufactured and fired to evaluate the practical aspects of cermet applications. Each device was operated for 70 hours under excess-air, methane flames with solid temperatures up to 1405°C. The surface oxidation and phase changes were assessed. Operating temperatures between 1200°C and 1350°C reduce damage to the material and provide promise of long-term, high-temperature operation.

9:00 AM
Numerical Fluid Dynamics of Surface-based Cellular Structures: *Daniel Padrao*[1]; Christopher Tuck[1]; James Paterson[2]; Frank Schoofs[2]; Ian Maskery[1]; [1]University of Nottingham; [2]United Kingdom Atomic Energy Authority

The divertor is a key component in tokamak-based nuclear fusion reactors to reduce plasma contamination and protect the walls by removing heat. Divertors are predicted to experience steady-state heat fluxes up to 20 MWm-2 and transients up to 1 GWm-2. Here we investigate a range of additively manufactured (AM), high-surface-area, cellular lattices as candidates for divertor cooling structures using computational fluid dynamics simulations. While AM structures have been examined for fusion, research using lattices is minimal so there is great opportunity to innovate.Thermal/hydraulic metrics, such as Nusselt number and friction factor, at low heat flux testing are used to indicate performance and predict the general properties for each lattice type. This allows for an appropriate selection of candidate lattice structures for future high heat flux testing. Initial results show increased cooling performance; with the potential for novel divertor cooling geometries which can only be achieved through AM lattices.

Materials: Lattices and Cellular III

Wednesday AM August 4, 2021

Session Chair: A. Panesar, Imperial College London

8:00 AM
Additively Manufactured Heterogeneously Porous Metallic Bone: *Pan Wang*[1]; Mui Ling Sharon Nai[1]; [1]Singapore Inst of Manufacturing Tech (SIMTech)

A compatible artificial bone implant requires large pores for enhanced nutrients transports, small pores to allow cell seeding and bone-like mechanical properties to avoid stress shielding. Herein, we report novel improved gyroid lattices with millimeter-scaled gyroid wall spacings and micrometer-scaled additional pores on the walls. Designs are successfully fabricated by electron beam melting using Ti-6Al-4V to high part qualities while exhibiting bone-like mechanical properties. The improved design also eliminates brittle failure by allowing the structure to deform more stably. Furthermore, we studied the size and boundary effects to revealed the non-trivial functions of built relative densities and geometrical imperfections, generally deviating that of modeling. The addition of edges to close up the lattice is also investigated in which is interestingly found to highly improve mechanical properties with minimal addition of density while the same pore sizes can be retained.

8:15 AM
A Numerical and Experimental Approach to Understand the Fatigue Performance of Additively Manufactured Lattices: *Valerio Carollo*[1]; Tyler London[1]; [1]TWI

Metallic cellular materials and lattices offer unique combinations of thermal, mechanical and acoustic properties that are oftentimes unachievable with fully dense materials. Additive Manufacturing (AM) is capable of producing complex shapes, topologies, and unit cells that could not otherwise be produced. Certifying and guaranteeing the performance of lattice design concepts remains a significant challenge since AM lattices almost always deviate from their ideal geometry due to manufacturing imperfections. This is a result of strut thickness variations, build orientation effects, local oversizing or under-sizing, and process-induced distortion.In this work, the influence of manufacturing defects on mechanical properties is investigated through experimental results and numerical models for prediction of the mechanical properties of the lattice structures. The numerical models take into account manufacturing defects using a stochastic finite element approach based on defects statistics. The model is calibrated and validated through the experimental data on specimens with varying lattice geometry.

8:30 AM
Finite Element Modelling of Defects In Additively Manufactured Strut-based Lattice Structures: *Ifeanyi Echeta*[1]; Ben Dutton[2]; Richard Leach[1]; Samanta Piano[1]; [1]University of Nottingham; [2]The Manufacturing Technology Centre

Additively manufactured strut-based lattice structures produced by powder bed fusion are prone to characteristic manufacturing defects. There remains a need for the development of a general finite element (FE) modelling framework that can include a range of defects into any strut-based lattice design. Such a framework would prove valuable for performing parametric studies of a given lattice structure to determine its sensitivity to specific defects. This paper presents a modelling framework for implementing a range of both form and surface defects into FE meshes of strut-based lattices. Intuitive mathematical definitions are provided for each of the manufacturing defects - a signed distance function forms the foundation for this framework, upon which surface meshes can be modified and converted into tetrahedral meshes. FE parametric studies are performed on lattice structures with different unit cell designs.

8:45 AM
Comparison between Ti-6Al-4V and 316L Stainless Steel Micro Lattice Structures Produced by Additive Manufacturing: *Mark Hartnett*[1]; Denis Dowling[2]; [1]Irish Manufacturing Research; [2]I-Form Advanced Manufacturing Research Centre

Lattice structures fabricated using the laser-based powder bed fusion technique, are of interest due to their high strength to weight ratios and energy absorption characteristics. This study compares the mechanical and material properties of micro lattice structures, formed from two alloys using the diamond base cell. The lattices were fabricated from Ti-6Al-4V, using a single point exposure method and from 316L stainless steel, using a conventional contour laser exposure method. Both lattice structures had a unit cell size 1.54 mm, with strut diameters in the range 200 to 400 µm. Compressive strength measurements of the printed structures demonstrated that both Ti-6Al-4V and 316L lattice's exhibited similar relative strength and relative energy absorption, however the 316L samples showed a higher relative elastic modulus. Analysis of the compressive behaviour showed that the Ti-6Al-4V alloy exhibited a more brittle failure mechanism, in contrast with the ductile failure mode obtained with 316L.

9:00 AM
On Comparative Computational Fluid Dynamics Analysis of Additively Manufactured Triply Periodic Minimal Surface Radially Gyroidal for Heat Sink Application: *Willem Groeneveld-Meijer*[1]; Guha Manogharan[1]; Sagar Jalui[1]; [1]Pennsylvania State University

Laser-powder bed fusion (L-PBF) additive manufacturing (AM) allows for manufacturing of complex geometries unable to otherwise be produced by conventional machining. Triply periodic minimal surfaces (TPMS) inherently lend themselves to L-PBF as complex, high surface area lattices. For heat sink purposes, high surface area TPMS allow for greater fluid contact within the heatsink volume and therefore higher possible thermal transfer per unit volume versus finned heatsinks. This paper presents a computational fluid dynamics (CFD) model of a radially gyroidal TPMS heat sink as compared to experimental physical testing data from an L-PBF Inconel 718 printed analogue. Key analysis factors are heat transfer per unit volume, pressure loss across the heatsink volume of 267.96cm3, and integrity of the CFD digital-twin model compared to the L-PBF test component. Research regarding the impact of surface area reduction from abrasive flow machining (AFM) on heat transfer capabilities of the L-PBF TPMS heatsink is ongoing.

9:15 AM
The Anisotropic Yield Surface of Cellular Materials: *Kaitlynn Conway*[1]; Zachary Romanick[1]; Lea Cook[1]; Jonathan Despeaux[1]; Luis Morales[1]; Marcus Ridlehuber[1]; Christian Fingar[1]; Daquan Doctor[1]; Garrett Pataky[1]; [1]Clemson University

Mechanical metamaterials are often limited in engineering applications because of uncertainty in their deformation behavior. This uncertainty necessitates large factors of safety and behavior assumptions to be included in mechanical metamaterial designs, detracting from the largest benefit of metamaterials: their ultralight weight. In this study, a yield envelope was created for both a bending dominated and a stretching dominated cellular material topology to improve the understanding of the response of cellular materials under various load types and orientations. Experimental studies revealed that the shear strength of a cellular material is significantly less than that predicted by the Mohr's criterion, necessitating a modification of the Mohr's yield criterion for cellular materials. Both topologies experienced tension-compression anisotropy and anisotropy dependent on the topology orientation during loading with the stretching dominated topology experiencing the largest anisotropies.

9:30 AM
Apparent Mechanical Properties of Sinusoid-based Lattice Structure: Numerical Analysis and Experimental Validation: *Mariela Gomez-Castaneda*[1]; Enrique Cuan-Urquizo[2]; Astrid Giraldo-Betancur[1]; Juan Alvarado-Orozco[3]; [1]Cinvestav; [2]Tecnológico de Monterrey; [3]CIDESI

Progress in additive manufacturing has benefited the fabrication of components with complex geometry, including those demanded in lattice materials or metamaterials. Here, computational simulations were carried out to investigate the deformation mechanisms, the apparent elastic moduli, and their relationship with the topology of two sinusoid-shaped structures. Tensile samples were fabricated with fused deposition modeling to validate the computations. Hence, a correlation between the topology´s parameters (amplitude-length and thickness-length ratios), relative density, the apparent stiffness and the apparent shear modulus is presented to contrast between structures with the same geometry-based design. We demonstrated high dependency of the mechanical properties upon topology´s parameters and the opportunity to achieve the same mechanical response with two different structures through relative density variation. Finally, the observed deviations between experiments and simulations might be related to the samples´ microstructural differences derived from the manufacturing process but further research is needed for its understanding.

9:45 AM
Applied Viscous Thread Instability for Manufacturing 3D Printed Foams: *Brett Emery*[1]; Daniel Revier[1]; Jeffrey Lipton[1]; [1]University of Washington

Traditional foams are fabricated via stochastic chemical processes that yield homogeneous material properties. Foams can exhibit a wide range of material properties by varying process controls allowing them to be used in many industrial and commercial applications. Previously, additive manufacturing could only produce foam approximations in the form of traditional lattice infill. Our work employs viscous thread printing (VTP) of thermoplastic polyurethane (TPU) on a fused filament fabrication (FFF) printer, exploiting the semi-viscous nature of extruded filament to randomly coil producing a new type of truly printed foam. Specimens were tested under compression to determine anisotropy and behavior under strain when compared to infill patterns, such as grid and cubic. This work establishes that VTP as applied to TPU can be used to manufacture programmable stiffness foams as a function of density, suited to a variety of needs and should be considered as an alternative to traditional foams and other printed lattice geometries.

Materials: Metals VI - Aluminum Alloys

Wednesday AM August 4, 2021

Session Chair: A. Basak, Pennsylvania State University

8:00 AM
Investigation of Defects Formation Mechanism and Its Reduction in Selective Laser Melting Fabricated Al7075 Alloy: *Mayank Patel*[1]; Akash Aggarwal[1]; Arvind Kumar[1]; [1]Indian Institute of Technology Kanpur

Selective laser melting of Al7075, a high-strength aluminum alloy is highly challenging because of its hot-cracking susceptibility. A comprehensive experimental-computational investigation has been carried out to understand the formation of solidification-cracking, porosity, and build surface quality and to predict optimum conditions for defect-free parts by varying laser power, scanning speed, baseplate heating, and re-melting. Detailed characterization and quantification of submicron-scale solidification cracks and porosities are carried out using high-resolution X-ray microtomography. We observed that conventional SLM processing results in crack formation because of insufficient liquid backfilling in between long columnar-dendritic grains formed towards build-direction, whereas a novel combination of re-melting and baseplate heating produces controlled solidification conditions which result in reduction of crack, porosity, and improvement in surface finish. Finally, the solidification path for all processing conditions is predicted with the help of high-fidelity multi-physics particle-scale SLM model. The model results are used for understanding defect formation and mitigation mechanisms.

8:15 AM
Operando Diffraction of Phase Evolution in Selective Laser Melting of Elemental Blends of Al-Sc and Al-Sc-Zr: *Jennifer Glerum*[1]; Samy Hocine[2]; Steven van Petegem[3]; Cynthia Chang[2]; Christoph Kenel[1]; Helena Van Swygenhoven[2]; David Dunand[1]; [1]MSE, Northwestern University; [2]Paul Scherrer Institute; [3]École Polytechnique Fédérale de Lausanne

New alloys must be designed specifically for additive manufacturing via selective laser melting (SLM) due to the rapid cooling rates (~106 K/s) and phase transformations out of equilibrium. High throughput alloy design and testing is more easily achieved by using elemental blend powder stock instead of costly, time-consuming prealloyed powders. Operando high-speed synchrotron diffraction allows for the study of phase evolution during the dissolution, reaction, and precipitation of strengthening phases at short time scales down to 50 µs. Operando and pre-/post-laser scanning diffraction was performed on a custom-built mini-SLM machine at the MS and microXAS beamlines of the Swiss Light Source to study direct Al-Sc-Zr alloy formation from blended elemental Al, Sc, and Zr powders as a function of laser parameters and sample size. The sample microstructure was imaged after laser scanning to characterize the sample porosity and the size and distribution of primary Al3(Sc,Zr) L12 precipitates.

8:30 AM
Metal Additive Manufacturing with Bessel Beams: *Thej Tumkur*[1]; Sheldon Wu[1]; John Roehling[1]; Tien Roehling[1]; Rongpei Shi[1]; Saad Khairallah[1]; Gabe Guss[1]; Michael Crumb[1]; Manyalibo Matthews[1]; [1]Lawrence Livermore National Laboratory

Metal additive manufacturing (AM) often results in defects, pores and columnar grains, leading to poor mechanical properties. Here, we show that a tailored spatial intensity distribution of the process laser, in the form of Bessel beams, enables microstructural control and leads to superior mechanical properties of 3D printed metals. Bessel beams are nondiffractive and propagate with longer depth of foci than conventional beams. In our experiments with stainless steel, post-mortem analysis of tracks and full builds produced using Bessel beams reveals grain refinement and larger melt pool volumes (in comparison to Gaussian beams). Highspeed imaging also reveals longer melt pool solidification times, which correlates to a greater propensity for equiaxed grain formation, as corroborated by high-fidelity powder-scale modeling of the melt pool dynamics. We will discuss the significance of our results and show that Bessel beams hold the potential to revolutionize metal AM. Prepared by LLNL under Contract DE-AC52-07NA27344.

8:45 AM
Mapping the Process Window for Reliable Metal Droplet-on-demand Manufacturing: *Nicholas Watkins*[1]; Eric Elton[1]; Victor Beck[1]; Aiden Martin[1]; Phillip Paul[1]; Andrew Pascall[1]; Jason Jeffries[1]; [1]Lawrence Livermore National Laboratory

Metal droplet on demand (DoD) additive manufacturing (AM) is an attractive alternative to the industry standard, laser-based techniques: low feedstock footprint, low overbuild quantity, less contamination and inclusions, and compatible with a larger range of materials. Although there has been a substantial amount of research in ink jetting in the past, there has been little effort in understanding the operational margins to reliably create stable, satellite-free droplets with liquid metals. In response, we probe the unexplored extremities of DoD printability using a custom liquid metal DoD system. The findings of this study will pave the way to faster design and implementation of reliable metal DoD systems that can significantly benefit the metal AM industry. Prepared by LLNL under Contract DE-AC52-07NA27344.LLNL-ABS-820119

9:00 AM
Powder Spreadability Measurements to Predict Performance in SLM Printers: *Aurelien Neveu*[1]; Filip Francqui[1]; Geoffroy Lumay[2]; Naveen Tripathi[1]; Olivier Rigo[3]; [1]GranuTools; [2]Liège University; [3]Sirris

Metallic powders are widely used in Additive Manufacturing (AM) processes, with for example Selective Laser Melting (SLM) and Selective Laser Sintering (SLS). In such operations, successive thin layers of powder are deposited with a ruler or with a rotating cylinder. The spreadability must be good enough to obtain homogenous successive powder layers leading to a good printer resolution. Four metallic powders (AlSi7Mg, Scallmaloy, Inconel, Inconel fine) performance has been studied. Powders spreadability has been determined with the GranuDrum instrument, a rotating drum enabling to quantify the influence of cohesion, shear-thinning/shear-thickening as well as thixotropic behavior, without applying a compressive load during the powder testing what fits with the conditions seen by powder in the AM processes. These measurements have been correlated to the powder performance in a SLM 3D printer, where a CCD camera is used to take several snapshots at different recoater speed (90, 140 and 240mm/s).

Materials: Metals VII - Stainless Steel and Nickel Alloys

Wednesday AM August 4, 2021

Session Chair: L. Yang, University of Louisville

8:00 AM
The Selective Laser Melting Process Development of 17-4 PH Stainless Steels with Pulsed-wave Lasers: *Evren Yasa*[1]; Andac Ozsoy[2]; Erkan Tureyen[3]; [1]Eskisehir Osmangazi University; [2]Middle East Technical University; [3]Gazi University

The main advantage of using Selective Laser Melting is its unique capability to produce highly complex geometries even involving internal cavities and good mechanical properties. Besides other differences in powder coating and gas circulation among various SLM machines, the type of laser (continuous or pulsed wave) is the most critical one. In addition to several process parameters to be optimized for a specific material, pulsed-wave lasers bring extra factors to consider. In this work, a pulsed-wave laser was used to develop process parameters for 17-4 PH stainless steel while keeping volumetric energy density, laser power and velocity to understand the effect of pulse related parameters on the outputs. As the point distance between consecutive laser spots (PD) was increased, the exposure time was also raised to keep the scan speed constant. This enabled achieving PDs with one extreme end approaching to CW-lasers while the other end aiming at keyhole effect.

8:15 AM
Linear Elastic Finite Element Calculations of Short Cracks Initiated from the Defects: Effect of Defect Shape and Size: *Arun Poudel*[1]; Shuai Shao[1]; Nima Shamsaei[1]; [1]Auburn University

The defects present in a component deteriorates its mechanical, especially fatigue performance. During loading, these defects influence the stress concentration, promote the fatigue crack initiation and thus, lead to a lower fatigue performance. In this study, the effect of defect shape and size on the Mode-I stress intensity factor (KI) of the short cracks initiating from both 2D and 3D internal defects was investigated using linear elastic finite element analysis (FEA). The shape of the defect was varied by altering the aspect ratio (width/height) from 0 to 1. Later, the dimensionless results from FEA were utilized to calculate the SIF in defects with half-span width of range 10-100 µm. As a result, the influence of defect shape on the SIF was only observed in the short crack length regimes and the measure of SIF was observed to increase with decreasing aspect ratio for a given crack length.

8:30 AM
Effect of Powder Characteristics on Tensile Properties of Additively Manufactured 17-4 PH Stainless Steel: *Arun Poudel*[1]; Arash Soltani-Tehrani[1]; Shuai Shao[1]; Nima Shamsaei[1]; [1]Auburn University

Laser beam powder bed fusion (LB-PBF) process uses metallic powders as feedstock, whose particle characteristics such as cohesion, compressibility, size distribution, etc., can vary and affect the mechanical performance of the fabricated parts. In this study, two powder batches of 17-4 precipitation hardening (PH) stainless steel (SS) supplied by EOS (Batch 1) and Carpenter Technology (Batch 2) were used to fabricate specimens using identity process parameters to understand the effects of particle characteristics on defect content as well as tensile performance of the LB-PBF specimens. Higher cohesion and compressibility as well as lower sphericity in Batch 2 resulted in specimens with higher porosity levels. During tensile testing, the higher porosity level in Batch 2 yielded lower ductility. In contrast, the microstructure was observed to be less sensitive to particle characteristics because of which the tensile strengths of the specimens were found to be comparable to each other.

8:45 AM
Use of Powder with Non-spherical Morphology in a Laser Powder Bed Fusion Additive Manufacturing Process: *Mahya Shahabi*[1]; Tianyu Zhu[1]; Yao Xu[1]; Jagannath Jayachandran[1]; Sneha Narra[1]; [1]Worcester Polytechnic Institute

Depending on the alloy and the powder manufacturing methods, the powder can be a cost contributor in powder bed fusion metal additive manufacturing processes. On the other hand, it is not always possible to produce spherical powders using gas atomization processes especially for materials with a high melting point. Hence, the focus of this work is to demonstrate the opportunity to work with powders with irregular morphology in a laser powder bed fusion process. We investigated the use of 17-4 precipitation hardening (PH) stainless steel water atomized powders that have a non-spherical morphology. Optimal deposition conditions were developed to achieve the part density that is comparable to samples fabricated with standard spherical powders. Overlap percentage between laser tracks was found to be the key factor for controlling porosity in the as-fabricated parts. This work demonstrates the possibility to use alternate irregular morphology powders in powder bed fusion processes.

9:00 AM
Sintering and Material Properties of 17-4PH Stainless Steel Fabricated by Atomic Diffusion Additive Manufacturing (ADAM): *Nandhini Raju*[1]; Peter Warren[1]; Ramesh Subramanian[2]; Ranajay Ghosh[1]; Seetha Raghavan[1]; Erik Fernandez[1]; Jayanta Kapat[1]; [1]UCF; [2]Siemens

The objective of this paper is to investigate the material properties of 17-4PH stainless steel printed by Atomic Diffusion Additive manufacturing technique. Samples with film cooling holes, impingement inserts, impingement holes in different orientations were manufactured in a Markforged Metal-X machine. Presence of cooling in these samples helps to understand printability and accuracy of internal cooling holes, as manufactured by Metal-X machine. Manufactured samples were washed and sintered to remove the plastic binder and achieve the maximum density. These samples were tested, both before sintering and after sintering, for density, microstructure analysis, CT scan, roughness, XRF to understand the material properties and its shrinkage, defects such as porosity. Results showed that sintered samples improved the density and provided nearly uniform shrinkage in all directions. Printed holes and their anomalies, selection of standards of testing will be discussed along with the material behavior of 17-4PH stainless steel before and after sintering.

9:15 AM
Effect of Heat Treatment on the Tensile Behavior of 17-4 PH Stainless Steel Additively Manufactured by Metal Binder Jetting: *P.D. Nezhadfar*[1]; Benoit Verquin[2]; Fabien Lefebvre[2]; Christophe Reynaud[2]; Robert Maxime[2]; Nima Shamsaei[1]; [1]Auburn University; [2]CETIM

Metal Binder Jetting (MBJ), a non-fusion-based powder bed additive manufacturing (AM) process, enables the fabrication of complex geometries with minimum residual stresses. Various materials have been successfully manufactured via the MBJ process; however, appropriate post-process heat treatments are required to enhance their mechanical performance as compared to the wrought or other additively manufactured counterparts. This study aims to investigate the effect of post-manufacture heat treatment on the microstructure and mechanical properties of MBJ 17-4 PH stainless steel (SS). Various heat treatment procedures following the standard routes for the wrought 17-4 PH SS are conducted to evaluate their effects on the tensile behavior of MBJ 17-4 PH SS. The mechanical behavior of the MBJ 17-4 PH SS in various heat treatment conditions is discussed based on their corresponding microstructure.

9:30 AM
A Comparative Study on the Microstructure and Texture Evolution of L-PBF and LP-DED 17-4 PH Stainless Steel during Heat Treatment: *P.D. Nezhadfar*[1]; Paul Gradl[2]; Shuai Shao[1]; Nima Shamsaei[1]; [1]Auburn University; [2]NASA Marshall Space Flight Center, Propulsion Department

This study aims to characterize the microstructure and crystallographic texture of 17-4 PH stainless steel (SS) manufactured via laser directed energy deposition (L-DED) and laser powder bed fusion (L-PBF), in both non-heat treated and heat treated conditions. It is found that the non-heat treated L-DED 17-4 PH SS possesses coarse columnar ferrite grains decorated with Widmanestatten ferrite grains, whereas the L-PBF counterpart has very fine and mostly equiaxed ferrite grains along with lath martensite. An identical stress relief (SR) temperature is obtained for both the L-PBF and L-DED 17-4 PH SS specimens based on the phase diagrams generated using Thermo-Calc. software. The SR step prior to CA-H1025 heat treatment resulted in texture weakening, and refined the grain structure to some extent. The non-heat treated L-PBF 17-4 PH SS specimen possesses strong cube and γ-fiber textures, while the texture transfers to a weaker γ-fiber components after performing CA-H1025 heat treatment.

9:45 AM
Additively Manufactured Hastelloy-X: Effect of Post-process Heat Treatment on Microstructure and Mechanical Properties: *Muztahid Muhammad*[1]; Reza Ghiaasiaan[1]; Paul Gradl[2]; Andre Schobel[3]; Donald Godfrey[4]; Shuai Shao[1]; Nima Shamsaei[1]; [1]Auburn University; [2]NASA Marshall Space Flight Center; [3]SLM Solutions Group AG; [4]SLM Solutions NA, Inc.

In this study, the effect of post-process heat treatment on the microstructure and mechanical properties of Hastelloy-X superalloy fabricated via two different additive manufacturing technologies, namely, laser beam powder bed fusion (LB-PBF) and laser powder directed energy deposition (LP-DED), is investigated. Microstructure was examined using scanning electron microscopy (SEM) and electron backscattered diffraction (EBSD) analysis, while mechanical properties were evaluated by macro-hardness testing using the Rockwell B method. Microstructure of the alloys was studied thoroughly after several heat treatments that involve stress-relieving (at 1066°C for 1.5 hours), hot isostatic pressing (HIP at 1163°C for 3 hours under 103 MPa pressure), and/or solution treatment (at 1177°C for 3 hours). The results revealed that, for both LB-PBF and LP-DED Hastelloy-X, the post-process heat treatments resulted in uniform grain structure as well as partial dissolution of carbides, although they have different grain sizes.

10:00 AM
Process Optimization and Mechanical Properties of Laser Powder Bed Fusion Built Haynes 230: *Ziheng Wu*[1]; Srujana Rao Yarasi[1]; Erfan Rasouli[2]; Ines-Noelly Tano[2]; Vinod Narayanan[2]; Anthony Rollett[1]; [1]Carnegie Mellon University; [2]University of California, Davis

Haynes 230 is a nickel-based superalloy that is widely applied in high-temperature applications, e.g., heat exchanger, because of its excellent high-temperature mechanical performances. As of today, Haynes 230 is not a standard alloy used in metal additive manufacturing (AM) primarily due to the potential hot cracking problem at fast solidification. Being able to additively fabricate components in Haynes 230 is attracted to applications that require additional advantages gained by adopting AM, e.g., higher design complexity. In this study, we successfully fabricated crack-free Haynes 230 in a laser powder bed fusion process through parameter optimization. Tensile, creep, and fatigue coupons were built and tested to show AM and wrought Haynes 230 have comparable mechanical properties. The microstructure was characterized to show how process parameters and heat treatments affect the severity of cracking and mechanical properties.

10:15 AM
Electron Beam Selective Melting of IN738LC Alloy; Defects Control, Microstructural Characterization and Mechanical Properties: *Yang Li*; Feng Lin[1]; [1]Tsinghua University

Non-weldable nickel-base superalloys, are irreplaceable materials for producing the aircraft turbine blades, which is usually produced by casting. But the mechanical properties are limited by defects such as cold shut, porosity and shrinkage. In this study,a non-weldable nickel-base superalloys, IN738LC superalloy specimens are succesfully prepared by Electron Beam Selective Melting. A new defect-free criterion is established and the processing window is determined in the defect-free specimens. The columnar crystal and single crystal are controllable to be prepared. The tensile tests at different temperature are conducted on the parallel to building direction (PBD) specimens and the orthogonal to building direction (OBD) specimens respectively. Different fracture mechanisms in PBD specimens and OBD specimens are identified by the fractographical analyses.

Materials: Polymers II - Material Extrusion

Wednesday AM August 4, 2021

Session Chair: C. Duty, University of Tennessee

8:00 AM
Comparison of Component Properties and Economic Efficiency of the Arburg Plastic Freeforming and Fused Deposition Modeling: *Felix Hecker*[1]; Felix Hecker[1]; Christine Driediger[1]; Elmar Moritzer[2]; [1]Paderborn University, Direct Manufacturing Research Center (DMRC); [2]Paderborn University, Kunststofftechnik Paderborn (KTP)

The additive manufacturing process Fused Deposition Modeling (FDM) is established in the industry for many years. A new, similar process to FDM is the Arburg Plastic Freeforming (APF). The main differences between both processes are the form of the starting material (FDM: Filaments, APF: Conventional granulate) and the material deposition during the layer formation (FDM: Melt strand, APF: fine molten droplets).Since the two processes can be used in similar applications, the aim of this study is to compare both processes in a holistic way. Furthermore, the advantages and disadvantages of the processes are to be highlighted. The systematic comparison between a Stratasys 400mc and the Freeformer 200-3X is divided into the areas of component properties, design limitations and economic efficiency. The material ABS-M30 (Stratasys) is used in both processes. The results show comparable component properties regarding mechanical and optical properties but also differences in design limitations and cost efficiency.

8:15 AM
Effect of process parameters on the vibration properties of PLA structure fabricated by additive manufacturing: *Fangkai Xue*[1]; Guillaume Robin[1]; Hakim Boudaoud[2]; Fabio Sanchez[2]; El Daya[1]; [1]Université de Lorraine, CNRS, Arts et Métiers ParisTech, LEM3, F-57000 Metz, France; [2]Université de Lorraine, ERPI, Nancy F-54000, France

Advances in Fused Filament Fabrication (FFF) enable the design and manufacturing of multi-material and multi-functional structure that can potentially be used to develop light weight and high damping structures for vibration control. However, very few studies mention the vibration characteristics of FFF printed structures. This paper investigates the effect of four process parameters (raster angle, nozzle temperature, layer height, deposition speed) on the vibration properties of FFF printed Polylactic Acid (PLA) structure through modal analysis and design of experiment. The effects of all four parameters show a good agreement on the first fives modes of resonance. It's found that raster angle significantly affects both resonance frequency (16.6%) and loss factor (7.5%). Meanwhile, the impact of the other three parameters is relatively low (less than 4%), which is different from previous research results on static mechanical properties. All these results provide a guidance for further application of FFF in vibration field.

8:30 AM
Exploring Polymer Healing Theory to Predict Adhesive Strength during Repair of Thermoplastic Parts Using Fused Deposition Modeling: *Charul Chadha*[1]; Albert Patterson[1]; Iwona Jasiuk[1]; James Allison[1]; [1]University of Illinois at Urbana-Champaign

Advancements in polymer technology have increased the production of high-valued parts using polymers. These parts are often produced in low volumes and have complex geometries, making them difficult to reproduce later especially when original tooling is no longer available. Reproduction of these parts from scratch using additive manufacturing (AM) can be time-consuming and at times economically infeasible. This paper explores the application of fused deposition modeling (FDM-extrusion based AM) to repair such parts and to print broken features on damaged parts. Polymer healing theory is then employed to understand the effect of print speed and print temperature on adhesive strength at the interface formed between the 3D-printed repair geometry and the original damaged part. The theory was verified using 3-point bending experiments. Results show that the adhesive strength at the interface is approximately proportional to the one-fourth power of print speed and increases with an increase in print temperature.

8:45 AM
The Effect of Fused Filament Fabrication Thermal Post-Processing Conditions on the Mechanical Strength and Dimensional Accuracy on ULTEM® 1010: *Callie Zawaski*[1]; Christopher Williams[1]; [1]Virginia Tech

Fused filament fabricated (FFF) additive manufactured parts are inherently anisotropic due to the weak bonds that form caused by the deposition of hot material onto material that has cooled below the glass transition temperature (Tg). While the polymer is above its Tg, the polymer chains have mobility to entangle resulting in stronger bonds between the polymer interfaces. However, the material must cool during printing in order to preserve the desired shape and prevent part deformation. In this paper, the authors propose a post-processing method for 3D printed thermoplastics to improve the strength of the parts by allowing them to remain above Tg without significant deformation. The method is tested using ULTEM 1010® where the parts are heated for up to 24 hours at 260°C. This post-processing technique can be applied to 3D printed thermoplastics in order to reduce or eliminate part anisotropy.

9:00 AM
Characterizing Internal Porosity of 3D-printed Fiber Reinforced Materials: *Frye Mattingly*[1]; Alan Franc[2]; Vlastamil Kunc[3]; Chad Duty[1]; [1]University of Tennessee, Knoxville; [2]Techmer PM; [3]Manufacturing Demonstration Facility, Oak Ridge National Laboratory

As the functional requirements for 3D printed parts become more demanding, the use of fiber reinforced materials in material extrusion printers is increasingly common. Although fiber-reinforced thermoplastics offer higher stiffness and strength, their internal volume often has a high degree of porosity which can negatively impact mechanical properties. This research surveys internal porosity across several material extrusion additive manufacturing platforms, primarily single screw extruder systems such as the Big Area Additive Manufacturing (BAAM) system. The porosity within the volume of an extruded bead was quantified through image analysis of cross sectional micrographs. The impact of processing parameters such as volumetric flow rate, temperature, and nozzle diameter were evaluated, as well as multiple hardware configurations and material conditions.

9:15 AM
The Effect of Stress Intensity Factor on Fatigue Life of Additive Manufactured Parts Made from Polymer: *Hayat EL Fazani*[1]; Rahul Shah[1]; Jason Coil[1]; Jeremy Laliberte[1]; [1]Carleton University

The fatigue characteristics of additively manufactured specimens was investigated. Acrylonitrile-butadiene-styrene (ABS) polymer was selected to manufacture AM fatigue coupons due to its low cost and wide applications. A total of 30 fatigue coupons were built on flat using Stratasys SST 1200es fused deposition machine. The coupons were manufactured at different build orientations. The objective is to determine which build orientation results in the most favorable fatigue behavior. The specimens were tested under low sinusoidal tension-tension fatigue loading. The stress intensity factor was estimated. The influence of stress intensity factor on fatigue life was examined. The investigation of fatigue crack growth as a function of the number of fatigue cycles was discussed. A numerical simulation of fatigue life estimation was performed using COMSOL Multiphysics software. Both experimental and numerical results showed that the fatigue coupons manufactured at 0° build orientation have a better fatigue life compared with the other build orientations.

9:30 AM
The Material Testing of Nanoparticle Doped 3D Printed ABS to Decrease Resistance and Create a Conductive Pathway: *Sara Damas*[1]; Cameron Turner[1]; [1]Clemson University

The technology to 3D print by low-cost fabrication has been around since the 1970's. Thanks to one of its founding fathers, Scott Crump, as of 1989, it is possible to 3D print in low-cost fabricated layers to obtain a solid component. The demand for 3D printed products has only gone up since. Nickel, copper, carbon, and electric paint nanoparticles were bound to Acrylonitrile Butadiene Styrene (ABS) using N-Methyl-2-Pyrrolidinone (NMP) by fused deposition modeling (FDM). When ABS is doped with nanoparticles, conductive properties are introduced to the filament which can then be used for strain measurements. This study concluded: When compared to the other nanoparticles, nickel produced the lowest resistance when doped into the ABS. Multiple layers of the NMP and nanoparticles yields a lower resistance, which subsequently yields higher conductivity. The methodology outlined in this paper successfully created individually isolated conductive pathways, where indeed NMP does improve the conductive performance of the nanoparticles.

9:45 AM
Mechanical Properties of High-performance Plastic Polyether-ether-ketone (PEEK) Printed by Fused Deposition Modeling: *Zezheng Wang*[1]; Haijun Gong[1]; [1]Georgia Southern University

Polyether-ether-ketone (PEEK) is a high-performance thermoplastic material with high heat resistance, high chemical resistance, high water resistance, and high wear resistance. Due to its distinguished strength and durability, PEEK is extensively used for aerospace, automotive, and medical applications. 3D printing PEEK filaments offer a new approach to make PEEK parts, fulfilling specific requirements of geometrical complexity. But the mechanical properties of 3D printed PEEK materials are not further explored. This study investigated the mechanical properties of PEEK materials fabricated using the fused deposition modeling (FDM) 3D printing process. Tensile test, hardness test, and impact test were conducted to the PEEK samples, in compliance with ASTM standards. The testing results were summarized and discussed, compared to the conventionally manufactured PEEK materials. This study also provides insights on employing FDM 3D printing process for making PEEK parts, based on its special mechanical properties and failure mode.

Physical Modeling: V Process Modeling

Wednesday AM August 4, 2021

Session Chair: M. Priddy, Mississippi State University

8:00 AM
Numerical predictions of bottom layer stability in material extrusion additive manufacturing: *Md Tusher Mollah*[1]; Raphaël Comminal[1]; Marcin Serdeczny[1]; David Pedersen[1]; Jon Spangenberg[1]; [1]Technical University of Denmark

Robocasting and 3D concrete printing are technologies that belong under the umbrella term material extrusion additive manufacturing. These two free form fabrication methods are used to produce 3D structures/components in materials such as ceramic pastes, thermosets, and concrete. Common for the materials is their viscoplastic behavior during deposition and structural buildup (i.e., increase in yield stress) after deposition. The material's complex nature makes it a non-trivial task to ensure that printed layers do not deform when depositing additional layers on top. In this paper, we numerically investigate the influence of the yield stress buildup of viscoplastic materials on the stability of the bottom layer during multilayer printing. Specifically, we have developed a computational fluid dynamics model that applies a scalar approach to alter the yield stress. The novel model provides fundamental knowledge on how to design the material's rheology, so the bottom layer can withstand both the hydrostatic- and extrusion-pressure.

8:15 AM
Using Medial Surfaces to Produce Graded Voronoi Cell Infill Structures for 3D Printed Objects: *Tyler Williams*[1]; Duane Storti[1]; Mark Ganter[1]; [1]University of Washginton

Many methods of additive manufacturing rely on infill structures to decrease part mass and print time. However, standard infill patterns generally use a uniform density or require time-consuming analysis to generate a density field tailored to part geometry. We propose a Voronoi cell based infill structure which uses the medial surfaces of the object to locate thin regions and increase local material density. The Voronoi cell structure reduces stress-concentrating transition points within the infill, producing a more even gradient in density, while the weighting scheme ensures that traditionally weaker portions of the model receive adequate internal support.

8:30 AM
Laser Spot Size and Scaling Laws for Laser Beam Additive Manufacturing: *Jordan Weaver*[1]; Jarred Heigel[2]; Brandon Lane[1]; [1]National Institute of Standards and Technology; [2]Third Wave Systems

Laser powder bed fusion requires the careful selection of laser parameters for each material and machine, which is a laborious process. Scaling laws based on the laser power, speed, and spot size; melt pool geometry; and thermophysical properties can potentially reduce this effort. Laser spot size is one critical parameter that is less well studied. Consequently, single track laser scans were generated with a spot size (D4s) range of 50 µm to 322 µm and melt pool aspect ratio range from 0.1 to 7.0. These were characterized by in-situ thermography, cross-sectioning, and optical microscopy. Scaling laws from literature which contain a minimum of three dimensionless parameters and account for changing absorption between conduction and keyhole mode provide the most accurate melt pool depth predictions (< 35 % difference from experiments), which is comparable to thermal simulation results from literature for a select number of cases.

8:45 AM
Discrete Element Modeling of Fused Deposition Modeling Process: Chelsea Menezes[1]; *Cameron Turner*[1]; [1]Clemson University

Fused Deposition Modeling components show anisotropic material properties as a result of the difference in bonding strengths between inter- and intra-layer particles. This difference occurs due to temperature gradient of the deposited filaments which affects the filament adhesion. Discrete Element Modelling (DEM) is a discontinuous methodology which follows the idea of treating filaments as discrete rigid particles with simplified geometries for calculating the thermal interactions between the particles. Models using this approach allow the investigators to correlate the adhesion effects between filaments based on experimental data which ultimately will allow for optimization of the relevant printing parameters.

Physical Modeling: VI Material Modeling A

Wednesday AM August 4, 2021

Session Chair: F. Medina, University of Texas at El Paso

8:00 AM
Exploring Transient Printing Processes and Defects of Various Builds during Additive Manufacturing: *Huiliang Wei*[1]; [1]Nanjing University of Science and Technology

Laser additive manufacturing involves complex physical processes. The research paradigm of can be reshaped using advanced phenomenological models along with typical trial-and-error experimental explorations. In this talk, the complex AM processes will be examined on multiple scales including the 1D track, the 2D layer and the 3D full build considering the complex transport of energy, mass, and momentum. The generation of various build profiles and printing defects under diverse conditions will be explored via the spatiotemporal variations of the temperature fields, the liquid metal flow in the freeform molten pool, and the repetitive thermal cycles during the layerwise printing processes. Relevant correlations of process, structure, and properties, and the development of mechanistic models revealing critical features of various geometrical and metallurgical factors will be discussed as well.

8:15 AM
Finite Element Simulation of Direct Deposition Additive Manufacturing for Fiber Reinforced Thermoplastics: *Zhaogui Wang*[1]; Douglas Smith[2]; [1]Dalian Maritime University; [2]Baylor University

Non-planar polymer direct deposition additive manufacturing has recently seen increased attention from industries, where the molten plastics beads are extruded through a heated nozzle directly into three-dimensional space to form lightweight truss-like structures. This promising method shortens the time of manufacturing and can produce structures without the stair effect appearance that occurs in traditional layered additive manufacturing processes. This paper investigates the flow dynamics of fiber reinforced thermoplastics melt during a direct deposition process. A vertical extrudate of polymer melt is modelled through the finite element method, where a non-Newtonian transient flow model is developed for this process. A quasi steady state for the deposition flow may be achieved, where the fiber orientation induced by the flow is evaluated through the Folgar-Tucker isotropic rotary diffusion model with the orthotropic-fitted closure approximation. Computed results indicate that fibers within the vertically deposited bead tend to highly align along the direction of extrusion.

8:30 AM
A Multi-grid Cellular Automaton Model for Simulating Dendrite Growth and Its Application in Additive Manufacturing: *Yefeng Yu*[1]; Yan Wentao[2]; Lin Feng[1]; [1]Tsinghua University; [2]National University of Singapore

The dendrite growth in casting and additive manufacturing is rather important and related to the formation of some defects. However, quantitatively simulating the growth of dendrites with arbitrary crystallographic orientations in 3-dimension(3D) is still very challenging. In the present work, we develop a multi-grid Cellular Automaton (CA) model for dendrite growth. In this model, the interfacial area is further discretized into a child grid, on which the decentered octahedron growth algorithm is performed. The model is comprehensively and quantitatively verified by comparing with the prediction of analytical models and a published x-ray imaging observation result, proving that the model is quantitatively and morphologically accurate. After that, with the temperature and velocity data extracted from a finite volume method-based thermal-fluid model, the model firstly succeed in reproducing the melting-pool-scale dendrite growth process of nickel-based superalloy in additive manufacturing process. The simulation results agree well with the experimental observation.

8:45 AM
A Periodic Homogenization Model Including Porosity to Predict Elastic Properties of 3d-printed Continuous Carbon Fiber-reinforced Composites: *Valentin Marchal*[1]; François Peyraut[1]; Yicha Zhang[1]; Nadia Labed[1]; [1]Université de Technologie de Belfort-Montbéliard

The additive manufacturing of continuous carbon-fiber reinforced composite is a simple way to obtain complex parts with good mechanical properties. However, it remains difficult to perform numerical simulations on such materials, as it is difficult to find the elastic coefficient of the whole material. Using a new model of periodic homogenization, which considers both the fiber rate and the porosity, would be a quick solution to predict the mechanical properties of the printed composite. Based on material studies and validated with mechanical tests, this simulation model allows the use of a homogeneous material to replace the composite material for the finite element analysis. This will strongly reduce the number of elements required in the model, leading to a decrease of the computation time. Hence, the numerical model will be more suitable to perform optimization processes.

9:00 AM
Effects of Local Fiber Orientation State on Thermal-mechanical Behaviors of Composite Parts Made by Large Area Polymer Deposition Additive Manufacturing: *Zhaogui Wang*[1]; Douglas Smith[2]; [1]Dalian Maritime University; [2]Baylor University

Short carbon fiber enhances the dimensional stability and material strength of composite parts created via large area polymer deposition additive manufacturing, which has been used for rapid prototyping of large-dimension composite parts and tooling. Nevertheless, the flow-induced fiber orientation formed during the material extrusion and deposition leads the deposited composites exhibit non-homogeneous thermal-mechanical behaviors. This study evaluates the fiber orientation state of a 20 wt.% CF/PEI composite fabricated by polymer deposition using the fully coupled flow/orientation approach. The material properties are computed by considering the deposited bead as heterogeneous segments with different local fiber orientation states. The heterogeneous thermal conductivity and expansion coefficient exhibit maximum local differences of 29% and 21%, respectively. The orientation-homogenized material properties are implemented to the finite element simulation for a large area additive manufacturing process of a single wall and notable differences are seen between results computed by employing the homogenous and heterogeneous properties.

9:15 AM

Simulation of Micro-void Development within Large Scale Polymer Composite Deposition Beads: *Aigbe Awenlimobor*[1]; Zhaogui Wang[2]; Douglas Smith[1]; [1]Baylor University; [2]Dalian Maritime University

Short carbon fiber composites are used in large-scale polymer deposition additive manufacturing due to their increased stiffness and strength and reduced thermal expansion and print distortion. While much attention has been given to interlayer properties, less is known about bead microstructure, including the effect that suspended fibers have on porosity. This paper develops a model for single fiber motion in a purely viscous flow that is simulated with a custom finite element fiber suspension analysis. Our fiber simulation is based on Jeffrey's model assumptions where translational and rotational velocities which zero applied forces and moments are computed. Velocity gradients along streamlines within the flow of polymer melt through a large-scale polymer deposition additive manufacturing flow field serve as input. The pressure distribution around a fiber is computed along the flow path including the die swell expansion at the nozzle exit. The simulation provides insight into micro-void formation within printed beads.

9:30 AM

High-fidelity Modeling of Binder-powder Interactions in Binder Jetting: *Zeshi Yang*[1]; Wentao Yan[1]; [1]National University of Singapore

Binder jetting is an emerging additive manufacturing approach that attracts rising attention in recent years. The part-building process in binder jetting is directly affected by the interaction between binder droplet and powder bed. In this work, a fluid-solid coupling model is developed. The spattering and agglomeration behaviors of particles and their effects on the droplet are simulated and analyzed. The validity of this model is proven by validating simulation results against theoretical analysis and experimental results in the literature. Additionally, according to simulation results, the movement of the agglomerates after droplet impinging plays an important role in printing dimensional accuracy. This model is applicable for printing parametric studies with different binder droplets, powder, and process parameters.

9:45 AM

Modeling Collapse Behavior in Large-scale Thermoset Additive Manufacturing: *Stian Romberg*[1]; Chris Hershey[2]; John Lindahl[2]; Abrian Abir[3]; Michael DeVinney[4]; Chad Duty[1]; Vlastimil Kunc[2]; Brett Compton[3]; [1]University of Tennessee, Knoxville; Oak Ridge National Laboratory; [2]Oak Ridge National Laboratory; [3]University of Tennessee, Knoxville; [4]

Over the last several years, 3D printing of thermoset polymer resins has progressed rapidly. Thermosets offer desirable properties and excellent compatibility with fibers. Additionally, they can be deposited at room temperature, avoiding the residual stresses and poor interlayer bonding caused by the large thermal gradients in thermoplastic material extrusion additive manufacturing (AM). However, pursuits to scale up thermosets have highlighted issues with print stability. This presentation will describe efforts to quantify deformation mechanisms in large-scale printed thermosets and to link measurable rheological properties to collapse in tall, thin printed walls using self-weight buckling and yielding models. Findings reveal that the observed buckling instability is governed by the recovered storage modulus of the material after a period of high shear stress representative of that experienced in the deposition nozzle. The talk will conclude with discussion of how these results can inform material design and print parameter selection for large-scale thermoset AM.

Process Development: V Extrusion

Wednesday AM August 4, 2021

Session Chair: R. Dwivedi, STEM and Robotics Academy

8:00 AM

Insertion and Air-gapped Retrieval of Part Quality Information in Additive Manufacturing Toolpaths for Cyber-Secure In-situ Process Monitoring: *Nathan Raeker-Jordan*[1]; Logan Sturm[1]; Christopher Williams[1]; [1]Virginia Tech

As a data driven process, additive manufacturing (AM) is vulnerable to cyber-attacks, notably sabotage attacks that can impact part quality. Side-channel in-situ monitoring systems (SCISMS) are one approach that has been proposed for AM part verification. However, in order to protect these SCISMS from cyber-attacks, they should be air-gapped, preventing direct transmission of known-good quality information. This paper presents a method for embedding part quality information into an AM toolpath. Known-good information is transmitted via AM machine operation side-channels to the SCISMS, which compares transmitted known-good information to in-situ side-channel measurements for verification. To validate the approach, a case study is presented in which a material extrusion machine, wherein information is encoded as extruder movement speeds, transmits 10496 bits of part quality information to the SCISMS with an average rate of 7.1 bits per second. This information is then used to verify the machine state (position, temperature, extrusion) over time.

8:15 AM

Feasibility Study of Large-format, Freeform 3D Printing for On-orbit Additive Manufacturing: Declan Jonckers[1]; Oliver Tauscher[1]; Enrico Stoll[2]; *Aditya Thakur*[1]; [1]Technische Universität Braunschweig; [2]Technische Universität Berlin

Large scale, on-orbit additive manufacturing (AM) and assembly is being considered as a modular and resource saving approach to facilitate permanent human presence in space. To realize this, a novel AM approach to freefrom fabricate large, functional structures in space has been developed. Combining the outreach of a free-flying CubeSat with a collaborative robotic arm and a 3D printer, large support-free thermoplastic structures can be manufactured beyond the size of the setup itself. The feasibility of the proposed fabrication approach was established using the Experimental Lab for Proximity Operations and Space Situational Awareness (ELISSA) system, where a modified fused filament fabrication setup was mounted on a free-flyer to 3D print free-standing structures. Using continuous navigation path incorporating infinite fabrication loop, over two meters long, support-free trusses were produced to well demonstrate the potentials of the proposed method in boundless direct printing of complex structures, independent of gravity or printing orientation.

8:30 AM

Variable Extrusion Width and Height for Interlocking Features in Fused Filament Fabrication 3D Printing: *Osama Habbal*[1]; Christopher Pannier[1]; Georges Ayoub[1]; [1]University of Michigan Dearborn

Following from the introduction of CONtinuously Variable EXtrusion (CONVEX) in material extrusion additive manufacturing, this work explores continuously varied bead height to improve interlayer adhesion in polymeric material extrusion additive manufacturing. A periodic waveform is used for the extrusion height instead of maintaining a constant extrusion height within a layer. We present machine codes that increase and decrease the extrusion width and height continuously along the extruded line. Subsequent extruded lines interlock with the waveform of the underlying extruded line. The effects on interlayer adhesion are assessed through tensile tests and double cantilever beam tests. Results are correlated with the increased interlayer contact cross sectional area and the spatial wavelength and amplitude of the extrusion height waveform. This work is limited to fully dense infill of prismatic regions of objects. Experimental results are forthcoming.

8:45 AM
A TRIZ-Based Analysis of the Fundamental Limits of Fused Filament Fabrication: *Jason Weaver*[1]; Cade Patterson[1]; [1]Brigham Young University

Each category of additive manufacturing has specific fundamental limitations bounded by the physics and material properties involved. For example, the speed of FFF processes is bounded by how quickly thermoplastics can be melted, deposited, and resolidified while retaining material properties and dimensional accuracy. Incremental improvements approaching these theoretical limits will continue to occur, but more radical changes are necessary to completely overcome the current constraints. This paper considers some of the fundamental limits bounding FFF processes and investigates possible avenues for future research to overcome these limits. The framework for this analysis is the "Theory of Inventive Problem Solving" (TRIZ), a formalized problem solving and ideation tool that generalizes design-specific problems into contradicting engineering parameters, then suggests universal design principles based on analogy to solutions in other systems and patents.

9:00 AM
Mechanical Evaluation of Topology and Toolpath Optimized Composite Structures Manufactured via Multi-axis Material Extrusion: *Joseph Kubalak*[1]; Alfred Wicks[1]; Christopher Williams[1]; [1]Virginia Tech

Planar material extrusion (ME) processes are insufficient for load-bearing applications due to the poor mechanical performance of inter- and intra-layer bonds. However, the deposition process inherently aligns fibers in the polymer matrix (e.g., composites) to the extrusion direction, presenting the opportunity to optimize part performance through toolpath customization. Whereas planar processes restrict this optimization to the XY-plane, recent advances in multi-axis ME enable toolpath optimization in full 3D. Previously, the authors presented a topology and toolpath optimization (TTO) workflow that optimizes material distribution and orientation for arbitrary 3D loading conditions, aligns deposition paths to those orientations, and orders them for collision-free deposition. In this presentation, the authors evaluate the results of the TTO workflow through the fabrication and mechanical evaluation of case study geometries. Relative to geometrically similar specimens fabricated using planar deposition, the multi-axis TTO specimens demonstrate increased mechanical performance due to improved deposition alignment to the load paths.

9:15 AM
Mechanical Characterization of Epoxy Components Manufactured via Reactive Extrusion: *Oliver Uitz*[1]; Carolyn Seepersad[1]; [1]University of Texas at Austin

Reactive extrusion is a new AM process that enables extrusion-based layer-by-layer deposition of thermoset polymers from liquid precursors that are mixed on demand at the point of application and cure at ambient conditions. Because the materials cure in situ, significant crosslinking can occur between material layers, resulting in parts with very little anisotropy. Moreover, the use of liquid thermoset precursors that cure in situ avoids the need for energy expenditures associated with heating the deposited material. This presentation describes a reactive extrusion AM testbed and the mechanical properties of parts fabricated with the testbed. When coupled with a large nozzle and high material flow rates, the reactive extrusion AM testbed described in this presentation is capable of creating strong, nearly isotropic parts in a fraction of the time it takes other conventional additive systems, while using appreciably less energy.

9:30 AM
Concrete Metering and Extrusion System for Infastructure-scale Printing: *Celeste Atkins*[1]; Brian Post[1]; Phillip Chesser[1]; Alex Roschli[1]; Alex Boulger[1]; Jesse Heineman[1]; Peter Lloyd[1]; Randall Lind[1]; Lonnie Love[1]; [1]Oak Ridge National Laboratory

Over the years a number of researchers and companies have begun 3D printing concrete. However, in most systems the only control to the flow of concrete is a single pump to the side of the machine that pumps the concrete to the end effector. This causes large amounts of latency in the flow of the concrete due to the distance of the pump from the end effector. This makes the material deposition difficult to control and creates defects in the print. The research on concrete 3D printing at Oak Ridge National Laboratory in the Manufacturing Demonstration Facility leveraged an approach used in other types of 3D printing systems by placing an extruder on the end effector to meter the flow accurately which functions in tandem with a remote pump. Several extruder designs were evaluated and tested. This paper will detail the process of extruder development and printing impacts.

Process Development: VI Novel Processes and Advances B

Wednesday AM August 4, 2021

Session Chair: X. Zhao, University of Pittsburgh

8:00 AM
Combining Technologies: In-situ Direct-write Techniques for Hybrid Injection Molded Electronics: *Joshua Krantz*[1]; Dario Loaldi[2]; Katherine Berry[1]; Corey Shemelya[1]; Davide Masato[1]; [1]University of Massachusetts Lowell; [2]University of Massachusetts Lowell; Technical University of Denmark

In this work, we explore the hybrid integration of injection molding with in-situ direct-write additive manufacturing. Specifically, we characterize a novel fabrication technique in which one prints structures directly onto an injection mold surface. During injection molding process, the polymer melt flows over the printed trace, and that trace is "transferred" from the mold into the polymer part. The resulting composite structure maintains all trace properties including: trace size, shape, and continuity. This transfer process enables volumetric integration of both structural electronics and/or mechanical reinforcement, enables wider printed curing/sintering temperature ranges, and improves surface finish compared to post-process printing. This work describes the relative surface energies of custom mold coatings which enable the printed traces to be "transferred" intact into the bulk polymer part. We also explore both mechanical and electrical properties of the final part including: adhesion, mechanical degradation, surface finishes, and integrated electrical functionality.

8:15 AM
Multiple-material powder bed fusion machine development: reducing cross-contamination between materials: *Scott Snarr*[1]; Andres Najera[1]; Joseph Beaman Jr.[1]; Derek Haas[1]; [1]University of Texas at Austin

Powder bed fusion is an additive manufacturing technology capable of producing fully dense, high strength parts with complex geometries. However, it is currently only able to fabricate parts comprised of a single material. Multiple-material capabilities would allow for an added level of design complexity and the matching of material properties to the functional requirements of a part. In order to achieve this, a full redesign of the current powder deposition system is required. Previous attempts to implement multiple-material powder deposition systems encountered issues with controlling the dimensional accuracy in the build direction and cross-contamination between materials. This research integrates an angled blade leveling mechanism along with a nozzle-based powder deposition system to solve these problems. A design of experiments was run to identify significant leveling parameters and to quantify material cross-contamination. A deposition and leveling system that creates a uniform height multiple-material powder bed with no significant cross-contamination of materials is demonstrated.

8:30 AM
Geometrical Analysis of Simple Contours Deposited by a 3D Printing Hexacopter: *Alexander Nettekoven*[1]; Nicholas Franken[1]; Ufuk Topcu[1]; [1]University of Texas Austin

A recently developed hexacopter testbed at the University of Texas at Austin can fly to a desired location and deposit polylactic acid on flat surfaces. To quantify the current printing capabilities of this 3D printing testbed, we print square contours of different sizes and analyze the printed results based on their geometrical properties. We also quantify the hexacopter's trajectory tracking of the desired contours to assess the absolute position accuracy. In quantifying the printing results, we lay the groundwork for using aerial robots in printing applications of medium- to large-scale objects, such as concrete printing.

8:45 AM

Material Pressure Sensing at the Nozzle in Direct-write Additive Manufacturing Enables the Precise Fabrication of Complex Parts: *Ali Asghari Adib*[1]; David Hoelzle[1]; [1]Ohio State University

Flowrate control remains a challenge in extrusion-based Direct-Write (DW) Additive Manufacturing (AM) due to the capacitive energy storage in the system. Current open-loop control methods are material- and nozzle-dependent and any deviations in these parameters require an updated control design. Independent of the DW AM extrusion system, being pneumatic or mechanical, material pressure at the nozzle is statically related to output flowrate, enabling material-independent flowrate control. Here, we report on the design and implementation of a pressure sensing module that enables the *in situ* material pressure measurements at the nozzle in any DW AM system, and paves the way for precise control of material extrusion for fabrication of three-dimensional parts. The successful material- and nozzle-independent fabrication of parts using different nozzle sizes and materials that have different non-Newtonian rheological properties is demonstrated, and the shape fidelity of the printed parts is characterized to confirm enhanced printing accuracy.

9:00 AM

A Modular Lightweight Additive Manufacturing System for Cementitious Materials with Diverse Aggregate Sizes: Bahram Asiabanpour[1]; *Mehrab Nodehi*[1]; Liam Omer[1]; Togay Ozbakkaloglu[1]; [1]Texas State University

In recent years several large-scale commercial AM-based construction machines have been introduced. However, proper lab-scale machines for training experts in automated construction and research-based activities such as material optimizations for the civil and structural engineers are not available. The only available small-scale apparatus in AM-based construction is limited to a minimal list of materials and properties. Those machines are not capable of fabricating samples from cementitious materials with a variety of aggregate sizes. This paper introduces a low-cost, modular AM-based construction system capable of extruding a wide variety of cementitious materials with diverse aggregate sizes. The system is capable of continuous extrusion with a variety of cross-section forms. As a proof-of-concept, the developed system is utilized to fabricate cement mortar with larger aggregate sizes with different materials mixture ratios. Mechanical and rheological properties of the conventional versus that of additively printed samples are also tested and compared.

9:15 AM

Fabrication of Bioinspired Optical Material with Self-sensing Capability via Thermal Field Assisted 3D Printing: *Dylan Joralmon*[1]; Tengteng Tang[1]; Harsheen Rajput[1]; Kailong Jin[1]; Xiangjia Li[1]; [1]Arizona State University

The creatures in nature possess unique smart material systems that can sense the environment change with evolved self-responsible architectures. For example, Japetella heathi octopus exhibits a remarkable ability to switch between transparency and pigmentation to evade the attention of predators. Here, we present a new approach to produce Japetalla heathi inspired smart material with self-responsible architectures by thermal field-assisted 3D printing. The levels of orientational and positional orders of liquid crystal in unique phases are modulated by the thermal field during the 3D printing. As a result, the 3D-printed material possesses a unique optical property that it can reversibly transit from transparent to opaque in response to external stimuli. The developed thermal field-assisted 3D printing provides a versatile manufacturing tool that enables the design and fabrication of bioinspired smart materials with complex 3D shapes for various potential applications, such as soft robots, flexible sensors, and smart anti-counterfeiting devices.

9:30 AM

Robot Trajectory Planning for Large Scale Additive Manufacturing: *Ademola Oridate*[1]; Oliver Uitz[1]; Mitch Pryor[1]; Carolyn Seepersad[1]; [1]University of Texas at Austin

Additive manufacturing (AM) in the construction industry has gained traction in recent years, with most machines using gantry systems. While easy to control, they are bulky because they need a build envelope as large as the intended structure. In contrast, robotic architectures are more compact and offer greater mobility and the flexibility for printing in various orientations and on existing structures otherwise unreachable with a gantry system. However, with the increased degrees of freedom, motion planning for robots adds extra complexity, especially since a major driver of AM for construction is the ability to create geometrically complex structures. This research explores trajectory planning methods to achieve 3D printing of structures directly from CAD files by using Virtual Fixtures (VFs) for guiding robots as they print on/around existing objects and incorporating sensor feedback for intelligent monitoring of the printing process.

9:45 AM

Review of Current Problems and Developments in Large Area Additive Manufacturing (LAAM): *Tyler Crisp*[1]; Jason Weaver[1]; [1]Brigham Young University

Current challenges characteristic of additive manufacturing (AM) include low production speed, poor mechanical properties, difficulty of utilizing multiple materials in a single part, limits of build volume, and higher material costs than other manufacturing methods. Large Area Additive Manufacturing (LAAM), first pioneered by Oak Ridge National Laboratory and Cincinnati Incorporated as Big Area Additive Manufacturing (BAAM), addresses many of these issues in high-volume, high output AM systems for polymers, metals, ceramics, and composites. Significant development has occurred in LAAM research to address the characteristic challenges of AM. This literature review categorizes and summarizes the challenges and solutions that have been presented in research related to LAAM and suggests further research to be conducted, including multi-material and multi-process hybrid manufacturing technologies.

Special Session: Data Analytics in AM III - Process Monitoring and Flaw Detection A

Wednesday AM August 4, 2021

Session Chair: S. Roychowdhury, GE Global Research Center

8:00 AM

In-situ Flaw Detection in Wire Arc Additive Manufacturing Using an Acoustic Sensor: *Benjamin Bevans*[1]; Andre Ramalho[2]; Aniruddha Gaikwad[1]; Ziyad Smoqi[1]; Joao Oliveira[2]; Prahalada Rao[1]; [1]University of Nebraska-Lincoln; [2]NOVA University of Lisbon

Wire Arc Additive Manufacturing (WAAM) is emerging as the process of choice for large area additive manufacturing. However, a key challenge in WAAM is the consistent deposition of flaw-free parts. The process is particularly susceptible to arc instabilities, which can lead to porosity and suboptimal layer integrity. Accordingly, the objective of this work is to detect flaw formation in WAAM using data acquired from an acoustic emission sensor. The sensor data was analyzed using graph-theory and wavelet filtering. Using the proposed approach, various types of flaw formation mechanisms, such as arc instability and material contamination, were detected in real-time. This approach allows the flaw to be detected, and therefore corrected before it is permanently sealed in by subsequent layers.

8:15 AM

Unsupervised Defect Classification of 2D SEM and 3D X-Ray CT Images from Laser Powder Bed Fusion: *Andrew Lang*[1]; Cesar Ortiz Rios[2]; Joseph Newkirk[2]; Robert Landers[2]; James Castle[1]; Douglas Bristow[2]; [1]The Boeing Company; [2]Missouri University of Science and Technology

This work discusses a method to classify defects in laser powder bed fusion using 2D images of layer samples taken by Scanning Electron Microscope (SEM) and 3D image stacks of a full part by X-Ray Computed Tomography (XCT). Images using SEM are taken of a sampled layer in a printed part and unsupervised classification of defects in the SEM images is performed with Otsu's thresholding method, K-means classification, and the Robust Automatic Threshold Selection algorithm. The performance of the classifiers, measured against human-generated ground truth defect labels, is improved by registering and fusing multiple SEM images taken under different settings and lighting conditions. Otsu's method is shown to be the best classifier for the 3D XCT dataset. Finally, the 2D sample is located in the 3D XCT array and the reliability of the 3D defect classification technique is validated.

8:30 AM

Acoustic Signatures in Metal Laser-powder Bed Fusion: Bradley Jared[1]; David Saiz[1]; Matthew Roach[1]; Scott Jensen[1]; Maher Salloum[1]; Constantin Brif[1]; Chase Zimmerman[1]; *Elaine Rhoades*[2]; Jonathan Pegues[1]; [1]Sandia National Laboratories; [2]Georgia Institute of Technology

In-situ process monitoring is highly desired within metal additive manufacturing as extensive efforts exist within the community using optical and thermal imaging modalities. Acoustic signatures represent an additional modality being explored in the presented work. Implementation costs for acoustic monitoring are relatively inexpensive compared to optical and thermal methodologies, and high frequency content can be easily accessed. Analyzing acoustic signals presents challenges, however, as individual process events prove difficult to isolate from extraneous disturbances and concurrent process activities. Techniques are being explored in both time and frequency domains to identify specific metal laser-powder bed fusion process events. Progress and challenges from cross-correlation, wavelet and time series pattern discovery methodologies will each be discussed. Anomaly detection for process monitoring is the desired end-goal of this work, so results and future work will all be presented within this context. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

8:45 AM

Detecting Defects Caused by Optical Lens and Focus-related Aberrations in Laser Powder Bed Fusion: *Aniruddha Gaikwad*[1]; Harry DeWinton[2]; Prahalad Rao[1]; Paul Hooper[2]; [1]University of Nebraska; [2]Imperial College

The objective of this work is to predict part defects caused by optics-related aberrations, such as variations in the laser focus height in the laser powder bed fusion process. To realize this objective we monitor images of the meltpool acquired from an in-process high-speed video camera. The key idea is to characterize the meltpool shape and spatter features. Various machine learning approaches, including both supervised and unsupervised machine learning approaches are trained to predict the laser focus height based on these features. As part of this objective, we test the hypothesis that pragmatic meltpool features selected based on physical understanding of the process, leads to higher fidelity (F-score) of detecting deviations in Laser Focus Height, as opposed to using so-called black box deep learning approaches.

9:00 AM

Machine Learning Enabled Laser Spatter and Flaw Detection in Laser Powder Bed Fusion Processes: *Brandon Abranovic*[1]; Jack Beuth[1]; [1]Carnegie Mellon University

This work focuses on the analysis of laser powder bed fusion images and acoustic data as a means to monitor laser powder bed additive manufacturing processes for key outcomes. This would enable robust quality assurance, control and optimization of component properties, and improvement of process stability while reducing operator burden. Process mapping was employed in determining parameter sets that would reliably induce keyholing, lack-of-fusion, bead-up, laser spatter, as well as fully dense components. Using data collected during builds using these parameter sets, bag of words (BOG), support vector machines (SVM), convolutional neural networks, and long-short term memory (LSTM) networks were shown to be successful in classifying flaws. Future work will involve the use of more advanced deep learning architectures such as U-Net to localize the detection of laser spatter in fusion images as well as the application of the more advanced transformer architecture to the processing of acoustic signals.

9:15 AM

Autoencoder-based Anomaly Detection for Laser Powder Bed Fusion: *Bumsoo Park*[1]; Aleksandr Shkoruta[1]; Sandipan Mishra[1]; [1]Rensselaer Polytechnic Institute

This research proposes a convolutional autoencoder for anomaly detection in melt pool images for laser powder bed fusion (L-PBF). Generally, image-based anomaly detection requires image filters that are manually engineered, and thus may require a large amount of engineering time. With autoencoders however, manually pre-selected features or laborious labelling of a large dataset are not required, as this machine-learning approach enables the unsupervised dimensionality reduction of high-speed melt pool images. Moreover, the distribution of lower-dimensional encoded image values forms clusters within the lower-dimensional feature space. Thus, anomaly detection can be performed by evaluating the encoded values of a newly acquired image with respect to existing clusters in data. The proposed algorithm is validated using experimental data from an instrumented L-PBF testbed, demonstrating capabilities of detecting process and sensor anomalies such as powder spattering or overheating.

9:30 AM

Automated Anomaly Detection of Laser-based Additive Manufacturing Using Melt Pool Sparse Representation and Unsupervised Learning: Xiyue Zhao[1]; Aidin Imandoust[2]; Mojtaba Khanzadeh[3]; *Farhad Imani*[1]; Linkan Bian[4]; [1]University of Connecticut; [2]University of North Texas; [3]Amazon.com; [4]Mississippi State University

Advanced thermal imaging is increasingly invested in additive manufacturing (AM) to improve the information visibility of meltpool and cope with process inconsistency. However, there are key challenges regarding the feasibility of current data-driven monitoring methodologies. First, high-resolution thermal images consist of millions of pixels captured by hundreds of frames, thereby leading to the curse of dimensionality in analysis. Second, generated data lack labels, which is a stumbling block in training data-driven models. The objective of this research is to advance the frontier of meltpool monitoring in metal AM by designing an automated and unsupervised anomaly detection on high-dimensional thermal data. We develop a deep variational autoencoder to generate a low-dimensional representation and reconstruction error of each input thermal image data. A novel Gaussian mixture model is integrated with the generative model to split latent space into homogenous regions and detect information of anomalies.

9:45 AM
In-situ Detection and Prediction of Porosity in Laser Powder Bed Fusion Using Dual-wavelength Pyrometry: *Ziyad Smoqi*[1]; Aniruddha Gaikwad[1]; Benjamin Bevans[1]; Md Humaun Kobir[1]; Alex Riensche[1]; James Craig[2]; Alan Abul-Haj[3]; Alonso Peralta-Duran[4]; Prahalada Rao[1]; [1]University of Nebraska-Lincoln; [2]Stratonics, Inc.; [3]ARA Engineering; [4]Honeywell

Flaws, such as porosity and voids in the parts processed using laser powder bed fusion (LPBF) have a deleterious effect on mechanical properties. Accordingly, the objective of this research is the in-situ monitoring and detection of porosity formation in LPBF. To realize this objective, we use meltpool temperature and shape profiles captured using a dual-wavelength imaging pyrometer (Stratonics, ThermaViz). A cuboid-shaped part (10 mm × 10 mm × 137 mm, material ATI 718Plus alloy) was built under ten conditions of laser power (120 – 370 W) and scanning speeds (800 – 3780 mm/s). The part porosity was assessed offline using X-ray computed tomography. The porosity variation was correlated with the meltpool shape, temperature, and spatter characteristics obtained from the pyrometer using a variety of machine learning approaches. Results of prediction show that the level (severity) of porosity can be predicted with an accuracy exceeding 90% (statistical F-score).

Special Session: Dimensional and Surface Characterization for Additive Manufacturing I

Wednesday AM August 4, 2021

Session Chair: J. Gockel, Colorado School of Mines

8:00 AM
Geometrical Deviations in Additive Manufacturing – Influences on the Manufacturing Accuracy: *Tobias Lieneke*[1]; Stefan Lammers[1]; Detmar Zimmer[1]; [1]Paderborn University / Direct Manufacturing Research Center

The advantages of Additive Manufacturing (AM) highlight the capability to become an inherent part within the product development process. However, AM-inherent challenges harm the industrial establishment, for instance the high geometrical deviations. Different process factors influence the manufacturing accuracy and lead to large dimension, form and location deviations. Published deviations are also difficult to compare, because they are based on several specimens that were manufactured with different processes, materials and machine settings. This fact emphasizes that reliable tolerances for AM are hard to define in standards. Within this investigation, a universally applicable method was developed to examine geometrical deviations for AM processes. The main aim of this method is the derivation of achievable tolerance values considering important influencing factors. Furthermore, due to the locally varying surface roughness of additively manufactured parts, several tactile and optical measurements were compared in order to select a suitable measurement method.

8:15 AM
Empirical and Simulated X-Ray Computed Tomography Probability of Detection Analysis for Additive Manufacturing and Calibrated Defect Artifact Development: *Felix Kim*[1]; Adam Pintar[1]; John Henry Scott[1]; Nikolai Klimov[1]; Sarah Robinson[1]; [1]National Institute of Standards and Technology

X-ray computed tomography (XCT) is an emerging industrial non-destructive testing (NDT) technique for additive manufacturing (AM). It shows great promise, in part because it is less susceptible to the complex part geometry and rough surfaces of AM parts that are problematic for other NDT techniques. The reliability of an NDT inspection process can be assessed by a probability of detection (POD) study, and the practice is expected to enable wider adoption of industrial XCT inspection. An empirical POD curve was estimated using calibrated artifacts and a statistical model incorporating reference measurement uncertainty. Empirical determination of a POD curve, however, can be costly in both time and money, which limit the number of practically-viable XCT measurements. For instance, it is not practical to study the effect of defect locations for wide ranges of defect sizes empirically with limited artifacts and measurements. In this presentation, the complete XCT simulation process will be discussed, and the empirical and simulated data will be compared. We explore the possibilities of incorporating simulated defect conditions that were not evaluated in the experiments to estimate a more comprehensive POD curve and using the simulation results to improve defect artifact designs. Finally, based on this study, we are developing improved calibrated defect artifacts using deterministic nanofabrication approaches, and the progress will be discussed.

8:30 AM
An Investigation on the Definition and Qualification of Form on Lattice Structures: *Maxwell Praniewicz*[1]; Jason Fox[2]; Christopher Saldana[1]; [1]Georgia Institute of Technology; [2]National Institute of Standards and Technology

The lack of uniform qualification techniques for additively manufactured components throughout industry currently limits their application in high risk applications. This stems from a shortage of proper tolerancing and product definition to convey design intent and required qualification. This definition is particularly difficult for complex lattice geometries. The results of studies in which the form of a lattice component is defined by theoretical supplemental surfaces are summarized, with specific attention to the role of data sampling in the evaluation of form. A new case study is presented where techniques borrowed from surface metrology, namely the construction of a bearing area curve, are used to evaluate the sampling cutoff for form evaluation. This method is first validated on the nominal geometry of three lattice designs. The flatness of two different faces of an AM lattice component are then evaluated using this technique. Initial results indicate this as a promising methodology.

8:45 AM
Effective Registration of Engineered Lattice Geometry: A Comparative Study of Measurement Methodologies: *Scott Jensen*[1]; Elliott Jost[1]; Benjamin White[1]; Anthony Garland[1]; David Moore[1]; David Saiz[1]; Brad Boyce[1]; Bradley Jared[1]; [1]Sandia National Laboratory

While engineered lattices are becoming easier and more common place to fabricate, inspection remains demanding and ambiguous. Each lattice can easily contain hundreds of struts, each of which may exhibit sagging, variations in diameter, variations in profile, crack-like surfaces, fused powder and inconsistent melting. In this study we fabricated over 40 stainless steel 316L FCC lattices using a range of laser power and scan speeds to generate a wide range of process effects during laser powder bed fusion. Each lattice was measured using calipers, optical microscopy and computed tomography (CT) and analyzed using various methods. Physical and optical registration of external struts were compared to both internal and external as captured using CT. The labor requirements for developing and implementing different analytic techniques was then compared to the quality of the metric each produced.SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

9:00 AM
Surface Improvement of Additively Manufactured Polypropylene Parts: K. Rybalcenko[1]; *Luis Folgar*[2]; G. Ioannides[1]; M. Haefele[3]; S. Josupeit[3]; M. Cabrera[1]; [1]Additive Manufacturing Technologies Ltd; [2]Additive Manufacturing Technologies Inc; [3]BASF 3D Printing Solutions GmbH

A study was done to analyze the vapor smoothing impact on Additively Manufactured Polypropylene (PP) components via PostPro® vapor smoothing process by AMT. The testing included surface properties, mechanical properties, and dimensional variation. Polypropylene is a common and versatile polymer used for a variety of applications in automotive, aerospace, medical, and consumer industries. However, surface post-processing is required for PP parts to be fully functional. The results of this study confirmed the excellent compatibility and enhanced results of Additively Manufactured Ultrasint® PP grades, producing high performance parts that can be used in a wide variety of applications.

Special Session: Hybrid AM Processes II - Process Planning and Characterization

Wednesday AM August 4, 2021

Session Chair: J. Lavin, Sandia National Laboratories

8:00 AM

Abrasive Flow Machining of Additively Manufactured Titanium: Thin Walls and Internal Channels: *Sagar Jalui*[1]; Todd Spurgeon[1]; Erik Jacobs[1]; Arnab Chatterjee[1]; Timothy Stecko[1]; Guhaprasanna Manogharan[1]; [1]The Pennsylvania State University

Metal additive manufacturing using Laser-Powder Bed Fusion (L-PBF) technique has enabled the metal manufacturing industry to use design tools with increased flexibility such as freeform internal channel geometries that benefit thermofluidic applications such as heat exchangers. A primary drawback of the L-PBF process is the as-built surface roughness, which is a critical factor in such surface-fluidic applications. In addition, complex internal channel geometries cannot be post-processed through traditional finishing and polishing methods, and require advanced finishing processes such as Abrasive Flow Machining (AFM). In this original study, the effects of AM design including geometrical changes at the inlets, internal channel and wall thickness of thin features are experimentally studied on Ti64 L-PBF parts. A novel surface roughness inspection technique using micro-CT data is also presented. A detailed statistical analysis is provided to better understand the relationship between AM design, AFM processing and final surface finish.

8:15 AM

Mapping Energy Consumption during Milling of Interlayer Ultrasonic Peened 316 Stainless Steel: *Kossi Avegnon*[1]; Md Rasel Uddin[1]; Preston Noll[1]; Robert Williams[1]; Michael Sealy[1]; [1]University of Nebraska-Lincoln

The energy consumed during milling has the potential to give insights on material properties without necessarily destroying the part. Previous research has focused on the development of empirical models to predict the energy consumption and its correlation with process parameters. However, little has been done to investigate the variation of energy consumption during the machining of secondary treated layers compared to as-printed layers. In this study, we use net cutting specific energy as a metric to gauge the energy consumed during the milling of interlayer peened 316 stainless steel samples. Energy consumption is mapped from the edge to the middle of each layer and from the top to the bottom of the build height. The results indicate a variation in energy consumed per layer through the built volume for the various samples.

8:30 AM

Ultrasonic Characterization of Frequency Dependence from Interlayer Milling and Peening 316 Stainless Steel during Additive Manufacturing: *Jazmin Ley*[1]; Cody Pratt[1]; Tony Wilson[1]; Luz Sotelo[1]; Michael Sealy[1]; Joseph Turner[1]; [1]University of Nebraska-Lincoln

Hybrid additive manufacturing enables functionally graded materials by using secondary processes and energy sources to alter specified locations throughout a build. These secondary processes and energy sources create microstructural changes, such as reducing local grain size average, increasing dislocation density, as well as imparting/relieving residual stresses. These changes in properties are not confined to the layer applied but can have possible compounding effects on previous layers. The ability to control the material properties within a localized region of a part provides significant advantages in part design and performance but presents unique challenges in the nondestructive evaluation (NDE) of such parts. In this work, 316 low carbon stainless steel samples were created using laser powder bed fusion (LPBF) with varying hybrid surface treatments and architectures. Ultrasonic responses, i.e., wave speed and backscatter measurements, were used to investigate the frequency dependence on the ability to detect interlayer spacing in hybrid-AM parts.

8:45 AM

Progress on Residual Stress Measurement (RSM) in Hybrid Additive Manufacturing: *Gurucharan Madireddy*[1]; Mark Wagner[1]; Jordan Michalek[1]; Michael Sealy[1]; [1]University of Nebraska-Lincoln

Interlayer surface treatments in additive manufacturing induces complex cumulative residual stresses. Hole drilling is a well-defined method to measure residual stress; however, the standard algorithms do not accurately convert complex heterogeneous strains into stresses. Thus, a new algorithm specific for hybrid additive manufacturing is needed to quantify changes from interlayer surface treatments. In this research, the experimental data required to develop an algorithm was generated by manufacturing coupon samples with various hybrid-AM processes. The coupon samples were manufactured using AlSi10Mg and 316 SS materials on powder bed fusion machine with interlayer surface treatments, such as ultrasonic peening and laser peening. The residual strains in the materials were captured by hole drilling through a strain gage and the stresses were compared to as-printed coupons. It was observed that the changes in the strains are dependent on the raster pattern of the surface treatments.

9:00 AM

Automated Process Planning for a 5-axis Hybrid Manufacturing System: *Xinyi Xiao*[1]; Sanjay Joshi[2]; Peter Coutts[2]; Edward Reutzel[2]; [1]Miami University of Ohio; [2]Penn State

Hybrid Manufacturing (HM) combining Additive Manufacturing (AM) and Subtractive Manufacturing (SM) technologies have recently been introduced and have the potential to address the shortcomings of AM, such as subsequent post-processing to improve poor surface finish and the removal of support structures. Combining these processes allows for the creation of complex geometries that are not possible with standard 5-axis machining alone. However, process planning for HM is a reasonably complex manual task and could benefit from automation. Critical steps in process planning include the decomposition of a part into additive and subtractive features, sequencing all features, and assigning toolpaths to these features. This presentation presents algorithms for decomposing the part and sequencing the additive and subtractive features in an automated manner, paving the way for a fully automated system for HM. Examples of a wide range of parts demonstrating the capability of the algorithm will be presented.

9:15 AM

Collision-free Solution for Multi-axis Hybrid Additive Manufacturing: *Xinyi Xiao*[1]; [1]Miami University

A hybrid additive manufacturing (HAM) integrates a multi-axis additive and subtractive process to gain befits from both processes. However, the current HAM process heavily relies on manual geometric reasoning to identify the additive and subtractive features in a non-collision manner. An input model to HAM has diverse information contents and data format, which hinders the feature recognition, extraction, and relations. Thus, the common use of a HAM is hindered by the lack of fully automated tools. Our proposed method integrates the collision-avoidance condition to the model decomposition step; thus, the decomposed volumes can then be associated with additional constraints, such as accessibility, connectivity, and toolpath planning to create an entire workspace for the HAM process ultimately. This approach classifies the uniqueness of automating the HAM system to build large and complex metal components that are non-achievable through traditional single AM/SM in automation and computational efficiency.

9:30 AM
New Robotic Work-cell for Hybrid Large-scale Metals Additive and Subtractive Manufacturing: *Joshua Penney*[1]; William Hamel[1]; Tony Schmitz[1]; Bradley Jared[1]; Aaron Cornelius[1]; Leah Jacobs[1]; Michael Buckley[1]; Jake Dvorak[1]; Ethan Vals[1]; Greg Corson[1]; Eduardo Miramontes[1]; [1]University of Tennessee

As large-scale metal additive manufacturing processes continue to improve in resolution, part material properties, and overall geometric tolerance, more industries desire to use these processes in a full production role, rather than a purely prototyping role. Since large-scale additive manufacturing, particularly using robotic Wire Arc Additive Manufacturing (WAAM) processes, produce near-net shape parts, it is necessary to perform finishing machining processes to meet production level tolerances. It is possible to fully print a part, remove it from the robotic WAAM system, transport it to a traditional machining center, and machine away the excess material, but this introduces issues with locating the part in the coordinate frame of the machining center and knowing how much material to remove. In this paper, a new hybrid work cell is proposed that integrates robotic WAAM, traditional machining, as well as geometric analysis of the printed part.

9:45 AM
Hybrid Laser Powder Bed Fusion of Aluminum Alloy Radio Frequency Resonators: *Alexander Riensche*[1]; Paul Carriere[2]; Ziyad Smoqi[1]; Andrew Menendez[1]; Pedro Frigola[2]; Nanda Gopal Matavalam[2]; Prahalada Rao[1]; [1]University of Nebraska-Lincoln; [2]Radiabeam

Radio frequency (RF) components are intricate, high-value components. Conventional manufacturing of RF components imposes two bottlenecks: cumbersome assembly of multiple parts that are produced with different processes, and lack of flexibility to rapidly customize design for targeting specific RF bandwidths. Laser powder bed fusion (LPBF) is an attractive solution to make RF components given its ability to accommodate design complexity and dimensional accuracy. However, a main impediment in LPBF is its poor surface finish. In this work, we apply a hybrid LPBF approach for making aluminum alloy RF resonators. The key idea is to use in-situ layer-wise machining to enable high quality finish on hard-to-access surfaces which are difficult, if not impossible, to machine or polish post-LPBF. Hybrid LPBF is shown to improve resonator RF performance (Q-factor) by enhancing both dimensional accuracy and surface finish.

10:00 AM
The Role of Interface in Additively Manufactured Interpenetrating Composites: *Jason Allen*[1]; Jiahao Cheng[1]; Xiaohua Hu[1]; Derek Splitter[1]; Maxim Gussev[1]; Amit Shyam[1]; [1]Oak Ridge National Laboratory

Additively Manufactured Interpenetrating Composites (AMIPCs) are a relatively new metal-metal chain composite in development for use in high energy absorption systems. The reinforcing phase is comprised of 316L austenitic stainless-steel that is additively manufactured in continuous lattice configurations while the matrix phase is comprised of A356 aluminum-silicon casting alloy which is cast into the reinforcing phase. Measurements and observations have shown that weakly bonded or open/porous interface between the reinforcement and matrix phases exhibits dramatically different mechanical properties of AMIPCs, which is not currently well understood. In this work, Finite Element Models (FEM) are used to model interface bonding between the composite phases. Mechanical tensile tests measurements of various composite volume fractions and varying degrees of casting infiltration are also examined and used to show consistency with the FEM results. The outcome provides insight into material design criteria and performance predictions for new hybrid material systems with exceptional damage tolerance.

Applications: Biomedical

Wednesday PM August 4, 2021

Session Chair: J. Obielodan, University of Wisconsin-Platteville

1:30 PM
Fabrication of Stretchable Sensors for Biomedical Applications: *Srikanthan Ramesh*[1]; Zhiheng Xu[1]; Jakob Hamilton[1]; Chaitanya Mahajan[1]; Scott Williams[1]; Denis Cormier[1]; Iris Rivero[1]; [1]Rochester Institute of Technology

Stretchable, biocompatible sensors play a vital role in quantitatively monitoring biological signals from human skin but remain difficult to produce at scale. A host of medical needs, from sensing physiological vitals to monitoring wound healing, can be accomplished using these sensors. Although recent studies have utilized photolithography and etching for sensor production, direct ink writing is a promising method for simplifying the fabrication process. Herein, we present a scalable approach that uses metal nanoparticle inks to write on biocompatible, elastic fibers made of polycaprolactone. A photonic sintering approach is then used to sinter the deposited nanoparticle ink to complete the fabrication of the flexible sensor. Nanoparticle concentration, substrate thickness, and sintering parameters are optimized to provide ideal conductivity and sensitivity to small strains. Conductivity performance of fabricated sensors alludes direct writing approach may be suitable for the large-scale production of sensors for biomedical applications.

1:45 PM
In-situ Sensing of Construct Quality in Biological Additive Manufacturing: *Sam Gerdes*[1]; Srikanthan Ramesh[2]; Prahalad Rao[1]; Azadeh Mostafavi[3]; Iris Rivero[2]; Ali Tamayol[3]; [1]University of Nebraska; [2]RIT; [3]University of Connecticut

Biological additive manufacturing (Bio-AM) has received attention as a potential means of biocompatible scaffold formation. This technology holds promise, but its study is primarily focused on material development, scaffold design, and printability analysis. While these are vital assessments, researching solely those aspects leaves the process itself as a "black box" where the inputs and outputs are known, but how the printing process affects the scaffold is unknown. Due to this deficiency of in-process knowledge, the printing process lacks repeatability. Further, without active in-situ monitoring, parts can only be determined as good or bad after the conclusion of the print, potentially wasting valuable time and resources on defective products. Therefore, it is our goal to gather in-process knowledge of one form of Bio-AM, extrusion-based Bio-AM, through the incorporation of a heterogenous sensing system to assess various indicators of scaffold quality.

2:00 PM
3D Bioprinting of Cell-laden Scaffolds for Skin Substitutes: *Fateme Fayyazbakhsh*[1]; Michelle Amato[1]; Michael Khayat[1]; Delbert Day[1]; Yue-Wern Huang[1]; Ming Leu[1]; [1]Missouri University of Science and Technology

Third-degree burns are hard-to-heal wounds and skin grafts as the gold standard for burn treatment are limited by shortage in donor site, graft rejection, and disease transmittance. In this research, we fabricated cell-laden scaffolds with human primary fibroblasts, gelatin, and alginate. We adopted the extrusion-based 3D printing technology as a minimally-invasive method for bioprinting. Different mixtures of hydrogels and cells are printed and cultured in complete culture media, maintained in a 5% CO2 incubator at 37□C for up to 14 days. To evaluate the effect of 3D printing process and bioink composition on cell viability, Live/Dead assay is used, followed by confocal microscopy. The structural integrity of scaffolds is investigated by measuring the rheological behavior, tensile strength, and shape fidelity. The results showed that the scaffolds support 3D cell culture for up to 14 days, which indicates the high potential of the bioprinted scaffolds for third-degree burn treatment.

2:15 PM

Biomass-dependent Mechanical Properties of 3D-printed PLA/Organosolv Lignin Composites: *John Obielodan*[1]; Tyler Tinkey[1]; Kyle Brown[1]; Peter Leonhardt[1]; David Knabe[1]; [1]University of Wisconsin-Platteville

The potentials of plant and wood biomass resources as viable alternatives to petroleum-derived polymers for the fabrication of engineering parts has been an active research focus. Herein we present the results of work showing the dependency of mechanical properties of 3D printed PLA/organosolv lignin biocomposites on lignin biomass resource. Organosolv lignin samples derived from both hardwood and softwood were respectively incorporated into PLA matrices and used for printing test samples using fused filament fabrication process. Significantly higher tensile strengths were obtained up to 100% for the hardwood-based material over the softwood for compositions up to 40wt% lignin, although with a trade-off on ductility. Also, room temperature aging of the hardwood-based material led to increase in mechanical properties that was not observed in the other material. The study highlights the competitiveness of the mechanical properties of 3D printed biocomposites based on informed choice of biomass resource and possible post processing aging.

2:30 PM

Finite Element Modeling of Failure Modes during 3D Printed Polymeric Bioresorbable Vascular Scaffold Crimping: *Caralyn Collins*[1]; Cheng Sun[1]; Henry Ware[1]; Yonghui Ding[1]; Huifeng Wang[1]; Guillermo Ameer[1]; [1]Northwestern University

Endovascular therapy using metal stents has been widely established to restore blood flow through blocked arteries. However, the permanent presence of the stents has resulted in high restenosis rates. Utilizing digital light processing-based stereolithography for fabrication, polymeric bioresorbable vascular scaffolds (BVSs) have emerged as a potential solution to these problems. Polymeric BVSs offer potential advantages by providing initial support to prevent recoil and slowly degrading to restore vasomotion and eliminate residual foreign materials. This transition brings new challenges corresponding to the drastically different material characteristics of metals and polymers. In particular, this study focuses on the crimping process for loading the BVS into a catheter prior to clinical deployment. We developed a numerical model to simulate the crimping process of 3D printed BVSs using experimentally measured bulk material properties in ABAQUS. We quantitatively evaluate potential failure modes for the candidate BVS design, which provides insight for further design optimization.

2:45 PM

Rotational Digital Light Processing for Edible Scaffold Fabrication: *Alexis Garrett*[1]; Arian Jaberi[1]; Auston Viotto[1]; Ali Tamayol[2]; Ruiguo Yang[1]; Ajay Malshe[3]; Michael Sealy[1]; [1]University of Nebraska-Lincoln; [2]University of Connecticut; [3]Purdue University

A key hurdle to overcome in the development of alternative meat-based protein is the manipulation of mechanical or mastic properties of the 3D scaffolds. These properties influence the mouth feel of the product and must be tunable to achieve a variety of meat analogous textures. The goal of this research is to develop an enabling printing technology to achieve texture in alternative proteins. In pursuit of this goal, a novel digital light processing (DLP) printer with a rotational collector plate was developed to enable radially cured layers with the ability to incorporate multi-material composite structures. The purpose of this research was to quantify the effect of cured layer orientation on the bulk mechanical properties of GelMA scaffolds. In addition, current photocrosslinking systems do not emphasize the edibility of the materials used in the process. Tartrazine, an edible photo-absorber, was investigated for improving print resolution during the crosslinking process.

3:00 PM

Accelerated Corrosion Behavior of Additive Manufactured WE43 Magnesium Alloy: *Rakeshkumar Karunakaran*[1]; Sam Ortgies[1]; Ryan Green[1]; William Barelman[1]; Ian Kobler[1]; Michael Sealy[1]; [1]University of Nebraska-Lincoln

Magnesium alloys are capable of withstanding high temperatures and pressures needed in oil and gas fracking operations followed by rapid and complete dissolution in days. Dissolvable magnesium plugs are used in fracking to enable longer lateral wellbores by eliminating mill outs and associated debris clogging. To increase extraction efficiency, the key technical challenge is determining how to increase the strength of a high corrosion rate magnesium device that enables higher pressures while maintaining high corrosion rates. Topologically modified dissolvable plugs fabricated by additive manufacturing is proposed as a solution to fabricate high strength and high corrosion rate fracture plugs. Corrosion of magnesium is dependent on surface area exposed to corrosive media and is easily manipulated by additive manufacturing. This study highlights the development of optimal powder bed fusion process parameters for WE43 magnesium alloy and investigates the corrosion behavior of printed WE43 in a salt solution concentrated with sodium bicarbonate to initiate highly accelerated corrosion. Printed WE43 corroded three times faster than an as-rolled sample and was driven by the mechanical and materials properties formed by printing.

3:15 PM

Aerosol Jet® Printing of 3D Micropillars Using Multiple Materials: *Miriam Seiti*[1]; Olivier Degryse[1]; Rory Gibney[1]; Eleonora Ferraris[1]; [1]KU Leuven

Aerosol Jet® printing (AJ®P) is a printing technique that deposits a functional ink (viscosity range: 1-1000 mPas), as a focused aerosol flow, on flat/curved, rigid/flexible substrates. Applications are mostly related to printed electronics, and recently AJ®P has revealed promises in depositing biological materials and surface structuring. The potential of AJ®P as a 3D printing technique for high aspect ratio structures has instead received limited exploitation. By tailoring the ink properties and composition, and by modulating the platen temperature (ambient-200°C), the evaporation of the ink solvent(s) during the process can be controlled to produce novel 3D microstructures. In this work, 3D micropillars using a silver nanoparticle, a poly(3,4-ethylenedioxythiophene)polystyrene sulfonate (PEDOT:PSS) and a collagen-based ink are printed at various aspect ratios and resolutions. The effect of inks composition, print strategies and shape control are discussed. These 3D microstructures can potentially be used for thermoelectric devices, biological interfaces, sensors, micro-pin arrays, etc.

3:30 PM

Post-processing of Additively Manufactured Covid-19 Nasopharyngeal Swabs at Scale: *Konstantin Rybalcenko*[1]; L. Folgar[2]; G. Ioannides[1]; R. Charlesworth[1]; J.G. Crabtree[3]; [1]Additive Manufacturing Technologies Ltd; [2]Additive Manufacturing Technologies Inc; [3]Additive Manufacturing Technologies Kft

A methodology to post-process oral/respiratory Additively Manufactured medical components at scale is presented. The system involves PostPro3D® smoothing machine, picking/racking module and is used to smooth the surfaces of Covid-19 Nasopharyngeal Swabs. Due to the Covid-19 pandemic there has been a surge in demand for specialized medical articles, particularly in Nasopharyngeal Swabs. Widescale population testing for Covid-19 has been put in place by many countries, with testing expected to continue in the foreseeable future. The presented process for large scale post-processing of Additively Manufactured articles has undergone all necessary medical verifications and has been already deployed in the field.

Applications: General IV

Wednesday PM August 4, 2021

Session Chair: M. Frank, Iowa State University

1:30 PM

Development of a Method to Derive Design Guidelines for Production-suitable Support Structures in Metal Laser Powder Bed Fusion: *Stefan Lammers*[1]; Tobias Lieneke[1]; Detmar Zimmer[1]; [1]Paderborn University

Solid support structures in metal laser powder bed fusion have a decisive influence on the economic applicability, component quality and process stability and represent a central challenge for widespread industrial use. As the connection of the components to the building platform by supports is essential, the negative effects must be minimized at the same time as the supporting effect is optimized. Within the scope of this study, a standardized method is developed that allows the investigation of several support structures and parameters with regard to their influence on the target variables: component quality, process efficiency and safety. In addition to the proof of general suitability, the applicability is investigated using so-called standard elements. Based on the experimental results, design guidelines are derived, which will serve as a basis for decision-making during the selection of support structure for individual application.

1:45 PM

Design of FDM Mesostructure for Thermoplastic Materials Under Manufacturability Constraints: *Albert Patterson*[1]; Charul Chadha[1]; Iwona Jasiuk[1]; James Allison[1]; [1]University of Illinois at Urbana-Champaign

Fused deposition modeling (FDM) is an extrusion-based additive manufacturing (AM) process, depositing material (typically thermoplastic) as uniform elements. The resulting structure is a tight (or controlled density) lattice of approximately isotropic meso-scale regions with 3-D macro-scale anisotropy; this structure can be designed to produce an easily manufacturable structured when subject to the proper manufacturability constraints. The present study explores various design strategies for laying out the material elements. After the conceptual development and discussion, two case studies will be provided to further demonstrate the concepts. This work will provide a baseline for future studies on AM-driven meso-scale design using other scanning-type AM processes (such as SLA, SLS, and SLM/DMLS) for polymer, metal, and composite materials.

2:00 PM

Conformal Cooling: An Analysis of Additive Cooling Channels: *Luke Meyer*[1]; Steven Patrick[1]; William Carter[1]; Andrzej Nycz[1]; Mark Noakes[1]; [1]Oak Ridge National Laboratory

Additively manufactured tools have gained interest for their ability to construct embedded cooling channels within a workpiece, conforming to critical surfaces with minimal post-machining. In applications such as hot stamping, cooling channels are a necessity to prevent the tool from overheating and to reduce overall cycle time. The channels traditionally entail straight-boring channels in a complex network, which takes a significant amount of planning, time to machine, and creates a very expensive tool, all while the channels may not be able to adequately cool the tooling surface. Through the use of flow analyses, thermal modeling, and collected data, a selection of stainless-steel additively manufactured tools with conformal cooling channels will be compared to a similar traditionally manufactured stainless-steel tool with straight-bored cooling channels.

2:15 PM

Design and Hybrid Additive Manufacturing for Electronic Components that Can Withstand Shock Loading: *Connor Gunsbury*[1]; Desiderio Kovar[1]; Carolyn Seepersad[1]; Michael Gammage[2]; [1]University of Texas at Austin; [2]Army Research Laboratory

Direct-write and aerosol deposition processes are well suited for additively manufacturing high value custom electronics in low quantities. These electronics may require shielding from shock loading. Bistable negative stiffness elements (NSEs) that are produced by direct metal laser sintering (DMLS) have been shown to be effective in mitigating shock loading. In this work, we explore a hybrid manufacturing approach utilizing aerosol deposition (AD) to write electronic components onto NSEs. In NSEs, concentric curved beam structures dissipate mechanical energy through elastic buckling, and "snap through" at a force threshold that is dependent on beam geometry and material properties, which reduces transmitted acceleration by orders of magnitude. Using AD, tin dioxide and silver films are deposited onto an ABS substrate to form a resistive circuit. The circuit is mounted to a bistable NSE to create a component that can withstand an extremely high-G mechanical shock.

2:30 PM

Multimaterial AM-aware Design of Asymmetric Acoustic Absorbers: *Tyler Wiest*[1]; Andrew Lawrence[1]; Michael Haberman[1]; Carolyn Seepersad[1]; [1]University of Texas at Austin

Materials that absorb sound waves asymmetrically have long been desired for a variety of acoustic applications. A material that exhibits asymmetric absorption of acoustic fields dissipates energy of an incident sound wave differently depending on the propagation direction. Using architected materials with multiple dissimilar materials is the most promising way to achieve this behavior. Multimaterial additive manufacturing (MM AM) processes have enabled fabrication of metamaterials with a greater variety of options for material and geometry. We design materials displaying asymmetric absorption such that they can be reliably manufactured using currently available MM AM processes while displaying performance that exceeds currently available material performance. Attainment of these prospective material combinations motivates specifications for a new MM AM process. We propose requirements for a build process that deposits high viscosity liquid with suspended heavy particles within a material matrix and seals them to form multi-material inclusions.

2:45 PM

Pushing the Limits of Printed RF: Advancing Towards Free-form Antennas, Waveguides, and Interconnects for X-band Applications: *Katherine Berry*[1]; Samuel Fedorka[2]; Bradley Pothier[2]; Eric Brown[2]; Craig Armiento[2]; Alkim Akyurtlu[2]; Gary Walsh[3]; Corey Shemelya[2]; [1]UMass Lowell; [2]University of Massachusetts Lowell; [3]U.S. Army Combat Capabilities Development Command Soldier Center

Advanced manufacturing techniques for electromagnetic applications have advanced by leaps and bounds with recent advances in printing techniques. As such, there has been a push to produce flexible, freeform RF components at higher and higher frequencies. This project evaluates the printing constraints of antenna, waveguide, and component interconnects in the X-band (8-12 GHz) using direct-write micro-dispensing. Specifically, we investigate three printed waveguide feed designs: grounded coplanar, microstrip, and single layer coplanar. Each waveguide is evaluated with a printed receiving antenna, filter, and interconnects to a chip-based power amplifier. All results are assessed for geometric accuracy, surface/interfacial properties, DC/RF conductivity, and RF performance. The printed results are compared to simulations and duel clad laminate PCB boards to assess the process parameters and explore overall system integration. This work describes the fundamental printing properties required for X-band printed antenna systems, and requirements to move RF printed electronics into full, conformal geometries.

Materials: Metals IX - AlSi10Mg

Wednesday PM August 4, 2021

Session Chair: S. Khairallah, Lawrence Livermore National Laboratory

1:30 PM

Investigation Towards AlSi10Mg Powder Recycling Behavior in the LPBF Process and Its Influences on Mechanical Properties: *Christian Weiss*[1]; Juri Munk[1]; Constantin Haefner[1]; [1]Fraunhofer Institute for Laser Technology (ILT)

Parts fabricated by Laser Powder Bed Fusion (LPBF) technique allow for a high material utilization of a single powder batch, since unfused powder material can be reworked and reused in subsequent manufacturing jobs. Due to process induced spatters however, the properties of the powder may change during recycling, which in turn can affect the mechanical properties of built parts. Therefore, more investigations on the recyclability of the powder material are needed. Within this work, the powder ageing behavior of the lightweight aluminum alloy AlSi10Mg in the LPBF process is investigated. A standard build job is developed and built with ageing powder in 10 consecutive jobs with no refreshing between the cycles. The powder properties as well as the mechanical properties at static load for standing and lying samples are investigated. The comprehensive analyses suggest that the powder coarsening may lead to improved mechanical properties during recycling for AlSi10Mg.

1:45 PM

Evaluation of Early Fatigue Damage Detection in Additively Manufactured AlSi10Mg: *Susheel Dharmadhikari*[1]; Amrita Basak[1]; [1]Pennsylvania State University

This paper presents two different methods for fatigue damage detection in notched AlSi10Mg specimens fabricated on a ProX-320 laser powder bed fusion equipment using recycled AlSi10Mg powders. The fatigue damage evolution is monitored using two heterogeneous sensors, namely, the force-displacement sensor and a confocal microscope. The force-displacement sensor captures the global stress-strain behavior of the specimens; however, it provides no information about the local damage near the notch. The force-displacement data, which shows a hysteresis-like behavior, is calibrated using a confocal microscope focused inside the notch of the specimen so that the onset of fatigue crack initiation can be detected at a crack opening displacement (COD) of ~10 micron. Using the force-displacement signal data, the energy dissipation rate and the material stiffness per cycle are computed. The results show a detection accuracy of 100% and 99.14% for the energy dissipation rate and material stiffness per cycle, respectively.

2:00 PM

Increasing Productivity in Laser Powder Bed Fusion Additive Manufacturing of AlSi10Mg: Aidan Tomlin[1]; Mark Mugavero[1]; Brittany Urwin[1]; Andrew Frost[1]; Justen Schaefer[2]; *Joy Gockel*[1]; [1]Wright State University; [2]University of Dayton Research Institute

A process development concern in additive manufacturing is the ability to increase the productivity while maintaining a low level of defects. This work investigated processing parameters to balance print speed and porosity for laser powder bed fusion of AlSi10Mg. The processing parameters that influence the build speed are the laser speed, hatch spacing and layer thickness. Single bead analytical modeling and experiments were used to determine the influence of processing parameters (laser power and speed) on melt pool size, predict lack-of-fusion porosity, and guide component experiments. Design of experiments was used to investigate the effect of additional processing parameters (laser speed, hatch spacing, and layer thickness) on porosity. With the goal of decreasing build time, layer thicknesses of 80, 100, and 120 µm were used. The increased layer thickness, balanced with speed and hatch spacing, yields a significant increase in build speed from typical AlSi10Mg processing parameters.

2:15 PM

Influence of Process Conditions on the Thermal Conductivity of Selective Laser Melted AlSi10Mg: *Arad Azizi*[1]; Jacob Goodman[1]; Fatemeh Hejripour[1]; Piyush Kulkarni[1]; Scott Schiffres[1]; [1]Binghamton University

AlSi10Mg alloy is commonly used in selective laser melting (SLM) due to its printability, relatively high thermal conductivity, low density and good mechanical properties. Thermal properties of AlSi10Mg are important to heat transfer applications including additively manufactured heatsinks, cold plates, vapor chambers and heat pipes. The thermal conductivity of samples fabricated in different orientations and energy densities will be discussed. The bulk thermal conductivity measurements were made via flash diffusivity, and local measurements were made with frequency domain thermoreflectance (FDTR). The properties are linked to the microstructural changes that occur in selective laser melted AlSi10Mg versus processing conditions.

2:30 PM

Powder Bed Fusion Additive Manufacturing of Curved-surface AlSi10Mg Parts: Surface Finish, Geometrical Deviation, and Microstructure: *Yue Zhou*[1]; Fuda Ning[1]; [1]Binghamton University

Powder bed fusion (PBF) additive manufacturing has been widely used for producing high-performance AlSi10Mg alloy parts with complex geometries, such as lattice structures, curved surfaces, etc. In this paper, we investigated the effects of curvature on the surface finish, geometrical deviation, and microstructures of the PBF-built AlSi10Mg sample with a sinusoidal curved surface. Specifically, profile surface roughness Ra and surface texture attributes Sa, Spc, Sk, Vmc were used to represent the surface finish. In addition, a three-dimensional point cloud was generated to characterize the geomatical deviations. Meanwhile, the as-built parts exhibited the primary a-Al phase and eutectic Al/Si phase, and the grain cell size and morphology changed with the varied curvatures. Herein, the smallest grain with more equiaxed morphology could be observed at the curvature C3 due to the largest nucleation density. The curvature-geometrical performance-microstructure relationship of the PBF-built AlSi10Mg parts with curved surface was systematically uncovered in this paper.

Materials: Metals VIII - Nickel Alloys

Wednesday PM August 4, 2021

Session Chair: E. Kinzel, Univ. of Notre Dame

1:30 PM

Energy Density Effect on the Keyhole and Lack of Fusion Porosity during Laser Powder Bed Fusion Process: *Subin Shrestha*[1]; Kevin Chou[1]; [1]University of Louisville

During the laser powder bed fusion (LPBF) process, keyhole pores or lack of fusion pores may form depending on the energy density used to fabricate the part. In this study, different levels of energy density are used to study the pores formed within the 2.5 mm × 2.5 mm × 1 mm Inconel 625 specimen. Micro-CT is used to characterize and measure the pores, and the results show that the keyhole porosity increases with an increase in energy density within the keyhole regime. In contrast, a lack of fusion porosity increased with a decrease in energy density. Besides, metallography is performed to observe the melt profile and the pores. The keyhole pores are a result of deep penetration melting and form within the track. In contrast, the lack of fusion pores formed between the tracks, due to incomplete melting of the tracks, or improper overlap between the scan tracks.

1:45 PM

Effects of Build Orientation and Heat Treatment on Neutron Irradiation Hardening in Inconel 625 Fabricated via Laser Powder Bed Fusion: *Mohanish Andurkar*[1]; Valentina O'Donnell[2]; Jan Lieben[3]; Tahmina Keya[3]; Greyson Harvill[3]; Scott Thompson[1]; John Gahl[2]; Bart Prorok[3]; [1]Kansas State University; [2]University of Missouri; [3]Auburn University

Various Inconel 625 coupons fabricated via Laser Powder Bed Fusion (L-PBF) were neutron irradiated using the inside reflector of the reactor at the University of Missouri Research Reactor (MURR). Effects of build orientation and heat treatment on neutron-induced hardening were investigated by inspecting L-PBF samples built vertically or at a 45º angle in the following heat-treated conditions: as-built (no heat treatment), 700 ºC for 1 hour, 900 ºC for 1 hour, and 1050 ºC for 1 hour. The microhardness results of L-PBF samples before and after neutron irradiation were compared with traditional wrought Inconel 625. All samples underwent an irradiation flux of 6.61 x 10^13 neutrons/cm²/s for 310 hours for an estimated damage of 0.012 dpa. Results indicate that as built L-PBF specimens are less prone to radiation hardening relative to their wrought counterparts. As-printed diagonal specimens were shown to harden by 8% as compared to 1.2% hardening in as-printed vertical specimens.

2:00 PM

Effects of Heat Treatment and Fast Neutron Irradiation on the Microstructure and Microhardness of Inconel 625 Fabricated via Laser-Powder Bed Fusion: *Tahmina Keya*[1]; Valentina O'Donnell[2]; Jan Lieben[1]; Ashley Romans[1]; Greyson Harvill[1]; Mohanish Andurkar[3]; John Gahl[2]; Scott Thompson[3]; Bart Prorok[1]; [1]Auburn University; [2]University of Missouri; [3]Kansas State University

The microstructure of Inconel 625 fabricated via Laser-Powder Bed Fusion (L-PBF) was investigated in as-printed and heat-treated conditions. The very high cooling rates inherent to the L-PBF process generally result in fine microstructures and complex residual stress fields which requires annealing to reduce stress and tailor the microstructure to obtain the desired mechanical properties. Inconel 625 alloy, a nickel-based superalloy, continues to be a common material employed with the L-PBF process. The unique microstructure produced by the L-PBF process and different phases introduced by different heat treatment processes require investigation to facilitate the material's wide range of applications. This paper investigates the influence of heat treatments at 700°C, 900°C and 1050°C for one hour on the microstructure and microhardness of the L-PBF parts. The parts were irradiated using 'fast' neutrons in University of Missouri Research Reactor Center (MURR). The microhardness before and after radiation are also compared.

2:15 PM

Residual Stress Measurements via X-ray Diffraction Cos-α Method on Various Heat-Treated Inconel 625 Specimens Fabricated via Laser-Powder Bed Fusion: *Mohanish Andurkar*[1]; Toshikazu Suzuki[2]; Masanao Omori[2]; Bart Prorok[3]; John Gahl[4]; Scott Thompson[1]; [1]Kansas State University; [2]Pulstec Industrial Co.; [3]Auburn University; [4]University of Missouri

The microstructure and residual stress of Inconel 625 fabricated using Laser Powder Bed Fusion (L-PBF) were experimentally investigated. As-built Inconel 625 samples were subjected to three different heat-treatment temperatures of 700°C, 900°C, 1050°C for one hour. Effects of these three-stress relieving heat treatment temperatures on nature and value of residual stress were studied. Residual stress measurements were recorded using a portable X-ray system. The system calculated residual stress using the cos a method. The Full Width Half Maximum (FWHM) of diffraction peaks in all samples were measured. The results indicate that tensile residual stress was present on the surface of as-built L-PBF sample and compressive residual stress on the surface of heat-treated samples compressive residual stresses after stress relief heat treatment. Vickers microhardness and residual stress of all samples were plotted together to understand their interrelationship and trend after each heat-treatment temperature.

2:30 PM

Additively Manufactured Haynes 230 by Laser Powder Direct Energy Deposition (LP-DED): Effect of Heat Treatments on Microstructure and Tensile Properties: *Muztahid Muhammad*[1]; Reza Ghiaasiaan[1]; Paul Gradl[2]; Shuai Shao[1]; Nima Shamsaei[1]; [1]Auburn University; [2]NASA Marshall Space Flight Center

The microstructure and tensile mechanical properties of Haynes 230 fabricated through laser powder directed energy deposition (LP-DED) were investigated, varying temperature heat treatments between 900°C to 1177°C following deposition. Scanning electron microscopy (SEM) was employed for microstructural analysis, whilst tensile testing was utilized to evaluate the room temperature mechanical properties of the alloy. In an as-deposited state, the initial microstructure consisted of cellular γ and M6C/M23C6 carbides. The cellular regions seem to be fully dissolved upon solutionizing at 1177°C for 3 hours. Following post-deposition heat-treatments, the carbides were observed to precipitate and grow along the grain boundaries as well as in the interior of grains. Solutionizing at 1177°C for 3 hours following stress-relieving yielded better ductility and had an insignificant effect on the strength.

2:45 PM

Microstructure Pore-stress Interactions and Their Influence on Scatter in AM Fatigue Life Data: *Luke Sheridan*[1]; Joy Gockel[2]; Onome Scott-Emuakpor[1]; [1]Air Force Research Laboratory; [2]Wright State University

It has been shown that defect and microstructure features can dictate the fatigue performance of AM components. The actual relationships between defects, microstructure, applied stress, and fatigue life, however, are not fully understood. Therefore, an investigation was performed to examine fatigue performance of AM alloy 718 components of three different processing pedigrees which helped solidify the dependence of fatigue life on defect content and microstructure. Failure defect size, microstructure size and the applied stress were noted, and these values were related to the total life of the part. It was shown that pores behave differently under different applied stresses, and that microstructure size has a direct correlation to the growth life of the component. Using the data collected here, a method for identifying critical pore sizes for AM inspection efforts was developed, and methods for rapid characterization of fatigue properties were introduced which facilitates AM material qualification and modeling efforts.

3:00 PM

Microhardness and Mechanical Properties in Additively Manufactured Inconel 718: *Cherish Lesko*[1]; Luke Sheridan[2]; Joy Gockel[1]; [1]Wright State University; [2]Air Force Research Laboratory

Mechanical properties can be linked to various material features including porosity, surface roughness, defects, microstructure and precipitation of undesirable phases which are demonstratively different between additively manufactured (AM) and wrought alloys. Vicker's Hardness (HV) testing can be correlated with various mechanical properties. In this work, the relationship between HV and process parameters is explored for nickel-based superalloy 718 (IN 718). The HV observations were made across a large design space of process parameters and relationships are determined using fundamental design of experiments (DOE) methods. Additionally, HV measurements were taken spatially across the samples and compared to determine within sample variation. Materials characterization methods were used to observe microstructure changes for correlation with HV data and the relationship of HV to mechanical properties is discussed. The results from this work can be used to guide the optimization of process parameters for improved mechanical properties in AM.

3:15 PM
Powder Reuse Effects on the Tensile Behavior of Additively Manufactured Inconel 718 Parts: *Arash Soltani-Tehrani*[1]; Nima Shamsaei[1]; Karthik Adapa[1]; Jaikp Mallory[1]; Ramesh Ramakrishnan[2]; [1]Auburn University; [2]Delta Air Lines

Inconel 718 (IN718), with a wide range of applications in aerospace industries and good weldability, is a popular powder feedstock in the laser beam powder bed fusion (LB-PBF) additive manufacturing (AM) process. Due to fabrication, handling, and storage costs, powder feedstock is commonly reused several times. Therefore, it is important to understand how the mechanical properties of LB-PBF parts can be affected by powder reuse given that powder characteristics may change after repeated recycling. This study aims to investigate the effect of powder reuse on the tensile properties of LB-PBF IN718 parts. Powder characteristics such as cohesion and compressibility will be quantified in order to shed light on the variations observed in the part performances. In addition, by correlating the state of the reused powder with tensile properties, the most critical metrics for quality aspects in powder reuse will be determined.

Materials: Polymers III - Powder Bed Fusion and Direct Write

Wednesday PM August 4, 2021

Session Chair: D. Smith, Baylor Univ

1:30 PM
Flowability Measurements of Different SLS Materials at Elevated Temperatures with a Modified Schulze Ring Shear Tester: *Moritz Rüther*[1]; Dietmar Schulze[2]; Hans-Joachim Schmid[1]; [1]University of Paderborn; [2]Ostfalia University of Applied Sciences

To process new materials on SLS equipment, knowledge about the flowability of the powders is essential. An established method for measuring the flowability of bulk materials is the Schulze Ring Shear Tester. However, it is problematic that in SLS 3D printers the material is applied at elevated temperatures, but so far measurements with the Ring Shear Tester under near-process conditions have not been possible. For this reason, parts of a commercial Schulze Ring Shear Tester (type RS-XS.s) were modified to enable reliable flowability measurements at elevated temperatures. The tasks of these modifications were to keep the temperature in the sample constant during a measurement and to prevent heat dissipation into the housing so that damage to the electronics could be excluded. With this modified ring shear tester, the flowability of various SLS materials was measured for different temperatures and the results will be presented.

1:45 PM
Low Temperature Laser Sintering on a Standard System: First Attempts and Results with PA12: *Dennis Menge*[1]; Hans-Joachim Schmid[1]; [1]Paderborn University

The laser-sintering process has been a very established AM process for many years. Disadvantages of LS are the low material variety and the thermal damage of the not processed material. The low temperature laser sintering attacks at this point and processes powder material at a build chamber temperature lower than the recrystallization temperature. This drastic reduction in temperature results in significantly less thermal damage to the material. This work deals with the low temperature laser sintering of Polyamide 12 (PA12) on a commercial, unmodified laser sintering system to compare it to standardly laser sintered PA12 and to create the basis for low temperature laser sintering of high temperature materials on such a system. First results by changing the exposure parameters and by fixing parts on a building platform show a processing of PA12 on an EOS P396 at a build chamber temperature less than 100 °C instead of standard approx. 175 °C.

2:00 PM
The Influence of Grain Size Distribution of PA12 on Key Steps of the Polymer Laser Sintering Process: *Jens Sesseg*[1]; Paul Riedmann[1]; Sybille Fischer[1]; Hans-Joachim Schmid[2]; [1]EOS GmbH; [2]Paderborn University

As the industry pushes for higher resolution laser sintering, finer and finer powders are required. Yet, this changes the way powders behave during the process. The influence of finer particles on the dosing and coating process during laser sintering is being investigated in this project. PA12 laser sintering powder without flow additives was sieved to four fractions with grain sizes D50 of 42, 54, 61 and 66 µm. These fractions were characterized regarding powder flowability by FT4 powder rheometer. The dosing and coating behavior of these fractions was tested at both RT and at 168°C in separate experiments on an EOS P395 on which also test jobs were built with the fractions. The larger portion of fines in the finest fraction dominated the powder properties and led to significantly different powder behavior during the dosing and coating steps, as predicted by analytical measurements.

2:15 PM
A Control of Surface Quality in Selective Laser Sintering Additive Manufacturing with Reclaimed Polyamide Materials: *Feifei Yang*[1]; Tianyu Jiang[1]; Xu Chen[1]; Greg Lalier[2]; John Bartolone[2]; [1]University of Washington; [2]Unilever Research & Development

In selective laser sintering (SLS) additive manufacturing (AM), a substantial amount of polyamide 12 materials remains un-sintered, recyclable, and reusable. However, using reclaimed polyamide 12 powder in SLS results in undesirable part surface finish. Very limited research has been done on the improvement of part surface quality and results barely exist on improving or modifying the surface quality of parts using extremely aged powders (powders held close to the heat-affected zones). Aiming to improve the surface quality, we propose a novel approach for SLS with (extremely) aged polyamide 12 powders. By combining material preparation, powder and part characterizations, and SLS with a customized method of post-heating, we obtain parts with improved surface quality (e.g., reduced roughness and porosities, and eliminated un-sintered particles). Particularly, parts 3D-printed using the 30%-30%-40% new-aged-extremely aged mixed powders exhibit the smoothest and flattest surface with no unmolten particles and nearly zero porosity.

2:30 PM
Microstructure and Mechanical Properties in Polymer Powder Bed Fusion Processes: *Clinton Abbott*[1]; Nathan Crane[1]; [1]Brigham Young University

Laser Powder Bed Fusion (L-PBF) and Multi-Jet Fusion (MJF) are two prevalent processes in the field of Powder Bed Fusion Additive Manufacturing (PBFAM). Large Area Projection Sintering (LAPS) is a recent addition to PBFAM capable of producing parts with higher densities and better mechanical properties than possible with either L-PBF or MJF. This paper compares the tensile properties and microstructure of Nylon (PA12) parts produced using L-PBF, MJF, and LAPS methods. High density of LAPS parts did not guarantee better mechanical properties. Improved strain of LAPS parts is linked to maintaining higher temperatures in the part during printing followed by fast cooling, resulting in smaller crystallite sizes.

2:45 PM
Investigation into Laser Sintering of PEEK Using Commercially Available Low Powder Bed Temperature Machine: *Takashi Kigure*[1]; Yuki Yamauchi[1]; Toshiki Niino[2]; [1]Tokyo Metropolitan Industrial Technology Research Institute; [2]Institute of Industrial Science, The University of Tokyo

Polyetheretherketone (PEEK) is one of the highest-performance plastics in terms of heat and chemical resistance and mechanical strength. Laser sintering of PEEK requires high powder bed temperature above 300°C, and this pushes up machine price and pulls down powder recycle rate which leads to high material cost. The authors are proposing a modified laser sintering process which allows the bed temperature to be set lower than recrystallization temperature, namely low temperature process. In the previous work, laser sintering of PEEK at a bed temperature of 200°C have been successfully performed. In the present research, a bed temperature of 170°C, which is typical for PA12 process, was tested, and parts with a high relative density of more than 90% were obtained. This result shows that laser sintering of PEEK can be processed with a commercially available laser sintering machine resulting in drastic cost cut in terms of machine and material costs.

3:00 PM
Printability Assessment of Cellulose-Based Polymer Structures Using Direct Ink Writing: Zachary Hoopes[1]; Michael Karschner[1]; Jocelynn Kelly[1]; William Miney[1]; Zoubeida Ounaies[1]; *Amrita Basak*[1]; [1]Pennsylvania State University

In this paper, we demonstrate the preparation and printing of ethyl cellulose, a cellulose derivative, using a custom-modified direct ink writing (DIW) printer. Ethyl cellulose is widely used as a thin-film coating in controlled-release vitamins and medical pills as well as a thickener in the food, cosmetics, and other industries. It is therefore an attractive bio-mass derived polymer for 3D printing. Two types of ethyl cellulose, with different molecular weights (Mw), are dissolved in alpha-terpinol solvent to assess the feasibility of printing the polymer. In total, thirteen different slurries are prepared at different solid weight percent, stir time, stir temperature, and resting time. The results show that 10 wt. % ethyl cellulose slurry performs best for the initial printability assessment; following printing, this slurry holds its shape, and shows uniform thickness in rectangular and snake patterns.

3:15 PM
Effects of Fiber Length Evolution in Carbon Fiber-reinforced Epoxy Composites for Direct Ink Writing: *Nadim Hmeidat*[1]; Daniel Elkins[2]; Hutchison Peter[2]; Vipin Kumar[3]; Brett Compton[1]; [1]University of Tennessee, Knoxville; [2]Virginia Tech; [3]Oak Ridge National Laboratory (ORNL)

Fiber-reinforced polymer composites have been extensively utilized as feedstock materials for material extrusion additive manufacturing (AM) to improve the strength, stiffness, and functionality of printed parts. However, sparse attention has been devoted to investigating the effects of feedstock formulation and processing parameters on the evolution of fiber length distribution (FLD) and mechanical properties of the 3D-printed composites. This talk focuses on the use of short carbon fiber-reinforced epoxy composites as ink feedstocks for direct ink writing (DIW) to investigate the evolution of FLD during ink processing. Relationships between fiber content, mixing time, FLD, ink rheology and printing behavior, and mechanical properties of the resulting printed composites will be highlighted. Furthermore, the effects of print parameters—print speed and nozzle size—on the mechanical anisotropy and fiber orientation distribution (FOD) in the printed composites will be discussed. Implications for the development of better fiber-filled inks for AM will also be discussed.

Physical Modeling: VII Material Modeling B

Wednesday PM August 4, 2021

Session Chair: J. Allen, Oak Ridge National Laboratory

1:30 PM
Influence of Oxygen Content on Melt Pool Dynamics in Powder Bed Fusion Processes: *Hou Yi Chia*[1]; Wentao Yan[1]; [1]National University of Singapore

In the powder bed fusion process, exposure to oxygen and its incorporation into the melt pool is inevitable. Although oxygen exposure is conventionally recognized as a source of problems, recent experiments show otherwise, where the deliberate oxidation or introduction of oxygen actually improves the process and part quality. Hence, the influence of oxygen on the powder bed fusion process warrants further investigation. Yet, in-situ observation of the oxygen incorporation and its influence on melt pool dynamics is experimentally inexpedient, while oxygen-related effects in numerical models remain lacking. Thus, this work aims to shed light on the effect of oxygen content on melt pool dynamics through the use of thermal-fluid flow simulations. Our simulations have captured the oxygen absorption mechanism during melt pool formation and reveal its influence on the Marangoni effect and the subsequent oxygen distribution in the melt pool. The qualitative results obtained agree with experimental observations.

1:45 PM
Particle Segregation by Size during Powder Spreading Process of Powder Bed Based Additive Manufacturing: *Hui Chen*[1]; Wentao Yan[1]; [1]National University of Singapore

Numerical simulations based on discrete element method are performed to study the scraping-type powder spreading process of additive manufacturing for powder particles normally distributed from 5 to 65 µm. It is found that, in the collecting stage of powder spreading, fine particles gather in the bottom zone of the powder pile, while coarse particles trend to move upwards in the powder pile. Due to the particle segregation by size in the collecting stage, the powder layer will not be uniformly paved on the substrate. The particles paved on the substrate become coarser and coarser along the spreading direction. The potential approach to eliminate the particle segregation by size is replacing the scraping-type powder spreading by a discharging-type powder spreading.

2:00 PM
A Method of Predicting Powder Flowability for SLS: *Doug Sassaman*[1]; Tim Phillips[1]; Joseph Beaman[1]; Matthew Ide[2]; Craig Milroy[3]; [1]University of Texas Austin; [2]Exxon Mobil Research and Development; [3]TRI Austin

In this work, we propose a method for pre-screening material systems for Selective Laser Sintering (SLS) using a combination of Revolution Powder Analysis (RPA) and machine learning. To develop this method, nylon was mixed with alumina or carbon fibers in different wt.% to form material systems with varying flowability. The materials were measured in a custom RPA device and the results compared with powder bed density measured by spreading a layer of powder into a pocket of known volume using a counter-rotating roller. Machine learning was used to draw correlations between the RPA data and powder bed density, allowing RPA to pre-screen low volumes of material and determine their suitability for SLS. The result is a material-agnostic method to predict if a powder will spread to adequate density in a SLS machine using a counter-rotating roller.

2:15 PM
Modeling Light Scattering Vat Photopolymerization Resins with Monte Carlo Ray Tracing: *Keyton Feller*[1]; Viswanath Meenakshisundaram[1]; Timothy Long[1]; Robert Mahan[1]; Christopher Williams[1]; [1]Virginia Tech

Vat photopolymerization (VP) of suspension resins exhibit lower resolution compared to their homogenous counterparts due to the filler particles redistributing light intensity through scattering. In order to predict curing and improve printed resolution of these resins, the authors have demonstrated a Monte Carlo ray-tracing simulation to model the scattering behavior. Using inputs of material optical constants, projected intensity distribution, and medium working curve constants resultant cure profiles can be predicted. Simulated cure profiles were validated by VP printing of a custom photocurable styrene-butadiene latex (SBR) resin with a mean particle radius of 70 nm. Cure profiles of SBR loadings from 5 vol% to 30 vol% were simulated and produced cure depths within 50 µm of experimental values. Utilization of this simulation enables reasonably accurate estimations to aid in resin formulation and provides the basis for future work in bitmap correction to increase print resolutions.

2:30 PM
Multi-physics & Multi-materials Modeling of Steel/Inconel Functionally Gradient Material Fabricated with Laser-based Directed Energy Deposition: *Wei Li*[1]; [1]The University of Texas at Dallas

Fabricating metallic Functionally Gradient Materials (FGMs) with Directed Energy Deposition (DED) process has been studied extensively in recent years. Most of studies are focused on experimental observation and material characterization. These experimental study procedures are very time-consuming and costly. Some modeling studies tried to use Finite Element Method simulating FGMs building process, but the modeling study's complexity and accuracy are far from adequate. The goal of this research is to fill the above gaps by establishing a novel multi-physics & multi-material thermal fluid model to fundamentally investigate the building process of FGMs with DED. Temporal and spatial thermal distribution, phase change, fluid dynamics in molten pool, material distribution, and FGM geometry were calculated with high fidelity. As a demonstration, a DED fabrication process for Stainless Steel/Inconel FGM structure was simulated with this novel modeling tool. After that, simulation results were validated with experimental observation data, including material composition and FGM geometry.

2:45 PM
Cellular Automata Modeling of Layer-wise Microstructure Convergence as Functions of Material and Processing Variables: *Matthew Rolchigo*[1]; Robert Carson[2]; Gerald Knapp[1]; John Coleman[1]; James Belak[1]; [1]Oak Ridge National Laboratory; [2]Lawrence Livermore National Laboratory

Microstructures produced via alloy-based Additive processes typically exhibit highly textured columnar grain structures resulting from epitaxial growth of substrate grains. As the first several layers of a microstructure will depend strongly on the substrate and greatly differ from the majority of a build's microstructure, it is necessary for the calculation of constitutive properties to simulate microstructures representative of the "steady-state" grain structures that make up the majority of real parts. We employ the OpenFOAM computational fluid dynamics software with cellular automata (CA) modeling to better understand this evolution of grain structure with the number of deposited layers. Results will focus on microstructure convergence as functions of substrate (texture and grain size), processing (scan pattern), and material (interfacial response and nucleation). *Work performed under auspices of the U.S. DOE by LLNL under contract DE-AC52-07NA27344 and Oak Ridge National Laboratory under U.S. Government Contract DE-AC05-00OR22725, and supported by ECP (17-SC-20-SC), a collaborative effort of U.S. DOE Office of Science and NNSA.

Process Development: VII In-situ Monitoring

Wednesday PM August 4, 2021

Session Chair: J. Newkirk, Missouri University of Science and Technology

1:30 PM
Powder Spread Process Monitoring in Polymer Laser Sintering and Its Influences on Part Properties: *Helge Klippstein*[1]; Florian Heiny[1]; Nagaraju Pashikanti[1]; Monika Gessler[2]; Hans-Joachim Schmid[1]; [1]Paderborn University; [2]EOS GmbH Electro Optical Systems

Confidence in additive manufacturing technologies is directly related to the predictability of part properties, which is influenced by several factors. To gain confidence, online process monitoring with dedicated and reliable feedback is desirable for every process. In this project, a powder bed monitoring system was developed as a retrofit solution for the EOS P3 laser sintering machines. A high-resolution camera records each layer, which is analyzed by a Region Based Convolutional Neural Network (Mask R-CNN). Over 2500 images were annotated and classified to train the network in detecting defects in the powder bed at a very high level. Each defect is checked for intersection with exposure areas. To distinguish between acceptable imperfections and critical defects that lead to part rejection, the impact of these imperfections on part properties is investigated.

1:45 PM
In-situ Detection of Laser Powder Bed Fusion Process Signatures Based on Sensor Fusion Approach: *Ivan Zhirnov*[1]; Dean-Paul Kouprianoff[2]; Mikael Åsberg[1]; Pavel Krakhmalev[1]; [1]Karlstad University; [2]Central University of Technology

A large amount of process monitoring data can currently be produced for the laser powder bed fusion process. There are more than 50 parameters that have an impact on the build quality, which cause a large number of process signatures. The accuracy of machine learning depends on the diversity of the data rather than on the quantity. In this research, different types of sensors are used to investigate the in-situ formation of cracks and delamination. Specific digital representation of crack formation was found and compared for different materials. This paper describes a multi-sensor setup and current results relating to the process signature of single tracks and layers for different LPBF machines. The proposed approach will be used in preparation for well-characterized labelled data for machine learning quality prediction.

2:00 PM
Design and Implementation of Laser Powder Bed Fusion Additive Manufacturing Testbed Control Software: Ho Yeung[1]; *Keely Hutchinson*[2]; Dong Lin[2]; [1]National Institute of Standards and Technology; [2]Kansas State University

The National Institute of Standards and Technology (NIST) developed a facility titled the Additive Manufacturing Metrology Testbed. The testbed provides an open control architecture as well as a plethora of sensor systems for advanced research into the laser powder bed fusion additive manufacturing processes. This paper reviews the testbed control software design and implementation. Scan path planning, galvo motion control, and laser power control are detailed with select highlights that may be relevant to additive manufacturing researchers and system developers. Comparison with the commercial machine control software is made, recent experiments utilized the advanced features of the testbed control software are also discussed.

2:15 PM
Image Registration and Matching Error in 2D and 3D for Laser Powder Bed Fusion: *Andrew Lang*[1]; Cesar Ortiz Rios[2]; Joseph Newkirk[2]; Robert Landers[2]; James Castle[1]; Douglas Bristow[2]; [1]The Boeing Company; [2]Missouri University of Science and Technology

This work outlines a method to register 2D and 3D images taken post-process and in situ from 301L stainless steel parts printed by Laser Powder Bed Fusion. The process uses DREAM.3D, an open source software that provides for data transport in a non-proprietary format. The Robust Automatic Threshold selection technique is used to create a boundary point cloud of the part from each image. The Iterative Closest Point technique is applied to the point clouds for both 2D images and 3D image stacks to create an affine transformation matrix for registration. Multiple 2D SEM images of the same sampled layer are taken under different settings and imaging conditions and registered to a common target. Images from post-process X-ray Computed Tomography and an in situ short-wave infrared camera create 3D image stacks, which are directly registered in 3D space. Registration accuracy is validated by creating a correspondence list of the closest point in the registered point clouds and the matching error is calculated using mean average error. Mean average error is computed using point-to-point and point-to-plane methods; the point-to-plane method is shown to be more reliable. Finally, the registered 3D images are down sampled to the lower resolution image dimensions and fused to the nearest point to create an array containing corresponding in situ and post-process data.

2:30 PM
Investigations on Optical Emissions and Their Relation to Processing Parameters and Processing Regimes in the Laser Powder Bed Fusion Process: *Christopher Stutzman*[1]; Abdalla Nassar[1]; [1]Penn State University

Additive manufacturing (AM) is a rapidly growing field where complex components are produced without complex tooling. While the desire to move into new defect critical industries exists, it is important to understand that AM processes can, and often do, create flaws within the component. Therefore, it is important to monitor the process to determine when flaws are formed. Here we study the plume fluctuations that occur during the deposition of nickel alloy 625 via a custom-built, off-axis multi-spectral sensor during a laser powder bed fusion process. We show that spectral emission lines from the vapor plume relate to processing parameters used during deposition and can be used to enable sensor-based process map development. We conclude by proposing a novel calibration technique which will permit the correction of intensity variations thus enabling analysis on the fly. Expected applications of the work include real-time sensing and control of PBFAM build conditions.

2:45 PM
Optical Emission Sensing for Laser-based Additive Manufacturing – What Are We Actually Measuring?: *Christopher Stutzman*[1]; Abdalla Nassar[1]; Wesley Mitchell[1]; [1]Penn State University

Additive manufacturing is a rapidly growing industry in which complex components can be produced directly from a CAD file. While this process can easily produce complex components, the propensity for defect formation is not small. Therefore it is important to develop sensing procedures to ensure that quality components are produced. Traditionally, melt pool imaging has been a source of significant interest due to the assumption that one could measure the temperature and geometry of the melt pool directly to understand the process. Unfortunately, the co-axial or meltpool camera data is not always interpreted correctly. Here, we show that under certain conditions, melt pool measurements produced from a coaxial camera do not accurately represent the melt pool. Further, by using an off-axis camera filtered to observe excited titanium plume emissions, we show that the excited vapor plume above the melt pool significantly obscures measurements, particularly at high energy.

Special Session: Data Analytics in AM IV - Process Monitoring and Flaw Detection B

Wednesday PM August 4, 2021

Session Chair: B. Jared, Sandia National Laboratories

1:30 PM
Microstructure and Tensile Test Data Alignment for Additive Manufacturing Data Registration: *Shaw Feng*[1]; Albert Jones[1]; Yan Lu[1]; [1]National Institute of Standards and Technology

Microstructural and tensile test data are becoming increasingly available and important in additive manufacturing (AM). These data can be used as inputs to a variety of data-analytics tools, which have capabilities to control the AM process and ensure the part quality. Microstructure data can be used to predict properties, and tensile test data can be used to identify fractures and stress-strain relationships. A major impediment to using these two types of data is that they are in two different local coordinate systems. To establish the required, material-process-property relationships, these data must be aligned with build data that include melt pool and X-ray Computed Tomography (XCT) data that are also in separate local coordinate systems. This paper proposes a procedure to correlate local coordinate systems and relate microstructure and tensile test data to other types of data. Data registration, i.e., data correlation and organization, is also included in the paper.

1:45 PM
Powder Features Affecting Structural and Mechanical Properties of Additively Manufactured Inconel 718: A Machine Learning Analysis: *Mohammad Shahadath Hossain*[1]; Daniel Silva[1]; Aleksandr Vinel[1]; Jia Liu[1]; Nima Shamsaei[1]; [1]Auburn University

The aim of this paper is to select important Inconel 718 powder properties that can have significant effect on the structural and mechanical properties of Laser-Beam Powder Bed Fusion manufactured specimens. The dataset used was provided by NASA and contains powder rheological, morphological, and chemical composition properties. The output variables considered are melt pool depth, high cycle fatigue life, porosity volume fraction and porosity size. Initially, Pearson correlation coefficient matrix is used to reduce the number of predictor features. Several statistical and machine learning algorithms including stepwise regression, LASSO, and random forest regression are used to identify the powder properties that have the strongest impact on the selected outputs. The variables identified using the different statistical and machine learning techniques are similar, which increases the confidence of the findings.

2:00 PM
Automated Detection of Part Quality during Two Photon Lithography via Deep Learning: Brian Giera[1]; *Xian Lee*[2]; Sourabh Saha[3]; Soumik Sarkar[2]; [1]Lawrence Livermore National Laboratory; [2]Iowa State University; [3]Georgia Tech

Two photon lithography (TPL) requires exhaustive parameter optimization process to identify a suitable light dosage that sufficiently cures a photo-reactive polymer. This involves experts analyzing routinely-collected video of every part. This laborious process limits the adoption of TPL as an industrial-scale additive manufacturing technology. Here, we solve this critical issue via deep learning, leveraging TPL video to train algorithms that automatically predict part quality at 95% accuracy in milliseconds. We demonstrate a general procedure to curate labeled TPL video data set that we publicly released. We implement and evaluate several deep learning model architectures and find we can reliably classify both the state of photo-polymerization and overall part quality, eliminating the need for human oversight during the parameter optimization step. Furthermore, these algorithms can be used for real-time part quality monitoring.This work was performed under the auspices of the U.S. Department of Energy by LLNL under Contract DE-AC52-07NA27344.

2:15 PM
Heterogenous Sensing and Scientific Machine Learning for In-process Anomaly Detection in Laser Powder Bed Fusion – A Single-track Study: *Aniruddha Gaikwad*[1]; Brian Giera[2]; Ibo Matthews[2]; Prahalad Rao[1]; [1]University of Nebraska; [2]Lawrence Livermore National Laboratory

The objective is to predict the build quality of a track of fused material as a function of process signatures derived from a pyrometer and high-speed optical video camera integrated into a laser powder bed fusion additive manufacturing system. The central hypothesis of this work is that the accuracy of anomaly prediction improves significantly when machine learning models incorporate process signatures that are based on fundamental knowledge of the process regime, as opposed to purely data-driven machine learning algorithms, such as deep learning convolutional neural networks. To test the efficacy of such a scientific machine learning hypothesis over 1000 single tracks (stainless steel 316L) of length 5 mm were fused under 121 different laser power and laser velocity combinations. During the process of fusing the single tracks, meltpool-level signatures were acquired using an in-situ pyrometer and high-speed optical video camera located coaxial to the laser.

2:30 PM
Predictive Control of Porosity in Laser Powder Bed Fusion: *Paromita Nath*[1]; Sankaran Mahadevan[1]; [1]Vanderbilt University

This work presents a Bayesian methodology for layer-by-layer quality control of an additively manufactured part by integrating a physics-based simulation model with monitoring data acquired from advanced sensors, diagnosis of existing porosity, prediction of porosity in future layers, and adjustment of process parameters. From the data collected by online monitoring of the process after every layer, the porosity in the current (partially finished) part is diagnosed, and the porosity in the final part is estimated, both using a predictive model. A finite element based thermal model is first developed to simulate the powder bed fusion process. The temperature profile obtained from the monitoring is then used with the simulation model to predict porosity in the part being manufactured. If the predicted porosity is more than the specified tolerance, the process parameters for printing the next layer such as laser power and laser speed are adjusted to control porosity.

2:45 PM
Using Deep Convolutional Neural Networks for Process Shift Detection, Root Cause Isolation and Defect Prediction in Metal Additive Process: *Subhrajit Roychowdhury*[1]; Jing Yu[2]; Naresh Iyer[1]; Xiaohu Ping[1]; [1]GE Global Research Center; [2]California Institute of Technology

The quality and yield of additively manufactured parts continue to be challenged due the lack of approaches that can robustly monitor the process to detect process shift and isolate root causes to guide appropriate corrective actions. Towards that end, we demonstrate the application of Deep Learning on down-beam camera data to capture process shifts, isolate root cause and predict defects. Specifically, we train an architecture composed of Inception-v1 modules for deep neural networks to learn to detect process shift detection and defect prediction. Our early outcomes demonstrate that an Inception-v1 based architecture trained using downbeam camera data ingested from full part-builds, and produced under varying combinations of process parameters, can detect process shift and isolate root cause between power and spot size shifts with up to 90% accuracy.

3:00 PM
Porosity Analysis of Laser Powder Bed Fusion Parts Using the Statistics of Extremes: *Mahya Shahabi*[1]; Anthony Rollett[2]; Sneha Prabha Narra[1]; [1]Worcester Polytechnic Institute; [2]Carnegie Mellon University

Quality assessment of additively manufactured parts is crucial for industrial adoption of additive manufacturing for fatigue-critical components in the aerospace sector. Current quality assessment methods for additively manufactured parts include the addition of witness specimens to the build and the use of expensive and time-consuming characterization and testing procedures. Not only the "fitness-for-purpose" remains unknown while investigating witness specimens, but also fatigue testing and 3D characterization techniques such as computed tomography are expensive and time-consuming. In this study, we propose using a sub-section of the samples to predict the largest pore size within the sample by applying statistics of extremes on cross-sectional porosity data. Results from this work demonstrate that the model precision depends on the volume of interest and the defect density. There are potential opportunities to extend this quality assessment method to both 3D porosity data and complex geometries.

3:15 PM
Layer-wise Certification for Direct Energy Deposition Processes based on Melt Pool Morphology Dynamic Analysis: Mahathir Mohammad Bappy[1]; Chenang Liu[2]; Linkan Bian[1]; *Wenmeng Tian*[1]; [1]Mississippi State University; [2]Oklahoma State University

The repeatability issue is a major barrier for wider adoption of additive manufacturing (AM) technologies in mission-critical applications. The defects will significantly compromise the mechanical properties of the fabricated parts. Therefore, there is an urgent need in reliable AM process certification. The paper proposes a new layer-wise certification method by leveraging morphology dynamics of layer-wise melt pool images. Specifically, the variability in intra-layer melt pool morphologies is formulated as the optimal transport problem, and the Wasserstein metric is used to characterize the minimum amount of work necessary to transport between two consecutive melt pools. Subsequently, multiple new layer-wise features are extracted based on those Wasserstein metrics, and supervised machine learning methods can be applied for anomaly detection. The proposed method is validated using the direct energy deposition (DED) process, which demonstrates satisfactory anomaly detection performance.

Special Session: Dimensional and Surface Characterization for Additive Manufacturing II

Wednesday PM August 4, 2021

Session Chair: H. Wang, Texas A&M University

1:30 PM
Influence of Measurement and Sampling Strategy on Analysis of Surface Finish in Laser Powder Bed Fusion Additive Manufacturing of Nickel Superalloy 625: *Jason Fox*[1]; Adam Pintar[1]; [1]National Institute of Standards and Technology

In laser powder bed fusion (LPBF) additive manufacturing (AM), parts are built through a complex process with size scales that span sub-micrometer to millimeters. This large range and complexity of the build process creates surfaces with complex topographies, large height ranges, and steep slopes when compared to machined surfaces. This causes uncertainty that a surface measurement sufficiently represents the full surface from which it was sampled. The goal of this work is to better understand the measurement and sampling strategy (e.g., point spacing, size and number of measurement regions) to aid development of measurement routines for AM parts. In this work, the height data from a large, as-built nickel superalloy 625 surface built by a commercial LPBF system was subdivided to assess variation in areal surface texture parameters across the surface. The result of this work provides an important step in developing guidance for the measurement of as-built AM surfaces.

1:45 PM
Surface Roughness Variation in Laser Powder Bed Fusion Additive Manufacturing: *Rachel Evans*[1]; Joy Gockel[2]; [1]Wright State Universtiy; [2]Wright State University

The surface roughness of an additively manufactured part produced through laser powder bed fusion has a significantly higher roughness than surfaces produced through traditional manufacturing processes. This roughness can have a significant impact on mechanical properties such as the fatigue life. Additionally, there is still a lack of understanding of the variation of the surface roughness and the appropriate metrics to represent the surface. This work presents line of sight measurements across several large surfaces with changing processing parameters and layer geometry. The measured areas are divided into regions where surface measurement metrics are calculated, and the surface variation within and across the surface is discussed. The calculated metrics and variation are related to the expected impact that the surface will have on the mechanical performance. Results from this research will provide guidance towards surface roughness metric specifications to ensure quality parts with consistent mechanical performance.

2:00 PM

Predicting Surface Geometry for Steady-state FFF Printing: Ibraheem Malik[1]; *Christopher Pannier*[1]; [1]University of Michigan - Dearborn

For fused filament fabrication, commercial slicers calculate a toolpath from a CAD model using a fixed geometry model of the extruded bead surface, causing geometrical inaccuracies in printed parts. In this work, extrusion and bead geometry models are fitted for polymer (PLA, ABS) and bound metal filament at varying extrusion speeds. The top surface of the immediately extruded lines was scanned with an in-situ laser line scanner. The collected data was fit to two common model geometries: ellipse and rounded box. The fit model and was used to predict the surface of subsequent layers with low error (0.5% RMSE) and is an improvement upon fixed geometry models.

2:15 PM

Investigations for the Optimization of Visual and Geometrical Properties of Arburg Plastic Freeforming Components: *Felix Hecker*[1]; Felix Hecker[1]; Christian Elsner[1]; Elmar Moritzer[2]; [1]Paderborn University, Direct Manufacturing Research Center (DMRC); [2]Paderborn University, Kunststofftechnik Paderborn (KTP)

Arburg Plastic Freeforming (APF) is an additive manufacturing process with which three-dimensional, thermoplastic components can be produced layer by layer. Visual and geometrical properties are a major criterion for characterizing the resulting component quality. The aim of this study was to investigate the influences on visual and geometrical properties of APF components depending on process parameters. Initially the focus was on the analysis of the shrinkage behavior of ABS-M30 (Stratasys). On the basis of the results and an existing procedure by Arburg, an optimized procedure for determining the scaling factors was developed. With this developed procedure a higher dimensional accuracy of the components can be achieved. In addition, it was investigated whether an adaption of the form-factor based on a mathematical model depending on the component geometry makes sense. The results were transferred into manufacturing guidelines, which allow the user of the APF-technology to optimize process parameters much more efficiently.

2:30 PM

Real-time Geometry Quality Management During Directed Energy Deposition Using Laser Line Scanner: *Liu Yang*[1]; Hoon Sohn[1]; Eden Binega[1]; Jack C P Cheng[2]; Ikgeun Jeon[1]; [1]Korea Advanced Institute of Science and Technology; [2]The Hong Kong University of Science and Technology

Additive manufacturing (AM) is a powerful and promising manufacturing technology due to its advantages of mass customization, transition to pre-order manufacturing, and small-quantity production of custom-designed products. However, current situation of lacking quality management in 3D printing process is the key barrier of adopting this advanced technology. Geometry inaccuracy of 3D printed components is one of the main quality problems for AM, especially when the final product requires high precision in its geometry. In this study, a real-time geometry estimation method for continuous monitoring during the direct energy deposition (DED) process was developed using a laser line scanner. Our proposed methodology comprises (1) real-time track-by-track scanning and geometry extraction of multi-layer multi-track component during printing process, (2) real-time plotting and comparison of the as-designed and as-built models, and (3) geometry control of next track to achieve geometry compliance to target geometry.

2:45 PM

Location and Orientation Dependency in Surface Roughness of Nickel Super Alloy 625 Parts: Statistical and Distributional Analysis: *Saina Abolmaali*[1]; Alexander Vinel[1]; Jason Fox[2]; Jia Liu[1]; Daniel Silva[1]; Nima Shamsaei[1]; [1]Auburn University; [2]National Institute of Standards and Technology

Surface roughness is an important characteristic of additively manufactured parts, as it can impact various mechanical properties, such as friction or fatigue life. Further, surface roughness can change significantly depending on a number of factors: part geometry, build plate location, process parameters or powder characteristics. Generally, it has been previously established that printing angle has a significant effect on surface roughness. In this study we reanalyze a dataset constructed based on Laser-Beam Powder Bed Fusion manufactured nickel super alloy 625 parts, with the goal of evaluating the effect of location and print orientation on variability of surface roughness, particularly relative to printing angle. Different combinations of location-orientation-angles factors are tested using ANOVA, with the findings significant. In addition, we further consider the question of characterizing surface roughness measures as applied to additive manufacturing and explore distributional analysis (particularly extreme value theory) as a way to qualify these measures.

3:00 PM

Locational Dependency of Additively Manufactured Parts: Effects of Surface Roughness on Fatigue Behaviors: *Seungjong Lee*[1]; Muztahid Muhammad[1]; Jingyi Zheng[1]; Shuai Shao[1]; Nima Shamsaei[1]; [1]Auburn University

Surface roughness (SR) can vary significantly when parts are fabricated at different locations on the build plate build because of the gas flow and powder recoating process in current additive manufacturing techniques. In this study, intra-build SR variation across locations was investigated for laser beam powder bed fused 316L stainless steel. The build platform was divided into 4 quadrants to assess the location-dependent variation of SR. Uniaxial stress-controlled fatigue tests were conducted using a servo-hydraulic system. The SR from the four quadrants was analyzed using One-way Analysis of Variance (ANOVA) method and further verified SR's location dependency. Linear regression analysis was also performed to correlate fatigue lives with SR values at different stress amplitudes. ANOVA analysis revealed that there are statistically significant differences in SR values across different locations. Linear regression was also successful in correlating fatigue lives with SR and stress amplitudes.

3:15 PM

Effect of Surface Texture on Deformation Behavior during Shot Peening of Electron Beam Melted (EBM) Ti-6Al-4V: *Mustafa Rifat*[1]; Saurabh Basu[1]; Edward De Meter[1]; Guha Manogharan[1]; [1]Pennsylvania State Unversity

Surface finishing of Additively Manufactured (AM) parts is important to mitigate detrimental roughness textures and induce compressive residual stress. Such finishing processes often rely on surface deformation which is complicated due to anisotropy in components resulting from AM processes. Here, a workflow based on 3D finite element methods (FEM) is presented to study these effects. The evolution of Electron Beam Melted (EBM) Ti-6Al-4V surfaces during shot peening is characterized using white light profilometry. These surface profiles are then digitally scaled to create numerical work pieces comprising rough surfaces. By using indentation as a template of unit impacts during shot peening, strain energy absorption behavior of rough surfaces resulting from EBM are analyzed using the FEM-based workflow. These insights are then used to delineate the evolution in EBM surface roughness during shot peening.

Poster Session on General AM

Tuesday PM August 3, 2021

Session Chair: E. MacDonald, University of Texas-El Paso

A Deep Learning Approach to Defect Detection in Additive Manufacturing of Titanium Alloys: *Xiao Liu*[1]; Alessandra Mileo[1]; [1]Dublin City University

In Additive Manufacturing (AM) of titanium alloys, the formation of defects in parts is typically related to the stability of the meltpool. With increased instability and size of the meltpool comes an increase in the level of emissions generated as the laser processes the material. Recent developments in in-situ monitoring and process control allows the collection of large amounts of data during the printing process. This includes data about emissions, which are made available as 2D representations in the form of colour images. However, it is still a manual process to inspect these 2D representations to identify defects, which does not scale. Given recent advances in Deep Learning for computer vision and the availability of large amounts of data collected from in-situ monitoring, our approach to leverage Deep Learning techniques to characterise abnormal emissions to automatically identify defects during the printing process.

Additive Manufacturing of Cu on 316L Stainless Steel via Inconel 718 Intermediate Layers: *Xinchang Zhang*[1]; Tan Pan[1]; Yitao Chen[1]; Frank Liou[1]; [1]Missouri University of Science & Technology

Joining of dissimilar materials is becoming increasingly prevalent to combine differing material properties to enhance product design flexibility and performance. In this study, pure copper was built on 316L stainless steel (SS316L) by laser-based additive manufacturing technology in which copper was deposited layer-by-layer on SS316L with Inconel 718 intermediate layers. The goal is to fabricate multi-metallic structures with improved thermal conductivity. The direct joining of Cu on SS316L would result in porosities at the interface and the consequent poor mechanical properties, which could be addressed by Inconel 718 intermediate layers. The microstructure, chemical composition, tensile properties, and micro-hardness were characterized in the dissimilar materials using scanning electron microscopy, energy dispersive spectroscopy, tensile test with digital image correlation technique, and hardness tester. Results confirm excellent bonding when Inconel 718 intermediate layers are introduced.

Additive Manufacturing of Two-phase Lightweight, Stiff and High Damping Carbon Fiber Reinforced Polymer Microlattices: *Zhenpeng Xu*[1]; Chan Soo Ha[2]; Xiaoyu (Rayne) Zheng[1]; [1]University of California, Los Angeles; [2]Virginia Tech

Carbon fiber reinforced polymer composite (CFRP) is known for its high stiffness-to-weight ratio and hence is of great interest in several engineering fields such as aerospace, automotive, and defense, etc. Such a composite is not suitable for energy dissipation as failure occurs with very little or no plastic deformation. Herein, we present an extendable multi-material projection microstereolithography process, capable of producing cellular materials reinforced by short fibers that achieve simultaneously high specific stiffness and damping coefficient. We designed and additively manufactured CFRP microlattices with soft phase architected into selected stiff-phase struts. Our results revealed that the damping performance can be significantly enhanced by the addition of only a small fraction of the soft phase. The design and additive manufacturing strategy allow for optimizing mutually exclusive properties. As a result, these CFRP microlattices achieved high specific stiffness per density comparable to commercial CFRP, technical ceramics and composites, while dissipative as elastomers.

Aerosol Jet® Printing on Fiber-based Paper Substrates for Smart-packaging: *Akash Verma*[1]; Eleonora Ferraris[1]; [1]KU Leuven

Smart packaging is an evolving technological area that allows for adding electronic functionalities into the packaging of a product. Elements as RFID antenna, LED printed circuits and sensors can be added and realized using Printed Electronics techniques. Aerosol Jet® Printing (AJ®P), being a direct write technique with rapid prototyping ability, is used to fabricate such printed labels. This area has not been explored with AJ®P yet. In this work, a silver nanoparticles ink was printed onto a fiber based paper substrate. The substrate was chosen to be bio-degradable, cheap and conventionally used in the packaging industry. Electrical resistances of silver tracks were measured on numerous paper substrates. The best combination was chosen based on the ink-substrate interaction and the electrical performance. RFID antenna and smart LED circuits were printed and validated to prove the ability of AJ®P as smart packaging printing technique.Keywords: smart packaging, Aerosol Jet® Printing, printed electronics

Anomaly Segmentation in Thermal Tomography Process Monitoring for Laser Powder Bed Fusion Using Texture Analysis: *Alexander Groeger*[1]; Tanvi Banerjee[1]; Joy Gockel[1]; John Middendorf[2]; Tom Spears[3]; [1]Wright State University; [2]ARCTOS; [3]OpenAdditive

Process monitoring in laser powder bed fusion automated by artificial intelligence will significantly help manufacturers save time by detecting processing anomalies and suggesting corrective actions when intolerable defects are identified. For these systems to perform analysis and draw conclusions, in-situ sensor imagery needs to be analyzed and segmented for anomalous activities within each layer. Image segmentation is performed on in-situ thermal tomography collected during an additive manufacturing build using texture analysis. This analysis uses a deep learning convolutional neural network to encode images into a low dimensional space describing combinations of textural features. This texture-feature space is visualized using dimensionality reduction to find groups that describe unique textural signatures. These groups can be labeled by field experts and compared to material characterization data, enabling the model to classify where thermal events are occurring on the build layer and identify defect locations in the fabricated material.

Tensile and Fatigue Characteristics of Miniature AlSi10Mg Specimens Fabricated Via Powder Bed Fusion: Shashank Garikipati[1]; Andrew Banks[1]; *Susheel Dharmadhikari*[1]; Amrita Basak[1]; [1]Pennsylvania State University

Laser powder bed fusion (L-PBF) offers a unique opportunity to manufacture complex components that are difficult to fabricate using traditional processes. However, due to complex thermal cycles during the layer-wise fabrication process, critical mechanical properties are expected to differ from the traditionally manufactured parts. To study this variation, this work reports the tensile and fatigue results obtained from miniature AlSi10Mg specimens tested on an in-house developed mechatronic system. During testing, the specimens are first subjected to a quasi-static tensile loading until rupture to understand the tensile properties – particularly the elastic modulus, the yield strength, and the ultimate tensile strength. The strain-controlled fatigue tests are then performed with a mean tensile strain to subject the specimens to a low cycle fatigue. The material hysteresis of the specimens is studied through the force-displacement curves at different stages during the fatigue life and estimates for total energy lost are computed.

Detecting Layerwise Build Defects Using Low-cost Imaging and Machine Learning: Bradley Jared[1]; *Devon Goodspeed*[1]; Michael Haines[1]; Shuchi Khurana[2]; [1]University of Tennessee, Knoxville; [2]Addiguru, LLC

Process monitoring is a timely and necessary topic in metal laser-powder bed fusion as interest continues to cost effectively improve part confidence and simultaneously reduce inspection and qualification cycle times. The identification of build defects will be demonstrated using low cost optical hardware retro-fitted onto a Farsoon FS271M powder bed system. The existing system captures static powder bed images during each layering step. It then utilizes customized machine learning algorithms to detect powder bed anomalies, re-coater streaking and hopping, and part swelling. After discussing the equipment and approach, its efficacy will be exhibited in 316L stainless steel using varying build artifacts intended to introduce build errors or to yield acceptable parts. The utility of the existing hardware and software in detailing excessive part deformations and internal porosity will also be explored.

Effect of Impact Angle on Deposition of LiNbO3 films by Micro-cold Spray: *Stephen Bierschenk*[1]; Michael Becker[1]; Susanne Lee[2]; Desiderio Kovar[1]; [1]The University of Texas at Austin; [2]L3Harris Technologies, Inc.

Micro-cold spray is the process of accelerating solid nanoparticles through a nozzle and impacting them at high velocity onto a substrate to deposit nanostructured films. By moving the substrate beneath the fixed nozzle, patterned films of metals and ceramics can be deposited at room temperature without a mask. Experiments conducted with direct axial impact of LiNbO3 nanoparticles result in amorphous films that are limited to thicknesses of 10 µm because the deposition efficiency decreases with film thickness. Experimentally, the radial velocity can be controlled by varying the substrate angle up to 60° from the axial position. We have performed complimentary multi-physics modeling to determine the range of impact angles and velocities that particles experience for these experiments. The effects of radial impact velocity of the nanoparticles on the resulting film deposition efficiency and film morphology will be discussed.

Impact of Porosity Type on Microstructure and Mechanical Properties in Selectively Laser Melted IN718 Lattice Structures: Samarth Ramachandra[1]; *Bharath Bhushan Ravichander*[1]; Behzad Farhang[1]; Aditya Ganesh-Ram[1]; Manjunath Hanumantha[1]; Juan Marquez[1]; Gavin Humphrey[1]; Nahid Swails[1]; Amirhesam Amerinatanzi[1]; [1]The University of Texas at Arlington

Laser Powder Bed Fusion (LPBF), one of the most employed additive manufacturing techniques for metals, has opened new dimensions in realizing strong and weight reducing structures. In this study, Inconel 718 (IN718) unit cell designs, were fabricated through the LPBF technique and analyzed. Among the plethora of lattice structures in existence, BCC, BCC-Z, FCC, FCC-Z, Gyroid, Diamond and Schwarz structures have been selected to focus on. A relationship between the mechanical properties including yield strength, failure stress and strain, and hardness with each type of unit cell was established. Also, the effect of the possible defects on the hardness value was examined using microstructural analysis on samples. Scanning Electron Microscopy (SEM) analysis was also performed to examine the possible defects and its effect on the hardness of the as-built part.

Laser Powder-bed-fusion of Tungsten Materials for Fusion Energy Applications: *Alberico Talignani*[1]; Shiqi Zheng[1]; Philips Depond[2]; Maria Strantza[2]; Jianchao Ye[2]; Yinmin (Morris) Wang[1]; [1]University of California, Los Angeles; [2]Lawrence Livermore National Laboratory

Tungsten is an important material for plasma facing component in fusion reactors. To fabricate tungsten components via additive manufacturing such as laser powder-bed-fusion has unique advantages compared to conventional methods. Unfortunately, bulk tungsten suffers from intrinsic brittleness, as its ductile-to-brittle transition temperature (DBTT) is around 500-700 K. It thus remains a great challenge to fabricate tungsten materials without macrocracks. This presentation reports our recent progress on the L-PBF of tungsten material, where two different L-PBF machines are adopted to form near fully dense tungsten samples. We present the characteristic microstructures and residual microstrains in these materials in order to investigate and understand the microcracking mechanisms. We discuss possible strategies to overcome the challenging issue of micro- and macro-cracking in these high melting temperature refractory metals. The work at Lawrence Livermore National Laboratory was performed under auspices of Department of Energy under contract DE-AC52-07NA27344.

Scan-by-Scan Part-Scale Thermal Modelling for Defect Prediction in Metal Additive Manufacturing: *Terrence Moran*[1]; Derek Warner[1]; Nam Phan[2]; [1]Cornell University; [2]Naval Air Systems Command

A part-scale thermal modeling concept is implemented to predict thermal defect distributions in additively manufactured components. Utilizing the principle of superposition, the complete thermal history of part-scale builds can be simulated within the time frame required for real physical builds, without spatial or temporal coarsening. Demonstrating the concept on a real component with typical laser powder bed fusion parameters, the simulations show that in addition to power schedule, thermal defects depend on component geometry, scanning strategy, and heat accumulation. The features governing defect formation at the part-scale are analyzed, and a simple rule for predicting defect formation is presented.

Thermal Modeling in Additive Manufacturing Using Graph Theory: Validation with Laser Powder Bed Fusion for a Large Impeller Part: *Reza Yavari*[1]; Paul Hooper[2]; Prahalad Rao[1]; [1]University of Nebraska; [2]Imperial College

This poster summarizes results from the graph theory approach for thermal modeling, along with recent experimental validation for a large impeller part. The objective of this work is to use the graph theory approach to predict the thermal history of large-volume parts made using the laser powder bed fusion (LPBF) process. To realize the foregoing objective, we build a 316L stainless steel part of outside diameter 155 mm and height 40 mm resembling an impeller-like shape on a Renishaw AM250 LPBF system; the build time for this part is approximately 16 hours. Surface temperature measurements were obtained using a calibrated long wave infrared thermal camera. Using the graph theory-based thermal simulation strategy, we predict the surface temperature distribution trends with mean absolute error of approximately 10% of experimental temperature measurements and in less than 85 minutes (1/10thof the build time).

Towards the Residual Stress Prediction in Wire Arc Additive Manufactured Parts Using a Finite Element Thermomechanical Model: *Matthew Register*; Matthew Priddy[1]; [1]Center for Advanced Vehicular Systems

Predicting residual stresses in WAAM built parts is a growing area of research due to its increased application in advanced manufacturing techniques. Using the finite element (FE) method, a sequentially couple thermomechanical model has been created to predict the presence of residual stresses in thin wall and rastered parts made with maraging (M250) steel. During thermal model calibration efforts, experimental temperature data has shown unique data spikes which are caused by an unknown phenomenon. Our research is focused on understanding these phenomena and the role parameters such as heat source inputs, boundary conditions, material properties, print speed, print path, and idle time play in improving thermal model accuracy and ultimately predicting residual stresses in WAAM built parts. With this in mind, a design of experiments has been conducted to provide a framework for effective thermal modeling calibration of the WAAM process in the hopes of improving residual stress prediction.

Variable Hysteresis of Pantographic Lattices: *Zachary Romanick*[1]; Kaitlynn Conway[1]; Garrett Pataky[1]; [1]Clemson University

Pantographic lattices are comprised of continuous beam ligaments with traditionally zero or low compliant connections. High contrast micro-properties have been shown to produce the ability to undergo very large macro-deformations while at the local beam connections the material remains in the elastic regime. This is a unique property impossible with the rigid connections in lattice materials. Altering the local beam connections provides the opportunity to achieve programmable properties. Deviating from the commonly desired frictionless connections, this study used spacers to impart local changes in the connections to study the effect on cyclic hysteresis. Due to their thin aspect ratio, beams tend to translate out of plane during large displacements, an effect of Poisson's ratio, thus the spacers proved to resist this movement. The addition of spacers decreased the load on the lattice at the same displacement by 21% and increased the hysteresis of the lattice by 5%.

Voxel-based Damage Reconstruction and Its Application for Component Repair Using Additive Manufacturing: *Xinchang Zhang*[1]; Wei Li[2]; Frank Liou[1]; [1]Missouri University of Science & Technology; [2]The University of Texas at Dallas

Repairing damaged components is a critical application for additive manufacturing, particularly for directed energy deposition (DED), where new layers of materials are deposited in the damaged areas to restore its original shape. Reconstructing the damaged volume is essential to provide the geometry for printing. In this investigation, voxel-based damage reconstruction methodology was introduced. The models of nominal and damaged parts were transformed into voxel representation, after which boolean operation was performed to extract the damage. This approach was evaluated in terms of accuracy of the reconstructed damage. Case studies were then conducted to exhibit the application of this approach for repair. For this, the nominal and damaged models were obtained by 3D scanning, and they were utilized for processing. The acquired damage was sliced into layers to generate repair toolpath. Subsequently, materials were deposited back on the worn area by DED experiments, illustrating the functionality of the proposed methodology.

Poster Session on Materials

Tuesday PM August 3, 2021

Session Chair: E. MacDonald, University of Texas-El Paso

Additive Manufacturing of Cu-Ni-Tool Steel Multi-metallic Structures: *Xinchang Zhang*[1]; Lan Li[1]; Tan Pan[1]; Frank Liou[1]; [1]Missouri University of Science & Technology

Cooling capability of casting dies/molds is critical to lead to less cycle times and resist thermally-induced defects. Traditionally, cooling channels are designed in dies to cool the components. In this study, a new Cu-Ni-Tool Steel multi-metallic structures was designed and fabricated by additive manufacturing to take advantage of the excellent thermal conductivity of Cu. Multiple layers of Ni were inserted between Cu and tool steel as direct depositing Cu on tool steel results in cracking. The fabricated Cu-Ni-Tool Steel structures were heat-treated to study the effects of heat treatment on the properties of the structures. Microstructure characterization, elemental distribution, tensile testing, and hardness measurements were conducted on the as-fabricated and heat-treated parts. Besides, the residual stress of the structures were measured by X-ray diffraction, and was compared with simulation results. This investigation shows Cu-Ni-Tool Steel multi-metallic structures can be successfully fabricated by additive manufacturing, benefiting the design of casting dies/molds.

Large Area Projection Sintering of Chocolate: *Clinton Abbott*[1]; Dunstan Chi[1]; Nathan Crane[1]; [1]Brigham Young University

Large area projection sintering (LAPS) is a recent development in the field of powder bed fusion additive manufacturing (PBFAM) processes. Current research is focused on application to polymer powders, but expansion of this method to other materials may better demonstrate unique advantages of LAPS for temperature sensitive materials such as decreased thermal gradients and lower peak temperatures. The longer sintering times also enable processing of higher viscosity materials and achieving higher density. This poster details the processing of chocolate powder using LAPS to produce 3D objects and tiled images.

Inspection and Detection of Porosity in Additively Manufactured Parts with Different Geometries: *Sabrina D'Alesandro*[1]; Joy Gockel[1]; Andrew Harvey[1]; [1]Wright State University

Laser Powder Bed Fusion (LPBF) is an additive manufacturing process that iteratively deposits metal powder over the build plate and melts it with a laser. To make LPBF more efficient with higher quality material, an experiment was completed using in-situ monitoring sensors to observe the LPBF process as it prints nickel-based super alloy 718. The experiment was focused on observing defects in the printing process such as pores. The machine was set to print to coupons of differing geometries using the same processing parameters. The different thermal histories resulting from changing geometry for the two LPBF parts created different defect characteristics. The defects were characterized using computed tomography to understand the relationship between geometry and porosity and were related to the results of the in-situ monitoring. The implications of this research highlight the ability to monitor defects in-situ, which help ensure that future materials have a higher level of quality.

Directed Energy Deposition of Stellite 21 Hardfacing Coatings: *Ziyad Smoqi*[1]; Joshua Toddy[2]; Scott Halliday[2]; Jeffrey Shield[3]; Prahalad Rao[3]; [1]University of Nebraska-Lincoln; [2]Navajo Technical University; [3]University of Nebraska

The goal of this work is the crack-free deposition of a multi-layer Cobalt-Chromium alloy coating (Stellite 21) on Inconel 718 substrate using the directed energy deposition (DED) additive manufacturing process. Stellite alloys are used as coating materials given their resistance to wear, corrosion, and high temperature. Deposition of Stellite with DED is desirable because the microstructure evolved is typically finer compared to weld overlay processes, such as plasma transfer arc, which in turn improves the hardness of the coating. The main challenge in DED of Stellite coatings is the proclivity for crack formation during printing. The objective of this work is to characterize the effect of the laser power (input energy) and localized laser-based preheating on the physical properties of the coating, namely, crack formation, microstructural evolution, dilution of the coating composition due to diffusion of iron and nickel from the substrate, and microhardness.

Influence of Process Conditions on the Thermal Conductivity of Selective Laser Melted AlSi10Mg: *Jacob Goodman*[1]; Arad Azizi[1]; Fatemeh Hejripour[1]; Piyush Kulkarni[1]; Scott Schiffres[1]; [1]Binghamton University

AlSi10Mg alloy is commonly used in selective laser melting (SLM) due to its printability, relatively high thermal conductivity, low density and good mechanical properties. Thermal properties of AlSi10Mg are important to heat transfer applications including additively manufactured heatsinks, cold plates, vapor chambers and heat pipes. The thermal conductivity of samples fabricated in different orientations and energy densities will be discussed. The bulk thermal conductivity measurements were made via flash diffusivity, and local measurements were made with frequency domain thermoreflectance (FDTR). The properties are linked to the microstructural changes that occur in selective laser melted AlSi10Mg versus processing conditions.

Effect of Build Parameters on the Material Properties of Printed Parts Produced by Multi-jet Fusion: *Andrew Chen*[1]; Ailin Chen[1]; Jake Wright[2]; Andrew Fitzhugh[2]; Aja Hartman[2]; Jun Zeng[2]; Grace Gu[1]; [1]University of California, Berkeley; [2]HP Labs

Multi-jet fusion (MJF) is a novel additive manufacturing (AM) process for the powder-bed fusion of thermoplastic polymers. In recent years, MJF has been established as a promising manufacturing technique for the rapid prototyping and production of fully functional, large-scale components. However, the effects of common build volume parameters (such as part orientation, location, and spacing) on mechanical properties are currently not well understood. This study aims to provide a comprehensive description of the trends in mechanical properties observed in polyamide (PA)-11 and polyamide-12 samples printed via MJF. Tensile, flexural, and impact specimens were printed using varying build volume packing parameters and tested according to the corresponding ASTM standards. Fracture surfaces were studied and characterized to further understand the method of failure propagation through MJF-printed parts. The results of the present work are useful in determining an optimal packing algorithm for the purposes of optimizing desired mechanical properties of printed parts.

Enabling Direct Ink Write Edible 3D Printing of Food Purees with Cellulose Nanocrystals: *Connor Armstrong*[1]; Liang Yue[1]; Yulin Deng[1]; Jerry Qi[1]; [1]Georgia Institute of Technology

Additive manufacturing using edible feedstock offers a unique method of producing visually appealing meals with customizable nutrition profiles. Direct ink write (DIW) 3D printing is a popular choice for edible 3D printing due to its low cost and open framework for broad material choices. However, the breadth of food suitable for DIW 3D printing is hindered due to the limited selection of rheological modifiers which facilitate shear thinning behavior that are safe for human consumption. We present cellulose nanocrystals (CNCs) as a safe and renewable rheological modifier capable of enabling 3D printing of a variety of foodstuffs, specifically spinach puree, tomato puree, and applesauce. We first analyzed the rheological characterization of foodstuffs combined with varying volume fractions of CNCs to produce shear-thinning, printable inks. The print quality of different inks was then analyzed via image processing. Finally, we demonstrated the capability of these inks by printing a variety of structures.

Investigation on the Properties of Reinforced IN718 Structures Fabricated Using Laser Powder Bed Fusion: *Bharath Bhushan Ravichander*[1]; Behzad Farhang[1]; Aditya Ganesh-Ram[1]; Manjunath Hanumantha[1]; Samarth Ramachandra[1]; Yukti Shinglot[1]; Amirhesam Amerinatanzi[1]; Narges Shayesteh[1]; [1]The University of Texas at Arlington

Inconel 718 (IN718) superalloy, known for its high strength and corrosion resistant behavior, is widely used in aerospace and automotive industries. Laser power bed fusion (LPBF), one of the commonly used techniques of additive manufacturing, enables the fabrication of structures with a variety of local properties. Using the same material, components with spatially varying properties can be fabricated through applying different processing parameters. In this study, IN718 composite structures were fabricated using four types of rod reinforcements with different geometry. A different set of process parameters was used to fabricated reinforcing rods compared to that of the main part. The bonding quality at the interface between the main part and reinforcements was determined by defect analysis on the microstructure results. Also, Vickers hardness test was performed at the interface in order to examine the mechanical properties of the samples. It was found out that a similar level of densification and hardness value, slightly less than the plain sample, can be achieved using helical and arc reinforcing rods. By contrast, significantly lower density and hardness was observed for the sample reinforced by square rods compared to the plain sample.

Investigating the Effect of Heat Transfer on the Homogenity in Microstructure and Properties of Inconel 718 Alloy Fabricated by Laser Powder Bed Fusion Technique: *Behzad Farhang*[1]; Bharath Bhushan Ravichander[2]; Aditya Ganesh-Ram[2]; Samarth Ramachandra[2]; Manjunath Hanumantha[2]; Whitney Hall[2]; Ann Dinh; Amirhesam Amerinatanzi[2]; Narges Shayesteh Moghaddam[2]; [1]University of Texas at Arlington; [2]The University of Texas at Arlington

Laser powder bed fusion (LPBF) of metallic components is associated with microstructure and properties inhomogeneity in the fabricated components. In a recent work by the authors, a novel technique of considering a border surrounding the main part during the LPBF fabrication is proposed to address the issue of microstructure inconsistency across the cross section of LPBF-fabricated parts. This study, on the other hand, aims to investigate the effect of such border on the microstructure homogeneity along the build direction of LPBF-fabricated parts. For this purpose, a cubic sample surrounded by a cubic border was fabricated to control the rate of heat transfer and then improve the microstructure properties across the cross section. Also, a sample with identical dimensions and the same process parameters was printed without border as a reference to be compared. To investigate the variation of the properties along the build direction, microstructure and hardness results were compared between areas near and away the substrate for both samples. For the area away from the substrate, in both samples, a deeper pool, less surface porosity and higher Vickers hardness was observed compared to the area near the substrate. It was found out that, regardless of the focused area, the sample fabricated with border possesses deeper pools, higher level of density as well as higher hardness value. However, in term of homogeneity along the build direction, no significant improvement was observed for the sample fabricated with the cubic border.

Study of Spatter Formation and Effect of Anti-spatter Liquid in Laser Powder Bed Fusion Processed Ti-6Al-4V Samples: Aditya Ganesh-Ram[1]; Manjunath Hanumantha[1]; *Bharath Bhushan Ravichander*[1]; Behzad Farhang[1]; Samarth Ramachandra[1]; Narges Shayesteh Moghaddam[1]; Amirhesam Amerinatanzi[1]; [1]The University of Texas at Arlington

Spatter deposition has been found to have serious effects on mechanical properties of the metal parts printed using laser powder bed fusion technique. The spatter powder formation can cause unfavorable changes in phases and impurity content and may result in the formation of defects in the as-fabricated parts. This study is the first of its kind focusing on mitigation of spatter formation through a novel technique of spraying nonflammable welding liquid during the LPBF process. Identifying the spatter particle size distribution and dampening its formation have been the focus of this study. Characterization of the powder spatter behaviors for Ti-6Al-4V have been made through image processing, microstructure characterization, and compositional analysis. The findings of this study will help in improving the mechanical properties and reducing the post-processing procedures required for the parts processed by LPBF. This study is believed to bring a new perspective in production planning and print quality optimization to obtain an enhanced performance from laser powder bed fusion technique.

Rheological Scaling and Modulation to Improve the Extrudability of Metal Filament by Fused Filament Fabrication: *AMM HASIB*[1]; Bruno Azeredo[1]; [1]Arizona State University

To minimize the shrinkage effect after debinding and sintering during metal additive manufacturing by Fused Filament Fabrication (FFF), metal content closer to the random close packing (~0.64) were homogeneously dispersed in polymer matrix in a hot melt extruder. This was done by re-engineering the feedstock mixing, which influences the melt rheology and controls the filament extrusion domain in terms of shear rate susceptibility. In this correlative study, a framework of rheological scaling was presented for two different feedstock mixing method and it was shown that, even with the high zero shear viscosity metal composites prepared by solution mixing process, showed controlled shear thinning behavior to be in the targeted extrusion zone and hence we were able to extrude 63.4 vol.% metal filaments without the use of any additives. Our experimental outcome of zero shear viscosity scaling fits well with the theoretical model of Krieger and Dougherty. Thermogravimetric analysis and micro-computed X-ray tomography were employed to quantify the homogeneity in both global and micro-scale. SAOS (Small amplitude oscillatory shear) test was carried to elucidate the composite filament's transition point from viscoelastic to solid state which creates the onset of jamming. Finally, it was shown that, due to the increased green part density, 3D printed and sintered part exhibited 76% linear shrinkage reduction while compared to the traditional method. This mixing strategy and analysis gave us insight on how to scale and modulate the feedstock melt rheology to create dense 3D printed metal parts with negligible shrinkage using Fused Filament Fabrication (FFF) technique.

Processing of In Situ Titanium Metal Matrix Composites via Directed Energy Deposition and Selective Laser Melting: *Kellen Traxel*[1]; Amit Bandyopadhyay[1]; [1]Washington State University

Demand for advanced material development via powder-based metal additive manufacturing (AM) methods has increased with growing AM adoption; however, limited process-microstructure-properties relationships exist for AM-produced advanced composite materials. In this poster, we present several of our works on the development of an in situ reactive, oxidation-resistant titanium metal-matrix composite reinforced with boron nitride (BN) and boron carbide (B4C) via both directed energy deposition (DED) and selective laser melting (SLM). Detailed characterization and testing reveal the efficacy of ceramic reinforcement towards tailoring the microstructure and properties of these composites, particularly regarding high-temperature oxidation performance. While initially developed using DED, careful processing optimization via SLM resulted in high-density bulk composites that can be used in high-temperature applications. Our results demonstrate that DED can be utilized as a platform for preliminary material development before the utilization of powder-bed-based methods such as SLM for full-scale production.

Lattice Infill Pattern Design for Increased Green Part Strength and Sintered Density in Metal Binder Jetting: *Amanda Wei*[1]; Kazi Rahman[1]; Christopher Williams[1]; [1]Virginia Tech

Selective jetting of binder is a critical element of the binder jetting additive manufacturing process, as it defines part geometry and serves as the structural matrix that provides sufficient handleability in green parts. However, preliminary results suggest that binder inhibits sintering and decreases final achievable part density. To balance the conflicting needs between providing both sufficient green part strength and higher sintered part density, the authors explore selective jetting of an architected shell and lattice infill design approach. Preliminary experimental results of printed 316L stainless steel demonstrate that architected parts are capable of simultaneously reaching comparable green part strength to fully bound powder, while also providing an 8% increase in sintered part relative density.

Exploring Variability in Melt Pool Attributes with High-speed Imaging: *David Guirguis*[1]; Christian Gobert[1]; Conrad Tucker[1]; Jack Beuth[1]; [1]Carnegie Mellon University

Laser powder bed fusion (L-PBF) is one of the well-established and widely used metal additive manufacturing technologies in the market. The technology has been under rapid growth and profound advancement. However, the uncertainty and variability in the quality of produced parts are still of major concern. Understanding the melt pool dynamics and morphological variability is important to determine process parameters for the enhancement of mechanical properties and microstructural control. In this work, we characterize and explore the variability in the melt pool by utilization of high-speed imaging. Quantification of the melt pool dynamics and morphological variation is performed with different combinations of process parameters. Furthermore, we study the correlation between the process parameters and the variation in melt pool dimensions and shape attributes.

Poster Session on Process Development

Tuesday PM August 3, 2021

Session Chair: E. MacDonald, University of Texas-El Paso

Effects of Centrifugal Disc Finishing for Surface Improvements in Additively Manufactured Gears: *Foxian Fan*[1]; Nick Soares[1]; Sagar Jalui[1]; Aditya Savla[1]; Aaron Isaacson[1]; Guhaprasanna Manogharan[1]; Timothy Simpson[1]; [1]Penn State University

Additive Manufacturing(AM) is well suited to rapidly produce complex and customized geometries economically for low production runs. However, there is an inherent need for post-AM machining and surface finishing in most metal AM applications. Centrifugal Disc Finishing(CDF) is a media-based mass finishing process that can be employed to improve surface finish of external geometries of AM parts with complex geometry. This original study aims to understand the influence of CDF processing conditions on Ti64 gear teeth fabricated via Powder Bed Fusion(PBF). Statistical analysis is conducted to analyze the effectiveness of CDF to improve surface roughness of different build surfaces of the AM gear teeth. In addition, both contact profilometer and X-ray Computer Tomography(CT) techniques are applied to evaluate its effectiveness to measure CDF and AM surface finishing. Findings from this study on CDF of gear AM will benefit metal AM community by better understanding the impact of CDF processing conditions for surface improvements in mass finishing of metal AM parts.

Quantification of the Effects of Deposition on Spatter Formation and Dynamics in Laser Powder Bed Fusion via Dynamic X-ray Radiography: Yao Xu[1]; Joseph Pauza[2]; Anthony Rollett[2]; *Sneha Prabha Narra*[2]; [1]Worcester Polytechnic Institute; [2]Carnegie Mellon University

Spatter refers to the ejection of powder and molten material that can result in defects such as denudation, contamination, and porosity. The key to effectively reduce spatter is to understand the dynamics of spatter formation, of which connection between processing parameters and spatter formation is missing in the literature. Computer vision was applied on high-frequency X-ray images captured during laser melting to analyze spatter. For different laser power, velocity combinations and powder sizes, the ejection quantity, velocity, and travel distance are different. For instance, delayed ejections were observed for larger powders that can be attributed to induced chamber gas flow instead of recoil pressure. Also, spatter behavior including ejection-to-fall lifetime was quantified as a function of power and velocity for Inconel 718 and Ti-6Al-4V. This work provides insights regarding dominating mechanisms that contribute to spatter under different processing conditions. This, in turn, can provide guidance for minimizing spatter.

Enabling Deposition of Removable Support Structures in Large-format Material Extrusion: Benjamin Woods[1]; *Joseph Kubalak*[1]; Christopher Williams[1]; [1]Virginia Tech

Large-format material extrusion (LFME) systems are limited in their ability to produce parts with overhanging features. This is due to (i) the use of screw-style extruders, which render material changes for depositing a release material mid-build impractical, and (ii) the use of post-process machining tools, which cannot access all deposited features, to remove the sacrificial support structures. The authors address these constraints through a novel multi-material process in which a water-soluble material is deposited via a secondary extruder to serve as a sacrificial interface between the printed support structures and part. After printing, the interfacial layers are dissolved, allowing the support structure to be removed without post-process machining. Additionally, a method for dividing the printed support structures into smaller, removable chunks is demonstrated to enable facile removal from complex, hollow large-scale printed objects. Utilizing these processes in conjunction, a geometry was manufactured that would traditionally be considered un-manufacturable in LFME.

Closed-Loop Control of Meltpool Temperature in Directed Energy Deposition: *Benjamin Bevans*[1]; Ziyad Smoqi[1]; James Craig[2]; Alan Abul-Haj[3]; Brent Roeder[4]; Bill Macy[5]; Jeffrey Shield[1]; Prahalada Rao[1]; [1]University of Nebraska-Lincoln; [2]Stratonics, Inc.; [3]ARA Engineering; [4]R3 Digital Sciences; [5]Macy Consulting

This work concerns the laser directed energy deposition (DED) additive manufacturing of stainless-steel parts. In this work, we achieved closed-loop control of the meltpool temperature. We demonstrate that maintaining the meltpool temperature at a steady state through closed-loop control of laser power leads to the following outcomes: (1) mitigation of microstructure heterogeneity, and (2) reduction in porosity of parts.

A Review of Wire-fed AM Process Monitoring and Data Analytics: Bradley Jared[1]; *Matthew Roach*[1]; [1]University of Tennessee, Knoxville

The need for process monitoring and data analytics in metal additive manufacturing (AM) is an essential aspect of its development as a method for manufacturing high-consequence components. Of interest are wire-feed technologies, many of which have been researched extensively within the welding community. Their use in additive manufacturing is less mature, however, and introduces multiple new research challenges. Since existing research on process monitoring is sparse, this review will examine work in process monitoring and data analytics applied to wire-feed deposition processes for welding and additive manufacturing. Current state-of-the-art in process monitoring and data analytics will be identified, and proposed future research directions will be discussed to address technological gaps and needs.

On Ultrasound Powder Stream Focusing and Applications to Powder-fed Laser Directed Energy Deposition: *Alexander Martinez-Marchese*[1]; Mazyar Ansari[1]; Asier Marzo[2]; Marc Wang[1]; Ehsan Toyserkani[1]; [1]University of Waterloo; [2]Public University of Navarre

Powder-fed laser directed energy deposition (LDED-PF) is a technique that can be used for both repairing and building metal components. Usually, powder particles are conveyed using an aerodynamic nozzle to form a powder stream directed towards the melt pool, where the particles are melted due to the laser energy flux. The working distance of the nozzle can be varied to adjust the width of deposited tracks. However, this affects the resolution of the printed features due to a lower catchment efficiency and uneven heat transfer between the laser and the powder. In this study, we propose the use of a novel ultrasound array to focus the particles in the powder stream using ultrasound radiation forces. The design of this novel ultrasound array will be presented and its effect of the sound field on the LDED-PF particle stream maximum concentration and effective width will be discussed.

Cost Analysis of Metal Additive Manufacturing via FDM Desktop 3D Printers: *Jeffery Betts*[1]; Frank Brinkley[1]; Adam Vitale[1]; Matthew Priddy[1]; [1]Mississippi State University

Metal based additive manufacturing (AM) has led to cost savings in rapid prototyping and one-off production. However, the high cost-to-entry for metal AM has limited widespread adoption.. The introduction of metal filament for FDM 3D printers is attempting to fill the gap to make metal AM more economical and accessible. Printing metal parts via FDM does not intend to replace ‘conventional’ AM processes, but hopes to provide a cost-effective alternative. The present work utilized the affordable and readily available Creality Ender 3 V2 with UltraFuse 316L Metal 3D filament. A cost analysis of this process is conducted against parts built using powder bed fusion (PBF) and direct metal laser sintering (DLMS). To analyze cost to part performance, mechanical testing and porosity analysis are performed. This research hopes to determine the efficacy of a low-cost alternative to traditional metal-based AM, making it accessible to all.

Controlling Powder Bed Cohesion in Binder Jetting (BJ): *Colton Inkley*[1]; Brennen Clark[1]; David Martin[1]; Joseph Spencer[1]; Jacob Lawrence[1]; Nathan Crane[1]; [1]BYU

BJ has increased in popularity and capability since its development at MIT and offers advantages such as fast build rates, integrated overhang support, low-power run requirements, and is versatile in material options. However, defects arise during layer spreading and printing that are not readily removed during post-processing. This study explores methods of reducing particle rearrangement and ejection from binder deposition by applying small amounts of moisture to increase the cohesive forces between powder particles. This is achieved using a piezo-electric disk to atomize water and mist the BJ powder bed. Complications arise because BJ’s powder spreading process is most successful when the cohesive strength between particles is small. This was addressed by applying the moisture application after spreading new powder. This ensures that the powder is spread before powder moistening, and while minimizing changes in print time.

Origami-inspired Deployable Structures Using Fused Deposition Modeling with Embedded Fabric: *Tyler Stevens*[1]; Spencer Abbott[1]; Nathan Crane[1]; [1]Brigham Young University

Origami, a traditional Japanese paper folding art, has been applied to a wide range of engineering applications ranging from soft robotics to deployable satellites. Additive Manufacturing has sought to take advantage of various properties of origami including the ability to transform between flat, space-efficient unfolded states and complex, folded states with added functionality such as electronics. By selectively printing on the fabric, printed regions gain the rigidity of the added material and non-printed regions retain the flexibility of the fabric, becoming the hinges or ‘creases’ of an origami-like structure. This research builds upon that of other researchers by developing a process to print 3D deployable origami-inspired structures using multiple textile layers. The resulting parts of this technique can be unfolded into a 3D structure larger than the original build plate. Additionally, the textile provides added strength making it ideal for creating container-like structures which, when unfolded, can be quickly deployed.

The Effect of Processing Parameters on Melt Pool Geometry and Surface Formation in Laser Powder Bed Fusion: *Edwin Glaubitz*[1]; Joy Gockel[1]; Orion Kafka[2]; Jason Fox[2]; [1]Wright State University; [2]National Institute of Standards and Technology

The surfaces of components created using additive manufacturing (AM) often have a higher roughness than those created with other manufacturing methods. This has been shown to negatively impact the fatigue performance of AM components. However, there is a limited understanding of how the surface is formed and how processing parameters influence the surface formation. To better understand the surface roughness in components built using laser powder bed fusion AM, the relationship between contour processing parameters and melt pool size is analyzed for nickel-based superalloy 718. This understanding is used to build components with various parameters forming consistent melt pool sizes. The surface topography is measured using 3D surface profilometry and the area of the contour melt pool is measured metallographically. Relationships identified between melt pool size and surface roughness will be used to inform future process parameter development to improve performance of AM components.

Microstructural and Mechanical Characterization of Laser Powder Bed Fusion of IN718 Overhangs: Manjunath Hanumantha[1]; *Behzad Farhang*[2]; Bharath Bhushan Ravichander[1]; Aditya Ganesh-Ram[1]; Samarth Ramachandra[1]; Ellen Finley[1]; Nahid Swails[1]; Amirhesam Amerinatanzi[1]; [1]The University of Texas at Arlington; [2]University of Texas at Arlington

Inconel 178 (IN718), a nickel-chromium based superalloy known for its superior properties is used in aerospace, oil, and gas industries. Due to its high hardness feature, IN718 is difficult to manufacture using conventional methods. Laser powder bed fusion (LPBF) technique can be used to fabricate IN718 parts with high precision. During fabrication of overhang structures, supports are typically employed, which significantly increases the use of resources such as material consumption and postprocessing. The focus of this study is to determine the angle at which an overhang structure can be fabricated without employing supports. To this aim, the angled-overhang samples with varied angles (30°-90°) were manufactured with no support. The effect of overhang state on the microstructural and mechanical properties of the LPBF-processed IN718 samples was analyzed. According to the microstructural analysis, the deepest melt pools in the overhang sample seemed to be at a hanging angle of 45°. Moreover, the overhang sample fabricated at 45° had the greatest Vickers hardness value of 382.90 HV. This study urges a reconsideration of the common approach of selecting supports for overhang samples in the LPBF process when a higher quality of the as-fabricated parts is desired.

Detecting Hidden Process Anomalies Causing Defects Using In-situ Process Monitoring: *Jonathan Ciero*[1]; Sabrina D’Alesandro[1]; Dylan Christman[1]; Kyle Ryan[2]; Shuchi “SK” Khurana[3]; Christopher Barrett[2]; Thomas Spears[2]; Joy Gockel[1]; [1]Wright State University; [2]Open Additive, LLC; [3]Addiguru

Processing anomalies in laser powder bed fusion additive manufacturing have the potential to produce defects in the fabricated material that are detrimental to the mechanical performance. The use of in-situ process monitoring can detect where these anomalies occur. In-situ monitoring provides the ability to detect off-nominal process behavior that can be used support qualification and certification of AM parts. Three different in-situ sensors were used to collect data over a laser powder bed fusion build of Alloy 718. The build was created with hidden processing anomalies at various layers throughout the build height. These anomalies are created through strategic changes in different processing parameters for single and multiple layers before returning to nominal conditions. Analysis of the process monitoring data was used to find the anomalous locations and the parts are characterized to determine the impact on the defect structure within the material.

Using Acoustic Sensors to Review Sample Integrity During Selective Laser Flash Sintering of Ceramics: *Christina Nissen*[1]; Deborah Hagen[1]; Desiderio Kovar[1]; Joseph Beaman[1]; [1]The University of Texas at Austin

Current production Solid Freeform Fabrication (SFF) in ceramics involves the use of added polymers which must be removed in later stages of fabrication through pyrolysis, as without these added polymers ceramic is subject to the effects of thermal shock during fabrication. This added stage makes the process inefficient, and additionally limits the thickness of parts that can be produced. Current research in this area is looking to remove these polymers from the process entirely, so that ceramic powders are sintered directly, removing the time intensive pyrolysis from the process. The integrity of the sintered sample must be reviewed individually after each attempt as efforts to measure current and temperature alone of samples in situ have not been enough to determine part integrity. Our current research reviews the application of an acoustic wave time-of-flight measurement system in situ to detect process-initiated defects in Selective Laser Flash Sintered (SLFS) ceramics, as both a research aid and an improvement to overall process control during the SLFS process.

Evaluating the Extrudability of Common Feedstocks for Fused Filament Fabrication Systems: *Zaky Hussein*[1]; Christine Ajinjeru[1]; Chad Duty[1]; [1]University of Tennesse, Knoxville

Previous work established a model for determining the printability of polymer feedstocks in Material Extrusion systems based on the properties of the material and the processing parameters of the system. Failure to meet this criterion represents the actual volumetric flowrate falling below that of the desired volumetric flowrate. The extrudability of polylactic acid and acrylonitrile butadiene styrene was mapped over a range of processing parameters on small-scale Fused Filament Fabrication system. The system printed hollow cylindrical samples one bead thick over a range of deposition temperature and speeds for each material. The actual flowrate was experimentally determined from the print time and printed volume and compared to the specified flowrate. A normalized flowrate was calculated and used to determine if the criterion for pressure-driven extrusion was satisfied. The effects of deposition temperature and speed were characterized for successful pressure-driven extrusion to match the printability model criteria in an FFF system.

0gon - A Revolutionary New Optical Scanner for Additive Manufacturing: *Charles Bibas*[1]; [1]175 E Shore Rd.

The core engine of an SLS/SLM AM printer is the Optical Scanner. Typically, either a galvanometer (GS) or a Polygonal Mirror (PM) scanner has been used, but both have been pushed to their mechanical limits. Both scanners suffer from inconsistency in energy deposition because of changes in Optical Path Length (OPL), Surface Beam Speed (SBS), and angle of incidence(T).The Øgon Lens Free Optical Scanner (patented by Tecnica, Inc., Great Neck, New York), on the other hand, provides a simple scanning method, linear transfer functions, fixed OPL, and an incident beam normal to the work surface. This presentation describes the optics of the Øgon and compares it head to head with the GS. The study shows the Øgon delivers a linear transfer function, where the optical path length, surface beam speed, and T, the angle of incidence (and therefore the beam size and shape) are constant.

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