

**International Solid Freeform Fabrication Symposium  
An Additive Manufacturing Conference**

August 10-12, 2015

AT&T Executive Conference Center

The University of Texas at Austin

(Casual attire is appropriate)

**Monday AM**

**7:30** Registration – AT&T Center Third Floor Lobby  
**8:00-8:15** Welcome and Announcements (AT&T Center Salon C)  
Dave Bourell, The University of Texas at Austin

**Opening Plenary**

**8:15-8:45 Product Liability in Additive Manufacturing**

*Patrick Comerford, McCarter & English*

3D Printing/Additive Manufacturing (“3DP/AM”) presents new legal challenges because the technology expands the definitions of “manufacturer”, “supplier” and “product.” The physical world largely defines the roles of the traditional manufacturing process presently. The supplier provides material to a manufacturer who takes a tested and approved design and physically makes the product or part at a specific location. The product or part is then inspected, packaged and shipped from that plant or facility to the retailer, reseller or customer.

The 3DP/AM world is not as clear. The physical world’s limitations and structure have been replaced by the relative freedom of the digital world. If you can create it on a screen through 3D CAD software, digital photography, or 3D Scanning, you can conceivably create a physical manifestation of the object from the screen into the real world. How does this new freedom create challenges for answering "who is a manufacturer?" What are the standards for the designs, process and materials? Where are the limits of contract and insurance law to insulating exposure for liability? What are the potential quality control benefits of the new manufacturing method? When there is injury or damage, who will be held responsible?

My interactive presentation will show the parallels between traditional manufacturing of the past and how similar challenges were faced and translated by the courts and the present day. I will set forth best practices going forward to control and manage the uncertainties created by the new technology by updating and tailoring the old understandings before applying them to the new roles and responsibilities. I will also discuss the incredible potential present for today's inventors and manufacturers to shape the future litigation. Last, I will explore the underappreciated upside of the technology to the quality and safety controls of manufacturers.

## **Process Development I: New Processes**

Salon C

Session Chair: Phill Dickens, University of Nottingham

### **8:45-9:05 Electrodeposition and Electroless Deposition for Additive Manufacturing**

*D.B. Robinson, R.K. Nishimoto, M.S. Bartsch, C.L. Arrington, C.G. Jones, J.D. Sugar, M. Homer*, Sandia National Laboratories

Electrochemical deposition (using an externally applied current) and electroless deposition (using a chemical reductant to deposit onto a catalytic surface) are among the oldest additive manufacturing methods for metals and semiconductors. In most cases they are inherently two-dimensional, typically depositing films on the order of microns per hour. However, large quantities of material can be deposited onto high-surface area substrates. While most other additive manufacturing techniques cannot easily or efficiently define features smaller than 100 micrometers, electrochemical methods can be controllably applied on scales ranging from Angstroms to kilometers. We will describe efforts by ourselves and others to apply these deposition methods, in combination with two- and three-dimensional patterning techniques, to create or augment three-dimensional structures.

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### **9:05-9:25 A Novel Projection based Electro-Stereolithography (PES) Process for Composite Printing**

*Y. Pan<sup>a</sup>, A. Patil<sup>a</sup>, C. Zhou<sup>b</sup>*, <sup>a</sup>University of Illinois at Chicago, <sup>b</sup>University at Buffalo, The State University of New York

Most current additive manufacturing processes can only process one material in one build. Few of them are able to fabricate multiple materials and composites, with limited choices of materials. In this research, we propose a novel Additive Manufacturing (AM) process, which is able to fabricate composites with high resolution and fast speed, and a big domain of material choices. The proposed process integrates projection-based stereolithography and electrophotography approaches by using a photoconductive film and digital micro-mirror device (DMD). Hence we name the process as Projection based Electro-Stereolithography (PES). In PES, a photoconductive film is used to collect charged particles in the regions illuminated by light. More specifically, a laser beam is scanning on the film to create a latent image on the film and then a layer of charged particles is attracted to the illuminated area. A liquid bridge system and a stamping system are developed to transfer particles from the film to liquid resin precisely. Furthermore, a digital mask is used to pattern the light irradiation of the DMD chip to selectively cure the photopolymer liquid resin and particles of that layer. By transferring particles with designed patterns to the liquid resin in a projection based stereolithography system, we will be able to fabricate composites with various materials at microscopic resolutions very quickly. Challenges in this novel manufacturing process, including the particle pattern forming, transferring of particles, and curing control, are discussed. The corresponding key parameters of the particles collecting, dropping and curing in the PES system are identified. A proof-of-concept PES testbed has been developed and a couple of tests have been performed to validate the feasibility of the proposed additive manufacturing approach.

**9:25-9:45      Photopatterning of Freeform Surfaces using a Modular Robotic System**

*A. Oliver, C.R. Stevens, L. Chin, A.J. Hart, Massachusetts Institute of Technology*

Additive manufacturing by photopolymerization (e.g., stereolithography) is attractive due to its high resolution, and its compatibility with soft and hard polymers, composites, and biomaterials. While traditional stereolithography machines are designed to build on planar substrates, the capability to build three-dimensional structures on curved and textured objects would be very useful for manufacturing of structurally integrated sensors and electronics, and for customizing biomedical implants. To realize this concept, we have designed and built a robotic system capable of maskless photopatterning on large-scale objects. The system incorporates a six-axis robot, a high-precision rotary stage, and a custom DLP-based end effector, and is controlled by custom software that references a three-dimensional scan of the target object taken offline and then kinematically positioned in the workspace. The system has 5  $\mu\text{m}$  feature resolution, repeatability of  $\sim 20 \mu\text{m}$ , and accuracy of  $\sim 100 \mu\text{m}$ , over a work volume of 8 L. We describe the design, operation, and performance limits of the system, along with its initial use to pattern standard photoresist and a cell-laden hydrogel onto a metal sphere, and a bone, respectively. In light of our findings, we also reflect on the capabilities and limitations of hardware and software needed to further the convergence of robotics and additive manufacturing processes.

**9:45-10:05      Additive Manufacture of Large Structures: Robotic or CNC Systems?**

*Y. Bandari, S. Williams, J. Ding, F. Martina, Cranfield University*

Additive manufacture of metre scale parts requires direct feed processes such as blown powder or wire feed combined with lasers or arcs. The overall system can be configured using either a robotic or Computer Numerical Controlled (CNC) gantry system. There are many factors that determine which of these is best and this will be presented in this paper. Some factors are inherent to the specific process type such as accuracy/resolution and any requirement for reorientation of the feedstock and heat source. Other factors depend on the particular application including material type, shielding options, part size/complexity, required build strategies and management of distortion. Further considerations include the incorporation of ancillary processes such as cold work, machining or inspection. The relative influence of these factors will be discussed. Cost implications for the different approaches will be highlighted based upon the type of process being utilized. Examples are provided where both robotic and CNC options have been evaluated and the best solution found.

**10:05-10:35      BREAK**

**10:35-10:55      Active Device Fabrication using Fiber Encapsulation Additive Manufacturing**

*M. Saari, M. Galla, B. Cox, E. Richer, P. Krueger, A. Cohen, Southern Methodist University*

Fiber Encapsulation Additive Manufacturing (FEAM) is a novel solid freeform fabrication process in which a fiber and a matrix are co-deposited simultaneously within a single printer along straight and curved 2-D and 3-D paths. Using a FEAM approach in which the fiber is a metal wire and the matrix is a thermoplastic polymer, simple electromechanical devices such as voice coils, inductive sensors, and membrane switches have been successfully produced. This paper will present an overview of the FEAM process, describe several fabricated devices, and discuss recent developments in controllably stopping and starting the wire, and in creating

electrical junctions between individual wires, which together enable much more complex devices to be made.

### **10:55-11:15 High Viscosity Jetting of Conductive and Dielectric Pastes for Printed Electronics**

*J. Ledesma-Fernandez, C. Tuck, R. Hague, University of Nottingham*

Ink-jet printing of multiple materials in 3 dimensions is a promising alternative to traditional patterning methods due to its flexibility, scalability and accuracy. However, the printability of the inks is strongly restricted by material properties such as surface tension and viscosity. Dispensing high viscosity fluids on a drop-on-demand approach is a potential solution that can facilitate the incorporation of new materials to the jetting catalogue. Consequently, in this study 2 micro-dispensing valves are used in combination with a mechanical stage to deposit conductive and dielectric pastes with viscosities of  $15.3 \pm 0.2$  and  $0.638 \pm 0.005$  Pa·s (at 25°C and  $10 \text{ s}^{-1}$  shear rate) respectively. Crucial printing parameters such as pressure, temperature, pulse shape and drop spacing are studied in order to optimise the process. Additionally, post-printing characteristics such as contact angle of different materials and cured layer profiles are also measured and taken into account during the designing of the 3D patterns to minimise the negative effects of the thickness miss-match of different materials. Finally, the manufacturing capability of the set-up is demonstrated by the fabrication of a functional device using a combination of “pick-and-place” components and high viscosity jetting.

### **Freeform and Additive Manufacturing Excellence Awards Presentations**

#### **11:15-11:35 Bioprinting Living Tissues and Organs**

*Ibrahim T. Ozbolat, Penn State University*

Bioprinting is an emerging field that is making a revolutionary impact on the medical sciences. It offers great precision for spatial placement of cells, proteins, genes, drugs and biologically active particles to better guide tissue generation and formation. This emerging biotechnology appears to be promising for advancing tissue engineering toward functional tissue and organ fabrication for transplantation, drug testing, research investigations, and cancer or disease modeling, and has recently attracted growing interest worldwide among researchers and the general public. This talk presents possibilities in bioprinting scale-up functional tissue and organ constructs and discusses alternative approaches, their limitations and promising directions for new research prospects.

#### **11:35 - 12:05 From Single to Multi-Material, Multi-Functional Additive Manufacturing.**

*Richard Hague, University of Nottingham*

As is now widely recognized, Additive Manufacturing offers many potential advantages to both users and industry, with one of the principal benefits being in the extended levels of design freedom and complexity that can be incorporated into a component. For single material additive manufacturing – most notably the powder bed fusion techniques, which are of particular relevance and interest to industry today – we are beginning to see examples emerging that incorporate complex lattice structures or components that involve a degree of topology optimization or parts consolidation in their design. Though many of these emerging examples are impressive, by their single material nature, they also are limited to being used as “passive” components that require integration into a larger system in order to impart functionality beyond

the mainly structural.

However, taking the concept of design freedom beyond the geometrical domain to one where multiple materials are simultaneously deposited opens up the potential for the creation of functionalized, “active” devices “printed” in one build operation. However, though simple in concept, this discrete deposition of dissimilar materials throughout the volume of a part creates significant technical challenges, particularly in the deposition of useful materials.

In this presentation, the author will highlight the work undertaken over the past 20 years in exploring AM processes, materials and design and will focus on the current activities of the research group at Nottingham where there is an emphasis on multifunctional Additive Manufacturing. This research is predominantly, but not exclusively, utilising jetting based technologies for the deposition of both structural and functional materials for electronic, pharmaceutical and biological structures and devices and varying length scales.

**12:05-1:30 LUNCH**

## Monday PM

### **Modeling I: CAD/CAE**

Room 201

Session Chair: Ming Leu, Missouri University of Science & Technology

#### **1:30-1:50 Improving Volumetric Accuracy of AM Parts using Adaptive Slicing of Octree based Structure**

*S.K. Malyala*, National Institute of Technology Warangal

In Additive Manufacturing (AM) processes, the layer-by-layer fabrication of complex geometries may lead to stair casing and thus error resulting in volumetric inaccuracies in the model. Using thinner slices reduces the staircase error and improves part accuracy, but there is a tradeoff between number of layers and the build time for manufacturing part. This paper presents an octree based structure to improve the accuracy as well as reduce the build time. In the current work, firstly is converting STL file into a modified boundary octree data structure (MBODS) and then calculating the non-uniform slice thicknesses (adaptive slicing) from the octree representation. This slice thickness at any height is computed from the AM machine parameters and the smallest octree size at that available height. After the computation of the variable slice thicknesses has been completed, the part is virtually manufactured and the part errors are calculated. The virtually manufactured part and physical models are inspected to evaluate the volumetric errors. This algorithm uses an octree approach to improve the volumetric accuracy. And build time for the two different case studies are also done

#### **1:50-2:10 Multi-direction Slicing of STL Models for Robotic Wire-feed Additive Manufacturing**

*D. Ding, Z. Pan, D. Cuiuri, H. Li, S. van Duin*, University of Wollongong

Robotic wire-feed additive manufacturing technology is possible to directly fabricate metallic overhangs without support structures through multi-direction deposition. To automatically produce complex components with overhangs, an efficient multi-direction slicing algorithm to slice CAD models into a set of proper layers is required. This paper reports the concept and implementation of a new strategy for multi-direction slicing of CAD models represented in STL format. An input STL model is firstly decomposed into sub-volumes using a simple curvature-based volume decomposition method. Accordingly, each sub-volume is able to be built in a single direction. Then a depth-tree structure is introduced to regroup the decomposed sub-volumes and provide the slicing sequences. Consequently, sub-volumes are separately sliced along their associated appropriate build directions in sequence. The proposed multi-direction slicing strategy is shown to be simple and efficient for STL models with sharp edges.

#### **2:10-2:30 Developing an Algorithm to Produce NURBS based Model from the STL File**

*Manmadhachary*, National Institute of Technology Warangal

Manufacturing of Bio-medical model is one of the current trends in Additive Manufacturing (AM). Stereo Lithography (STL) files were widely used for fabrication of physical Bio-model in AM. The STL files are generated from Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) data using Medical Scanning systems. STL is a neutral file format which cannot be modified. To overcome this and develop a customized prosthesis, recreation of the STL file became essential. In this paper, an automatic surface reconstruction algorithm is proposed to

obtain surfaces and solid model from the STL file. And STL file is primarily divided into an equal thickness of slices along the Z-axis direction. In each slice, contour data information is created as Common Layer Interface (CLI) file. These contours points are used to develop surfaces by using the non-uniform rational basis spline (NURBS). Further these surfaces are transformed into the solid models. Finally by applying this algorithm, modified STL model can fulfill required specifications of a prosthesis.

### **2:30-2:50      Quantifying Mechanical Property Degradation of Cellular Material using As-fabricated Voxel Modeling for the Material Extrusion Process**

*S.-I. Park, D. Rosen, Georgia Institute of Technology*

When fabricating cellular material using the material extrusion process, manufacturing errors arise due to approximation of geometries during slicing and tool-path generation, as well as the finite filament size. Moreover, since a cellular material generally consists of a large number of structural elements such as struts and plates, it has large bounding surfaces to be approximated during the AM process which can increase manufacturing error. The errors degrade the mechanical properties of a fabricated cellular material. In this paper, an as-fabricated voxel modeling approach is proposed to quantify mechanical property degradation. An additively manufactured strut is modeled using voxels based on material extrusion and its effective structural characteristics such as a cross-sectional area and the second moment of area are evaluated. The property degradation is assessed by comparing mechanical properties from tensile tests and performing discrete homogenization with obtained structural characteristics.

### **2:50-3:10      Recognizing 2D Non-linear Geometric Features in Material Microstructure using 2D Cylinderlet Based Method**

*N. Jeong, Y. Wang, D. Rosen, Georgia Institute of Technology*

To integrate material information into CAD systems, geometric features of material microstructure must be recognized and represented, which is the focus of this paper. 2D non-linear microstructure features, such as circular arcs, can be found computationally from microstructure image using 2D image processing methods, including the 2D circular Radon-like transform followed by the circle overlaying method. After computing the circular Radon-like transform, prominent circular features are indicated by large values in the coefficient set. By finding such peak values in the 2D Radon-like transform domain, radii and center coordinates of the circular arcs can be identified. After the circular Radon-like transform is applied, the circle overlaying method is used to identify start/end points of the circular arcs. In order to demonstrate feature recognition capabilities, synthetic and Fused-Deposition ABS plastic parts are used as examples.

### **3:10-3:40      BREAK**

### **3:40-4:00      Object Geometry and Fabrication Complexity in Additive Manufacturing Processes**

*A.M.M. Ahsan, B. Khoda, North Dakota State University*

This study aims to investigate whether the shape complexity of object promotes fabrication complexity in Additive Manufacturing (AM) processes. Freeform objects with complex geometry will generate contours with features that can be difficult to fabricate using AM techniques. In this paper, the shape complexity of an object is quantified along the four

dimensions, namely slenderness factor, height factor, width factor, and fill factor. These factors are measured and analyzed for a 3D object using computational geometry techniques. The weightage of the individual factor is determined using Hypothetical Equivalents and Inequivalents Method (HEIM). The normalized weighted sum of the four factors gives the measure of the object's shape complexity which in turn provides the ease of fabricatability matrix of a 3D object. By using this matrices, we propose a framework to optimize the process plan for free form complex geometry.

#### **4:00-4:20 FE-Optimization and Data Handling for Additive Manufacturing of Structural Parts**

*T. Reiher, R. Koch*, University of Paderborn

Additive Manufacturing (AM) offers high potential due to its freedom of design for structural parts. Especially in combination with FE-based topology optimization an optimal use of material and thus significant weight reductions can be expected. However, the application of AM is hampered by different additional manufacturing processes along the entire production chain and data handling induced restrictions.

Disadvantages emerge from a lack of adjustment of the entire design process for AM. First the optimization algorithms are not targeted to the opportunities and restrictions of AM - represented by design rules - like the design of support structures. Secondly, the CAD software is not adjusted to AM in particular. Creating freeform shaped surfaces based on the optimization results is significantly less convenient than building defined blocks or turning parts following the needs of conventional machining. The indispensable subsequent interpretation of optimization results regarding the design rules and the possibilities of CAD-tools counteracts optimal results. This paper considers different approaches for a Topology Optimization (TO)-shape regaining on different sample parts including telecommunication satellite parts. An innovative design methodology is presented getting crucial for creating high quality designs.

#### **4:20-4:40 A Digital Material Design Framework for 3D Printed Heterogeneous Objects**

*P. Huang<sup>a</sup>, Y. Li<sup>a</sup>, Y. Chen<sup>a</sup>, J. Zeng<sup>b</sup>*, <sup>a</sup>University of Southern California, <sup>b</sup>HP Labs

In this paper, we present a material design framework which produces 3D printable material distribution for given 3D shape and user requirements. The framework consists of three stages. In the first stage, continuous material distribution across the object is generated to achieve the given user requirement. In the second stage, a material dithering method is developed to approximate the continuous material distribution into 3D printable materials. An N-level tile based material pattern library is developed for the dithering method to provide close approximation results. Finite element analysis is used to evaluate the performance of the approximation. Finally, slicing data is generated that can be sent to 3D printer for fabrication. Cubic mesh is chosen to mimic the 3D printing process, and its resolution is carefully selected based on the specification of 3D printers. Concept verification of the design framework is conducted by comparing the simulation and physical experimental results. Several test cases are used to demonstrate the effectiveness of our framework.

#### **4:40-5:00 Selective Laser Sintering of Diamond Lattice Structures: Experimental Results and FEA Model Comparison**

*C. Neff<sup>a</sup>, N. Hopkinson<sup>b</sup>, N. Crane<sup>a</sup>*, <sup>a</sup>University of South Florida, <sup>b</sup>University of Sheffield

Nature utilizes multiple materials with varying properties to create high performance, integrated



systems. In contrast, most additive manufacturing processes are limited to a small set of compatible materials to fabricate a device. However, the large geometric freedom of AM could be used to create the effect of multiple properties by creating lattice structures. Prior work has focused on using this concept to reduce weight in high stiffness structures. This paper will consider the use of a diamond lattice structures to create the effect of materials with a low elastic modulus materials. Low stiffness regions are advantageous for energy absorption, vibration isolation, and reduction of stress due to dimensional or temperature mismatches. The diamond lattice possesses Face-Centered-Cubic (FCC) elemental configuration possessing tetrahedral angles of  $109^\circ$  between elements. This allows for a pliable moment exerted on the structure yielding a flexible and energy absorbent arrangement. A range of devices was fabricated in Nylon 12 (PA 2200) through Laser Sintering (LS) process with variable element size (thickness) and unit cell size. The effective stiffness of the structures is compared as a function of these parameters and compared to numerical simulation. The results show the possibility of tuning the effective elastic modulus by over four orders of magnitude

## **Modeling II: Powder Bed Fusion I**

Salon C

Session Chair: Y.B. Guo, The University of Alabama

### **1:30-1:50      Parameter Determination and Experimental Validation of a Wire Feed Additive Manufacturing Model**

*K.S. Kumar, T.E. Sparks, F. Liou*, Missouri University of Science & Technology at Rolla  
Laser metal deposition with wire feed is one of the additive manufacturing methods with great scope and robustness. Process parameters plays an important role in controlling the process and obtaining an ideal manufactured part. Simulations tools are highly essential in determining the ideal parameters and melt pool conditions. The current work is a transient 3D model of wire feed additive manufacturing which realizes the heat transfer and fluid flow behavior of the process with varying laser power and power density. The model was programmed in Python and a 1 KW Gaussian beam fiber laser was used to conduct experiments. The effect of laser exposure to the scanned and deposited profile on Ti-6Al-4V alloy is obtained. The comparison of simulation and experimental results shows that this model can successfully predict the temperature profile, and solidified metal profile. The optimum input parameters based on material properties can be identified using the model.

### **1:50-2:10      Mesoscopic Simulation of Heat Transfer and Fluid Flow in Laser Powder Bed Additive Manufacturing**

*Y. Lee, W. Zhang*, The Ohio State University

Laser-powder bed fusion (L-PBF) additive manufacturing involves complex physics such as heat transfer and molten metal flow, which have a significant influence on the final build quality. In this study, transport phenomena based modeling is used to provide a quantitative understanding of complex molten pool transients. In particular, a three dimensional (3D), transient numerical model is developed for L-PBF additive manufacturing by solving the governing partial differential equations of mass, momentum and energy conservation. The individual powder particles are resolved using the volume of fluid method (VOF) method with a fine mesh size of 3 mm (thus at meso-scale). The powder particle arrangement including particle size distribution

and packing density are taken into account in placement of individual particles calculated using discrete element method. Moreover, the model considers Marangoni shear stress, an important driving force for molten metal flow. The numerical model is used to quantitatively study the effect of laser power, scanning speed, and powder size distribution on the bead geometry and formation of balling defect.

### **2:10-2:30 Identifying Process Parameters for High-Density 316L SS Parts by Combining Simulations and Experiments using Data Mining**

*C. Kamath*, Lawrence Livermore National Laboratory

A challenge in laser powder-bed fusion is the selection of appropriate process parameters that result in parts with desired properties. While we can use extensive experimentation and complex simulations to determine the optimal parameters, this can be time consuming and expensive. Instead, we propose a more efficient method that uses data mining techniques to intelligently explore and analyze the design space of parameters. Using 316L stainless steel as an example, we discuss how we have exploited prior knowledge, design of computational experiments using a simple model of laser melting, and single-track experiments to determine the process parameters for parts with density greater than 99% at powers up to 400 W (Watts).

### **2:30-2:50 Simulation of Selective Beam Melting on the Powder Scale: Mechanisms and Process Strategies**

*A. Bauereiß, C. Körner*, University Erlangen-Nuremberg

Selective electron beam melting (SEBM) is especially interesting for the processing of high performance materials like titanium, titanium aluminides or nickel-base superalloys. In SEBM the beam can be moved with very high velocities, allowing unique scanning strategies. For these high performance materials it is crucial to understand the correlation between process and material parameters, process strategy and resulting microstructure.

In this contribution a numerical approach based on the Lattice Boltzmann Method is presented which is used to simulate selective beam melting processes on the scale of individual powder particles. The physical model takes into account absorption of the beam within the stochastic powder bed, melting and solidification, evaporation and selective loss of elements with low vapor pressure, wetting effects and full hydrodynamics of the melt pool. It is shown how the numerical tool can be used to understand the basic mechanisms during powder consolidation and to evaluate different process strategies.

### **2:50-3:10 Computer Simulation of Selective Laser Melting**

*A.T. Nimavardi, J. Pan*, University of Leicester

We present a computer simulation technique that has the potential to be used for optimisation of selective laser sintering/melting (SLS/SLM) to minimise residual stresses. Residual stresses in engineering components can be calculated using the classical finite element method by combining plasticity theory with heat transfer analysis. However it is extremely difficult to deal with adding new materials in a finite element model for such calculation, which is what happens in SLS/SLM. In this talk, an alternative computational technique, called as the material point method (MPM), is presented which has no difficulty in dealing with either adding or removing materials in a finite element model. The MPM was initially developed for plasticity analysis of extremely large deformation problems; it has been applied to a wide range of other problems. In

this talk, a preliminary demonstration example will be presented to show the potential of the method for simulating SLS/SLM.

**3:10-3:40      BREAK**

**3:40-4:00      Mesoscopic Simulation of Main Physical Phenomena in Metal Powder Bed Fusion**

*S. Khairallah, A. Anderson, A. Rubenchik*, Lawrence Livermore National Laboratory  
A 3D model is developed to simulate laser powder bed fusion at the mesoscopic level. The model consists of a direct laser beam interacting with a random bed of stainless steel 316 particles on a solid substrate. The model reveals the main physical processes that take place during laser scanning. In particular the study emphasizes the importance of the vapor recoil pressure and the Marangoni effects on pool dynamics, melt track surface quality, material densification and the creation of sparks as observed in the actual experiment. Appropriate surface cooling in terms of radiation and evaporative cooling is accounted for.

**4:00-4:20      A Temperature-Thread Multiscale Modeling Approach for Efficient Prediction of Part Distortion by Selective Laser Melting**

*C. Li<sup>a</sup>, J.F. Liu<sup>a</sup>, Y.B. Guo<sup>a</sup>, Z.Y. Li<sup>b</sup>*, <sup>a</sup>The University of Alabama, <sup>b</sup>Shandong University of Technology

Selective laser melting (SLM) is a powder bed based additive manufacturing process to manufacture functional parts. The high-temperature process will produce large tensile residual stress which leads to part distortion and negatively affect product performance. Due to the complex process mechanism and coupling multi-physics phenomena, the micro-scale single laser scan modeling approach is not practical to predict macro part distortion since it demands an exceedingly long computational time. In this study, a temperature-based multiscale modeling approach has been developed to simulate material phase transition of powder-liquid-solid for fast prediction of part distortion. An equivalent body heat flux obtained from the micro-scale laser scan can be imported as “temperature-thread” to the subsequent layer hatching process. Then the hatched layer with temperature field can be used as a basic unit to build up the macro-scale part with different scanning strategies. The temperature history and residual stress fields during the SLM process were obtained. In addition, the part distortion can be predicted with a reasonable accuracy by comparing with the experimental data.

**4:20-4:40      Stress-Thread Multiscale Modeling of Deflection and Residual Stress for Metal Parts by Selective Laser Melting**

*C. Li, C.H. Fu, Y.B. Guo*, The University of Alabama

Selective laser melting (SLM) is a widely used laser additive manufacturing process to producing functional metal parts. The severe temperature gradient resulted from rapid powder melting and solidification in SLM results in high tensile residual stress and part distortion. Traditional modeling approaches are limited to the single microscale laser scan, which is not capable of predicting the distortion and residual stress of a macro part due to the extremely high computational cost. In this work, a stress-thread multiscale modeling approach enabling fast prediction of part distortion and residual stress of a macro part has been proposed. A concept of equivalent heat source has been developed for the microscale laser scan model. Local residual stress field can be predicted in the mesoscale layer hatch model using the equivalent heat source.

Then the residual stress field is imported (i.e., stress-thread) to the macroscale part model to predict residual stress and part distortion. This multiscale modeling approach has been applied to a single layer deposition process with four different scanning strategies, namely, horizontal sequential, vertical sequential, successive, and least heat influence. The stress fields from different laser scanning vectors are modeled by the stress transformation. The deflection and residual stresses were predicted. Also, the layer deflection was validated with the experimental data.

#### **4:40-5:00 Part-level Finite Element Simulation of Selective Laser Melting**

*N. Hodge, R. Ferencz, R. Vignes*, Lawrence Livermore National Laboratory

Selective Laser Melting (SLM) is a manufacturing process which can realize significant benefits over traditional manufacturing processes, including significantly shortened time between design and manufacture of parts, and the ability to create parts with much more geometric complexity than has previously been possible or tenable. However, the extreme sensitivity of the results to input parameters results in a process that is difficult to predict, and thus control. Indeed, it is not uncommon for the resulting parts to vary significantly from their as-designed geometry, due to the influence of extreme and inhomogeneous thermal gradients. The goal of this research is to determine the physics needed to represent this problem at the part scale, and to develop the numerical methods necessary to simulate the problem.

The first part of the presentation will present a review of the continuum modeling strategies and numerical methods. The current work uses a model originally published by Gusarov, et al., to represent the effect of the laser. The material is considered a multi-physics continuum, with a coupled thermal-solid material model. The thermal model includes features to represent the phase changes, as well as different constitutive parameters to define the behavior of the different solid states (powder vs. bulk). The coupling happens via both the usual mechanisms, as well as the dependence of the material properties on the phase.

The second part of the presentation presents studies of the correlation between the numerical solutions and various experimental results. Several experimental configurations have been studied in an effort to characterize the effect of the process parameters on the final part, with the samples being on the centimeter scale. The experimental results derived from these samples will be compared to the simulation solutions, and in particular, residual deformations and stresses will be discussed.

#### **Applications I: Cellular Structures and Topology Optimization**

Room 203

Session Chair: Li Yang, University of Louisville

#### **1:30-1:50 Adaptive Topology Optimization in Non-academic Applications**

*N. Leathe*, Sandia National Laboratories

Topology optimization algorithms, coupled with additive manufacturing, allow of the computational enhancement of mechanical system performance under predicted loading conditions. These algorithms optimize the mechanical structure for the desired outcome. This presentation will look at a handful of applications using adaptive topologically optimized structures to improve stiffness while maintaining weight and thus the desired mechanical

performance. A comparison between the computational modeling and physical data will be presented.

### **1:50-2:10 Integration of Topology Optimization with Efficient Design of Additive Manufactured Cellular Structures**

*L. Cheng<sup>a</sup>, P. Zhang<sup>a</sup>, E. Biyikli<sup>a</sup>, J. Bai<sup>a</sup>, S. Pilz<sup>b</sup>, A.C. To<sup>a</sup>*, <sup>a</sup>University of Pittsburgh, <sup>b</sup>ANSYS, Inc.

Cellular structures are promising candidates for additive manufacturing to design lightweight and complex parts to reduce material cost and enhance sustainability. In the paper, we focus on the integration of the topology optimization with the additive manufactured cellular structures. In order to take advantage of these two technologies for lightweight manufacturing, a totally new design and CAD method is developed to build up the bridge between the optimal density distribution and the cellular structure. First, a systematic theoretical and experimental framework is provided to obtain the mechanical properties of cellular structures with variable density profile. Second, a revised topology optimization algorithm is introduced to optimize arbitrary 3D models with given boundary conditions. In this process, the minimum compliance problem and allowable stress problem are considered to get the relative density distribution. Third, CAD methods are developed to obtain the function between the local relative density and the variable density of cellular structure. With the aid of the function, one can convert the density distribution to the cellular vertex radius distribution and build variable density cellular structures in the given parts. Finally, a real part named pillow bracket is designed by this process to illustrate the efficiency and reliability of the new method.

### **2:10-2:30 Minimum Compliance and Constrained Stress Topology Optimization for Additive Manufacturing**

*L. Cheng, E. Biyikli, J. Bai, A.C. To*, University of Pittsburgh

Additive manufacturing (AM) technologies, make it possible to fabricate components and devices with complex geometries. With the ability to remove materials from the design domain and satisfy the boundary conditions and certain performance metrics at the same time, topology optimization has drawn increasingly more attention for AM. The optimal topology of a structure involves great geometric and materials complexity, which can take full advantage of the unique capability of AM technologies. In this presentation, a new topology optimization algorithm called the Proportional Topology Optimization (PTO) is proposed to systematically remove the redundant material from the design domain for 3D parts. PTO method is a non-gradient and heuristic optimization algorithm, which is simple to understand but efficient and accurate to implement. Minimum compliance and constrained-stress mass minimization problems for 2D and 3D structures are solved by PTO respectively, and the results of these two problems are compared with each other for the same geometries and loading. After the topology optimization, computer-aid design (CAD) and design for manufacturing (DFM) methods are proposed to construct the optimal topology structure for additive manufacturing and further experiments.

### **2:30-2:50 Proportional Topology Optimization of Natural Frequency: Algorithm, 3D Printing, and Testing**

*X. Wang, E. Biyikli, L. Cheng, A.C. To*, University of Pittsburgh

Frequency optimization has an important role in engineering structures to avoid resonance. This paper introduces a new topology optimization method called the Proportional Topology

Optimization (PTO) that maximizes the minimum natural frequency in the system in order to keep the resonant frequency away from external excitation frequency range. PTO is a non-sensitivity algorithm that aims to solve the difficulties associated with sensitivity-based methods. It is easy to understand and the main idea of this algorithm is assign the design variables to elements proportionally to the value of which has a relation with the target function. The classical stress and compliance problems have been solved using this algorithm and this paper would focus on the frequency optimization.

Apart from the checkerboard and mesh dependent phenomena that are commonly found in static topology design problems, multiple eigenvalue, modes switch and localized modes also occur in optimal dynamic topology design, especially the last issue. Localized modes emerge in areas with lower densities and causes oscillation during the optimization process. Standard approaches such as the SIMP or modified SIMP, employed in conjunction within the PTO algorithm, do not resolve the issue. A new polynomial interpolation function proposed by Wang penalizes the Young's modulus and is able to alleviate this problem. Starting from analysis of the continuity of frequency when the topology of the structure changes and the cause of localized mode, the polynomial interpolation function is shown to satisfy the guideline for construction of function between stiffness and densities.

This polynomial penalization function for Young's modulus is employed in the PTO method for frequency optimization. Several numerical examples will be presented where our results show that the PTO method maximizes the minimum natural frequency of structures and reaches an almost completely black/white solution. Hence the polynomial interpolation penalization successfully avoids localized modes.

A new reconstruction method by using cellular structure will also be used to deal with the intermediate density. By the integration of topology optimization and cellular structure, several parts will be optimized and reconstructed for further testing by additive manufacturing.

### **2:50-3:10      Lattice-skin Structures Design with Orientation Optimization**

*Y. Tang, Y.F. Zhao, McGill University*

Parts with complex geometry can be produced by an additive manufacturing process without a significant increase of fabrication time and cost. One application of AM technologies is to fabricate customized lattice structures to enhance products' performance with less material and less weight. Thus, design methods of customized lattice structures have recently attracted great research interests. Most existing design methods only consider the distribution of lattice struts' thickness as a primary design variable for customized lattice structures. Few of them notice the importance of lattice orientation with regard to its structural performance. In this paper, a design method for customized lattice-skin structures is proposed to optimize the distribution of lattice orientations inside the design domain. In this design method, an initial Functional Volume (FV) is divided into several sub-FVs and connected with additional Functional Surfaces (FSs). The orientation of uniform lattice in each sub-FV is regarded as the design variable. To optimize the design variables, an equivalent analysis model based on the effective orthotropic properties of lattice structures is built. On the basis of this model, genetic algorithm is applied to obtain the optimized distribution of lattice orientations. Two case studies are provided at the end of this paper to validate the proposed design method.

### **3:10-3:40      BREAK**

**3:40-4:00 Shear Properties of the Re-entrant Auxetic Cellular Structure Made via Electron Beam Melting**

*L. Yang<sup>a</sup>, O. Harrysson<sup>b</sup>, D. Cormier<sup>c</sup>, H. West<sup>b</sup>*, <sup>a</sup>University of Louisville, <sup>b</sup>North Carolina State University, <sup>c</sup>Rochester Institute of Technology

While the tensile/compressive mechanical properties of the re-entrant auxetic cellular structure have been relatively well modeled, their shear properties including the shear modulus and shear strength have not been investigated. This paper focuses on the modeling and experimental verification of the shear properties of this auxetic structure. With the establishment of shear properties, the comprehensive material property model for the re-entrant auxetic structure will enable its homogenization and further applications.

**4:00-4:20 A Study of the Manufacturing Issues of Metal Cellular Structures via Powder Bed Fusion AM**

*S. Zhang, L. Yang, B. Stucker*, University of Louisville

Cellular structures are widely used in many engineering applications, because of their light weight, high strength-to-weight ratio, high energy absorption, etc. Many previous research and development works are largely focused on structural design while ignoring the material properties. In this work, a combined material/structural geometry model is employed, which integrated material properties and geometrical features, on Ti-6Al-4V octahedral cellular structures. The impact of fabrication process on both the geometrical and mechanical characteristics of the cellular geometries fabricated via selective laser melting (SLM) was investigated. The results provide a guideline to the manufacturing issues of cellular structures using laser melting additive manufacturing.

**4:20-4:40 Performance of Additively Manufactured Negative Stiffness Honeycombs under Impact**

*D. Correa, K. Bostwick, M. Haberman, C. Seepersad*, University of Texas at Austin

Negative stiffness honeycombs materials are comprised of negative stiffness beams arranged in ordered arrays and are capable of providing isolation from impacts and returning to their initial shape. In previous research, the authors have limited investigations on the behavior of negative stiffness honeycombs to quasi-static loading conditions. This paper investigates the behavior of similar negative stiffness honeycombs under impact. The construction of an impact testing rig for the experimental evaluation of negative stiffness honeycombs is discussed. Experimental results from impact tests performed on honeycomb prototypes manufactured using selective laser sintering (SLS) in nylon 11 material are presented and compared with analytical and FEA predictions as well as quasi-static test results. Additionally, the effect of ambient temperature on the behavior of nylon 11 honeycombs under impact is also discussed.

**4:40-5:00 Fabrication of Cellular Ceramic Preforms via Binder Jetting**

*D. Snelling, C. Suchicital, A. Druschitz, C. Williams*, Virginia Tech

Metal Matrix Composites (MMCs) combine two dissimilar materials - metal matrix and ceramic core materials - to provide unique mechanical properties including low density, high specific strength, high specific modulus, high thermal conductivity, and wear resistance. The ceramic cores in these materials are limited to ceramic fibers and open cell stochastic ceramic foams due to geometric constraints imposed by traditional manufacturing processes. The geometric design freedom offered by Additive Manufacturing (AM) could enable a designer to realize ceramic

preforms with complex cellular geometries that are designed to achieve multiple functions (e.g., low mass and increased stiffness). The goal of this work is to explore the use of Binder Jetting as a means of fabricating cordierite structures of designed mesostructure for use as ceramic preforms for MMCs. In this paper, the authors describe their exploration of the appropriate printing process parameters and post-process sintering parameters that enable successful fabrication of complex cordierite artifacts. Measurements of bulk density, linear shrinkage, porosity, and x-ray diffraction are conducted on pre- and post-sintered printed cordierite structures are conducted.

## **Materials I: Titanium I**

Salon AB

Session Chair: Tom Starr, University of Louisville

### **1:30-1:50      Microstructure and Mechanical Property of Electron Beam Selective Melting Ti6Al4V/TiAl Structural Gradient Material**

*W. Ge*, Tsinghua University

Electron beam selective melting (EBSM) is an additive manufacturing technique that directly fabricates three-dimensional parts in a layerwise fashion by using an electron beam to scan and melt metal powder. In recent years, EBSM has been successfully used in the additive manufacturing of a variety of materials. Previous research focused on the EBSM process of a single material. In this study, a novel EBSM process capable of building a gradient structure with dual metal materials was developed. A powder-supplying method based on vibration was put forward. Two different powders can be supplied individually and then mixed. Two materials were used in this study: Ti6Al4V powder and Ti47Al2Cr2Nb powder. Ti6Al4V has excellent strength and plasticity at room temperature, while Ti47Al2Cr2Nb has excellent performance at high temperature, but is very brittle. A Ti6Al4V/Ti47Al2Cr2Nb gradient material was successfully fabricated by the developed system. The microstructures and chemical compositions were characterized by optical microscopy, scanning microscopy, and electron microprobe analysis. Results showed that the interface thickness was about 300  $\mu\text{m}$ . The interface was free of cracks, and the chemical compositions exhibited a staircase-like change within the interface.

### **1:50-2:10      Microstructural Characterization of Ti-6Al-4V Made by Electron Beam Melting**

*J. Beckman<sup>a</sup>, M. Seifi<sup>b</sup>, M. Dahar, O. Harrysson<sup>c</sup>, N. Klingbeil<sup>a</sup>, J. Beuth<sup>d</sup>, J. Lewandowski<sup>b</sup>*,  
<sup>a</sup>Wright State University, <sup>b</sup>Case Western Reserve University, <sup>c</sup>North Carolina State University, <sup>d</sup>Carnegie Mellon University

In process qualification studies, consistency of properties is often more important for technology acceptance than achieving any particular property goal. Therefore, an improved understanding of microstructural variability is crucial. With the proliferation of additive manufacturing technologies in recent years, process qualification is needed to ensure consistent properties of manufactured parts. Being able to correlate process variables, such as power and velocity, with resulting microstructure, as well as how varying microstructure affects bulk properties, can allow some control to keep properties consistent. Additionally, prior studies have shown orientation effects and anisotropy in fracture and fatigue properties of Ti-6Al-4V manufactured by electron beam melting process. To better understand variation in fracture and fatigue properties, detailed



characterization of the microstructure is needed to provide insight into how the microstructure can change in different orientation with respect to build direction using various techniques (e.g. SEM/EBSD).

### **2:10-2:30      Microstructural Tailoring and Fatigue Performance of Ti-6Al-4V Fabricated by Electron Beam Melting Additive Manufacturing**

*P.A. Morton, H. Mendoza, J. Mireles, R.B. Wicker, University of Texas at El Paso*

Intentional spatial microstructural gradients have been achieved through the electron beam melting (EBM) additive manufacturing (AM) process by means of controlling thermal energy input and altering scanning strategies. The microstructural tailoring achieved can be used to spatially control mechanical properties to selectively strengthen or weaken desired locations within an AM fabricated part. Part property tailoring can be used in damage tolerance design and potentially allow for controlled failure of aerospace components. Fatigue test specimens were designed with a stress concentrator to localize a failure region, and fabricated out of Ti-6Al-4V via EBM. Specimens that used the commercial Arcam Ti-6Al-4V (as-fabricated and machined) and additional specimens containing tailored microstructure (as-fabricated and machined) were tested. Load controlled fatigue tests were performed to determine cycle life. Differences in crack propagation rates were measured by fractography. Furthermore, effects of post-fabrication heat treatments were investigated for their effect on EBM microstructure. Preliminary work presented herein lays the groundwork for microstructural control enabled by EBM and establishes additional degrees of control within the AM process. Approved for Public Disclosure Case Number: 88ABW-2015-2367

### **2:30-2:50      An Investigation of Process Variables Required for Fully Equiaxed Microstructure in Additive Manufacturing of Ti-6Al-4V**

*S. Kuntz, N. Klingbeil, Wright State University*

A current challenge in additive manufacturing (AM) is the inability of existing AM processes to fabricate titanium structures with fine, fully-equiaxed solidification microstructure. Additive processes have attained Ti-6Al-4V microstructures with a mixture of columnar and equiaxed beta grains, and have achieved fully equiaxed beta grains in similar alloy systems. This suggests that fully equiaxed microstructure may be attainable in additive manufacturing of Ti-6Al-4V. The current work builds on previous analytical and numerical models of the thermal conditions governing solidification microstructure in beam-based additive manufacturing, where the focus was at the top surface of the melt pool. The present study employs a first-order approximation of solidification conditions at the deepest extent of the melt pool, examines why existing additive manufacturing processes are unable to produce fully equiaxed structures, and estimates the combination of process variables that would be required for fully equiaxed grain growth throughout the depth of the melt pool.

### **2:50-3:10      Multi-Objective Design of Experiments for Material Properties Optimization: Case Study on Laser Powder Bed Deposited Ti-6Al-4V**

*A.M. Aboutaleb<sup>a</sup>, L. Bian<sup>a</sup>, A. Elwany<sup>b</sup>, N. Shamsaei<sup>a</sup>, S.M. Thompson<sup>a</sup>, <sup>a</sup>Mississippi State University, <sup>b</sup>Texas A&M University*

Simultaneously optimizing the density and compressive yield strength of Ti-6Al-4V fabricated via Powder Bed Fusion-Laser (PBF-L) is a challenging problem due to the latent-complex relationships between them and the process parameters. Due to the large space of free variables

in PBF-L processing, optimizing several material properties is an extreme challenge. Hence, we develop a novel multi-objective sequential Design-of-Experiment methodology to optimize PBF-L process parameters for Ti-6Al-4V by taking advantage of available data from similar studies. Owing to the inevitable differences in experimental conditions (e.g. alloy composition, equipment type, etc.) of current and prior studies, using only prior data would introduce error. The proposed method accounts for such differences and iteratively calibrates the prior data based on the current experimental condition to minimize the number of experiments required to learn optimal PBF-L process parameters for targeted material properties.

### **3:10-3:40      BREAK**

### **3:40-4:00      Residual Stress in Metal Specimens Produced by Direct Metal Laser Sintering**

*I. Yadroitsava, I. Yadroitsev*, Central University of Technology, Free State

Direct Metal Laser Sintering (DMLS) has great potential in Additive Manufacturing because it allows produce of full-density complex parts with the desired inner structure and surface morphology. Due to the nature of this process, DMLS parts have anisotropy of mechanical and structural properties. High-concentrated energy input lead to high thermal gradient which induces residual stress within the as-built DMLS part. High residual stress causes deformation of parts, changes their geometric dimensions and formation of cracks and even delamination of the parts from the substrate and the supports structures. The residual stress depends on material properties; geometry of the samples and support structures; process parameters as energy input, powder layer thickness, scanning strategy, hatch distances, preheating, etc. In this study, an X-ray diffraction technique and numerical simulation were used for investigation of the residual stress in SLM samples fabricated from stainless steel 316L and Ti6Al4V alloy. Conclusions regarding directions and values of stresses in SLM objects are given.

### **4:00-4:20      Linking Thermal History to Microstructure during AM of Ti-6Al-4V**

*J. Irwin<sup>a</sup>, P. Michaleris<sup>a</sup>, T. Reutzel<sup>a</sup>, J. Keist<sup>a</sup>, G. Loughnane<sup>b</sup>*, <sup>a</sup>The Pennsylvania State University, <sup>b</sup>Wright State University

The microstructure of additively manufactured Ti-6Al-4V undergoes complex changes throughout the deposition process. Due to the repeated thermal cycling that occurs with each layer, modeling this evolution poses a greater challenge than modeling the microstructure of a single-cycle heat treatment. Following the work of Kelly and Charles, a model has been developed which calculates the phase fractions, morphology, and alpha lath width given a thermal history. Dissolution of the alpha phase is modeled as 1D plate growth of the beta phase, while alpha growth is modeled by a Johnson-Mehl-Avrami model. The alpha phase is divided into colony and basketweave morphologies based on an intragranular nucleation temperature. Evolution of alpha lath width is calculated using an Arrhenius equation. The Kelly-Charles model developed here is optimized using the Nelder-Mead simplex algorithm. The optimized model gives an error of 24% relative to experimentally measured lath widths, compared to 106% for the original Kelly-Charles model.

**4:20-4:40      Emittance Measurements of Metallic and Ceramic Powders and Melts at High Temperatures - Present Status and New Opportunities**

*S. Mekhontsev, L. Hanssen, S. Grantham, V. Khromchenko, M. Vlasea, NIST*

Knowledge of spectral emittance of materials is essential for non-contact thermometry, heat transfer modeling, and prediction of directed energy sources coupling with the target (for example, in laser-based material processing and manufacturing). Even the latest “emissivity-free” multi-spectral methods of radiation thermometry, which do require absolute knowledge of emittance, can greatly benefit from validation using the material of interest with well-known absolute temperature of the surface.

The paper reviews present status and new opportunities for measurements of spectral emittance of powders and melts of metal and ceramic materials at temperatures above 1000 C in laboratory conditions. Paper also includes objectives and goals of the TEMPS facility under construction at NIST, which is aimed at establishment of measurement traceability and best practices for non-contact thermometry in additive manufacturing to improve the reproducibility and control of manufacturing processes.

**4:40-5:00      Toward Enabling Spatial Control of Ti-6Al-4V Solidification Microstructure in the Electron Beam Melting Process**

*S. Narra, R. Cunningham, D. Christianse, J. Beuth, A. Rollett, Carnegie Mellon University*

In this work, the relationships between prior beta grain size in solidified Ti-6Al-4V and melting parameters in the Arcam Electron Beam Melting (EBM) process are investigated. Toward this goal, samples are built on Arcam equipment at Carnegie Mellon University by specifically varying the Arcam machine’s proprietary speed function and beam current. Optical microscopy is used to measure prior beta grain widths and estimate the number of prior beta grains present across a melt pool in both contour and raster regions. This understanding of the relationship between primary machine variables and prior beta grain widths is a step toward enabling the spatial control of as-built microstructure in the EBM process.

**Process Development II: FDM Processes**

Salon DE

Session Chair: Scott Johnston, The Boeing Company

**1:30-1:50      Multi3D: A 3D Printing System that Uses Multiple Technologies for 3D Electronics**

*D. Espalin, E. MacDonald, R. Wicker, The University of Texas at El Paso*

Through an America Makes award and a collaboration between industry (Stratasys, Lockheed Martin, and Northrop Grumman) and educational institutions (University of New Mexico and Youngstown State University), a multi-technology system has been developed to fabricate electronic devices using the material extrusion technology developed by Stratasys, Fused Deposition Modeling (FDM). To link the multiple required technologies, a six-axis robot was used as a build platform handler to transport a workpiece between manufacturing stations. Included in the system are two Fortus 400mc (FDM) machines for depositing thermoplastic materials, a CNC router for micromachining the feature details required for electrical circuits, and wire embedding technology for creating interconnections between electronic components. The challenges of bringing together this set of technologies will be discussed, and the anticipated

parts that it can fabricate, including miniaturized satellites for the aerospace industry, will be reviewed.

**1:50-2:10      A Novel 3D Printing Assisted Manufacturing Process for Mounting Electronic Circuit on Conformal Surfaces**

*A. Sharma, R. Rai*, University at Buffalo-SUNY

In this paper, we outline a hybrid process to print stretchable electronic circuits on non-planar surfaces. Using this process, the stretchable structures, generated using traditional printed circuit board fabrication technology can be printed on conformal surfaces using transfer printing by PDMS membranes. Three different configurations of stretchable structures for use in the circuits are also compared for their robustness of shape representation and structural strength. The application of the proposed process is illustrated through application examples.

**2:10-2:30      Embedding of SMD Populated Circuits into FDM Printed Objects**

*F. Wasserfall*, University of Hamburg

This paper introduces the concept of a highly integrated 3D-printing device which is capable of printing plastic parts with integrated, fully assembled electronic circuits in a single process. It is based on a standard FDM 3D-printer that has been augmented by a screw-driven conductive paste extruder for electronic circuit printing, a vacuum nozzle to pick and place SMD-components and a vision system to find and precisely align the components before placing. To control the printer, an existing host software system has been extended to synchronize the communication with the printer for interactive operations and to generate the required movements from camera data by means of image processing.

A number of objects, containing circuits on both the surface and inside of the object, has been successfully printed already. Quality and durability of the generated parts have been evaluated by analyzing the curing characteristics of the conductive ink during the process and the adhesion of the components which are placed directly on the wet ink. The design concept aims for a practical, affordable approach that can be widely used by developers to lower the entrance barrier to the field of 3D-printed electronics. Hence, the hardware is kept as simple as possible, avoiding complex and expensive components as laser or CNC-milling devices, focusing on algorithmic improvements in the preprocessing and control software. All developed hard- and software-components are available under open source licenses and compatible to common existing projects.

**2:30-2:50      Solvent Consolidation 3D Printing**

*R. Aman, E. Janosko, P. Mehta*, Rochester Institute of Technology

Filament extrusion (FE) processes have notoriously poor and anisotropic mechanical properties as compared to bulk or molded materials. This is in part because of the reduced interfacial bonding between and within layers. Additionally, parts produced using FE processes are generally porous and not water-tight. A new process, Solvent Consolidation 3D Printing (SC3DP), is proposed to produce fully dense and water-tight thermoplastic parts using traditional inkjet printing technology with solvents on a powder bed. The solvents reduce the glass transition temperature of the thermoplastic polymer powder below the ambient temperature and result in material flow and consolidation. An overview of the process, current capabilities and special considerations will be presented.

**2:50-3:10 Development of a Reliable Automated System for Removing ABS Parts from an FDM Machine**

*S. Bashyam, C. Seepersad*, University of Texas at Austin

Removing successfully printed ABS parts is difficult and can lead to broken parts and build surfaces. In order to have sufficient adhesion during a build, ABS parts will remain stuck to the build plate long after a build has been completed. This paper details the development and testing of an automated part removal process for ABS parts. The parameters involved in the process, including materials and temperatures, are documented. The part removal process can reliably remove parts with large and small surface areas and prepare the printer for subsequent prints.

**3:10-3:40 BREAK**

**3:40-4:00 A Method for Assessing the Rates of Mixing and Reaction in Reactive Ink Jet Printing (RIJP)**

*C. Sturgess, R. Wildman, C. Tuck, I. Ashcroft*, University of Nottingham

In current commercially available inkjet SFF systems the polymers used are conventionally UV curable, often the polymers processed are modified for the inkjet process. This modification is one of the main barriers to inkjet printing desirable polymers, with the high mechanical properties required by industry.

Removing this modification step is the driving force behind RIJP, through printing multiple monomers or pre-polymers onto the substrate - reactions which were previously unavailable can be used. Typically the reactions associated with RIJP are carried out in large scale reactors, but through the use of a layer approach minimising length scales the ability of diffusion to completely mix the reactants is possible.

As RIJP relies so heavily on diffusion, any effect on viscosity due to the proceeding reaction has the potential to greatly lower the final degree of cure. A new method has been explored to investigate the complex chemical and fluid dynamic problem. This method can track the reactants at a micron length scale and a millisecond time scale of a real RIJP case, tracking the reaction as it occurs.

**4:00-4:20 Design and Optimization of a High Temperature Microheater for Inkjet Deposition**

*A. VanHorn, W. Zhou*, University of Arkansas at Fayetteville

Inkjet deposition has become a promising additive manufacturing technique due to its fast printing speed, scalability, wide choice of materials, and compatibility for multi-material printing. Among many different inkjet techniques, thermal inkjet, led by Hewlett-Packard and Canon, is the most successful inkjet technique that uses a microheater to produce a pressure pulse for ejecting droplets by vaporizing the ink materials in a timespan of microseconds. Thermal inkjet has been widely adopted in many commercial 3D inkjet printers (e.g., 3D Systems ProJet X60 series) due to its low cost, high resolution, and easy operation. However, the viscosity of the printable materials has been limited to less than 40cP due to insufficient energy provided inside the nozzle to overcome the viscous dissipation of energy. This paper presents a study on the design and optimization of a high temperature microheater with a target heating temperature of more than 600°C (compared to ~300°C for current printhead) to increase the energy supply to the nozzle. The benefits are fourfold: 1) higher temperature will lead to faster vaporization of ink and thus higher jetting frequency and print speed; 2) higher temperature will

make it possible for jetting materials with higher boiling points; 3) higher temperature will reduce the viscosity of the ink and thus the viscous dissipation of energy; 4) higher energy supply will increase the magnitude of the pressure pulse for printing more viscous materials. In this paper, a high temperature microheater was designed with the following objectives: to reduce the electrothermal response time (and thus increase the jetting frequency), to reduce thermal stress in heaters, and to minimize uneven heat distribution. A literature survey was first conducted on design, fabrication, and operation of thin-film resistive microheaters. A multiphysics numerical model was then developed to simulate electrical, thermal, and mechanical responses of the microheater. The model was validated by comparison to experimental data and existing models obtained from literature. With proper parameterization of the design (geometry and materials), optimization is performed using a particle swarm optimization method. Results show the optimized high temperature microheater successfully operates at temperatures in excess of 600°C. The design optimization enabled better characteristics than the initial design with respect to the design objectives.

#### **4:20-4:40      The Heterogeneous Compensation for the Infiltrative Error of Binder Jetting Additive Manufacturing Processes**

*X. Ma, F. Lin, L. Zhang, Tsinghua University*

In binder jetting additive manufacturing, such as Three Dimensional Printing (3DP) and Patternless Casting Manufacturing (PCM, a process similar as ExOne and VoxelJet), the building error is mainly caused by the infiltration by the binder in the powder bed, and appear heterogeneous magnitude along different orientations because of the different infiltrating depth of the printed binder between the building direction and the binder printing direction. Current methods to compensating these error are mostly based on the contour equidistant offset and the model shrinkage, which couldn't deal with the heterogeneous infiltrative error. In this paper, we will propose a novel compensation method, in which the STL model will be counteracted heterogeneously in different directions to compensate the heterogeneous infiltrative distances of the binder in the powder. By this method, a sphere STL model will be transferred into an ellipsoid with variant axis length along different X/Y/Z directions. The method could greatly improve the dimensional accuracy of a series of additive manufacturing techniques which are based on the binder jetting onto powder bed.

#### **4:40-5:00      Study of Infill Print Parameters on Mechanical Strength and Production Cost-Time of 3D Printed ABS Parts**

*L. Baich, G. Manogharan, Youngstown State University*

The ever-growing adoption of Additive Manufacturing (AM) can be attributed to lowering prices of entry-level extrusion-based 3D Printers. It has enabled using AM for mainstream DIY, STEM education, prototypes and often, to produce custom complex commercial products. With the growing number of available printers and newer materials, the influence of print parameters specifically in-fill patterns on the mechanical strength and print costs need to be investigated. This study presents the correlation of in-fill pattern selection and several mechanical properties along with final part cost and production time. In-fill with varying design parameters are analyzed with respect to mechanical properties determined using ASTM standards, fabrication cost and time. Relevant applications are presented for all the varied in-fill designs. Findings from this study will help formulate criteria for relevant economically sound in-fill design pattern for real world applications.

## Tuesday AM

### **Modeling III: Powder Bed Fusion II**

Salon C

Session Chair: Annie Wang, Senvol

#### **8:15-8:35 Powder Bed Generation for Nanoparticle Thermal Analysis**

*A. Yuksel, M. Cullinan*, University of Texas at Austin

Micro Selective Laser Sintering ( $\mu$ SLS) has generated a great deal of attention recently because it can be used to fabricate parts with microscale features directly from 3-D CAD models.

However, much is still not well understood about how  $\mu$ SLS with nanoparticles differs from traditional SLS processes. For example, at sub-micron level, interactions between nanoparticles under laser heating creates near-field thermal effects which are not present at larger scales.

Therefore, in this paper we present a new model of the  $\mu$ SLS using the multiphase computational fluid dynamics simulation tool, MFIX, to generate an SLS powder bed with nanoparticles.

Within the MFIX framework, a discrete element model (DEM) is used in which solid particles can be generated by defining a position and radius. The solid particles interacting with the neighboring particles are distributed randomly into the powder bed domain with an initial velocity and a boundary condition, which creates the particle packing.

#### **8:35-8:55 Melt Pool Evolution Study in Selective Laser Melting**

*B. Cheng, K. Chou*, The University of Alabama

In selective laser melting (SLM) additive manufacturing, the completion of the entire scanning cross-sectional area of each layer build is consisted of many smaller scanning patches. Hence, the scanning length in each path may be too short to reach the quasi-steady state, thus, affecting the melt pool geometry, which is also effected by the process parameters. It is also known that the melt pool size correlates with the build part microstructures and properties. In this study, temperature simulations, finite-element based, of SLM is applied to track the thermal response during scanning of an individual patch. The results show that the process parameters determine the melt pool evolution, which affects the actual molten pool size in the regions defined by the raster scanning length. Manipulating the scanning path length and process parameters, based on the melt pool evolution information, may help to achieve a desired melt pool size for part quality controls.

#### **8:55-9:15 Simulations of Powder Bed Formation for Additive Manufacturing**

*D. Bolintineanu, J. Lechman*, Sandia National Laboratories

Several important additive manufacturing technologies rely on layer-by-layer deposition of powder-based materials (e.g. selective laser melting/sintering). We present discrete element method (DEM) simulations pertaining to the processing of such powders in the context of additive manufacturing. Several commonly used powder spreading approaches are modeled, and basic features of typical machine geometries are captured. Structural features of the powder bed are characterized as a function of processing parameters as well as powder properties, including particle size distribution and particle contact parameters (e.g. stiffness, friction and cohesion). In particular, heterogeneity in the surface of spread powder layers as well as the bulk of the powder bed are characterized. We show that significant heterogeneity persists on length scales comparable to the typical laser spot size and single powder layer thickness, which may have

important implications for larger-scale process models and ultimately for heterogeneity in manufactured parts.

**9:15-9:35 Process Mapping of Inconel 625 in Laser Powder Bed Additive Manufacturing**

*C. Montgomery<sup>a</sup>, J. Beuth<sup>a</sup>, S. Moylan<sup>b</sup>, L. Sheridan<sup>c</sup>, N. Klingbeil<sup>c</sup>*, <sup>a</sup>Carnegie Mellon University, <sup>b</sup>NIST, <sup>c</sup>Wright State University

Understanding laser powder bed additive manufacturing (AM) of nickel alloys is important for the widespread adoption of the technology. To promote adoption, melt pool geometry as well as microstructure prediction and control must be thoroughly understood. In this research Inconel 625 is investigated to determine optimal regions of processing space within the laser powder bed operating region.

Single bead and pad geometries are investigated along with solidification microstructure and defects by utilizing the process mapping approach developed at Carnegie Mellon University. The effect of powder addition on the process is also examined. Results from models are compared with experimental results to verify modeling techniques. Insights are gathered by comparing these results to those of other alloy systems in the laser powder bed operating space.

**9:35-9:55 Finite Element Modeling of Melting, Solidification and Remelting in Selective Laser Melting of Stainless Steel**

*G. Vastola, G. Zhang, Q.X. Pei, Y.-W. Zhang*, A\*STAR Institute of High Performance Computing

Achievement of high quality, dense parts is a cornerstone requirement in modern manufacturing. This is especially true in Additive Manufacturing, where the in-fill hatching and multi-layer scans introduce the risk of metallurgical debonding and layer delamination. In this respect, partial remelting of already-scanned tracks showed to positively affect part density and homogeneity. We present Finite Element Method three-dimensional simulations of Selective Laser Melting of stainless steel where we explicitly track phase transformations during scanning. In particular, we consider the powder, liquid and solid phases, and implement a numerical scheme that dynamically changes the local properties depending on local phase. This way, we are able to track the remelt material. We systematically investigate the remelt volume fraction as a function of the beam cross section area, and heat supply rate. Calculations reveal that there is an optimum beam shape that maximizes remelt volume without altering hatch spacing or beam power.

**9:55-10:25 BREAK**

**10:25-10:45 Prediction of Porosity in SLM Parts using a MARS Statistical Model and Bayesian Inference**

*G. Tapia, A. Elwany*, Texas A&M University

Predictive models that establish a linkage between process parameters and part properties have been identified as a high priority research need in Additive Manufacturing. We work with a Multivariate Adaptive Regression Splines (MARS) statistical model to predict the porosity of parts produced using Selective Laser Melting (SLM) process as a function of process parameters. The proposed predictive model is validated through a case study on 17-4 PH stainless steel test coupons manufactured on a ProX 100 SLM system.



**10:45-11:05 Modeling the Mechanical Behavior of Additively Manufactured 304L Stainless Steel**

*B. Reedlunn, D. Adams, J. Carroll, B. Song, J. Wise, M. Maguire, J. Bishop*, Sandia National Laboratories

Although the solidification process in additive manufacturing (AM) can generate exotic microstructures, the microstructure--property relationships of AM materials have not been extensively addressed in the literature. We have experimentally examined how crystallographic texture and grain morphology affect the mechanical behavior of 304L stainless steel fabricated by a process similar to LENS. A battery of tests was performed on AM material fabricated using three different laser powers, as well as on wrought 304L specimens. Microstructural information gathered from electron backscatter diffraction was then fed into a crystal plasticity model in an attempt to predict trends in the mechanical behavior. Time permitting; we will also compare the experimental results against the predictions of a macroscale viscoplasticity model.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

**11:05-11:25 Ejection Dynamics and Denudation Effects in Selective Laser Melting of Metal Powders**

*M. Matthews, G. Guss, A. Rubenchik, S. Khairallah, A. Anderson, W. King, S. Ly*, Lawrence Livermore National Laboratory

Molten droplet ejection, track formation and spatial denudation associated with laser irradiated metal powders are presented. High speed imaging is used to measure droplet speed as a function of material composition, gas environment, scan velocity and laser power for stainless steel and aluminum alloy powder layers. The results are compared with the comprehensive modeling including the melt under the effect of surface tension and the evaporation induced recoil momentum. The effect of laser spot size and power on denudation extent is studied and related to Eagar-Tsai laser parameter scaling. The role of different thermomechanical effects (thermal expansion, volume change due to the phase transformation and recoil pressure) on denudation of powder material is discussed.

**11:25-11:45 Approaching Faster Than Real Time Support Optimization**

*K. Zeng, N. Patil, C. Teng, P. Chalavadi, D. Pal, B. Stucker*, 3DSIM

Supports in laser powder bed fusion processes are necessary to counteract the thermal residual stresses induced during solidification. Support optimization in these processes is done primarily by trial and error or by using geometry-based rules. In order to enable predictive support optimization based upon physics, thermally induced residual stresses must be predicted based upon the scan vectors which will be used to create the geometry. For complex geometries, the scan patterns used in commercial machines create scan vectors of varying lengths. When varying length scan vectors are used in practice, the residual stress accumulation patterns become quite complex. In order to capture the complexity of the residual stress evolution accurately, a high-accuracy simulation tool is required. However, computational efficiency has historically made accurate prediction of residual stress impossible. To date no commercial software tool exists which can compute thermal and residual stress/strain history faster than the energy source scans the surface of the powder bed; and thus it has been faster to do support optimization via

trial error than via computation. Based upon preliminary research at the University of Louisville, 3DSIM was formed to commercialize an approach for predicting the full thermal and residual stress/strain history for any part built using a metal laser sintering machine faster than that part could be built. To date, 3DSIM has achieved computational efficiency improvements of over 10 million times compared to commercial FEA tools, which opens the possibility for computational-based support optimization. The support optimization tools being developed at 3DSIM which take advantage of this computational efficiency will be overviewed in this talk.

## **Applications II: Design Methods and Qualification**

Room 203

Session Chair: David Rosen, Georgia Tech

### **8:15-8:35 A Design Methodology for Custom Products using Multi-material AM**

*Z. Doubrovski, J. Verlinden, J. Geraedts*, Delft University of Technology

Among the main promises of Additive Manufacturing (AM) are economic fabrication of custom geometry, geometrically complex objects, and, for some AM technologies, objects that are composed of multiple materials. While the possibilities of the AM machines themselves are increasing, designers are facing challenges in designing products and defining properties that utilize these possibilities. In this context, investigate the shortcomings of currently available design tools and methods. Based on findings from interviews with pioneers in the AM industry and several design experiments, we formulated a design methodology that deals with these shortcomings. We present a methodology that encompasses two circular stages. The first circular stage concerns the matching of the AM affordances and is applied during the conceptual phases of the design process. In the second circular stage, which is applied during the embodiment phase, a customizable design is developed. An essential element in the second circular phase is the use of AM process related parameters to define the customizable design.

In most cases, the developed procedures include cumbersome workarounds, which are required to achieve desired result in the designs. Such workarounds indicate the need for the development of new instruments. We conclude the paper with prescribing an envisioned design approach including a description of characteristics of the instruments (hardware & software) that we believe need to be developed for AM.

### **8:35-8:55 A Framework for Additive Driven Design**

*M. Aguilo, B. Clark, J. Robbins, T. Voth*, Sandia National Laboratories

Additive Manufacturing (AM) can substantially reduce total life cycle costs by providing unprecedented access to a much wider design space. Engineered solutions that leverage this design freedom can provide a significant increase in performance and production margins. However, traditional tools and practices do not access this expanded design space. To leverage the design freedom of AM, particularly in a coupled physics setting and in the presence of multiple and complicated requirements, next generation designs must be treated as performance-based optimization problems rather than heuristics-based design processes.

Here we present a design environment built around performance-based optimization (e.g., Topological Optimization; TO) for multiple physics, load cases and constraints during optimization. This framework employs advanced optimization techniques and discretization algorithms and is designed to run on massively parallel HPC architectures. We will present optimization results that demonstrate the efficacy of the algorithms and design environment.

**8:55-9:15 Design Rules with Modularity for Additive Manufacturing**

*H. Jee, Y. Lu, P. Witherell, National Institute of Standard and Technology*

Design rules in additive manufacturing (AM) can help ensure manufacturability-compatibility between designs and processes and, in many cases, provide direct guidelines or constraints to an AM-destined design. If dependent on design rules, however, non-expert designers may be constrained by limited design variability under unfamiliar AM processes. This study proposes a methodological framework for developing modular design rules for AM. Design rules, established as sets of modular components and associated formalisms, can be more explicitly interpreted and efficiently implemented, independent of context. Design rules can be reconfigured, rather than re-defined, from individual component representing process-specific parameter for different AM builds and processes.

**9:15-9:35 Improving the Volumetric Efficiency of Injection Diesel Engine by using Additive Manufacturing Spiral Intake Manifold**

*K. Chakravarthy L, Vaagdevi College of Engineering Warangal*

This study was conducted to develop a spiral intake manifold model to predict gas flow in the intake system of a single cylinder internal combustion engine. The design and operational variables of inlet and exhaust systems are decisive to determine overall engine performance. The best engine overall performance can be obtained by proper design of the engine inlet and exhaust systems. Design of intake manifold was altered with variable shapes and dimensions using Pro-E software, which is used to develop 3D CAD models. The product was fabricated using Additive Manufacturing (AM) Technique. Engine performance characteristics such as specific fuel consumption and engine load were taken into consideration to evaluate the effects of the variation in the design of intake manifold. The main findings were that by using the new model, volumetric efficiency of the engine was enhanced at different injection pressures with different intake manifolds and varying loads. It was also found that different intake manifold dimensions influence the power output of a specific engine as predicted by the AM model.

**9:35-9:55 Residual Stress in Metal Parts Produced by Powder-bed Additive Manufacturing Processes**

*X. Wang, K. Chou, The University of Alabama*

In this study, residual stresses from the electron beam additive manufacturing (EBAM) and selective laser melting (SLM) processes, due to repeated thermal cycles, were investigated. Residual stresses play a crucial role in part performance, and thus, it is critical to evaluate the process-induced residual stresses in AM parts. Ti-6Al-4V and Inconel 718 parts produced by EBAM and SLM, respectively, were studied in residual stresses using the methodology established by Carlsson et al., a mechanical instrumented indentation technique, which is based on the experimental correlation between the indentation characteristic and the residual stress. The results show that the Ti-6Al-4V EBAM parts have a tensile residual stress in both Z-plane and X-plane, while the Inconel 718 SLM parts show a tensile stress and a compressive stress in the Z-plane and X-plane, respectively. Moreover, the Vickers hardness values of the parts built using SLM and EBAM are comparable to the literature data.

**9:55-10:25 BREAK**

### **10:25-10:45 Quantitative Characterization of Geometric Limitations and Dimensional Variation in FDM Parts**

*S. Bashyam, C. Seepersad*, University of Texas at Austin

When creating functional parts and assemblies, limited dimensional accuracy and resolution in FDM can lead to unguided iteration. By quantitatively characterizing the dimensional variation and geometric limitations, this iteration can be minimized. Test parts are fabricated to characterize problematic features and quantify dimensional accuracy and resolution. Results are analyzed and compiled to create an intuitive and comprehensive designer's guide to the limits of FDM fabrication.

### **10:45-11:05 Non-Destructive Evaluation of Additively Manufactured Parts via Impedance-based Monitoring**

*M. Albakri, R. Wheeler, C. Williams, P. Tarazaga*, Virginia Tech

The ability of Additive Manufacturing (AM) processes to fabricate complex geometries is somewhat hindered by an inability to effectively validate the quality of printed complex parts. Furthermore, there are classes of part defects that are unique to AM that cannot be efficiently measured with standard Quality Control (QC) techniques (e.g., internal porosity). Current QC methods for AM are limited to either destructive evaluation of printed test coupons, or expensive radiation-based scanners of printed parts for non-destructive evaluation. In this paper, the authors describe their use of impedance-based structural monitoring to indirectly measure printed part abnormalities. By bonding a piezoceramic (PZT) sensor to a printed part, the measured electrical impedance of the PZT can be directly linked to the mechanical impedance of the part. By observing deviations in the mechanical impedance of the part, as determined by this quick, non-intrusive electrical measurement, one is able to detect the existence of part defects. In this paper, the authors explore the effectiveness and sensitivity of the technique as a means for detecting of a variety of defect types and magnitudes.

### **11:05-11:25 Geometric Element Test Targets for Visual Inference of a Printer's Dimension Limitations**

*S. Chang, H. Li, N. Ostrout, M. Jhuria, S.A. Motaal, F. Sigg*, Rochester Institute of Technology

As technologies advance in the field of additive manufacturing, it increases the demand in using test targets to quantitatively appraise the performance of additive manufacturing processes and parts. This study presents a unique concept to address the dimensional and geometric viability of three-dimensional (3D) printers with test targets that are unique and complementary to those currently available, which we have named Geometric Element Test Targets (GETTs). The concept for the targets is to rely on positioning and spatial frequency of geometric shapes to induce failures that are indicative of the system's dimensional limitations. A distinguishing characteristic is that the dimensional failures can be inspected visually. Systematic evaluations of the limitations can be further conducted through contact or non-contact measurements. The initial GETTs include three suites of test targets: line, angular and circular suites. We will illustrate this concept with samples produced with a fused deposition modeling printer. The potential applications of GETTs include standardization, reference targets, in-line system control, and more.

**11:25-11:45 AM Round Robin Protocols: A Pilot Study**

*S. Moylan<sup>a</sup>, J. Land<sup>b</sup>, A. Possolo<sup>a</sup>, <sup>a</sup>NIST, <sup>b</sup>University of Maryland--College Park*

As the number of users of additive manufacturing (AM) steadily increases, and considering their demand for material and process specifications, the need for standard protocols for round robin studies is increasing accordingly. Researchers at the National Institute of Standards and Technology (NIST) have conducted and participated in several AM round robin studies with the aim not only to characterize the AM process and material but also to improve the understanding of AM round robin studies themselves. One simple study, a pilot round robin study investigating geometric performance of NIST-owned consumer-grade 3D printers, provides excellent examples of typical results and lessons learned. While individual printers produced relatively consistent results, there was significant variability between the printers. This variability existed despite best efforts to ensure participants followed consistent procedures in building the test parts. Further, the variability made it apparent that collecting pedigree data from each build was required to draw any conclusions about potential causes of the variability.

**11:45-12:05 Qualification of Limited-Production, Additively Manufactured Parts for Use in Long-Life, High Consequence Applications**

*N. Leathe, A. Brewer, Sandia National Laboratories*

Metal additive manufacturing offers the potential to revolutionize the manufacturing industry, however the ability to reliably transition into full-scale production depends wholly on qualification and the product assurance it provides. This presentation will look at the requirements and timeline for qualifying an additively manufactured part in a long-life, high-consequence application with added lead time and cost being considered. The evaluation of source material, formation process, post-processing, production, and surveillance of the product line have been considered. Thus, a preliminary qualification strategy will be proposed. With the discussion covering process controls, current qualification challenges, design considerations, and a rigorous screening regiment; all of which will enable the utilization of additive manufacturing technology for the production and certification of long-life, high consequence parts. The presentation will conclude with an outline of critical qualification gaps that must be addressed in order to reduce risk and increase confidence in additive manufacturing as an accepted alternative to conventional machining.

**Materials II: Nylon and Other Polymers**

Salon AB

Session Chair: Stefan Josupeit, University of Paderborn

**8:15-8:35 Correlation of In-Situ Layer-wise Thermal Properties of Nylon-12 in SLS**

*J. Gladstone, W. Wroe, T. Phillips, A. McElroy, S. Fish, J. Beaman, University of Texas at Austin*

Selective laser sintering (SLS) of Nylon-12 is a significant portion of the additive manufacturing market for structurally sensitive applications. Current methods of acceptance for such parts are based on the inclusion of ASTM tensile test specimens within the build volume to gage the overall quality of the build. The associated criteria are that the specimens exceed target minimum strengths in 3 directions. Here we begin looking at a more complete method of certifying parts for acceptance based on examination of the build conditions in each layer of the

part and comparing this to measured mechanical properties using tensile specimens. This paper examines the deeper relationship between SLS process parameters at the layer level and their influence on mechanical properties resulting from these potentially localized conditions. Infrared thermal imaging is utilized to map temperature profiles of SLS-built tensile bars, with images taken before, during, and after each layer-wise sintering. Mechanical properties and fracture conditions are then quantified and correlated with the conditions local to where the fractures occur, which allows comparison with conditions where more favorable mechanical properties have been obtained. In this paper, we focus on the z-axis mechanical properties - normal to the build layers. This axis typically has the lowest strength and ductility as noted in prior research, which is suspected to be related to poor layer-to-layer bonding. By focusing on this layer-by-layer thermal measurement, one can identify poor bonding conditions and potentially improve them as the part is built to expand overall part performance and certifiability.

### **8:35-8:55      Variability in Mechanical Properties of Laser Sintered PA-12 Components**

*M. Faes, Y. Wang, P. Lava, D. Moens, KU Leuven*

The quasi-static mechanical properties of Laser Sintered (LS) PA-12 material are highly influenced by the thermal history of the thermoplastic material during the production, as this impacts critical material properties such as the degree of crystallinity and porosity in the resulting component. Many process-related parameters, including preheating temperature, laser energy density, layer interaction time and post-build cooling cycle, were already shown to influence the thermal history significantly. Due to the large, mainly epistemic, variability in these parameters, the mechanical response of produced components is often difficult to predict and is moreover governed by non-isotropic constitutive equations. This work therefore focusses on the identification of this variability in the mechanical behavior and the validation of experimentally obtained non-deterministic material models. A non-deterministic (variable) constitutive model is built experimentally, based on 90 uniaxial tensile tests, performed on LS samples that were built under different orientations. This model is subsequently validated by building a well-defined benchmark sample, containing complex stress states upon loading. This sample is tested using Digital Image Correlation. Finally, a novel way of identifying non-isotropic material properties, the Virtual Fields Method, is applied to this benchmark sample to identify the constitutive parameters.

### **8:55-9:15      Characterization of Different PA Powders to Determine their Applicability for Laser Sintering**

*L. Verbelen, S. Dadbakhsh, J.-P. Kruth, P. Van Puyvelde, University of Leuven*

With the increasing use of laser sintering for the production of end-use parts, there is considerable interest in developing new and improved polymer materials for this technique. However, due to the complexity of the laser sintering process, materials are subject to very specific requirements in order to be easy processable.

To gain a better understanding of these material requirements, this study investigates several polyamide grades. The most used PA12 grade was thoroughly characterized and compared to other members of the polyamide family, including a PA11, a PA6 and another PA12 grade. The focus of this characterization was on the material properties that are essential for laser sintering, including powder characteristics, melt flow behavior and the final hardening of the polymer. Also preliminary sinter tests were conducted with the materials. The study revealed several

peculiar characteristics of polyamides that may further explain the current popularity of this material family for laser sintering.

**9:15-9:35 Robustness against Differential Shrinkage in PA12 during Laser Sintering: Importance of Rigid Amorphous Material**

*O. Verkinderen, P. Adriaensens, U. Hasselt, P. Van Puyvelde, B. Goderis, KU Leuven*

Up to now only a limited number of polymers is laser sinterable. In laser sintering a known problem is the differential shrinkage of the printed object upon cooling to room temperature. Semi-crystalline polymers display a stepwise decrease in specific volume when crystallizing, which - if not happening homogeneous over the build - causes curling and warping. In attempt to clarify why polyamide 12 (PA12) is relatively robust against differential shrinkage Wide Angle X-ray Diffraction, Small Angle X-ray Scattering, Differential Scanning Calorimetry and <sup>1</sup>H wideline Nuclear Magnetic Resonance were used to describe the PA12 solidification in its finest detail. This exercise revealed the presence of a significant fraction of rigid amorphous material inside the PA12 crystals. This material develops concomitantly with the PA12 crystals but causes a lower material shrinkage compared to when the solid fraction would be composed of pure crystalline material.

**9:35-9:55 Parameter Optimization for Preparing Carbon Fiber/Epoxy Composites by Selective Laser Sintering**

*W. Zhu<sup>a</sup>, C. Yan<sup>ab</sup>, T. Pan<sup>a</sup>, J. Yang<sup>a</sup>, S. Wen<sup>a</sup>, Y. Shi<sup>a</sup>, <sup>a</sup>Huazhong University of Science and Technology, <sup>b</sup>University of Exeter*

Carbon fiber (CF) reinforced thermosetting resin composites offer a wide range of high performance features including excellent strength, modulus and thermal resistance and light weight. Consequently, they are increasingly demanded by aerospace and automotive industries due to the tighter requirements of the transport vehicles for lightweight as well as higher payloads. Although thermoplastics and their composites have been widely used in additive manufacturing (AM), to date it is difficult to manufacture carbon fibers reinforced thermosetting composite parts via AM technologies. Therefore, this study developed a novel method based on selective laser sintering (SLS) to fabricate high-performance carbon fiber/epoxy resin composites. The response surface method was employed to study the processing parameters affecting the quality of final parts, and an optimized processing condition was obtained.

**9:55-10:25 BREAK**

**10:25-10:45 Design and Manufacturing of Shape Memory Polymer (SMP) / Shape Memory Alloy (SMA) Actuator via 3D Printing Technology**

*Y.J. Pyo<sup>a</sup>, Y.C. Park<sup>a</sup>, Y.H. Son<sup>a</sup>, C.S. Lee<sup>a</sup>, M.C. Choi<sup>a</sup>, Y.W. Chang<sup>a</sup>, S.-H. Ahn<sup>b</sup>, <sup>a</sup>Hanyang University, <sup>b</sup>Seoul National University*

SMA/SMP assisted actuators gives high energy to volume ratio as compared with the present motor drive system. These interesting properties of SMP / SMA gained an attention worldwide. They are applicable in small robot, micro fluidic valves & endoscope fields . However, SMA suffers through shape restoring problem. It does not come back to original shape with change in temperature. It is not reversible. To overcome this problem, we have developed SMP composed of nylon 12 to recover its original shape.

Previously, many researchers have reported works related to SMA & SMP to be used as

actuators. However, molding method is conventionally used for fabrication of actuators, and this can be expensive and complicated. In this work, we have used 3D printing technology, which is known to be an easy, fast & cost-effective process. Moreover, it is particularly useful for prototyping because of its ability to build diverse products in short time. In this study, we have designed and fabricated a novel shape memory composite in the form of the SMA/SMP using 3D printing technology.

To build shape memory composite, bilayer of Nylon 12 filaments and flexible PLA (Polylactic acid) was designed and fabricated using 3D printer. SMA of NITINOL wire was inserted between those bilayers to improve its recovering property. It was found that fabricating bilayer using PLA, gives elastic property to help restore its shape. Deformation and fixing rate of SMP was measured using DMA (Dynamic Mechanical Analysis). Moreover, operating characteristics, such as its change in overall length of shape memory composite and cyclic motion, are studied to optimize its operating condition of actuator.

### **10:45-11:05 Powder Ageing and Material Characteristics of Laser Sintered Thermoplastic Elastomer (PEBA)**

*N. Funke, H.-J. Schmid*, University of Paderborn

Understanding powder ageing mechanisms and their influence on part characteristics plays a decisive role in improving part quality and process know-how in general. This investigation deals with a polyether block amide (PEBA), a thermoplastic elastomer (TPE) based on polyamide that is specifically developed for laser sintering in order to establish a wide range of new applications. As is the case in every laser sintering application, parts are built within a cake of non-sintered powder. This powder ages thermally, but can be reused in a mixture with virgin powder. The new material has different ageing mechanisms and needs different test methods to determine powder age than those that have been established for other materials like polyamide 12. In this work, different test methods are investigated and tested for their suitability. Among the tested procedures that also include a range of chemical testing, methods focussing on powder and particle characteristics (e.g. bulk density, particle size) are the most promising. The corresponding results are correlated with material properties (e.g. tensile strength and elongation at break). This work thus helps to better understand the ageing of PEBA powder and therefore contributes to improve cost efficiency and reproducibility of TPE laser sintering.

### **11:05-11:25 Low Temperature Selective Laser Melting of High Temperature Plastic Powder**

*T. Niino, T. Uehara*, The University of Tokyo

In the typical plastic laser sintering or melting system, powder bed temperature is maintained above the recrystallization temperature of the powder material to prevent the parts under process from warping until the whole layers have been processed. This countermeasure can elegantly suppress the part warping, but it also brings problems which are caused by heating the powder bed to such high temperature. For high temperature plastic such as polyetheretherketone(PEEK), heating around or more than 300°C is required. Due to this requirement, for example, machine cost is extremely high and powder recyclability is very low. The authors had introduced another countermeasure that prevents part warping by anchoring the in-process parts to a rigid base plate which the part is processed layer by layer instead of heating the powder bed to such a high temperature. In the current research, application of this method to the process of PEEK powder is tried, and a simple test piece of which relative density is more than 90% was successfully



obtained with preheating temperature of 200°C. In this paper, mechanical performances of obtained parts are presented, and several problems with the process of PEEK powder are discussed as well.

### **11:25-11:45 A SLA Based Conformal Piezo-Resistive Self-sensing Sensor Fabrication Process**

*G. Siwach, R. Rai, University at Buffalo-SUNY*

A sensor is unobtrusive if it doesn't interfere with the design, mechanical properties, and the functionality of the structure it is integrated with. This paper discusses the development of unobtrusive piezo-resistive sensors and their production using additive manufacturing. Short carbon fibers were dispersed in an acrylate resin and subsequently cured with UV DLP 3D printer to be used as a strain-sensing device. Varying the amount of carbon fiber resulted in resistivity variation of the composite. The composite was found to be piezo-resistive, and gauge factor at a concentration of 12% carbon fiber by volume was obtained through mechanical load testing.

### **11:45-12:05 Study on Inhibition Mechanism of Polymer Parts in Selective Inhibition Sintering Process**

*H. Nouri, B. Khoshnevis, University of Southern California*

The selective inhibition sintering (SIS) process is an additive manufacturing technique that builds parts based on powder sintering. In this process parts are made upon deposition of a solution, called inhibitor, at the boundary profile. The inhibited boundary profile acts as a sacrificial mold that can be easily removed, leaving a chemically pure part. One of the influential factors in fabrication resolution by SIS is the proper selection of an inhibitor. The best inhibition mechanism results in ease of separation of the part from undesired regions while maintaining part accuracy. In this paper, we investigate a framework for selecting an appropriate inhibitor for the process. Different experiments have been performed and inhibition theory has been studied on polyamide samples. Specifically, as an alternative to exhaustive experiments on solutions and polymers, a hybrid method based on crystallization is proposed to characterize the effectiveness of the inhibitor. Differential Scanning Calorimetry (DSC) tests are used to study the changes in crystallinity of the polymer. It is found that the sintering period increases as crystallinity of the polymer decreases. Results show that polymer samples exposed to sodium hypochlorite solution have longer sintering periods.

## **Materials III: Ferrous Metals**

Room 103

Session Chair: Alexander Taube, DMRC/University of Paderborn

### **8:15-8:35 Mechanical Response of 304L Stainless Steel Fabricated by Directed Energy Deposition Methods and Comparisons to Wrought Material**

*D. Adams<sup>a</sup>, J. Carroll<sup>a</sup>, B. Song<sup>a</sup>, M. Maguire<sup>a</sup>, T. Palmer<sup>b</sup>, B. Reedlunn<sup>a</sup>, J. Bishop<sup>a</sup>, J. Wise<sup>a</sup>, J. Michael<sup>a</sup>*, <sup>a</sup>Sandia National Laboratories, <sup>b</sup>Penn State University

Quasi-static and high strain rate testing of additively manufactured 304L stainless steel has determined the mechanical response of this material across a broad range of strain rates from  $\sim 10^{-5}$  to  $10^3$  s<sup>-1</sup>. Both compression and tensile tests show that the yield stress of the additively

manufactured stainless steel exceeds that of baseline ingot-derived bar stock with the largest differences in yield stress exhibited in the quasi-static regime. In order to better understand mechanical response, we have characterized composition, porosity, microstructure (includes grain size, phase distribution, grain morphology, and crystallographic texture), dislocation density, and residual stress of each form of stainless steel. Our presentation includes discussion of stainless steel made using 500 W incident-beam-power Laser Engineered Net Shaping (LENS<sup>®</sup>) as well as that made using higher power (2.0 kW and 3.8 kW) LENS-like processes. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

**8:35-8:55 Investigation on the Process and Property of 316L Stainless Steel-Inconel 718 Multi-material Fabricated by Selective Laser Melting**

*Y. Zhou, X. Zhou, Q. Teng, Q. Wei, Y. Shi*, Huazhong University of Science and Technology  
316L stainless steel and Inconel 718 alloy multi-material samples were fabricated by selective laser melting with a novel approach which combined power-bed with power-feed. Their interfacial characteristics were analyzed by scanning electron microscopy, energy dispersive spectroscopy and electron back scattered diffraction techniques. The diffusion of part of Fe and Ni element was observed at the bond interface suggesting good metallurgical bonding. Quantitative evidence of good bonding at the interface was also obtained from the tensile tests, fracture features and the variation in microhardness of both sides.

**8:55-9:15 Defect Characterization for Material Assurance in Metal Additive Manufacturing**

*B. Jared, B. Boyce, J. Madison, J. Rodelas*, Sandia National Laboratories  
Additive manufacturing offers unprecedented opportunities to design complex geometries and materials for performance gains inaccessible under conventional manufacturing constraints. However, to facilitate adoption in high consequence applications, fundamental questions regarding the reliability and repeatable performance of additive metals must be answered. Powder bed fusion processes introduce intrinsic difficulties in predicting final part performance since defect formation can occur at any time during the build process, and existing commercial systems have limited capabilities for process control and/or defect tracking. On-going research will be discussed that is focused on characterizing the nature of critical defects in a precipitation strengthened stainless steel and quantifying their impacts on mechanical material properties. Work is also identifying their formation mechanisms with the intention of implementing process control to eliminate their formation and/or process monitoring to identify their presence in-situ. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This document has been reviewed and approved for unclassified, unlimited release under SAND2015-2902A.

**9:15-9:35 Effect of Post-Processing on the Microstructure and Mechanical Properties of Ultra-Low Carbon Steel Fabricated by Selective Laser Melting**

*B. AlMangour, J.-M. Yang*, University of California, Los Angeles

In this study, the effects of heat treatments and hot-isotactic pressing (HIP) on the microstructure and mechanical properties of ultra-low carbon steel produced using selective laser melting (SLM) were investigated. Powder and prototypes characterizations including XRD phase analysis, microstructural observations, and hardness were performed. It was found that heat treatments at 1000°C and HIP process improved inter-particle bonding and decrease hardness. Significant increases in the grain size were observed for the annealed specimens at 600°C and above as well as after HIP due to recrystallization and further grain growth.

**9:35-9:55 Fatigue Behavior of Selective Laser Melted 17-4 PH Stainless Steel**

*A. Yadollahi<sup>a</sup>, N. Shamsaei<sup>a</sup>, S. Thompson<sup>a</sup>, A. Elwany<sup>b</sup>, L. Bian<sup>a</sup>*, <sup>a</sup>Mississippi State University, <sup>b</sup>Texas A&M University

In this investigation, fully-reversed strain-controlled fatigue tests were conducted on Selective Laser Melted (SLM) 17-4 PH stainless steel (SS). Cylindrical 17-4 PH rods were fabricated vertically-upward using optimized process parameters to ensure a dense product. Post-fabrication heat treatments (solution annealing and aging) were applied on half of the as-built samples. Fatigue behavior and tensile properties of the as-built and heat treated samples were investigated and compared with available data from the literature. The microstructure analysis and fractography were performed to discern the failure initiation sites, crack propagation path, and fracture surface morphology. Fatigue lives of SLM 17-4 PH SS specimens were found to be significantly shorter than their wrought counterparts. It was also found that heat treatment hardens the SLM 17-4 PH SS specimens while also shortens their fatigue life in the high cycle regime. The presence of defects, which serve as crack initiation sites, and more sensitivity of heat treated specimens to impurities, due to higher hardness, were the main reasons for these observations.

**9:55-10:25 BREAK**

**10:25-10:45 Mechanical Properties and Microstructural Characterization of H13 Tool Steel Manufactured by Selective Laser Melting**

*A. Taube<sup>a</sup>, M.J. Holzweissig<sup>a</sup>, F. Brenne<sup>a</sup>, M. Schaper<sup>a</sup>, T. Niendorf<sup>b</sup>*, <sup>a</sup>University of Paderborn, <sup>b</sup>Technische Universität Bergakademie Freiberg

Hot work tool steels are widely used due to their high level of toughness and hardness at sound high temperature fatigue resistance. Selective laser melting (SLM) can be used cost efficiently to process small to medium batches of components exhibiting a high geometrical complexity. In this study, the microstructure as well as resulting mechanical properties of samples processed by SLM were investigated and related to the process conditions during SLM. It was found that the microstructure is predominantly martensitic with distinct fractions of retained austenite imposed by the time-temperature history during processing. In course of tensile testing the metastable austenite transforms to martensite leading to remarkable strain hardening. Obviously, ferritic/martensitic steels can be robustly processed via SLM allowing for direct application without necessity of further heat treatment.

**10:45-11:05 Wear Studies in Binder Jet Additive Manufactured Stainless Steel - Bronze Composite**

*C. Ingenthron, H. Ludwig, T. Joel, K. Agarwal, W. Sealy*, Minnesota State University Mankato  
Additive Manufactured (AM) components can be used for form, fit or function. If these components have to replace the traditionally manufactured parts, they must be evaluated for their properties. One of the properties which is very important in many cases is the wear of material in service. The aim of this research is to study the wear behavior of additive manufactured components under dry sliding conditions.

Small cylindrical disks of stainless steel 420-bronze composite were made by binder jet AM process with layer thicknesses of 50  $\mu\text{m}$ , 100  $\mu\text{m}$  and 200  $\mu\text{m}$ . These disks were subjected to varying wear rates using pin-on-disk test based on ASTM standards. Different sliding distances and speeds were used on samples to understand the wear phenomenon. The weight of samples before and after tests was recorded to calculate wear rates. Wear debris and samples after testing were evaluated under a scanning electron microscope (SEM) to reveal changes in microstructure. Testing results are presented in this paper along with a discussion on how the wear occurs in the SS420-Bronze composite. This information can be used for designing the products from this AM process to match the requirements in service.

**11:05-11:25 The Effects of Heat Balance on the Void Formation within Marage 300 Processed by Selective Laser Melting**

*T. Burkert<sup>a</sup>, A. Fischer<sup>b</sup>*, <sup>a</sup>BMW Group, <sup>b</sup>University Duisburg-Essen

This contribution shows the results of a study that was conducted on the effects of varying selective laser melting (SLM) process parameters on the formation of microstructural voids within a maraging steel (type: Marage 300, AMS6514). Due to the large number of process variables the most influential parameters were identified first. These were energy input resulting from scanning speed, hatch distance, and layer thickness as well as the preheating of the platform. On the basis of the variation of these parameters the most abundant voids were identified and characterized by metallographic studies. Subsequently tensile tests derived information about the influence of such voids on the mechanical properties. Based on these analyses the reasons for the generation of such voids are discussed followed by strategies in order to prevent them. This allowed for the well-aimed optimization of the processing parameters resulting in a nearly void-free SLM processing of such maraging steel.

**11:25-11:45 Selective Inhibition Sintering of High Temperature Metal Alloys**

*M. Petros, P. Torabi, B. Khoshnevis*, University of Southern California

The application of Selective Inhibition Sintering (SIS-metals) to high resolution, bronze alloy parts has proven effective in previous research. It is of interest to investigate the application of the process to higher temperature alloy base materials, namely low alloy steel. There are multiple steps in qualifying a new material in SIS-metal. A fundamental road map for qualifying a new material is first introduced. Next, green parts are built using the SIS-metal beta machine previously developed at the Center for Rapid Automated Fabrication Technologies (CRAFT) at the University of Southern California. The parts are sintered in a high temperature, high vacuum furnace. The sintering profile for the new material is tuned, and the inhibition of sintering is characterized for printed regions. Parts are post processed via abrasive blasting. Results are presented in the form of part builds and preliminary tensile strength data.

### **11:45-12:05 Investigation on High Strength Bainitic Steel Crack-Free Fabrication using Improved HDMR Process**

*Y. Fu, G. Wang, H. Zhang, X. Wang, L. Liang, X. Zhou*, Huazhong University of Science and Technology

High strength bainitic steel parts shaped by conventional fabrication processes have high hardenability and tend to cracks. This paper presents an improved hybrid deposition and micro-rolling (HDMR) process which is a weld-based additive manufacturing process integrating micro-rolling, on-line aging treatment and electromagnetic preheating with wire and arc additive manufacturing. This process is used for high strength bainitic steel crack-free additive manufacturing. Compared to normal HDMR process, the tensile strength of the part fabricated by the improved HDMR process is up to 1280 MPa. And the hardening microstructure is reduced, the cracks are inhibited. The results show that the proposed process is capable of using high strength bainitic large-scale parts steel crack-free additive manufacturing.

### **Process Development III: Process Modeling and Control**

Salon DE

Session Chair: Adam Cohen, Southern Methodist University

### **8:15-8:35 Design of Experiments for Uncertainty Quantification of FEA Modeling in DMLS Additive Manufacturing**

*L. Ma, J. Fong, B. Lane, S. Moylan, J. Filiben, A. Hecker, L. Levine*, NIST

In direct metal laser sintering (DMLS) finite element (FE) simulations, input of accurate material and simulation parameters is critical for accurate prediction of process signatures. It is challenging and expensive to measure and control all possible material properties and process parameters. In this research, we developed 3D thermal DMLS FEA models with several laser scans on both one layer of metal powder and on solid metal substrates. Meanwhile, the same scans were processed on NIST's EOS M270 DMLS machine. Temperature results from in-situ thermographic measurements were compared with those of the FEA modeling and showed agreement. We applied a design of experiment approach which varied simulation parameters to evaluate the uncertainty quantification of DMLS FEA modeling results. Design of experiments provides an exploratory tool to weigh a large number of factors, optimize alternative modeling approaches, and determine which of the many approaches can predict AM process performance for quality control.

### **8:35-8:55 An Experimental-Numerical Investigation of Heat Transfer during Selective Laser Melting**

*M. Masoomi<sup>a</sup>, A. Elwany<sup>b</sup>, N. Shamsaei<sup>a</sup>, L. Bian<sup>a</sup>, S. Thompson<sup>a</sup>*, <sup>a</sup>Mississippi State University, <sup>b</sup>Texas A&M University

The heat transfer in and around a part being fabricated via Selective Laser Melting (SLM) is numerically simulated while considering surrounding powder bed effects modeled via an effective thermal conductivity. By accurately simulating the powder bed heat transfer during SLM, mechanical properties of parts can be better predicted; hence, the dynamic thermal properties and morphologies of the powder bed are considered. Heat transfer to previously-deposited layers and the build plate are also simulated. In order to validate the presented model, thermocouples were embedded into a build plate used during SLM; to measure build plate and

powder bed temperature responses due to laser irradiation and deposition of a 17-4 PH stainless steel (SS), thin-walled structure. The 17-4 PH SS powder was characterized for size distribution and thermal conductivity. The part/powder-bed heat transfer during SLM is shown to non-negligible and thus impactful towards powder reusability. The convection and radiation heat transfer from deposition layer to surrounding gas/chamber is also quantified.

### **8:55-9:15      Dynamic Resolution Control in a Laser Projection based Stereolithography System**

*C. Dagli, Y. Pan, University of Illinois at Chicago*

In a typical Additive Manufacturing system, it is critical to make a trade-off between the resolution and build area for applications in which varied dimensional sizes, feature sizes, and accuracies are desired. The lack of the capability in adjusting resolution dynamically during building processes limits the use of AM in fabricating complex structures with big layer areas and small features. In this paper, a novel AM system with dynamic resolution control by integrating a laser projection in vat photopolymerization process is presented. Theoretical models and parameter characterizations are presented for the developed AM system. Accordingly, the process planning and mask image planning approaches for fabricating models with varied dimensional sizes and feature sizes have been developed. Multiple test cases based on various types of structures have been performed.

### **9:15-9:35      In Situ Temperature and Distortion Measurements for PBF Model Validation**

*A. Dunbar<sup>a</sup>, E. Denlinger<sup>a</sup>, P. Michaleris<sup>a</sup>, P. Guerrier<sup>b</sup>, R. Buchannan<sup>b</sup>, J. Heigel<sup>a</sup>, T. Simpson<sup>a</sup>,  
<sup>a</sup>The Pennsylvania State University, <sup>b</sup>Moog Inc.*

An experimental setup is designed and constructed allowing workpiece in situ distortion and temperature to be measured during deposition using the Powder-Bed Fusion process. The experimental setup is designed for use in commercial machines such as the EOS and Renishaw manufacturing systems. In situ measurements of temperature and distortion are needed to validate thermo-mechanical models of Additive Manufacturing processes. In situ temperatures are measured using thermocouples and an Infrared thermal imaging camera, while a Differential Variable Reluctance Transducer is used to record in situ distortion. In addition, a thermomechanical model of the Powder-Bed Fusion process is developed and the calculated results are compared to the in situ measurements showing close agreement.

### **9:35-9:55      Characterization of Transport Phenomena during Direct Laser Deposition of Ti-6Al-4V via Dual Thermography**

*G.J. Marshall<sup>a</sup>, J. Young II<sup>a</sup>, N. Shamsaei<sup>a</sup>, J. Craig<sup>b</sup>, T. Wakeman<sup>b</sup>, S. Thompson<sup>a</sup>, <sup>a</sup>Mississippi State University, <sup>b</sup>Stratronics, Inc.*

Understanding the thermal phenomena associated with Direct Laser Deposition (DLD) is necessary to begin manipulating fabricated part properties. In this study, a thermally-monitored Laser Engineered Net Shaping (LENS) system is used with time-invariant (uncontrolled) build parameters to construct Ti-6Al-4V cylinders with two different build paths. Both paths utilize a circular contour with serpentine hatch fill; however, successive layer patterns are varied and the effects compared between 90° and 120° angular pattern shifts. During fabrication, the part's thermal history and melt pool temperature are recorded via an in-chamber infrared (IR) camera and a dual-wavelength (DW) pyrometer, respectively. These tools are used for non-destructive

thermographic inspection (NTI) of the part to ensure target quality and/or microstructure. A unique calibration method for the IR camera utilizing the DW pyrometer data is presented and a calibration correction factor was utilized for high temperature ranges. The melt pool was found to be 40-50% superheated reaching temperatures up to 2500°C at times. The temperature characteristics of two different layers were compared for different hatching patterns and the results show that for a given point in time, maximum temperatures can vary based on laser raster. Temperature gradients varied and peaked at about 1000°C/mm along the diameter of the small rods. This can lead to anisotropy in microstructural and mechanical properties allowing for unique property growth per build path. Cooling rates within the melt pool appear to increase as maximum melt pool temperature increases, for instance, from 16,000°C/s - 41,000°C/s.

#### **9:55-10:25 BREAK**

#### **10:25-10:45 Voxel-wise, Directed-energy Deposition of Overhanging Structures**

*A. Nassar, E. Reutzel, Pennsylvania State University*

Conventional additive manufacturing is a layer-by-layer process, reliant on the sequential deposition of 2-1/2 D layers oriented along a build axis. During directed energy deposition a feed-stock is directed into a continuous melt pool formed by a laser or electron beam. The ability to produce overhangs is limited due to the gravitational, surface tensions, and fluid-flow force acting on unsupported melt pools. Here, we present a novel, directed-energy-deposition technique where vertical and overhanging structures are formed by laser power modulation and the motion of a laser beam in three dimensional space along the build-up direction, rather than strictly in a single layer. We demonstrate that highly-overhanging Ti-6Al-4V structure, i.e. in which the overhang angle exceeds 45 degrees with respect to the x-y plane, can be deposited using the developed technique. High-speed imaging is used to gain insight into the physics of the process. The use of a pulsed or power-modulated beam is found to be critical to the formation of overhangs.

#### **10:45-11:05 Layerwise Monitoring of Cooling Rate in EBM Processing of Ti64**

*M. Abdelrahman<sup>a</sup>, T. Starr<sup>a</sup>, S. Ridwan<sup>b</sup>, J. Mireles<sup>b</sup>, R. Wicker<sup>b</sup>, <sup>a</sup>University of Louisville, <sup>b</sup>University of Texas at El Paso*

Post-solidification cooling rate affects the microstructure and influences mechanical behavior of parts fabricated using the Electron Beam Melting (EBM) additive manufacturing process. This paper describes an approach for monitoring and recording the cooling rate at each point in the part as it is built. A 3D template is created by slicing the part solid model into layers with thickness and orientation that match the actual build. A thermal imaging camera system monitors the temperature of the build area throughout the build process. The 3D template is registered to successive thermal images from the camera system before and just after scanning. True temperature is obtained by adjusting the emissivity depending on whether the image is powder or dense metal. The temperature and cooling rate are recorded at each point within the fabricated part as the layer cools. The cooling rates at solidus and alpha-beta transus temperatures are estimated at each point in every layer. This data can ultimately be used as a 3D Quality Certificate (3DQC) ensuring that each volume element of the part has the desired microstructure and mechanical properties.

**11:05-11:25 Process Monitoring of Directed-energy Deposition of Inconel-718 via Plume Imaging**

*A. Nassar, B. Starr, E. Reutzel*, Pennsylvania State University

Laser-metal interactions typically results in vaporization and plume formation. These phenomena are complex and depend upon the details of the laser-vapor-melt interactions. As such, plume characteristics are sensitive to changes in process characteristics. Here, a spectroscopy-based imaging technique is presented for the monitoring of directed energy deposition of Inconel 718. Plume geometry is shown to be related to the processing parameters and geometry of single-bead deposits.

**11:25-11:45 Optical, Layer-wise Monitoring of Powder Bed Fusion**

*B. Foster, E. Reutzel, A. Nassar, B. Hall, S. Brown, C. Dickman*, Pennsylvania State University

In powder bed fusion additive manufacturing, pre-placed layers of powder are successively fused to form three-dimensional components. During part build-up, flaws in the material or part geometry can occur and lead to an unacceptable part quality. Common flaws include porosity, poor surface finish, and thermal deformation. Here, a layer-wise imaging technique is presented for process monitoring. The technique relies on collection and analyses of images taken under oblique illuminations of fused and pre-placed powder layers. Results of three-dimensional reconstruction of image data and identification of potential flaws are presented.

**12:05-1:20 LUNCH**



## Tuesday PM

### **Modeling IV: Various Applications**

Salon C

Session Chair: Denis Cormier, Rochester Institute of Technology

#### **1:20-1:40 Solid Mechanics Based Design and Optimization for Support Structure Generation in Additive Manufacturing**

*C. Zhou, G. Zhao, S. Das*, University at Buffalo

Support structures are typically required to hold parts in place in various additive manufacturing processes. Design of support structure includes identifying both anchor locations and geometries. Extensive work has been done to optimize the anchor locations to reliably keep part in position, and minimize the contacting area as well as the total volume of the support structures. However, relatively few studies have been focused on the mechanical property analysis of the structure. In this paper, we proposed a novel design optimization method to identify the anchor geometry based on solid mechanics theory. Finite element analysis method is utilized to study the stress distribution on both the support structure and main part. Particle Swarm Optimization (PSO) algorithm with a novel constraining handling strategy is employed to optimize the design model. A gradient descent local search algorithm is utilized to quickly locate the global solution in the vicinity explored by PSO. The developed optimization framework is deployed on a bottom-up projection based Stereolithography process. The experimental results show that the optimized design can efficiently reduce the material used on support structure and marks left on the part.

#### **1:40-2:00 Effect of Extrudate Swell, Nozzle Shape, and Convergence Zone on Fiber Orientation in Fused Deposition Modeling Nozzle Flow**

*B. Heller, D. Smith, D. Jack*, Baylor University

Recent advances for improving the mechanical properties of materials used in Fused Deposition Modeling (FDM) include the addition of chopped carbon fibers to the filament feedstock. During processing, the flow field within the polymer melt orients the fiber suspension, which is important to quantify since fiber orientation influences mechanical and thermal properties. This paper presents a computational approach for evaluating polymer melt flow and fiber orientation within a FDM nozzle taking into consideration the converging flow in the nozzle, fluid expansion caused by extrudate swell, and nozzle exit shape. Finite elements are used to evaluate the Stokes' flow in an axisymmetric nozzle and fiber orientation tensors are evaluated along streamlines within the flow using the Fast Exact Closure and Folgar-Tucker isotropic rotary diffusion. Fiber orientation is shown to increase in the shear-dominated flow through the nozzle, however, alignment is found to decrease in the expansion flow of the die swell.

#### **2:00-2:20 Advancing 3D Printing of Metals and Electronics using Computational Fluid Dynamics**

*D. Keicher<sup>a</sup>, S. Mani<sup>a</sup>, M. Essien<sup>b</sup>, A. Cook<sup>a</sup>, J. Lavin<sup>a</sup>, C. Sanchez<sup>a</sup>, S. Homeijer<sup>a</sup>, J. Chen<sup>a</sup>*,  
<sup>a</sup>Sandia National Laboratories, <sup>b</sup>Integrated Deposition Systems

The interest in Additive Manufacturing (AM) has increased significantly of late, with many users exploring a variety of technologies for end use applications. The increased interest in AM provides an opportunity to advance critical technologies by addressing issues that limit AM capabilities and limit successful adoption of current commercial products. Fed material

technologies such as Laser Engineered Net Shaping (LENS) for 3D metal printing and Aerosol Based (AB) printing for electronics provide two similar platform technologies whereby predicting and controlling the fed material stream (metal powders or aerosol droplets) can provide significant benefit to move these technologies well beyond the current state of the art. Computational fluid dynamic modeling has been used to predict how changes in these technologies may be applied to significantly enhance both LENS and AB processes. Model-driven technology improvements have been identified and prototypes developed for LENS and AB technologies, with good agreement between experiment and predicted outcomes. The presentation will discuss the results of modeling and experimental work and provide details on the impact of these developments on the LENS and AB printing technologies. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

**2:20-2:40      Modeling and Characterization of Microstructure Evolution in Single-Crystal Superalloys Processed through Scanning Laser Epitaxy**

*A. Basak, R. Acharya, S. Das, Georgia Institute of Technology*

This paper focuses on microstructure evolution in single-crystal alloys processed through Scanning Laser Epitaxy (SLE); a metal powder-bed based additive manufacturing technology aimed at the creation of equiaxed, directionally-solidified or single-crystal structures in Nickel-base superalloys. Galvanometer-controlled movements of the laser and high-resolution raster scanning result in improved control over the melting and solidification processes in SLE. Characterization of microstructural evolution as a function of the complex process physics in SLE is essential for process development, control and optimization. In this paper an ANSYS CFX based transient flow-thermal model has been implemented to simulate microstructure characteristics for single-crystal superalloys such as CMSX-4 and René N5. Geometrical parameters and melt pool properties are used to estimate the resulting solidification microstructure. Microstructural predictions are compared to experimental metallography and reasonably good agreement is achieved. This work is sponsored by the Office of Naval Research through grants N00014-11-1-0670 and N00014-14-1-0658.

**2:40-3:00      Lattice Boltzmann Simulation of Multiple Droplet Interaction on Non-ideal Surfaces for Inkjet Deposition**

*W. Zhou, University of Arkansas*

Inkjet deposition enables a more efficient, economic, scalable manufacturing process for a wider variety of materials than other traditional additive techniques. The interaction dynamics of inkjetted droplets on surfaces are crucial for controlling the formation of the printed patterns, the accuracy of which is critical to the functionalities of the printed device (e.g., electronics). However, little research has been reported on this front due to the prohibitive computational cost of simulating the dynamics of multiple droplet interaction on surfaces. Recently, Zhou et al. reported an efficient numerical solver based on Lattice Boltzmann Method (LBM) that enabled the simulation of multiple droplet interaction dynamics on an ideal surface (i.e., smooth and homogeneous). In this model, the final shape of the droplets always relax back to the equilibrium shape (i.e., spherical cap) prescribed by the static contact angle of the idea surface, which does not provide any useful information on the final printed pattern. In order to simulate the printed

pattern in real world, it is necessary to take into consideration of the contact angle hysteresis phenomenon on a non-ideal surface, which is caused by the surface roughness and chemical inhomogeneity of the surface. In this paper, a dynamic contact angle boundary condition is developed to take into account the contact angle hysteresis effect based on the previously reported LBM model. The improved LBM model was validated with experimental data from literature. The influence of the printing conditions, droplet spacing, and surface conditions on the two-droplet interaction dynamics were investigated with the validated LBM model. Interesting phenomena were observed and discussed. The interaction of a line of six droplets on a non-ideal surface was simulated to demonstrate the powerful capability of the developed numerical solver in simulating real-world inkjet printing process.

### **3:00-3:20      Computational Modeling and Experimental Validation of Melting and Solidification in Equiaxed Superalloys Processed through Scanning Laser Epitaxy**

*A. Basak, R. Acharya, R. Bansal, S. Das, Georgia Institute of Technology*

This paper focuses on simulation-based optimization of the Scanning Laser Epitaxy (SLE) process applied to gas turbine hot-section components made of nickel-base superalloys. SLE creates equiaxed, directionally-solidified and single-crystal microstructures from superalloy powders melted onto like-chemistry substrates using a fast scanning, high power laser beam. In this paper, a transient coupled flow-thermal approach is implemented to accurately simulate the melting and solidification process in SLE. The laser movement is modeled as a Gaussian moving heat source, and the thermophysical properties of the alloys are adjusted based on the thermal field. Simulations for different superalloys such as IN100, René 80 and MAR-M247 are performed and the instantaneous melt pool characteristics are recorded. Comparisons of the simulations with experimental results show reasonably good agreement for the melt depth. Feedback control is implemented, and demonstrated to produce superior quality SLE deposits. This work is sponsored by the ONR through grants N00014-11-1-0670 and N00014-14-1-0658.

### **3:20-3:40      Inkjet Printing at Megahertz Frequency**

*J. Miers, W. Zhou, University of Arkansas*

Inkjet printing enables more efficient, economic, scalable manufacturing for a wider variety of materials, than other traditional additive techniques. However, the jetting frequency of commercial inkjet techniques is mostly limited to ~10 to 100 kHz. This paper presents an investigation of the possibility of jetting at megahertz frequencies in order to boost the productivity of inkjet by ~100 times. The key to this problem is rooted in droplet formation dynamics, a subject that has been extensively studied for over 300 years. Hence, the focus of this paper is to understand the limitations of generating droplets at a megahertz frequency and explore possible solutions for overcoming these limitations. The paper begins with a review of literature on the dynamics of droplet formation, including historical background and notable modern insights. A numerical model is then developed for the simulation of droplet formation dynamics. The numerical model is validated against existing analytical models and available experimental data from the literature. Aided by insights gained from scaling analysis, the validated model is then used to study the effects of different process parameters on high frequency jetting. The study finds energy density input to the nozzle is the key to achieve megahertz frequency printing.

## **Applications III: Electronics, Mechatronics, Robotics**

Room 203

Session Chair: April Cooke, Commonwealth Center for Advanced Manufacturing

### **1:20-1:40 3D Circuit Fabrication Based on Origami Folding and Direct Writing**

*D. Deng, N. Yodvanich, A. Araujo, Y. Chen*, University of Southern California

3D circuits have a lot of potential applications in electric devices with different scales due to its compact design and efficiency. The spatial layout of 3D circuit design, however, adds difficulty and complexity in the fabrication process. In this paper, a hybrid process of origami folding and direct writing is developed to implement 3D circuit design and fabrication in an easy manner. During the origami folding process, a thermal responsive film is used as the base active material, then the film is coated with photocurable resin as passive material on both sides using the mask-image-projection-based Stereolithography process. After the sandwiched structure is fabricated, it can be deformed into a desired 3D structure under heating environment. Before putting the 2D structure into the oven, a direct writing technique is used to deposit conductive material onto the structure by following circuit design patterns. Hence a 3D circuit design can be realized through the shape transformation of a flat 2D structure. The method effectively turns the 3D complex circuit design and fabrication problem into a 2D problem, provides a much faster and more efficient way to fabricate 3D circuits in the future. Process parameters as well as design criteria are analyzed in the paper. Verification test cases are performed to demonstrate the capability of the presented method.

### **1:40-2:00 3D-inkjet Printing of Flexible and Stretchable Electronics**

*J. Vaithilingam, E. Saleh, C. Tuck, R. Wildman, I. Ashcroft, R. Hague, P. Dickens*, The University of Nottingham

Inkjet printing of conductive tracks on flexible and stretchable materials have gained considerable interest in recent years. Conductive inks including inks with silver nano-particles, carbon based inks, inks containing poly (3,4-ethylenedioxythiophene) (PEDOT) doped with polystyrene sulfonic acid (PSS) are being researched widely to obtain a printed electronic patterns. In this study, we present drop-on-demand inkjet printing of conductive silver and PEDOT:PSS on flexible and stretchable substrate. Process conditions for the inkjet printing of silver nano-particles and PEDOT:PSS were optimised and simple strain gauge patterns were printed. Surface profile, surface morphology and resistivity of the printed patterns were examined. The printed silver patterns were observed to be highly conductive; however when stretched, the patterns did not conduct due to the origination of cracks. The measured conductivity for the PEDOT:PSS patterns was significantly lower than the silver patterns, and they remained conductive when stretched for more than 50%.

### **2:00-2:20 Piezoelectric Device Fabrication Based on 3D Printing Barium Titanate Ceramics**

*X. Song, Z. Chen, L. Lei, Y. Yang, Q. Zhou, Y. Chen*, University of Southern California

Barium Titanate ( $\text{BaTiO}_3$ ) is widely used as the piezoelectric materials due to their excellent electromechanical properties. Conventional methods in fabricating piezo-component are expensive, time-consuming and limited to relatively simple structures. Ceramic suspension based Stereolithography (SL) provides a low-cost way of fabricating piezoelectric components with complex geometries directly from computer-aided design (CAD) models. In such a process, fine

piezoelectric ceramic powders are mixed with liquid photocurable resin to form composite slurry. After green parts are fabricated from the mixed slurry, post processes including polymer burn-out and high temperature sintering are performed to convert the composite green parts into dense piezoelectric components. Key challenges involved in the ceramic suspension based SL process include layer recoating and photocuring of composite slurry with high viscosity and low light penetration. In this paper, we present a novel Mask-Image-Projection-based Stereolithography (MIP-SL) process for BaTiO<sub>3</sub> suspensions by integrating ceramic tape-casting and bottom-up projection methods. Various approaches to increase the solid loading in green parts are discussed, including material preparation, image projection, layer recoating and separation. Main parameters in the process are analyzed, such as blade height, recoating speed, sliding speed and pressing speed. Test cases were built using a developed prototype system based on the presented process. Post processing of composite green parts fabricated by our process is discussed. Tested piezoelectric properties of the sintered parts are also presented in order to fabricate functional piezoelectric sensors and actuators.

### **2:20-2:40 Additive Manufacturing of Conformal Piezo-electric Sensors**

*J. Wang, G. Siwach, R. Rai, University at Buffalo-SUNY*

A sensor is unobtrusive if it doesn't interfere with the design, mechanical properties, and the functionality of the structure it is integrated with. This paper discusses the development of unobtrusive piezo-electric sensors and their production using SLA based additive manufacturing process.

### **2:40-3:00 Design of Passive Dynamic Walking Robots for Additive Manufacture**

*F. Modica, F. Stöckli, K. Shea, ETH Zurich*

Ongoing research in the direction of printable non-assembly mechatronic systems give rise to the need for multi-material printing, including electronics. However, there are robotic systems that do not use electronic components and still exhibit complex dynamic behavior. Passive dynamic walking robots, for instance, are able to walk down a slope without actuators or control. Towards the goal of printing functional non-assembly passive dynamic walking robots using Fused Deposition Modeling (FDM), this paper explores designing and fabricating such robots and all necessary components using single material FDM. It is especially interesting to see that FDM, which has large fabrication inaccuracies, can be used to fabricate such robots, since they are generally sensitive to small perturbances. Two configurations of passive dynamic walkers are redesigned and fabricated in this paper. For one of them all components are printed in one job and only little assembly after printing is needed. However, the gait cycle of the second configuration is much more sensitive to small parametric changes and therefore more flexible prototyping is needed in order to allow adjusting of the robot after printing. Moreover, FDM printed robotic joints with sufficient smoothness and axial stiffness are required and a variety of different joint assemblies is designed and tested on the robot prototypes. Even though the most stable gait for the second robot is achieved using a metal bearing instead of the FDM printed ones, this is not necessary for the first robot. The approach to prototyping with FDM presented in this paper allows to achieve functionality through design iteration without incurring significant cost. To arrive at feasible solutions modular design approach allows to combine different joints, legs, feet and balancing weights and the connection points of the different elements are adjustable after printing, which makes it possible to shift the center of gravity and other variables of the robot.

### **3:00-3:20 4D Printing of Soft Robotic Facial Muscles**

*J. Cai, Z. Alderman, J. Stabach, A. Vanhorn, C. Mullikin, W. Zhou, University of Arkansas at Fayetteville*

4D printing is an emerging technology that prints 3D structures with smart materials that can respond to external stimuli and change shape over time. 4D printing represents a major manufacturing paradigm shift from single-function static structures to dynamic structures with highly integrated functionalities. Direct printing of dynamic structures can provide great benefits (e.g., design freedom, reduced weight, volume, and cost) to a wide variety of applications, such as sensors and actuators, and robotics. Soft robotics is a new direction of robotics in which hard and rigid components are replaced by soft and flexible materials to mimic actuation mechanism in life, which are crucial for dealing with uncertain and dynamic tasks or environments. However, little research on direct printing of soft robotics has been reported. This paper presents a study on 4D printing of soft robotic facial muscles. Due to the short history of 4D printing, only a few smart materials have been successfully 4D printed, such as shape memory and thermo-responsive polymers, which have relatively small strains (~8%). In order to produce the large motion needed for facial muscles, dielectric elastomer actuators (DEAs), operating like a capacitor with a sheet of elastomer sandwiched by two compliant electrodes and known as artificial muscle for its high elastic energy density and capability of producing large strains (~380%) compared to other smart materials, is chosen as the actuator for our robotic facial muscles. In this paper, a literature survey on 4D printing, soft robotics, and DEAs are first presented. A soft robotic face is then designed to achieve facial emotions by the motion of its lips and pupils actuated by the DEAs. DEAs are then printed and characterized for maximum strain and breakdown strength under different pre-stretch conditions. An experimentally validated numerical model is developed to simulate the response of the dielectric elastomers, which is used to optimize the design of the DEAs. The face is finally printed, assembled, and tested for different emotions. This study demonstrates a 4D printed soft robotic face for the first time and the potential of 4D printing of soft robotics.

### **3:20-3:40 3D Inkjet Printing of Conductive Structures using In-situ IR Sintering**

*E. Saleh, J. Vaithilingam, C. Tuck, R. Wildman, I. Ashcroft, R. Hague, P. Dickens, University of Nottingham*

In this study we investigate the inkjet printing of a silver nanoparticle ink and the optimization of IR sintering conditions to form 3D inkjet-printed conductive structures. The understanding of the interaction between the silver layers and the sintering conditions are key elements to successfully build conductive tracks in 3D.

The drop size of conductive ink on glass substrates as well as on sintered conductive film was measured to optimize the printing resolution. The resistivity of the sintered deposition was studied in a planar X-Y direction as well as in a vertical Z direction to analyze the effects of stacking hundreds of silver layers in different deposition orientations. Using the results of the optimized printing and sintering conditions, conductive tracks were demonstrated forming simple 3D inkjet-printed structures powering electronic components.

## Materials IV: Titanium II

Salon AB

Session Chair: Scott Thompson, Mississippi State University

### 1:20-1:40 Quantitative Characterization of $\alpha$ and $\beta$ Microstructures for Single- and Multi-layer Builds of Additive Manufactured Ti-6Al-4V for Process Map Development

*L. Gliebe<sup>a</sup>, Z. Francis<sup>b</sup>, N. Klingbeil<sup>a</sup>, J. Beuth<sup>b</sup>*, <sup>a</sup>Wright State University, <sup>b</sup>Carnegie Mellon University

Microstructural characterization is conducted on single layer pads, multi-layer pads, and thin wall specimens of Ti-6Al-4V manufactured via the LENS<sup>®</sup> process. Optical and electron microscopy techniques are used to evaluate  $\alpha$  and  $\beta$  microstructures. Specifically, polarized light imaging is used to determine prior  $\beta$  grain widths, and back-scattered electron or electron back-scatter diffraction imaging is used to estimate average  $\alpha$ -lath thicknesses via the mean linear intercept method executed with a Fovea Pro<sup>™</sup> plug-in to ImageJ<sup>™</sup>. Additionally, Vickers micro-hardness measurements are collected and correlated to  $\alpha$ -lath thicknesses. Single- and multi-layer pad microstructure data is also correlated to known beam powers and velocities used for manufacturing. Also, the cyclic variation in microstructure resulting from layer-by-layer material deposition is explored via hardness testing for one thin wall sample. Through these investigations, this work aims to contribute new potential target outcomes for use in solidification microstructure process mapping approaches.

### 1:40-2:00 Microstructural Sensitive Fatigue Modeling of Additively Manufactured Ti-6Al-4V

*A. Sterling, B. Torries, N. Shamsaei, S. Thompson, S. Daniewicz*, Mississippi State University

A common issue in powder-based Additive Manufacturing (AM) techniques is porosity. While process parameters can be controlled to limit this occurrence, complete elimination without post-processing is difficult. Because porosity can significantly affect fatigue behavior of AM parts, it is important to understand and model this material trait. In this study, the porosity, including void distribution and morphology, in various Ti-6Al-4V specimens fabricated via Laser Engineered Net Shaping (LENS) was determined prior to fatigue testing. Fractography was performed to determine the specimen's transition through crack initiation and propagation stages. These results were used to calibrate a microstructure-sensitive fatigue model for predicting the fatigue behavior of as-built and heat treated LENS Ti-6Al-4V.

### 2:00-2:20 Application of a Microstructural Characterization Uncertainty Quantification Framework To Widmanstätten $\alpha$ -Laths in Additive Manufactured Ti-6Al-4V

*G. Loughnane<sup>a</sup>, S. Kuntz<sup>a</sup>, N. Klingbeil<sup>a</sup>, J. Sosa<sup>b</sup>, J. Irwin<sup>c</sup>, A. Nassar<sup>c</sup>, E. Reutzel<sup>c</sup>*, <sup>a</sup>Wright State University, <sup>b</sup>The Ohio State University, <sup>c</sup>The Pennsylvania State University

This work applies statistical analysis and uncertainty quantification tools developed for characterizing virtual microstructures in three dimensions to a two-dimensional experimental investigation of Ti-6Al-4V Widmanstätten  $\alpha$ -lath thicknesses obtained from back-scattered electron (BSE) or electron back-scatter diffraction (EBSD) images on two thin-walled samples manufactured via the LENS<sup>®</sup> process. The Materials Image Processing and Automated Reconstruction (MIPAR<sup>™</sup>) software optimizes unique recipes for conversion of the BSE or EBSD images to binary data, and subsequently computes the inverse of the linear intercept for

each  $\alpha$ -lath. Mean  $\alpha$ -lath thicknesses and discrete probability density functions (PDFs) of inverse intercepts are used to make quantitative comparisons of  $\alpha$ -lath structures at different heights throughout the thin walls. Real-time thermal data collected during the LENS<sup>®</sup> experiment is then compared to quantitative microstructural results in order to determine trends between  $\alpha$ -lath structures, thermal gradients, and melt pool areas across experimental process parameters.

### **2:20-2:40 The Investigation on Microstructure and Mechanical Property of Titanium Alloy Additive Manufacturing Part by HDMR Technology**

*L. Liang, G. Wang, H. Zhang, X. Zhou, X. Wang, Y. Fu*, Huazhong University of Science and Technology

The paper presents a new approach to fabricate titanium alloy by the hybrid deposition and micro-rolling(HDMR) technology. A titanium alloy aviation part has been manufactured by HDMR technology. The effect of the process parameters on the manufacturing process and mechanical properties are analyzed in this paper. The results show that HDMR technology significantly refines columnar grain of titanium alloy and eliminates microstructure anisotropy which is an ordinary microstructure of metal additive manufacturing(MAM) part. The tensile strength, yield strength, elongation and impact property are significantly improved by HDMR technology compared with that of the wire and arc additive manufacturing(WAAM) part. Without the huge forging press or rolling mill of forging technology, HDMR technology is likely to change the conventional titanium alloy parts manufacturing method with its specific feature of short cycle, pollution-free and simple device. The technology has a great potential to manufacture metal parts for the aerospace and aviation industry.

### **2:40-3:00 Analysis of Porosity and Chemistry Changes due to Localized Processing Modifications in Electron Beam Melted (EBM) Ti-6Al-4V**

*M. Benedict<sup>a</sup>, J. Mireles<sup>b</sup>, R. Wicker<sup>b</sup>*, <sup>a</sup>Air Force Research Laboratory, <sup>b</sup>University of Texas at El Paso

Intentional spatial microstructural gradients have been achieved through the electron beam melting (EBM) additive manufacturing (AM) process by means of controlling thermal energy input and changing scanning strategies. The microstructural tailoring achieved can be used to spatially control mechanical properties to selectively strengthen or weaken desired locations within an AM fabricated part. Part property tailoring can be used in damage tolerance design and potentially allow for controlled failure of aerospace components. Fatigue test specimens were designed with a stress concentrator to designate a failure region, and fabricated out of Ti-6Al-4V via EBM. X-ray microtomography was employed to characterize the interfacial region between the conventionally processed Ti-6Al-4V region and the selectively strengthened region. The data from the microtomography investigation was analyzed using advanced image segmentation routines to quantify the size and location dependence of detected porosity on the novel scanning strategy. Additionally, an investigation of location dependent material composition was conducted using energy dispersive spectroscopy to quantify the amount of aluminum volatilization that occurred due to increased energy densities in the region that received modified processing. Case Number: 88ABW-2015-2891



**3:00-3:20 A Microstructure and Hardness Study of Functionally Graded Materials Ti6Al4V/TiC by Laser Metal Deposition**

*J. Zhang<sup>a</sup>, Y. Zhang<sup>a</sup>, F. Liou<sup>a</sup>, J. Newkirk<sup>a</sup>, K.B. Taminger<sup>b</sup>, W. Seufzer<sup>b</sup>*, <sup>a</sup>Missouri University of Science and Technology, <sup>b</sup>NASA Langley Research Center

Crack free functionally graded material (FGM) Ti6Al4V-TiC has been fabricated by laser metal deposition (LMD) using TiC and Ti6Al4V powder which were premixed for different ratios. This study focuses on the influence of laser processing parameters and TiC compositional distribution on microstructure, Vickers hardness and phase. The microstructure is analyzed by scanning electron microscopy (SEM), x-ray diffraction (XRD) and hardness tests. Primary carbide, eutectic carbide and unmelted carbide are found in the deposit area. When laser power increased, the primary and secondary dendrite arm spacing increased. The laser power and scanning speed did not influence the Vickers hardness distribution significantly.

**3:20-3:40 Surface Modification on Porous Co-Cr Scaffolds Fabricated by Selective Laser Melting for Bone Implant Applications**

*C. Han, X. Cheng, J.W. Tan, Y. Yao, Q. Wei, Z. Zhang, Y. Shi*, Huazhong University of Science and Technology

Cobalt-chromium-molybdenum alloys with porous structures can be fabricated by additive manufacturing technique, which are attractive for use as scaffolds for bone implant applications. However, metallic implant are difficult to bond directly to living bone due to implant interface problems. Therefore, surface modification with scaffold material is required to improve biocompatibility and the interface surface. In this study, porous Co-Cr scaffolds fabricated by selective laser melting was modified by electrodeposition with biocompatible silk fibroin. The surface characteristics of porous scaffold before and after surface modification was evaluated with the atomic force microscopy, scanning electron microscopy, X-ray diffraction, water contact angle measurement. The mechanical properties including elastic modulus and compressive strength, were determined by compression tests.

**Process Development IV: Extrusion and Lithography**

Room 103

Session Chair: Adam Clare, University of Nottingham

**1:20-1:40 Extrusion-based Additive Manufacturing of the Moisture-Cured Silicone Elastomer**

*Y. Jin, J. Plott, A. Shih*, The University of Michigan

The extrusion-based additive manufacturing (AM) of moisture-cured silicone elastomer for complex freeform shape is studied. Due to its low elastic modulus and poor shape retaining ability during the layer-by-layer process, silicone elastomer AM is technically challenging. The experiment for extrusion of room temperature vulcanization silicone elastomer via time-pressure valve actuation is conducted to study effects of air pressure, nozzle size and speed, layer height and distance between silicone lines on the flow rate and cross-sectional geometry of silicone elastomer AM. The COMSOL<sup>TM</sup> Multiphysics simulation using the level function to track the silicone-air interface is applied to model the silicone flow. Modeling and experimental results of the diameter and flow rate of silicone under the free flowing condition has good agreement and shows the potential for model-based guidelines for AM of silicone elastomers. Effects of the

nozzle speed, layer height, and distance between two adjacent lines are investigated and demonstrate the feasibility and limitations of AM of silicone elastomer.

### **1:40-2:00 Rate Limiting Tradeoffs in Machine Design for Extrusion-based Additive Manufacturing**

*J. Go, A.J. Hart*, Massachusetts Institute of Technology

While adoption of traditional additive manufacturing (AM) technologies continues to new materials and applications, it is vital to understand the performance limits of these technologies in order to envision new machine and process designs. Among these methods, extrusion-based AM (i.e., fused deposition modeling, FDM) is uniquely compatible with a wide variety of high performance polymer and composite materials, and can be employed across an unprecedented range of length scales from microscale wires to vehicle structures. We present a quantitative analysis of the factors limiting the rate and quality of extrusion-based AM. We first perform decoupled analysis of the fluid mechanics and heat transfer within the extruder, and the dynamics of the motion system as constrained by the build volume, extruder mass, and accuracy requirements. These analyses are then coupled to derive scaling laws limiting the production rate of extrusion-based AM. Our analysis is validated by measurements of the print speed versus part size and complexity using small- and medium-size FDM systems. Finally, leveraging these insights, we present preliminary validation of a new extrusion-based AM platform having significantly greater throughput than current desktop and industrial FDM systems.

### **2:00-2:20 Effect of Fabrication Temperature on Aqueous Freeform Extrusion Fabrication**

*J. Li, M. Leu, G. Hilmas*, Missouri University of Science and Technology

An experimental study was conducted to investigate the effect of temperature on ceramic parts produced by paste extrusion based additive manufacturing followed by sintering. A computer-controlled gantry system equipped with a piston extruder was used to extrude aqueous alumina paste. The system includes a temperature control subsystem that allows for freeform extrusion fabrication inside a low-temperature ( $<0^{\circ}\text{C}$ ) chamber. It can also be used for fabricating parts on a hot plate at ambient or higher temperatures ( $\geq 20^{\circ}\text{C}$ ). Test specimens were fabricated from aqueous aluminum pastes at  $-20^{\circ}\text{C}$  in the low-temperature chamber and also on the hot plate at  $40^{\circ}\text{C}$ . The minimum angles achievable by these two processes for part fabrication, without use of support material, were compared. Also compared were the relative density and mechanical properties of the parts obtained after sintering. Microstructures were examined via scanning electron microscopy in order to obtain a deeper understanding of the effect of fabrication temperature.

### **2:20-2:40 Methods of Extrusion on Demand for High Solids Loading Ceramic Paste in Freeform Extrusion Fabrication**

*W. Li, A. Ghazanfari, M. Leu, R. Landers*, Missouri University of Science and Technology

Fabrication of highly dense parts with complex geometry by paste-extrusion-based solid freeform fabrication processes require a precise control of the extrusion flow rate to dispense material on demand, which is often referred as Extrusion-On-Demand (EOD). The extrusion process for aqueous ceramic pastes is complex and difficult to control due to their non-Newtonian behavior, compressibility and inhomogeneity. In this study, three methods of EOD (based on ram extruder, needle valve, and auger valve) are introduced and investigated for the

extrusion of high solids loading (i.e., >50%, volumetric) aqueous alumina paste. Optimal extrusion process parameters for these methods are determined through printing tests and analysis. The extrusion performance in terms of extrusion start and stop accuracy, as well as flow rate consistency, is compared and analyzed for the three methods. Advantages and disadvantages of these three methods are also discussed.

### **2:40-3:00      Continuous Mask Video Projection Based Stereolithography for Fabricating Digital Models in Minutes**

*X. Li, H. Mao, Y. Chen*, University of Southern California

In a recent Science paper, a Continuous Liquid Interface Production (CLIP) process was presented that can achieve an order of magnitude faster building speed. The CLIP process is based on a special transparent and permeable window which allows both light and oxygen to get through. In this paper, we present an entirely different approach that can also achieve continuous layer fabrication. We demonstrate our approach can achieve an even faster building speed, which is 2 times faster than the fabrication speed of CLIP as reported in the Science paper. We discuss the challenging issues related to the continuous fabrication including resin feeding and the resin heating, and how our approach can address such critical issues. The system design and related settings for achieving an ultrafast fabrication speed (a few seconds per mm) are presented. The relationship between process parameters and building quality are also discussed. Finally we presented the limitations of the process and our future research.

### **3:00-3:20      Effects of Oxygen Inhibition and Post-Processing on Exposure Controlled Projection Lithography Process Accuracy**

*Y. Zhang, D. Rosen, A. Jariwala*, Georgia Institute of Technology

Exposure Controlled Projection Lithography (ECPL) is a mask-projection stereolithography process which can be used to create micro lenses on flat or curved substrates. In the ECPL process, the ultraviolet light patterned by the dynamic mask passes through a transparent substrate to cure the photopolymer resin to a certain shape. The dimension of the part can be controlled by the exposure time and functional pixels in the dynamic mask. In this paper, a new modified process planning method is presented with the considerations of post-processing and oxygen inhibition, which can vary part dimensions significantly. The effects of post-processing and oxygen inhibition are studied and characterized. The accuracy of the lateral and vertical dimension of the cured part gets improved by the new method. Experimental validation is obtained by fabricating samples using the ECPL system.

### **3:20-3:40      Investigation of Separation Force for Bottom-up Stereolithography Process from Mechanics Perspective**

*C. Zhou, H. Ye, S. Das*, University at Buffalo

Relative to the free surface stereolithography (SLA) process, the bottom-up process has several advantages that include better vertical resolution, higher material filling rate, less production time, and less waste of photopolymer materials. However, one of the major concerns of the bottom-up SLA process is that the built-up part may break due to the resultant force generated during the pulling up process. This resultant force may become significant if the adhesive mechanism between the two contact surfaces (i.e., newly cured layer and the bottom of the resin vat) produces a strong bonding characteristic. In this work, the traction force is monitored using FlexiForce<sup>®</sup> force sensors. The experimental data are analyzed in order to obtain the initial guess

for the fracture properties of the separation process. Then the separation process has been modelled based on the concept of Cohesive Zone Model (CZM) in order to study crack propagation behavior in the field of fracture mechanics. The classic bi-linear traction-separation law is adopted in the present work as the nominal constitutive law that relates the resultant traction and the separation distance between the two contact surfaces. The results from simulation are compared with experimental data, a good agreement for maximum traction force is found, and the discrepancy is discussed.

## **Process Development V: Tolerances and Process Parameters**

Salon DE

Session Chair: Alaa Elwany, Texas A&M University

### **1:20-1:40 Position Dependency of Surface Roughness in Parts from Laser Beam Melting Systems**

*S. Kleszczynski<sup>a</sup>, A. Ladewig<sup>b</sup>, K. Friedberger<sup>b</sup>, J. zur Jacobsmühlen<sup>c</sup>, D. Merhof<sup>e</sup>, G. Witt<sup>a</sup>,*

<sup>a</sup>University of Duisburg-Essen, <sup>b</sup>MTU Aero Engines AG, <sup>c</sup>RWTH Aachen University

Laser Beam Melting is a promising technology for the production of complex structures. During batch production of multiple identical parts in a single build job, we observed parts with deviating surface roughness in certain areas, which all faced away from the laser. This suggests a dependency of surface roughness on the part position in the build chamber. In this work we systematically reproduce and analyze this effect. We place a hollow pyramid with twelve faces at nine positions on the substrate plate and build this setup twice, using an imaging setup for process documentation. Surface roughness is measured by contact profilometry on three lines for each pyramid face. Our experiments reproduce the effect. Based on these findings we present a hypothesis for the cause and show micrography and SEM images to support our theory. As a consequence, the position relative to the laser should be considered in the design phase for parts with high surface quality requirements.

### **1:40-2:00 Systematical Determination of Dimensional Tolerances for Additive Manufacturing**

*T. Lieneke, G. Adam, S. Leuders, F. Knoop, S. Josupeit, P. Delfs, N. Funke, D. Zimmer,*  
University Paderborn

Additive manufacturing processes create parts and assemblies layer by layer without formative tools. Thus, the processes offer many benefits. Especially the great design freedoms provide new potentials for the part development. In order to profit from these benefits it is necessary to consider the manufacturing limits and restrictions. This applies in particular to the geometrical accuracy. Technical parts are designed computer-aided on nominal shape. However, the nominal shape exists only theoretically, because the physical manufacturing process always leads to geometrical deviations. These geometrical deviations can harm the fulfillment of function and assembly of parts due to the interaction of various geometric deviations. Therefore, the acceptable deviations need to be limited, which is typically done by tolerances. Thus, the project “Dimensional Tolerances for Additive Manufacturing” (DT-AM) at the “Direct Manufacturing Research Center” (DMRC, University of Paderborn, Germany) has two different aims. The first aim is the determination of dimensional tolerances that can be stated if additive manufacturing is workshop-commonly used. A workshop-commonly usage describes the application of

standardized or often used machines, materials, process parameters and machine settings. Secondly, relevant process parameters and manufacturing influences will be optimized in order to reduce dimensional deviations. To achieve both aims a method was developed first. This method identifies relevant influential factors on the geometrical accuracy for the processes fused deposition modeling, laser sintering and laser melting. As a result process specific Ishikawa diagrams are given that list factors, which influence the geometrical accuracy. Within a second step, factors were selected from the Ishikawa diagrams that are expected to affect the geometrical accuracy mainly. For these factors, relevant value variations and gradations were defined in order to perform experimental investigations that quantify the factors influence on the geometrical accuracy. This paper will present both, the developed method and the results of the experimental investigation together with its interpretations. Finally, the next steps will be pointed out the project is heading for.

**2:00-2:20 Per-feature Addition of Machining Allowance with Toleranced AMF File**

*H. Srinivasan, O. Harrysson, R. Wysk, North Carolina State University*

While current metal AM processes can create parts with the mechanical properties required for high performance applications, they remain incapable of meeting the required surface quality and dimensional tolerances. Therefore, finish machining is required before parts can be put into use. In order to ensure successful finish machining, a sufficient machining allowance must be added to surfaces before additive manufacture. In this work, we describe a scheme in which volumes representing machining allowance are automatically generated and added to those features of a part which are to be finish machined. The volumes are generated by offsetting mesh vertices using an optimization based approach. In order to identify the surfaces to be offset, the part is represented by a toleranced AMF file in which surfaces are demarcated as belonging to specific manufacturing features. Finally, for additive manufacture, the allowance volumes and the part are combined and processed to create a single manifold STL file.

**2:20-2:40 Exploring Model-Based Engineering Concepts for Additive Manufacturing**

*R. Lipman, J. McFarlane, National Institute of Standards and Technology (NIST)*

Robust geometry and tolerance representations for additive manufacturing are needed for precise part specification and interoperability with downstream activities such as manufacturing, inspection, and long-term archiving. There is a disconnection between process-independent part geometry and tolerances and process-dependent information requirements for additive manufacturing. Existing and emerging standards for part geometry (ASTM AMF, 3MF, ISO 10303 STEP) and tolerances (ASME Y14) contain information related to the additive manufacturing process. Details of the standards will be discussed and how their use and improvement can benefit the additive manufacturing process and integrate them into model-based engineering.

**2:40-3:00 Toward Better Build Volume Packing in Additive Manufacturing: Classification of Existing Problems and Benchmarks**

*L. Araújo, E. Özcan, J. Atkin, M. Baumanns, C. Tuck, R. Hague, The University of Nottingham*

In many cases, the efficient operation of Additive Manufacturing (AM) technology relies on build volumes being packed effectively. Packing algorithms have been developed in response to this requirement. The configuration of AM build volumes is particularly challenging due to the multitude of irregular geometries encountered and the potential benefits of nesting parts.

Currently proposed approaches to address this packing problem are routinely evaluated on data sets featuring shapes that are not representative of targeted manufacturing products. This study provides a useful classification of AM build volume packing problems and an overview of existing benchmarks for the analysis of such problems. Additionally, this paper discusses characteristics of future, more realistic, benchmarks with the intention of promoting research toward effective and efficient AM build volume packing being integrated into AM production planning methodologies.

### **3:00-3:20 The Influence of Powder Feedstock Characteristics on Powder Bed Additive Manufacturing**

*T. Horn, O. Harrysson, H. West, North Carolina State University*

Powder bed metal additive manufacturing processes such as Electron Beam Melting (EBM) or Laser Melting (LM) show significant promise for the manufacture of a variety of regulated components for aerospace and biomedical applications. These processes have demonstrated the ability to fabricate complex geometries from numerous alloys with precision at or below 100 microns. The reduction/elimination of component specific tooling, the precise control over local component geometry and the reduction of material waste are considered some of key advantages associated with these processes. However, the lack of understanding surrounding the influence of powder feedstock characteristics on processing outputs presents a major barrier to the widespread use of powder bed metal processes. Furthermore, even for powder systems with well documented characteristics (e.g. Ti6Al4V, CoCr, etc.) the influence of factors such as morphology, size distribution and reuse/recycling on powder characteristics and subsequently on component performance is poorly understood. A clear understanding of the effects associated with powder reuse is essential for reliable and consistent processing in a production environment. This presentation targets initial efforts to address this major information gap for direct metal additive technologies.

### **3:20-3:40 Influence of Process Parameters and Fluid Physical Properties on Surface Quality and Dimensional Accuracy of Selective Inhibition Sintering (SIS) of Metallic Parts**

*P. Torabi, M. Petros, B. Khoshnevis, University of Southern California*

Selective Inhibition Sintering (SIS) is an additive manufacturing process for the fabrication of high quality metallic parts directly from their CAD data. The SIS-metal beta machine previously developed at the Center for Rapid Automated Fabrication Technologies (CRAFT) at the University of Southern California has proven effective for the fabrication of high resolution bronze parts. Yet, the surface quality and the dimensional accuracy of the parts need to be further studied and enhanced. This paper investigates the influence of process parameters such as saturation level of the inhibitor fluid, layer thickness and droplet sizes; and the inhibitor fluid physical properties such as viscosity and surface tension on surface quality and dimensional accuracy of the parts. A Design of Experiments (DOE) approach will be utilized in this research to achieve the desired results.

### **3:40-4:00 Aerosol Jet Direct Write Technology Analysis for Production Applications**

*S. Johnston, M. Bennett, M.R. Miller, Boeing Research & Technology*

The use of Direct Write (DW) technologies in production is currently limited as quality control measures are needed to ensure part reliability. The development of a production process using an Aerosol Jet (AJ) DW system has been established and implemented. The development of quality

control measures involved gas atomization analysis, material viscosity measurements, and mass flow measurements. The AJ system relies upon atomization of liquid materials (usually inks) for deposition that ultimately become electrically conductive pathways. The ability to have consistent and repeatable material deposition onto the substrate is directly related to the atomization of the ink material. An analysis of the atomized ink material using the pneumatic atomization method in the AJ system has been conducted using a Malvern Spraytec droplet analyzer. The Spraytec analyzer uses laser diffraction to determine the droplet size and distribution ranging from 0.100 to 2000 microns. Atomization analysis of commercially available silver inks were compared with deionized water at room temperature. Data analysis indicate that a correlation between flow parameters and the resulting atomized particle distribution exist, providing a possible prediction of flow parameters that will result in desired material atomization levels.

## POSTER SESSION

### AT&T Center Salon C

4:00-5:00 PM

Session Chairs: Christopher Williams, Virginia Tech  
Adriaan Spierings, Inspire AG

### 3D Printed Reduced Graphene Oxide Supercapacitor

*N. Southon<sup>a</sup>, H. Cader<sup>a</sup>, W. Rowlands<sup>b</sup>*, <sup>a</sup>University of Nottingham, <sup>b</sup>University of Loughborough  
A fully functional supercapacitor was fabricated solely with Additive Manufacturing techniques. The electrodes were reduced graphene oxide (rGO), with inkjet printed silver nano-particle ink for a current collector. The case of the supercapacitor was made of UV curable ink (VeroClear) which was inkjet-printed using an Objet Connex printer, and K<sub>2</sub>SO<sub>4</sub> was used as an electrolyte. A 4mg/mL GO dispersion in water modified with PEG (30wt%) and TWEEN20 (0.5wt%) was used for inkjetting the electrodes.

A thermal reduction in a non-inert atmosphere and a novel photo-induced reduction were tested. Electrochemical testing illustrated supercapacitive behaviour with thermally reduced electrodes. Cyclic voltammetry produced rectangular behaviour, indicative of a kinetically facile supercapacitor. Galvanostatic charge-discharge tests showed that during charging, the rate of diffusion of the electrolyte ions into the electrode was poor. Discharging of the supercapacitor showed an appropriate linear response. Cell capacitance was 228 $\mu$ F with electrode and package capacitance at 1.08Fm<sup>-2</sup> and 0.45Fm<sup>-2</sup>, respectively.

### Additive Manufacture of Novel Auxetic Structures

*J. Gorecki<sup>a</sup>, D. Hickman<sup>b</sup>, A. Gasper<sup>b</sup>, S. Kelly<sup>c</sup>*, <sup>a</sup>University of Liverpool, <sup>b</sup>University of Nottingham, <sup>c</sup>University of Loughborough

This poster details the design, fabrication, and testing of novel 3D auxetic lattice structures using Selective Laser Melting (SLM) and Laser Sintering (LS). The research encompasses three themes; auxetic foam structures, re-entrant bowtie structures, and a novel auxetic ring design. An auxetic foam structure is produced and using Computer Tomography a 3D computer model is created. Multiple design variations are produced using LS to demonstrate how the manipulation of this model allows the tailoring of key parameters to increase the capability and usability of the structure. Building on previous work into the manufacture of 3D re-entrant bowtie structures using Electron Beam Melting, it is established that it is possible to create these structures with SLM by specific reorientation of the part within the build volume. Design variations are created to assess the effects of curving the re-entrant struts on a bowtie lattice, however the effect on the Poisson's ratio are inconclusive. A novel auxetic ring is designed which produces a controlled increase of the inner diameter and a rotation of both bases of the cylinder structure. The design is investigated for a range of geometric parameters and manufactured using LS and SLM.

### Creating Embedded Radiofrequency Structures using PolyJet Material Jetting

*R. Dumene, P. Kennedy, C. Williams, D. Sweeney, G. Earle*, Virginia Tech

Embedding of integrated systems via Additive Manufacturing (AM) offers the potential to save weight, space, and time in the production of electronics and vehicles. Of specific interest are embedded electrical systems that operate in the radiofrequency (RF) range as they have great



potential utility in communication systems and aircraft avionics including navigation. However, systems in this frequency range pose unique manufacturing challenges such as the need to minimize impedance discontinuities in the system. Via a collaboration with Northrop-Grumman Corporation, the authors explored various techniques for embedding RF structures such as antennas and filters via a multi-material jetting AM process. Specifically, the dielectric constants and loss tangents of VeroWhite and TangoBlack polymers were determined to facilitate the design of RF structures with these materials. It is shown that measurements of S-parameters of the resultant embedded RF structures approach or match the performance of non-embedded electronics.

### **Flexible Tactile Sensor Developed using 3D Printing Technology**

*H. Kim<sup>a</sup>, I. Lee<sup>b</sup>, Y. Yang<sup>c</sup>, K. Lee<sup>d</sup>*, <sup>a</sup>Andong National University, <sup>b</sup>Chungbuk National University, <sup>c</sup>ETRI, <sup>d</sup>Pukyong National University

With recent technological developments, robotic technologies are being applied and used in multiple fields, including home, industry, and educational institutions. Researchers need technologies that can control robots, as well as sensors or devices that can receive external information. Of the five senses of the human body, the tactile sensor is a critical criterion that measures the required magnitude of power used to grip or move an object. The sensors of a sense of touch with resilience are required to respond to very small amount of power like human beings, and to equip robot's hand. To develop sensors with resilience of a sense of touch, the research first studied the development of systems and materials to receive exterior stimulus effectively. This research used carbon nanotube as a material. Carbon nanotube was selected because it has a high electrical conductivity and outstanding mechanical characteristics.

### **Fluid Flow in 3D Printed Capillaries**

*R. Lade<sup>a</sup>, L. Rodgers<sup>b</sup>, C. Macosko<sup>a</sup>, L. Francis<sup>a</sup>*, <sup>a</sup>University of Minnesota, <sup>b</sup>Stratasys Ltd.

We explore the fundamentals of fluid flow in 3D printed, open-channel capillaries created using fused deposition modeling (FDM). Printed capillaries have already been used in microfluidic devices and have potential applications in embedding electronics in plastic substrates. However, FDM parts possess rough and often porous surfaces, which complicates capillary flow. First, we evaluate the sealing ability of several techniques and show that a UV curable epoxy forms an effective water-tight coating. Then, we analyze the influence of print orientation on capillary flow, where capillaries printed in specific orientations are shown to exhibit more favorable flow. The unique surface topography of FDM parts is also shown to have an important impact on flow behavior, causing the liquid to travel down the capillary with a characteristic 'pulsing' movement. Comparisons are then made to capillaries printed using PolyJet technology, which involves printing with small, UV-curable droplets and yields much smoother printed surfaces. Based on these results, user-specific recommendations are made.

### **Investigation of Function Integrated Damping Structures Manufactured by Additive Manufacturing Technologies**

*T. Künneke, G. Adam, D. Zimmer*, University of Paderborn

Mechanical vibrations occur in almost all industrial applications. However, in technical systems mechanical vibrations are usually undesired. They can harm the function and lead to audible noise emission of technical parts. To mitigate these effects the damping of mechanical vibrations is necessary. Till now this is mostly done by additional damping elements which are adapted to

the vibrating components. These elements show different disadvantages. Thus, in order to minimize the manufacturing and assembly costs, to adjust the damping function to individually occurring mechanical vibrations and to reduce the weight, an integration of the damping function into existing structures of engineering system is expediently.

Additive manufacturing processes offer great design freedoms that are not given by established manufacturing technologies. These design freedoms can be used in the field of mechanical vibration damping. For example the direct integration of damping functions into structures of technical systems can be obtained by integrating complex internal structures into the components. Also, powder materials can be left inside the internal structures in order to act as particle damper.

Within the research project “Additive Manufactured Function Integrated Damping Structures” (AMFIDS) it will be investigated how damping functions can be integrated into existing structures by additive manufacturing processes. Further on, it should be analyzed how the damping function can be adjusted to different mechanical vibrations in order to obtain an optimized damping effect. The presentation will include first experimental results showing the advantages of function integrated damping structures. Furthermore, planned investigations will be described.

### **Experimental Study of Snap-fits using Additive Manufacturing**

*K. Torossian<sup>a</sup>, D. Bourell<sup>b</sup>, <sup>a</sup>ENISE, <sup>b</sup>The University of Texas at Austin*

A snap-fit is a mechanical joint system whose mating parts exert a cam action, flexing until one part slips past a raised lip on the other part, preventing their separation. The use of snaps in additive manufacturing (AM) is an approach for assembling components of parts too large to build in one piece in AM. There are broadly two types of snap-fits possible to encounter, permanent or non-permanent, depending on the design geometry. An experimental study was carried out to evaluate the mating/separating force for snap-fits regarding several geometrical parameters for additive manufacturing. The design chosen for this study has been established from the start to work on only one design. The parameters chosen for experimental investigation were the mating angle, the separation angle and the inner diameter of the mating part. All in all, 15 pairs have been designed and 3D-printed for evaluation. The force required to insert and separate the snap components was recorded and compared to the value based on a derived equation.

### **Inkjetting of 3D Microstructures: Ink and Process Characterization, and Lattice Development**

*A. Thompson, R. Garrard, C. Campanelli, University of Nottingham*

This poster documents investigations into hot melt inkjet printing of 3D microlattices. The authors review relevant literature around the fields of hot melt inkjetting, ink composition and development, and lattice design. Utilising Océ hot melt TonerPearls<sup>TM</sup>, deposited material is evaluated mechanically by DMA and compression testing, yielding a Young's modulus of 187 MPa in the xy plane and 166 MPa in the z plane. Compressive yield strengths of 8.8 MPa and 17 MPa are found for the xy and z planes respectively. Thermal characterisation is performed using DSC and finds the ink melt point to be 83°C and zero shear rate viscosity is also evaluated to be 10.90-38.08 cP for the range between 90-130°C. Using the PiXDRO LP50 printing system, design restrictions are identified through variation of relative layer offsets and an angle of ~45° is found for maximum overhang, relating to a layer offset of ~10 µm. The process of lattice

development is articulated, including voxel CAD development, slicing software and lattice iterations.

### **The Amorphorization of a Fe-based Bulk Metallic Glass during Selective Laser Melting**

*Y. Ou, N. Li, Q. Wei, Y. Shi, L. Liu*, Huazhong University of Science and Technology

Additive manufacturing is a promising technique in breakthrough the bottleneck of the processing of bulk metallic glasses stemming from the high strength at ambient temperature, wherein the keeping amorphous structure has become one of the most important issues that never happened in their crystalline counterparts. In the present work, selective laser melting with various energy densities was carried out to fabricate a Fe-based bulk metallic glasses part, and the effect of energy density on the microstructure of the 3D printed specimens was investigated systematically. The results revealed that the amorphous structure kept unchanged under a moderate energy density, while high energy density caused the crystallization and low energy density resulted in the formation of void-like defects. The phenomenon can be in-depth understood according to the effect of energy density on melt pool size and cooling rate with the aid of finite element simulation.

### **Exploring Variability in Material Properties of Multi-material Polyjet 3D-printed Parts**

*L. Bass, N. Meisel, C. Williams*, Virginia Polytechnic Institute and State University

With Additive Manufacturing (AM) capabilities rapidly expanding in industrial applications, there exists a need to quantify materials' mechanical properties to ensure reliable performance that is robust to variations in environment and build orientation. While prior research has examined process-parameter and environmental effects for AM processes such as extrusion, vat photopolymerization, and powder bed fusion, existing similar research on the material jetting process is limited. Focusing on polypropylene-like (VeroWhitePlus) and elastomer-like (TangoBlackPlus) materials, the authors first characterize the anisotropic properties of six different gradients produced from mixing the two materials in preset quantities. Three build orientations were used to fabricate parts and analyze tensile strength, modulus of elasticity, and elongation at break for each material. The authors also present results from an investigation of how aging of parts in different lighting conditions affects material properties. The results from these experiments provide an enhanced understanding of the material behaviors relating to PolyJet process parameters and can inform material selection when manufacturing load-bearing parts.

### **Selective Laser Melting of Aluminium Metal Matrix Composites**

*X. Li, L. Astfalck, P.G.W.-S. Drew, Y. Schliwa, T. Sercombe*, The University of Western Australia

Aluminium metal matrix composites (AMMCs) are important engineering materials with high specific strength and excellent stiffness. AMMCs have found applications in many industries including aerospace, aircraft and automotive. In conventional processing of AMMCs e.g. casting, the homogenous dispersion of the reinforcements is challenging. As an emerging additive manufacturing (AM) technique, selective laser melting (SLM) provides a promising alternative to fabricate AMMCs with homogenous dispersion of the reinforcements. However, due to the complex physical and chemical processes within SLM, the fabrication of AMMCs can be affected by many SLM-related and reinforcement-related parameters. In this work, SLM of Al12Si with three types of reinforcements SiC, AlN and B<sub>4</sub>C was compared. The influence of

SLM parameters and type of reinforcement on the relative density, microstructure, the interface between the matrix and the reinforcement as well as the mechanical properties of the fabricated components was investigated. This study provides necessary information for successful fabrication of AMMCs with desired mechanical properties.

### **Producing Nanostructured Metal Parts by Laser Forming and Friction Stir Processing**

*R. Li, T. Yuan*, Central South University, Changsha

The carbide in laser forming components exhibited network distribution, isolating the  $\alpha$ -Co phase which has excellent plasticity, thus reduced the toughness and can easily induce the crack. According to the metallurgical defects, this work will adopt the thermal and stress coupling effects induced by friction stir processing to modify the laser-clad coatings. The purpose of the friction stir processing is to adjust the network second phase to nano and dispersive distribution, and eliminate the crack, so as to improve the strong toughness of laser forming part. Firstly, the work characterized the FSP microstructural evolution by SEM/TEM with laser melted Co-Cr-Ni as represent alloy; and then, the project studied FSP of Co-Cr-Fe, Co-Cr-W, Ni35 alloys and verified the universality that FSP can adjust the network carbides to dispersive nanoparticles. Based on the above, an analytical model relating microstructural evolution, property and FSP strain rate was established.

### **Modeling of Powder Bed Processing - A Review**

*A. Flood, F. Liou*, Missouri University of Science and Technology

Many models have been developed to model powder beds and these methods can be implemented to model a powder bed for Selective Laser Sintering. Two of the main methods are Discrete Element Method (DEM) and the Geometric Method. The purpose of this paper is to analyze each of the methods highlighting first how each of the models creates the powder bed. The next aspect reviewed is the computational time and its causes. And lastly, each of the methods will be examined for their accuracy as shown from various experiments that have been reported in literature. In addition to these methods, there are several other methods that have been proposed that will be studied and compared to highlight the strengths and weaknesses of each method.

### **Understanding the Macroscale Mechanical Response of Additive Microstructures using Direct Numerical Simulation**

*J. Bishop, B. Reedlunn, D. Adams*, Sandia National Laboratories

The polycrystalline microstructures resulting from additive processes, such as LENS, can be significantly different than the microstructure of wrought materials with respect to grain size, morphology, and texture. In order to understand the impact of these microstructural differences on the macroscale behavior of the host structure, we perform a series of Direct Numerical Simulations (DNS) in which an idealized polycrystalline microstructure is embedded directly within small macroscale structure. A crystal-plasticity model is used to represent the grain-scale physics. The DNS simulations of the additive material are compared with analogous simulations that use a macroscale homogenized material model. Our numerical results will be compared to a set of calibration and validation experiments.

### **A Framework for Large Scale Fused Pellet Modeling (FPM) by an Industry Robot**

*Z. Wang, R. Liu, T. Sparks, F. Liou*, Missouri University of Science and Technology

Fused pellet modeling (FPM) is an important method in additive manufacturing technology, where granular material is used instead of filaments. In FPM, prototypes are constructed by the sequential deposition of material layers. As the size of the part increases, the problem of long build times and part deformation becomes critical. In this paper, methods for eliminating the void density during deposition and accuracy control principles for large scale FPM processes are studied. By analyzing the ab initio principles of this process, a mini extruder with variable pitch and progressive diameter screw for the large scale fused deposition is proposed. Based on polymer extrusion theory and non-Newtonian fluid properties, each of the design parameters are analyzed, such as the length of different function sections of screw, die shape of extruder nozzle, and the material properties. According to these analysis results, an extrusion process simulation for controlling the filament shape is carried out with multi-physics modeling software and proved the FPM could increase the building efficiency and deposition quality for large size parts.

### **$\mu$ -SLS of Metals: Design of the Powder Spreading System and the Powder Bed Actuation**

*N.K. Roy, M. Cullinan*, University of Texas at Austin

Nanopowders have a tendency to form agglomerates due to the presence of attractive van der Waals forces. In order to overcome this problem, we present a powder spreading mechanism design that can alleviate this phenomenon by using vibration compaction to produce a uniform powder distribution in the bed. Most SLS machines employ either a roller or a blade to spread the powder over the powder bed. However, in order to achieve layer thicknesses of few microns, a new design for the spreading mechanism which includes a combination of a precision blade and a precision roller is employed. Also, the design of a linear actuating system for displacing the powder bed with resolution of few tens of nanometers is presented for the  $\mu$ -SLS system. The detailed design of these systems along with proposed further studies to reduce the agglomeration of nanopowders in the powder beds are presented in this paper.

### **Microstructure and Property of TiB-reinforced Ti Alloy Composites by Laser Metal Deposition**

*Y. Zhang, J. Zhang, F. Liou, J. Newkirk*, Missouri University of Science and Technology

TiB-reinforced Ti alloy composites have been laser deposited with pre-alloyed Ti-6Al-4V-1B powder. The microstructure of the as-deposited and heat treated composites have been characterized in detail using scanning electron microscope (SEM). A homogeneous dispersion of needle-like TiB precipitates is formed in the Ti-6Al-4V  $\alpha/\beta$  matrix. TiB precipitates promote formation of small near equiaxed  $\alpha/\beta$  grain after  $\beta$  annealing process. The micro-hardness of the laser deposited composites increase 20-30% with 5 vol. % TiB precipitates compared to unreinforced Ti-6Al-4V deposits.

### **Fabrication and Test Characterization of Electronic Devices by using 2D and 3D Printing Methods**

*Y.S. Yang, I.-K. You, S.-H. Hong*, Electronics and Telecommunications Research Institute

The recent developments in printed electronics are expected to revolutionize the electronics industry. 2D printing such as an ink-jet printing is one of the most promising techniques for inexpensive large area fabrication of plastic electronics. In this study, we reported the fabrication of organic and inorganic thin-film transistors (TFTs) and their metal interconnects by ink-jet and

3D printing methods, respectively. We investigated dispersions of semiconductor and metal composites in printing solutions suitable for ink-jet printing and 3D printing, respectively, and monitored their physical properties. Ink-jet printing of these solutions could be carried out on a variety of substrates including Si and plastic substrates, whose flexible properties were crucial for the many applications considered for this technology. The electrical characteristics of TFTs were evaluated in terms of field effect mobility and ON/OFF ratio to identify the underlying mechanisms governing their behavior.

### **Depth of Cut Monitoring for Hybrid Manufacturing using Acoustic Emission Sensor**

*H. Gaja, F. Liou*, Missouri University of Science and Technology

Laser Metal Deposition LMD is a hybrid manufacturing process consist of a laser deposition system combined with a 5-axis CNC milling system. During laser deposition many parameters and their interaction affect the dimensional accuracy of the part produced, powder flow rate, laser power and travel speed are some of these parameters. Sensing the acoustic emission during milling marching gives feedback information regarding depth of metal being cut subsequent part dimensions, if an error in dimensions is found certain actions, such as remaching, close loop control, or laser remelting can be carried out to correct it. Thus a reliable hybrid manufacturing management system requires that a depth-of-cut detection system be integrated with the milling machine architecture. This work establishes, first a methodology to detect an acoustic emission signal, so that the acoustic emission characteristics of the milling could be analyzed. Second, it sought to relate these acoustic data to machining parameters to detect depth-of-cut.

### **Improvement and Application of Aerosol-based Printing Technology for Electronic Applications**

*D. Keicher, S. Mani, M. Essien, A. Cook, J. Lavin, S. Homeijer, C. Sanchez, J. Chen*, Sandia National Laboratories

Printed electronics technologies provide an opportunity to change the electronics industry. Replacing deposit, mask, and etch processes with direct printing methods can minimize tooling costs, reduce capital expenditure, and provide a more flexible manufacturing capability. Aerosol-based printing technologies have demonstrated the ability to print features as small as 10  $\mu\text{m}$  in a laboratory setting, but have yet to find wide use in commercial applications. The lack of a transition to industry can be attributed to several factors. Recent research in aerosol-based printing has led to the development of a more robust printing platform that is applicable to the direct printing technology area. The new technology, based on a patented Sandia National Laboratories technology, was developed to overcome the limitations of commercially available systems. The new technology provides a robust tool with simplified and stable operation. Recent developments are intended to meet expectations for commercial applications. This poster will present computational fluid dynamic modeling results developed to improve aerosol droplet collimation and focusing, overall print quality, and unassisted print times to beyond eight hours. The poster will also discuss experimental results of improved printing of metal nanoparticle lines and increased process stability. Principals of aerosol physics and aerodynamic focusing as applied to direct printing applications will be presented.

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Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

### **Direct Laser Deposition of Ti-6Al-4V from Elemental Powder Blends**

*L. Yan, X. Chen, W. Li, F. Liou, J. Newkirk*, Missouri University of Science and Technology  
Thin-wall structure Ti-6Al-4V has been deposited using Laser Additive Manufacturing from blended Ti, Al, and V elemental powders. Microstructure and composition distribution along height build direction were intensively investigated using optical microscopy, scanning electron microscopy/Energy Dispersive X-ray Spectroscopy (SEM/EDS), and microhardness testing. The microstructures of the as-deposited Ti-xAl-yV were studied using EDS to determine appropriate weight percentage for Al and V in the blended powders before mixing. The effects of laser power, laser transverse speed, and feeding rate on microstructure were investigated and optimized laser processing parameters were concluded.

### **How Substrate Properties Effect the Deposition Characteristics of Aerosol Jet Printed Features**

*E. Agee, H. Pan, B. Ludwig*, Missouri University of Science and Technology  
Aerosol jet printing is a relatively new process that involves the non-contact deposition of nebulized particles onto a substrate for use in printable electronics. The ability to print flexible patterns using nanoparticle ink has made aerosol jet printing more common in recent years. This study was conducted in order to determine a model that predicts the deposition quality and maximizes the bonding strength of silver nanoparticle ink on various substrates using aerosol jet printing. Substrates tested included glass, oxidized and non-oxidized silicon, polyethylene terephthalate (PET) film, perfluoroalkoxy (PFA) film, fluorinated ethylene propylene (FEP) film, ethylene tetrafluoroethylene (ETFE) film, and polyimide film. The ASTM test standard D3359-02 Method B was used to analyze the bonding characteristics of the silver nanoparticle ink to the various substrates. A titanium oxide coating was spin coated onto the glass and oxidized silicon substrates in an attempt to improve the adhesion of the silver nanoparticle ink to the surface. It was determined that the addition of the titanium oxide significantly increased the adhesion of the silver nanoparticle ink to the glass and oxidized silicon substrates. Once the adhesion was characterized, the surface morphology of the printed silver nanoparticle ink on each of the substrates was characterized using optical microscopy. The adhesion and deposition morphology results were related to the chemical bond formation and the substrate's surface energy properties.

### **Automation of Solid Ceramics Extrusion Process**

*L. White, W. Li, A. Ghazanfari, M. Leu, R. Landers*, Missouri University Science and Technology  
Solid Ceramics Extrusion (SCE) is a novel additive manufacturing process capable of fabricating fully dense advanced structural ceramics with complex geometries. This project focuses on the automation of two subsystems of the SCE system, namely, oil-feeding and infrared heating subsystems. The oil filling subsystem is a closed-loop control system consisting of a liquid level sensor and an electric pump. It is capable of pumping oil into the build tank and adjusting the level of oil automatically after each layer is extruded. The infrared heating subsystem consists of a customized light fixture and a stepper motor. It positions the infrared heating source above the part after each layer is extruded and turns it on/off automatically. Both systems were designed and programmed to work with LabView, which allows for the SCE process to become fully automated.

### **An Easy Releasable, Perforated Elastomer Membrane for Epidermal Electronic Devices**

*H. Denis, B.K. Mahajan, A. Kankipati, X. Huang*, Missouri University of Science and Technology

Epidermal electronic devices can be mounted directly on human or animal skin like temporary tattoos, and have the potential to revolutionize health and wellness monitoring techniques. These devices typically contain elastomer membranes as backing layers to protect the electronic devices from external scratching, while providing adhesion force to allow the devices to stay on skin. However, the majority of the epidermal electronic devices are attached to the skin using a releasing or transfer printing process that involves the use of water soluble tape, which is inconvenient and tedious to remove. Here, we develop an improved method using a releasing film for the elastomer membranes and silicone adhesive for better skin attachment. The releasing energy of individual interfaces of these stacked layers (releasing film, oil film, elastomer membrane, and silicone adhesive) were studied and measured using a tensile test machine to determine the optimum combination of membrane materials that will lead to easy membrane releasing on skin. Additionally, a 3D printed micro needle array is used as a mold to perforate the elastomer membrane to allow the water vapor from the skin to escape, allowing the membrane to stay on skin for periods up to a month.

### **A Low-cost Fabrication Method for Zinc Nanoparticles for Printable Transient Electronic Devices**

*T. Green, B. Mahajan, X. Huang*, Missouri University of Science and Technology

Transient electronic devices are made of materials that are bioresorbable. However, no mass fabrication method has been demonstrated yet due to limitations in processing bioresorbable materials. A novel approach for obtaining nanoparticles of transient metallic materials through mechanical milling method is proposed here. The resulting nanoparticles can be used to prepare inks that are suitable for inkjet printing. As a demonstration, zinc nanoparticles are obtained through a planetary ball mill with optimized milling parameters (milling time, milling speed, ball to powder weight ratio) with methanol as a process control agent. In addition, zinc nanoparticle ink using polyvinylpyrrolidone (PVP) as a binder has been prepared and demonstrated its capability to form a conductive pattern through a photonic sintering method using a pulsed xenon lamp. Characterization results of the nanoparticles and inks based on scanning electron microscopy (SEM) and X-ray diffraction (XRD) will be presented.

### **3D Extrusion Freeforming of Ceramics (EFF) using a CubePro<sup>®</sup> Printer**

*J. Lapeyre, J. Watts, G. Hilmas*, Missouri University of Science and Technology

This study is focused on the development of Al<sub>2</sub>O<sub>3</sub>/organic based filaments to feed into a 3D Systems 3D Printer, CubePro<sup>®</sup> to indirectly fabricate ceramic components. The methodology to create filaments requires a high shear compounding mixer to combine various thermoplastics with Al<sub>2</sub>O<sub>3</sub> powder. Printed cone samples were fabricated to observe the printer quality. The warping of ABS seems to affect the X and Y direction more than the Z direction. The PLA was close to the tolerance values in the X and Y direction, but not in the Z direction. Overall, the PLA resulted in lower quality prints and in some cases printing parts incompletely. The ABS printed the parts with a better quality, and with a lower failure rate, compared to PLA. A high shear mixer was used to acquire rheological data on both modified and unmodified filaments at 165°C. The data was linearized using a power law approximation to obtain the shear exponent. Future work will include conducting more rheological testing of ABS and PLA plastics at the



print temperature, 260°C, creation of a printable filament, development of a heating schedule for binder burnout, and conducting ASTM tests: C1674-11, C1161-13, and C830-00 to determine physical properties.

### **Influence of Layer Thickness and Raster Angle on the Mechanical Properties of 3D-printed PEEK and a Comparative Mechanical Study between PEEK and ABS**

*W. Wenzheng, G. Peng, Jilin University*

Fused deposition modeling (FDM) is a rapidly growing 3D printing technology. However, printing materials are restricted to acrylonitrile butadiene styrene (ABS) or poly (lactic acid) (PLA) in most Fused deposition modeling (FDM) equipment. Here, we report on a new high-performance printing material, polyether-ether-ketone (PEEK), which could surmount these shortcomings. This paper is devoted to studying the influence of layer thickness and raster angle on the mechanical properties of 3D-printed PEEK. Samples with three different layer thicknesses (200, 300 and 400  $\mu\text{m}$ ) and raster angles ( $0^\circ$ ,  $30^\circ$  and  $45^\circ$ ) were built using a polyether-ether-ketone (PEEK) 3D printing system and their tensile, compressive and bending strengths were tested. The optimal mechanical properties of polyether-ether-ketone (PEEK) samples were found at a layer thickness of 300  $\mu\text{m}$  and a raster angle of  $0^\circ$ . To evaluate the printing performance of polyether-ether-ketone (PEEK) samples, a comparison was made between the mechanical properties of 3D-printed polyether-ether-ketone (PEEK) and acrylonitrile butadiene styrene (ABS) parts. The results suggest that the average tensile strengths of polyether-ether-ketone (PEEK) parts were 108% higher than those for acrylonitrile butadiene styrene (ABS), and compressive strengths were 114% and bending strengths were 115%. However, the modulus of elasticity for both materials was similar. These results indicate that the mechanical properties of 3D-printed polyether-ether-ketone (PEEK) are superior to 3D-printed ABS.

### **Finite Element Analysis of Laser Metal Deposition**

*J. Jimenez, Missouri University of Science and Technology*

Laser Metal Deposition (LMD) is an additive manufacturing process that uses a laser to melt injected metal powder to create metal parts and components. Many industries that manufacture high precision metal components have expressed interest in using this technology; however, due to process uncertainties, it is generally not used for production. In order to enable feedback controls that will help control the quality of the parts created in LMD, a low-order analytical temperature model should be developed and validated. In this work, a finite element (FE) model is constructed for this purpose. Step response and sinusoidal response simulations will be performed using the FE model to generate data for the future development of low-order temperature models for control systems synthesis.

### **Linking Microstructure and Material Properties to Thermal Models for Laser Metal Deposition**

*D. Malta, Missouri University of Science & Technology*

Laser metal deposition (LMD) is an additive manufacturing process that utilizes a laser to melt blown metal powder to a metal substrate. During this process, high temperatures from the laser cause phase transformations and temperature gradients which can develop a nonuniform microstructure in the final part. Microstructure uniformity is important since it affects material properties, and hence the reliability of manufactured parts. In this project, ANSYS Workbench and Mechanical APDL software are used to develop transient thermal simulations of the LMD

process during which temperature is recorded over time. Models of temperature history can be combined with time-dependent microstructural development models to predict microstructure uniformity. Results from this project will ultimately be useful in linking processing parameters to the microstructure and material properties of deposited metals so that the LMD process can be manipulated to create optimized LMD manufactured parts with uniform material properties.

### **Numerical Simulation and Experimental Investigation of Arc Based Additive Manufacturing Assisted with External Longitudinal Static Magnetic Field**

*X. Zhou, H. Zhang, G. Wang, L. Liang, X. Bai, X. Wang, Huazhong University of Science and Technology*

This paper proposes a new arc based additive manufacturing method assisted with external longitudinal static magnetic field. An electromagnetic coupling numerical model has been established, which consists of droplet impingement, heat transfer and dynamics of molten pool. Comparing the simulation results between normal deposition and external longitudinal magnetic field assisted deposition, it shows that the external longitudinal static magnetic field induces the tangential stirring force in molten pool and drives the molten metal moving to the edge of the pool. This can reduce the temperature gradient in forming region. Furthermore, the related comparison experiments of single-bead deposition and multi-beads overlapping deposition are performed, it finds that the tangential stirring force can reduce the height of single-bead as well as increase the width of single-bead. The experimental results are in accordance with the simulation results. The changing of morphology of the bead is beneficial to multi-beads overlapping and capable of improving the surface accuracy for arc based additive manufacturing parts.

### **A High Temperature Polymer Selective Laser Sintering Testbed for Controls Research**

*S. Fish<sup>a</sup>, S. Kubiak<sup>b</sup>, W. Wroe<sup>a</sup>, J. Booth<sup>a</sup>, A. Bryant<sup>a</sup>, J. Beaman<sup>a</sup>, <sup>a</sup>University of Texas at Austin, <sup>b</sup>Stratasys Direct Manufacturing*

High Temperature Polymers under development over the last decade show great promise for Additive Manufacturing (AM) applications in aviation, medicine, and other fields based on their high strength and high temperature qualities. Selective Laser Sintering (SLS) of these materials, derived generally from the Poly Ether Ketone Ketone class of polymers is still somewhat immature however, and certifiably repeatable SLS parts with certifiable mechanical properties remain elusive. One barrier to this is the limited number and high cost of SLS machines capable of operating at the high ~300-350C temperatures needed to build with low internal thermal stress and tight process controls. Another barrier is the lack the instrumentation in the few machines available, to develop critical feedback control and associated flexibility in the thermal management of the material from feedstock to cooled part/part-cake. This paper describes the development and initial testing of a new laboratory SLS machine with the flexibility required in deriving optimal process control for polymer SLS including these high temperature polymer powders. With such a system validated for SLS operation, we will embark on multiple control development approaches to improve part/material property performance.

### **Printing Waveguides by Embedding Fiber Optics into a Substrate**

*B. Morrow, J. Luo, L. Gilbert, E. Kinzel, Missouri University of Science & Technology*

We present a potential approach for the printing of waveguides for integrated photonic circuits by embedding fiber optics into a melt pool created using a CO<sub>2</sub> laser on the circuit material. The

first step towards this printing is to bond single mode fiber into a soda-lime glass substrate. We embedded fiber at point welds using various laser powers and exposure times to test the effect of the energy input on the optical qualities of the embedded fiber. While stresses in the fiber before heating can cause the fiber to fail with higher energy inputs, it is possible to embed the fiber optic without loss of transmission into a soda-lime substrate. The mechanical effects of the embedding are also studied. While durability can be negatively affected by the process, the circuits are still useable. This gives promising results for the possible use of laser embedded fiber optics to cheaply and effectively create waveguides.

### **A Case Study of Topology Optimization for Additive Manufacturing**

*L. Henley, S. Meng, W. Tao, M. Leu, Missouri University of Science and Technology*

Topology optimization of a molding tool to be produced by additive manufacturing for use in composite manufacturing is presented in this poster. First, publically available software for topology optimization is surveyed and compared. Then the software SolidThinking Inspire Structures is chosen for the case study. The molding tool is optimized with the objective to minimize the amount of material under a given load and allowable deformation, for several load cases. Finite element analysis of the optimized molding tool is performed to verify the results obtained from the topology optimization software, as well as to compare with non-optimized tools under the same load and allowable deformation.

## Wednesday AM

### **Modeling V: Various Applications**

Room 202

Session Chair: Evren Yasa, Tusas Engine Industries, Inc.

#### **8:00-8:20      Parameter Estimation Based Real-time Metrology for Exposure controlled Projection Lithography**

*X. Zhao, D. Rosen*, Georgia Institute of Technology

The Exposure Controlled Projection Lithography (ECPL) is a layerless mask-projection stereolithography process, in which parts are fabricated from photopolymers on a stationary transparent substrate. To enable advanced closed-loop control for ECPL, an in-situ interferometric curing monitoring (ICM) system has been developed to infer the output of cured height. However, the existing ICM method based on an implicit model and rough phase counting is not fast and accurate enough. This paper reports on a new ICM method to address the modeling and algorithms issues confronted by the current ICM method. The new ICM model includes two sub-models: a sensor model of instantaneous frequency based on interference optics and a calibration model. To solve the models, a moving horizon exponentially weighted online parameter estimation algorithm and numerical integration are adopted. As a preliminary validation, offline analysis of interferograms acquired in an ECPL curing experiment is presented. The agreement between ICM estimated cured height and ex-situ microscope measurement indicates that the overall scheme of the new ICM measurement method with a well-established model, evolutionary estimation and incremental accumulation, is promising as a real-time metrology system for ECPL. The new ICM method is also shown to be able to measure multiple voxel heights consistently and simultaneously, which is desired in global measurement and control of ECPL.

#### **8:20-8:40      Planning Freeform Extrusion Fabrication Processes with Consideration of Horizontal Staircase Effect**

*A. Ghazanfari, W. Li, M. Leu, R. Landers*, Missouri University of Science and Technology

An algorithm has been developed to estimate the “horizontal” staircase effect and a technique is proposed to reduce this type of geometrical error for freeform extrusion fabrication processes of 3D “solid” parts. The adaptive rastering technique, proposed in this paper, analyzes the geometry of each layer and changes the width of each line of the raster adaptively in order to reduce the staircase error and increase the productivity simultaneously. For each line, the maximum width that results in a staircase error smaller than a predefined threshold is determined for decreasing the fabrication time or increasing the dimensional accuracy, or both. To examine the efficacy of the proposed technique, examples are provided in which staircase errors and fabrication times are compared between uniform and adaptive rastering methods for each part. The results show a considerable improvement in accuracy and/or fabrication time for all parts studied when using the adaptive rastering technique.

#### **8:40-9:00      Optimal Rastering Orientation in Freeform Extrusion Fabrication Processes**

*A. Ghazanfari, W. Li, M. Leu, R. Landers*, Missouri University of Science and Technology

Many researchers have tried to optimize the build direction of additively manufactured parts to minimize the vertical staircase effect. However, the horizontal staircase effect should also be

considered when fully dense parts are to be fabricated. In this paper, part inaccuracy due to the horizontal staircase effect is considered in order to determine the optimal rastering orientation in building the part. An algorithm is developed to estimate this inaccuracy and a technique is proposed to minimize it. The effect of rastering orientation on staircase errors is examined, and the particle swarm optimization method is used to determine the optimum rastering angle that leads to minimum errors for each layer. Several case studies are considered where the staircase errors are calculated with and without optimizing the rastering orientation. The results show that the errors can be reduced considerably when using the optimal rastering orientation. To verify the analytical results, parts are fabricated using a freeform extrusion fabrication process at various angles and the errors are compared.

### **9:00-9:20      Application of an RBF Neural Network for FDM Parts' Surface Roughness Prediction for Enhancing Surface Quality**

*E. Vahabli, S. Rahmati, Islamic Azad University*

To improve the surface roughness of parts fabricated using fused deposition modelling, modeling of the surface roughness distribution is used before the fabrication process to enable more precise planning of the additive manufacturing process and to optimize the effective production parameters. In this paper, a radial basis function (RBF) neural network model is proposed for estimation of the surface roughness based on experimental results. A specific test part capable of evaluating the surface roughness distribution for varied surface build angles is built. The most well-known analytical models are simulated and then the results are compared with those obtained using the proposed model. The results of the evaluation of four different build angle ranges confirm the capability of more fitted responses in the RBF network. The RBF network has a mean absolute percentage error and mean squared error of 4.65% and 2.347, respectively. The robustness of the network is studied based on the variation of the number sets of data input. Finally, the validity assessments confirm that better results were obtained using the recommended model.

### **9:20-9:40      Surface Roughness optimized Alignment of Parts for Additive Manufacturing Processes**

*P. Delfs, M. Töws, H.-J. Schmid, University of Paderborn*

The layered structure of Additive Manufacturing (AM) processes results in a stair-stepping effect of the surface topographies. In general the impact of this effect strongly depends on the build angle of a surface, whereas the overall surface roughness is caused by the resolution of the specific AM process. Aim of this work is the prediction of the surface quality (SQ) in dependence of the building orientation of a part. This results can finally be used to optimize the orientation to get a desired SQ. As some surfaces will not get well anyway, it is possible in this model to indicate surfaces which do not need to exhibit a good SQ. The model uses the digital .stl format of a part as this is necessary for all AM machines to build it. Each triangle is assigned with a SQ value e.g. a roughness value and with testing different orientations the best one can be found. Of course this approach needs a dataset for the SQs. This must be done separately for each AM process and is shown exemplary with a surface topography simulation for the laser sintering process.

### **9:40-10:10      BREAK**

### **10:10-10:30 Tool Path Planning for Free Form Heterogeneous Object**

*M.D. Habib, B. Khoda*, North Dakota State University

The tool path plan to fabricate free form heterogeneous part can be challenging because of frequent interruptions due to tool changes, tool start-stop and non-deposition time. Such interruptions depends upon object geometry and materiality. In this paper a computational algorithm is proposed to find out an optimal tool path expecting minimum interruptions due to concavity and overall minimum build time. The 3D object is sliced and free form contours are analyzed to determine the maximum continuous deposition length, minimum tool start-stop and non-deposition time. A time measurement model is developed to calculate the overall build time and non-deposition time and the outcome is comparable with commercial software. A specimen object is fabricated following the proposed algorithm and it demonstrates almost 9% build time improvement in each layer. Planning such a tool path for heterogeneous object will result minimum build time and reduce the total resource consumption during their fabrication process.

### **10:30-10:50 DC-Gain Layer-to-layer Stability Criterion in Laser Metal Deposition Processes**

*P.M. Sammons, D.A. Bristow, R.G. Landers*, Missouri University of Science and Technology

In Laser Metal Deposition (LMD), a metal-based additive manufacturing process, functional metal parts are fabricated in a layer-by-layer fashion. In addition to the in-layer dynamics, which describe how the process evolves within a given layer, the additive-fabrication property of LMD creates a second set of dynamics which describe how the process evolves from layer-to-layer. While these dynamics, termed layer-to-layer dynamics, are coupled with both the in-layer dynamics and process operating conditions, they are not widely considered in the modeling, process planning, or process control of LMD operations. Because of this, seemingly valid choices for process parameters can lead to part failure - a phenomenon commonly encountered when undergoing the laborious procedure of tuning a new LMD process. Here, a layer-to-layer stability condition for LMD fabrications is given, based on the shape of the powder catchment efficiency function, which provides insight into the layer-to-layer evolution of LMD processes and can be useful in process planning and control. The stability criterion is evaluated for various operating points and regions for stable and unstable operation are identified. Simulation results are then presented showing both stable and unstable layer-to-layer LMD fabrications. The simulated behavior successfully predicts the results seen in both stable and unstable experimental depositions.

### **10:50-11:10 A Reverse Compensation based Computation Framework for Deformation Control in Stereolithography**

*K. Xu, Y. Chen*, University of Southern California

Shape deformation is one of the biggest issues in the mask-image-projection-based Stereolithography (MIP-SL) process. Volumetric shrinkage, combined with factors such as thermal cooling during the photopolymerization and support-constrained layer-by-layer building process, leads to complex part deformation that is hard to control. In this paper, a closed-loop computation framework based on a reverse compensation approach is presented to reduce the shape deformation of fabricated parts. During the compensation process, the shape deformation is firstly calculated, either by using FEA simulation or physical measurements. Both approaches are demonstrated with their advantages and disadvantages discussed. An algorithm is presented for identifying the optimal correspondence between the deformed shape and the given nominal

CAD model. Accordingly a new CAD model based on the determined compensation can be constructed. The intelligently designed CAD model, when used in fabrication, can significantly reduce the part deformation when compared to the nominal CAD model. Several test cases have been performed to demonstrate the effectiveness of the presented computation framework. Limitations and future work are also discussed in the paper.

### **11:10-11:30 An Algorithm-based Method for Process-specific Three-Dimensional Nesting for Additive Manufacturing Processes**

*A. Arndt, H. Hackbusch, R. Anderl*, Technische Universität Darmstadt

The additive manufacturing process chain starts with the creation and use of 3D CAD data. Further essential steps within the process chain include pre-processing, manufacturing, post-processing, and component use. Particularly the progress towards the digitalization of the manufacturing process chain requires a comprehensive concept and implementation of the process chain *3D CAD for Additive Manufacturing*. The process steps modelling, nesting, and slicing as well as the universal usage of a uniform data format require extensive research activities to enable the utilization of the aforementioned advantages. To achieve optimal and high-quality results through additive manufacturing, the process- and technology-specific orientation and positioning of components within the virtual space, the so-called nesting, is essential. Primarily the nesting step is examined in this paper. From a scientific perspective it is a matter of examining this process and furthermore to analyze the optimal insertion of supporting structures, since the critical machine-specific parameters have been insufficiently studied. Within this paper a new multi-criteria optimization based on a conceptual algorithm is proposed. The most important point is the consideration of a technical and not only geometric nesting process.

### **11:30-11:50 Modeling and Direct Measurements of Powder Absorptivity with Application to Additive Manufacturing**

*C.D. Boley, A.M. Rubenchik, S.S. Wu*, LLNL

We have investigated, by calculations and experiment, the optical absorption of a powder of metal spheres. The calculations include ray tracing with Fresnel absorption and multiple reflections. A particle pack algorithm is employed to set up a powder layer with spheres having a distribution of sizes. We demonstrate that multiple reflections greatly increase the total absorptivity from its flat-surface value, especially for highly reflective metals. We calculate the powder absorption for a selection of materials, size distributions, and powder layer thicknesses. The effect of the beam size is also discussed. Experimentally, a simple method is developed for direct calorimetric temperature-dependent absorptivity measurements. Samples with a thin layer of powder on a thin Ta foil are uniformly irradiated using a diode-array laser emitting at 975 nm. Small thicknesses ensure temperature uniformity across the sample. The temperature is monitored by thermocouples and an IR camera. A scheme for removing the effects of convective and radiative losses is implemented. The resulting measurements are compared with the modeling predictions.

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## **Applications IV: Material/Process Selection and Optimization**

Room 203

Session Chair: Wenchao Zhou, University of Arkansas

### **8:00-8:20 Development of a Desktop 3D Printer Online Database**

*M. Perez, L. Herrera, D. Espalin, R. Wicker*, University of Texas at El Paso

The recent expiration of patents by additive manufacturing equipment suppliers has resulted in the release of hundreds, possibly thousands, of new desktop 3D printers. Some printers are being sold by well-known companies, already established within the additive manufacturing industry, while others have been designed by enthusiasts and do-it-yourselfers. There is significant range in the quality of these printers in terms of the features they offer and the accuracy of parts they produce. Many of these printers perform exceptionally, offering excellent parts, while others perform at a subpar levels. The popularity that at-home 3D printing has experienced has caused desktop 3D printer sales to soar in the last few years. Yet, there is no standardized method available to rate and qualify these printers so that consumers can make an educated purchasing decision. Researchers at the W.M Keck Center for 3D Innovation have devised a method of testing desktop printers using a quantitative ranking model. Many printers have already been tested using this method, including those from Stratasys, MakerBot, and 3D Systems. The ranking model, has been employed in the development of an online database that allows users to see testing results as well as compare system features, including cost, size, build volume, and others. This database will be updated as new systems are released onto the market allowing users to compare printers and make the best possible purchase according to their specific needs.

### **8:20-8:40 Selecting the Most Cost-Effective Location for AM Production**

*A. Wang*, Senvol

This presentation will illustrate how additive manufacturing (AM) production facilities have different cost structures in different locations around the world, and how these differing cost structures can lead to a competitive advantage for AM production. Numerous relevant cost variables (e.g. AM machine, consumables, labor, energy, real estate, post-processing) will be examined. The analysis will show how each cost variable is location-dependent - for example, labor rates are lower in China than in the U.S. - and how each cost variable contributes to the total cost of the final AM part that is produced. A framework will be presented that manufacturers and service bureaus can use to analyze the cost structure of an AM production facility and determine the most cost-effective location. The results of a case study that Senvol conducted for the Government of Canada will be shared. The case study analyzes and compares the AM production cost structures in five countries (U.S., Canada, China, UK, Mexico).

### **8:40-9:00 Development of an Economic Decision Support for the Application of Additive Manufacturing in Aerospace**

*G. Deppe, C. Lindemann, R. Koch*, University of Paderborn

Additive Manufacturing offers a high potential in aerospace industry due to its freedom of design and the ability to manufacture complex and lightweight parts. The low number of units, high quality standards and fast response time are special challenges that have to be met especially in the Maintenance, Repair and Overhaul sector. Thus, companies have to decide at which point it is economic to apply Additive Manufacturing. However, companies lack experience on this new technology. This is why a tool is required that takes into account the above mentioned crucial



points and supports the decision process. This paper will analyze aviation's characteristics with regard to Additive Manufacturing. Therefore a process analysis of current repair workflows will be conducted to identify a feasible application for Additive Manufacturing. Additionally the supply chain will be examined to indicate the benefit which the technology can generate in this highly demanding field. The findings are integrated into a methodology that supports the decision whether to apply Additive Manufacturing on the basis of a calculation taking into account costs, time and quality.

**9:00-9:20 Additive Manufacturing in South Africa - Discussion of New Initiatives after two decades of development**

*D.J. De Beer*, North West University

Additive Manufacturing (AM) or Rapid Prototyping (RP) made a humble start in South Africa in 1991 with one SLA 250. Introduction to academic research followed through two FDM systems bought by the CSIR in 1994, which were made available to the author to conduct research through a sabbatical spent at the CSIR in 1995. To close the gap between SA and the AM world leaders at that stage, various fundamental and application-based research projects were started by individual universities and the CSIR. In a sense, it created further problems, as it raised significant expectations within industry and academia regarding AM's future in SA. As with typical "new technology trigger trends", the SA activities started at zero level, reached the typical "peak of inflated expectation", entered the valley of "disappointment" for some users and also left some in dissolution (and desolation for the instigators / researchers), entering the slope of enlightenment and into the plateau of productivity, into productivity. The paper and presentation will draw on highlights achieved over two decades that culminated in a national organisation, the SA AM Landscape and the recent consortium-based Collaborative Programme on AM (CPAM) funded by government. It will also attempt a forecast in terms of future initiatives.

**9:20-9:40 Systematic Approach for the Economic Application and Comparison of AM Part Candidates**

*C. Lindemann, T. Reiher, U. Jahnke, R. Koch*, University of Paderborn

One of the crucial points for bringing the Am technology to new users and new industries are economic aspects. A systematic approach for the economic application and the comparison of AM part candidates is crucial for the integration of additive manufacturing into existing businesses. The selection needs to be based on technical, economical and strategic aspects. This paper presents an approach to help end users to find appropriate measures, which are capable of bringing AM into their businesses.

**9:40-10:10 BREAK**

**10:10-10:30 Feasibility Study of Small Scale Production Based on Additive Manufacturing Technologies**

*M.W.M. Cunico, J. de Carvalho*, University of São Paulo

Along the last years, the complexity of products has been growing progressively, while the product development life-cycle tended to be reduced. In addition to that, additive manufacturing technologies increased their role in the product development process, resulting in reduction of errors and products release time. In spite of these benefits, the main application of these

technologies is still focused on initial phases of projects and results in high costs of parts and low volumes. On the other hand, although conventional productivity processes results in low costs and high volumes, the investment related to these processes are high and the implementation time are long. For that reason, the main goal of this work is to investigate the possibility of application of additive manufacturing technologies for small and medium scale production. Along this work, the main direct and indirect processes which are used for small and medium scale production were studied and a numerical cost model were developed for each one. In order to compare the benefits and disadvantages among the processes, 3 parts were selected and analysed through such models. By the end, the main cost, payback; amortization and takt time were identified and the most suitable process was found in accordance with annual part demand.

### **10:30-10:50 Polymer Recycling and Additive Manufacturing in an Open Source Context Optimization of Processes And Methods**

*F. Cruz, S. Lanza, H. Boudaoud, S. Hoppe, M. Camargo, University of Lorraine*

Polymer recycling is a way to reduce environmental impacts of accumulation of polymeric waste materials. However, low recycling rates are often observed in conventional centralized recycling plants mainly to the challenge of collection and transportation for high-volume low-weight-polymers in conventional centralized recycling plants. As the democratization of open-source 3D printers is going forward thanks to initiatives such as FabLab environments, there is a growing interest on how to use this technology to improve the efficiency of use of raw materials. Studies have been proposed in order to recycle waste polymer into open-source 3D printer feedstock.

The recycling of high-density polyethylene (HDPE) issued from bottles of used milk jugs through use of an open-source filament fabricator system called RecycleBot has been evaluated. In this study, we propose an evaluation of the mechanical recyclability of Polylactic Acid (PLA), material widely used in the open-source 3D printing context, in order to establish the viability of this recycled material to be used in the open-source 3D printers. The degradation of the material's mechanical and rheological properties after a number of cycles of multiple extrusion and printing processes is evaluated. The characterization of recycled raw materials for open-source 3D printing has implications not only to reduce the environmental impact of polymers waste, but also it will allow us to understand the technical requirements and challenges for development of open-source filament recycle machine/process.

The coupling of open-source 3D printers and filament extruders can offer the bases of a new distributed polymer recycling paradigm, which reverses the traditional paradigm of centralizing recycling of polymers where is often uneconomic and energy intensive due to transportation embodied energy. Moreover, this characterization also will allow the exploration of new source of materials and new composite materials for open-source 3D printing, in order to improve the quality of products made by this technology.

### **10:50-11:10 Protection Measures against Product Piracy and Application by the Use of AM**

*U. Jahnke, J. Buesching, T. Reiher, R. Koch, University of Paderborn*

Presently the implications Additive Manufacturing (AM) on intellectual properties are discussed in public. Here AM is often mentioned as a driver for product piracy as it allows to produce and to copy objects with any geometries. Imitators need a lot of information to copy an object accurately. As reverse-engineering has been identified as the most important information source for product imitators, AM can also help to reduce the threat of product piracy when correctly

applied in the product development. Due to the layer wise production process that allows the manufacturing of very complex shapes and geometries, the reverse-engineering process can be complicated by far. By this, quite contrary to the public opinion, AM can increase the needed effort of imitators and strongly reduce the economic efficiency of product piracy. This paper will show different protection measures and a methodological approach of how to apply these measures to a product. Beside the protective effect some measures allow a traceability of parts over the products lifecycle and thus support the quality management of AM processes and additively produced parts.

### **11:10-11:30 A Glance at the Recent Additive Manufacturing Research and Development in China**

*X. Xing<sup>a</sup>, L. Yang<sup>b</sup>*, <sup>a</sup>Harbin Engineering University, <sup>b</sup>University of Louisville

This paper reviews some of the recent additive manufacturing research and development works in China. Many AM research activities in China focuses on direct energy deposition processes, powder bed fusion processes, direct write bio-printing and stereolithography, as well as some of the development works with the AM systems. For applications, AM has been increasingly adopted in various areas including aerospace, biomedical, optical devices, MEMS, tooling, construction and automobile. Based on the review, several potential areas for international collaboration between China and the U.S. were suggested.

### **Materials V: Polymer Extrusion and Inkjet**

Salon AB

Session Chair: Marlon Cunico, University of São Paulo

### **8:00-8:20 Designing Material Distribution for Fiber Reinforced Polymers in Fused Deposition Modeling Products**

*R. Hoglund, D. Smith*, Baylor University

Mechanical properties of products produced with the Fused Deposition Modeling (FDM) process are known to be dependent on bead direction, especially when short fiber reinforcement is added to the polymer filament feedstock. As a result, the structural performance of fiber-filled FDM parts is expected to be improved by simultaneously computing preferred deposition directions while optimizing the internal support structure. This paper presents a topology optimization method for computing the material distribution within a fiber-reinforced polymer composite FDM part that incorporates the non-isotropic mechanical properties of the bead structure. Unlike the well-established homogenization topology optimization method which determines pointwise orthotropic properties by increasing the complexity of the design problem, our approach takes advantage of the simplicity of the SIMP method where the underlying orthotropic orientation is assumed. Computed results show the effect that the orientation of fiber filled bead orthotropic microstructure has on part topology for 2D and 3D FDM parts.

### **8:20-8:40 Experimental Investigation of Mechanical Properties of 3D-Printing Built Composite Material**

*Y.-T. Kao, T. Dressen, D.S. Kim, S. Ahmadizadyekta, B.L. Tai*, Texas A&M University

This paper studies the mechanical behaviors of a new composite material manufactured by 3D printing and polymer impregnation techniques. This composite uses 3D-printed plaster with an

open-cellular structure as a frame to encapsulate the silicone resin (PDMS) to form a solid body. Because of the vastly different characteristics of the materials that make it up, the composite could have a wide variety of mechanical behaviors. In this study, design of experiment was performed with four-point bending tests using different composition ratios and sizes of open cells to determine the mechanical properties of the composite. These properties include maximum flexural stress maximum flexural stress ( $\sigma_{\max}$ ), flexural secant modulus of elasticity ( $E_f$ ), and toughness indices ( $I_5$  and  $I_{20}$ ). The experimental results show that both  $E_f$  and  $\sigma_{\max}$  are proportional to the plaster content and the unit cell size, while  $I_{20}$  had an opposite trend. The  $E_f$  ranged from 20 to 280 MPa, and  $\sigma_{\max}$  ranged from 0.3 to 1.2 MPa for a 25%-75% plaster content and 3.25-6.5 mm cell size. Statistical analysis further confirmed the differences between these cases. This paper has demonstrated the capability of this composite to exert different mechanical properties for functional applications.

#### **8:40-9:00 Development of a 3D Printable Elastomeric Blend Based on ABS**

*G. Siqueiros, D. Roberson, University of Texas at El Paso*

A very important aspect for the advancement of material extrusion 3D printing is the creation of new materials with a wide variety of physical properties. The focus of this study reflects on the development of rubberized ABS where the viscoelastic aspects of the material can be tuned. The capability of tunability is an advancement over the state of the art where urethane materials currently occupy the market segment for flexible materials. Here our novel blends were evaluated based on mechanical testing, fracture surface analysis using scanning electron microscope and the rheological characteristics were determined based on dynamic mechanical analysis. A head to head comparison with a commercially available urethane material was also made.

#### **9:00-9:20 Evaluation of 3D Printable Sustainable Composites**

*D. Roberson, C. Rocha, M. Pinon, The University of Texas at El Paso*

Poly lactic acid (PLA) is rapidly becoming the mainstay material for use in desktop grade 3D printers based on FDM technology in part due to the environmental sustainability of this polymer. While biodegradability is an advantage; as compared to other materials used by FDM-type platforms, there is a lack of desirable physical attributes. The work presented here evaluates the altering of the physical properties of PLA through the addition of sustainable additives. Here, the physical properties of PLA were modified while, at the same time the two desirable aspects of 3D printer compatibility and biodegradability were retained. Rheological analysis of the material systems was performed by dynamic mechanical analysis and failure analysis of 3D printed tensile specimens was carried out through the use of scanning electron microscopy. Finally, biodegradability of the novel PLA-based material systems was assessed based on in-soil exposure testing.

#### **9:20-9:40 3D Printing with Natural Fiber Reinforced Filament**

*J.I. Montalvo N., M.A. Hidalgo, Universidad Autonoma de Occidente*

The purpose of this Project is to obtain a 3d printing filament using different plastic matrices and sugar cane bagasse as the filler and test it in a 3d printer. In order to do this, a reverse engineering process was made to several 3d printer extruders to determine how to change the extruder in order to be able to print with the filament. To obtain the filament, a plastic extruder was modified to obtain a compound filament of 1.75 mm using a 3x4 design of experiments with

the factors percentage of fiber (10% 20% 30%) and type of matrix(PE,PP,ABS,PLA). The filaments obtained were tested to determine the mechanical properties and finally were used in a 3d printing to compare results.

#### **9:40-10:10 BREAK**

#### **10:10-10:30 Mechanical and Thermal Properties of FDM-Parts Manufactured with Polyamide 12**

*F. Knoop, V. Schoeppner*, University of Paderborn

Fused Deposition Modeling (FDM) is an Additive Manufacturing (AM) technology which is used for prototypes, single-part production and also small batch productions. For use as a final product, it is important that the parts have good mechanical properties, high dimensional accuracy and smooth surfaces. The knowledge of the mechanical properties is very important for the design engineer when it comes to the component design. End-use products out of the FDM process have to resist applied forces. In this paper, investigations were conducted with the polymer Polyamide 12 (FDM Nylon 12) from Stratasys Inc. This polymer can be processed with three different tip sizes resulting in different layer thicknesses from 178  $\mu\text{m}$  to 330  $\mu\text{m}$ . Thus, the mechanical properties were determined for these layer thicknesses and for different orientations on the build platform. In addition to the mechanical properties the thermal properties (e.g. with a DSC analysis) are also investigated.

#### **10:30-10:50 Additive Manufacturing of Soft and Composite Parts from Thermoplastic Elastomers**

*M. Saari, M. Galla, B. Cox, P. Krueger, A. Cohen, E. Richer*, Southern Methodist University

Thermoplastic elastomers (TPEs) are low-durometer materials that can support large strains without breaking, making them attractive materials for producing 3-D printed soft components. However, prefabricated TPE filament, especially those with low hardness, cannot be used in typical filament feed extrusion mechanisms that are popular in material extrusion-based 3-D printers today.

Therefore, we have developed a mini-screw extruder, small enough to be incorporated on a typical 3-D printer system, and capable of extruding various TPE formulations directly from commercially available pellets. This paper presents the design and thermal analysis of the mini-extruder, experimental testing of the 3-D printing process for TPEs with hardness in the range of 5-52 Shore A, and compression and tension tests of the properties of printed parts. By combining 3-D printing of soft TPEs with rigid thermoplastics, the new system also opens up new possibilities in additive manufacturing of soft and hard composite parts.

#### **10:50-11:10 Characterization of Multi-material Interfaces in PolyJet Additive Manufacturing**

*I. Vu, L. Bass, N. Meisel, B. Orler, C. Williams, D. Dillard*, Virginia Tech

Relatively few engineering devices and structures are monolithic, as combinations of materials are often needed to obtain the necessary functionality, performance, weight, and cost requirements. The PolyJet material jetting Additive Manufacturing (AM) process allows the realization of products that are composed of multiple (blends of) materials, and thus opens new opportunities for expeditiously achieving functional and performance targets. However, little is known about the interactions at the interfaces of these disparate printed materials. To study the

interfacial properties of printed composite materials, a Stratasys PolyJet system was used to fabricate double cantilever beam specimens featuring a soft acrylic layers (TangoBlackPlus) sandwiched by two stiffer acrylic strips (VeroWhitePlus). These specimens were evaluated to characterize the fracture resistance of the composite materials. Failures nominally occurred at the interface between the two types of materials. Further testing is providing insights into the effects of print direction, postcuring, and interface architecture on the resulting fracture energies. These studies suggest the opportunities for designing printed interfaces with improved performance and durability for multi-material AM products.

### **11:10-11:30 The Effect of Build Orientation on the Mechanical Properties in Inkjet 3D-Printing**

*J. Mueller, K. Shea*, ETH Zurich

It is known that part orientation plays an important role in 3D printing and especially in inkjet 3D printing, where the layers are more distinct than in other processes. Despite many investigations in this direction, previous research focused mainly on build orientations along the three main axes X, Y and Z. For advanced purposes such as optimization, however, it is important to know what happens in combined alignments between the main axes. The authors hypothesize and show that the transition is not linear and that, despite prior studies, the weakest properties are not found when the parts are aligned along the Z direction. The discovered effects can partially be attributed to shear forces in the material, which act between the layers when the parts are not aligned orthogonally to the main axes. To accurately characterize the three-dimensional space, the mixture design method has successfully been introduced to the area of 3D printing and proven to be an efficient tool that can also be used for other processes. With the results of this study, designers and engineers are now able to analyze and predict part properties on a much higher level than before.

## **Materials VI: Aluminum, Non-Metallics and Glass**

Salon D

Session Chair: Chris Tuck, University of Nottingham

### **8:00-8:20 Thermal Treatments of Al Alloy AlSi10Mg Processed by Laser Beam Melting**

*A. Mertens<sup>a</sup>, O. Dedry<sup>a</sup>, D. Reuter<sup>b</sup>, O. Rigo<sup>b</sup>, J. Lecomte-Beckers<sup>a</sup>*, <sup>a</sup>University of Liege, <sup>b</sup>Sirris Research Center

Recent studies have shown that AlSi10Mg processed by Laser Beam Melting (LBM) exhibits a much finer microstructure when compared to its cast counterpart as a consequence of the much faster cooling rates imposed in the LBM process. Such microstructural refinement causes a significant increase in strength and hardness, to such an extent that as-fabricated LBM AlSi10Mg was reported to present hardness value of  $127 \pm 3$  Hv0.5, similar to the hardness of high pressure die cast AlSi10Mg in the aged condition (i.e. 130-133 Hv) [Thijs et al., *Acta Mater.*, 61(2013), 1809-1819]. Yet, little attention has been given so far to the influence of thermal treatments on the microstructure and mechanical behaviour of LBM AlSi10Mg. The present work hence aims to investigate the effect of two different types of heat treatments - i.e. (i) stress relief and (ii) solutionizing and ageing - on the microstructure, hardness and tensile properties of LBM AlSi10Mg.

**8:20-8:40      Fatigue Performance Enhancement of Selectively Laser Melted Aluminium Alloy by Heat Treatment**

*I. Maskery, N. Aboulkhair, C. Tuck, I. Ashcroft, R. Wildman, N.M. Everitt, R. Hague, University of Nottingham*

We measured the stress-strain behaviour and fatigue performance of the aluminium alloy Al-Si10-Mg manufactured by selective laser melting (SLM). This process, specifically the rapid cooling of the metal from its molten state, results in a fine microstructure, generally providing high hardness but poor ductility. We used a heat treatment to alter the microstructure of the material from its as-built state. This significantly improved the ductility and fatigue performance. The elongation at break for the heat treated material was nearly three times greater than that observed for the as-built material, and the fatigue strength at  $10^6$  cycles was around 1.6 times as high. Combined with the design freedoms of additive manufacture, this development increases the suitability of lightweight SLM parts for use in the aerospace and automotive sectors, where good fatigue performance is essential.

**8:40-9:00      Mechanical Properties of Selective Laser Melted AlSi10Mg: Nano, Micro, and Macro Properties**

*N.T. Aboulkhair, A. Stephens, I. Maskery, C. Tuck, I. Ashcroft, N.M. Everitt, University of Nottingham*

Selective laser melting (SLM) of Aluminium alloys has acquired huge interest at both the industrial and research levels. Aluminium poses more of a challenge to SLM than some other candidate materials such as titanium alloys, stainless steels, and nickel-based alloys because of its properties (thermal diffusivity, infrared absorptivity, etc.) and has been known to result in relatively porous parts. However, numerous recent studies have reported successful production of dense AlSi10Mg parts using SLM. In this study, we report on the nano, micro, and macroscopic mechanical properties of dense AlSi10Mg samples fabricated by SLM. Nanoindentation revealed the hardness profile across individual melt pools building up the parts and its interrelation to the microstructure and chemical elements distribution. Micro-hardness testing showed anisotropy in properties according to the build orientation. Lastly, the tensile and compressive behaviors of the parts were examined showing relatively high compressive strain.

**9:00-9:20      Preparation of Nylon-12 Coated Al<sub>2</sub>O<sub>3</sub> Particles for Indirect Selective Laser Sintering**

*J. Daher, S.J. Martin, G. Forte, Loughborough University*

Selective laser sintering (SLS) is a powder bed process which has been traditionally used to additively manufacture polymer parts. However, there has been growing interest in expanding the material capabilities of SLS to metals and ceramics; As such, a method of coating ceramic powder particles with a lower-temperature-melting polymer binder is required for indirect SLS of highly dense ceramic part. It has been identified that the parts built via indirect SLS, contain a degree of porosity related to a number of processing and sintering parameters, one of which is correlated with initial binder content. A dissolution-precipitation method was used to coat alumina (Al<sub>2</sub>O<sub>3</sub>) particles with nylon 12 (Duraform PA) powder. As high density is desirable, a 1% polymer binder was used to coat a set amount of Al<sub>2</sub>O<sub>3</sub> powder. Initial FTIR results indicate that the 1% polymer content is present in random batches of powder after coating process. XPS also demonstrated that carbon is present both in loose powder sample and a sintered part. Whilst

it is possible to coat ceramic powders with the PA12, there remained difficulties in agglomerate formation and the breaking down of powders before they were ready to be sintered once coated.

**9:20-9:40 In situ Monitoring of Ceramic Materials Manufactured using Binder Jetting Technology**

*J. Mireles, J. Gonzalez, S. Ridwan, R. Wicker, The University of Texas at El Paso*

Binder jetting additive manufacturing is an emerging technology with a wide range of commercial materials that can be processed, including metals and ceramics (316 SS, 420 SS, Inconel 625, Iron, Silica). In this project, aluminum oxide ( $Al_2O_3$ ) precursor powder was used for part fabrication. Various build parameters (e.g. layer thickness, saturation, particle size) were modified and different sintering profiles were investigated to achieve nearly fully dense parts. The materials were characterized to analyze microstructure and physical properties post-fabrication and a camera was installed to evaluate the process during fabrication. An in situ monitoring setup was developed aimed for part qualification that can be applied toward any material system processed using binder jetting technology. The results presented here demonstrate potential methods for integrated metrology and part quality monitoring aimed toward part qualification.

**9:40-10:10 BREAK**

**10:10-10:30 Fabrication of 3D Polymer-metal Nano-composites in a Single Step by Two-photon Induced Polymerisation and Metal Salt Reduction**

*Q. Hu, Y. Liu, R. Wildman, C. Tuck, R. Hague, University of Nottingham*

Metamaterials are novel artificial multi-material constructs with sub-wavelength-sized periodic structures containing both conducting (metal) and dielectric (polymer) components. Their unique - but previously unachievable - properties have any interesting applications. The current techniques for metamaterials manufacturing are mainly based on traditional microchip patterning techniques, e.g. photolithography combined with metal deposition, that are expensive, multistep and slow. Two-photon lithography, an advanced additive manufacturing technique, is suitable to manufacture 3D complex micro/nano structures in a fast and cost-efficient way. Both polymeric structures and metallic structures have been independently demonstrated by two-photon induced polymerisation and metal salt reduction. In the current work, we show the combination of the two reactions in a single step and demonstrate that 3D polymer-metal nano-composites can be fabricated simultaneously from a mixture of polymer resin and metal salt. IPL-Au hybrid nano-structures will be shown and characterized. The role of photoinitiator and free-radicals in the two competing processes - photopolymerisation and photoreduction - will be discussed.

**10:30-10:50 Material Compatibility In Multifunctional Printing**

*C. Mahajan, M. Meda, S. Williams, D. Cormier, Rochester Institute of Technology*

Multifunctional printing is an emerging area of additive manufacturing that holds tremendous promise. Whereas the majority of AM processes are typically used to produce structural components, researchers are now starting to integrate additional materials into additively manufactured parts that serve other functions such as electrical conduction, heat generation, sensing, or actuation. Fabrication of these multifunctional devices is generally achieved using multi-material printing in which one or more deposited materials are in ink or paste form. When dissimilar materials are combined, however, attention must be paid to how they will interact



during deposition, drying, thermal processing, and in service. Improperly chosen inks/pastes may exhibit poor wetting of the substrate, drying defects, lack of adhesion, or other problems. This paper aims to provide useful guidelines for proper ink/paste formulation to improve multi-material compatibility. Issues such as co-solvent selection, surfactants, humectants, solid loading fraction, and surface pre-treatment via atmospheric plasma are discussed. Specific demonstrations of ink-substrate interactions are provided using conductive inks printed on a variety of polymer additive manufacturing substrates.

#### **10:50-11:10 Selective Laser Melting of a Bismuth Telluride Thermoelectric Material**

*A. El Desouky, A. Read, P. Bardet, M. Andre, S. LeBlanc*, George Washington University  
Selective Laser Melting (SLM) technology is a rapidly growing solid freeform fabrication tool because it is cost effective, reduces production time of complex shapes, and accommodates a range of material systems such as metals, ceramics, polymers, intermetallics and composites. This work presents the first-ever results for SLM performed on a semiconducting thermoelectric material, bismuth telluride ( $\text{Bi}_2\text{Te}_3$ ), using a Nd:YLF pulsed laser. The evolution of the localized melt lines formed under different processing parameters such as initial green density, laser power and scan speed was investigated. The variation in initial green densities of the specimens had no significant effect on the melt zone. Melt lines were evident on the top surface of the powder compacts under all investigated processing conditions. However, cross-sections taken across the melt lines revealed material removal at the irradiation site with minimum consolidation in the subsurface. Finite element modeling results concur with experimental results showing that the highest temperature was localized only at the top surface, and powder layers in the subsurface experienced temperatures well below the melting temperature of bismuth telluride. Experimental and simulation results demonstrate that it is possible to laser melt  $\text{Bi}_2\text{Te}_3$  powder, which enables new possibilities in additive manufacturing of complex 3D semiconductor thermoelectric components.

#### **11:10-11:30 Selective Laser Melting of an $\text{Al}_{86}\text{Ni}_6\text{Y}_{4.5}\text{Co}_2\text{La}_{1.5}$ Metallic Glass Composite with Commercial Pure Titanium Powder**

*X. Li<sup>a</sup>, J. Wang<sup>b</sup>, Y. Yang<sup>b</sup>, M. Qian<sup>c</sup>, T. Sercombe<sup>a</sup>*, <sup>a</sup>The University of Western Australia, <sup>b</sup>Chinese Academy of Sciences, <sup>c</sup>RMIT University,

Recently, intrinsic brittleness of monolithic bulk metallic glasses (BMGs) has been addressed by the fabrication of bulk metallic glass matrix composites (BMG-MCs) by introducing secondary crystalline particles into metallic glass matrix. However, the fabrication of BMG-MCs using conventional methods (e.g. casting) is limited regarding complex geometry that can be achieved and secondary particles that can be added. As an emerging additive manufacturing (AM) technique, selective laser melting (SLM) provides a promising alternative to fabricate BMG-MCs. In this study, single line scans at different laser powers and scan speeds were carried out using SLM equipment on a pre-fabricated porous  $\text{Al}_{86}\text{Ni}_6\text{Y}_{4.5}\text{Co}_2\text{La}_{1.5}$  BMG-MCs preform with CP-Ti as secondary phases. The densification, microstructural evolution, phase transformation and mechanical properties of the scan tracks were systematically investigated and found to be closely related to the power and scan speed used. This work provides the necessary fundamental understanding that will lead to the fabrication of large-size, crack-free BMG-MCs with high density, controllable microstructure and mechanical properties using SLM.

## **Process Development VI: Laser-Based Processes**

Salon E

Session Chair: Martin Baumann, University of Nottingham

### **8:00-8:20 Temperature History within Laser Sintered Part Cakes and Its Influence on Process Quality**

*S. Josupeit, H.-J. Schmid*, University of Paderborn

The temperature distribution and history within laser sintered part cakes is an important aspect regarding the process quality and reproducibility of the polymer laser sintering process. Especially the temperature history during the build and cooling phase is decisive for powder ageing effects and the development of part quality characteristics. In this work, a measurement system for three-dimensional in-process temperature measurements is set up and the influence of different parameters on the inner part cake temperature distribution and history is analyzed. Important factors are not only geometrical build job parameters like the part packing density and build height, but also process parameters like the layer thickness and bulk powder density. Individual in-process temperature profiles at different positions within a part cake are finally correlated with powder ageing effects. The results of this work help to understand the temperature history dependency of powder and part properties and can therefore be used to develop optimized process controls.

### **8:20-8:40 Use of an Alternative Ink in the High Speed Sintering Process**

*L. Fox, A. Ellis, N. Hopkinson*, The University of Sheffield

High Speed Sintering is a polymer Additive Manufacturing process, which builds parts by the use of inkjet printing and infrared lamp technology, as opposed to lasers and optics used in Laser Sintering. For High Speed Sintering to be a viable method to build fast moving consumer goods the ability to use different inks is critical. This research investigated the effects of using two separate inks in the High Speed Sintering process. This work shows it is possible to use inks from different suppliers, which opens up a wider supply chain.

### **8:40-9:00 Towards High-quality Selective Beam Melting Technologies: Modeling and Experiments of Single Track Formation**

*W. Yan<sup>ab</sup>, W. Ge<sup>b</sup>, J. Smith<sup>a</sup>, F. Lin<sup>b</sup>, W. Liu<sup>a</sup>*, <sup>a</sup>Northwestern University, <sup>b</sup>Tsinghua University  
Additive Manufacturing of metals is a promising technology with the advantages of fabricating components with complex shapes, manipulating the compositions of the material and controlling the mechanical properties of the final products. The obstacles of its wide applications are mainly located in the low production speed and unstable fabrication quality such as dimensional accuracy and surface roughness. In this work, with the aim of improving the dimensional accuracy and surface roughness, “balling effect” in Selective Beam Melting was investigated through the modeling and experiments of single track formation. The finite element model with the changing properties of powder bed into account was able to predict the ideal shape of molten pool. Then according to conditions of flow stability, the distortion and irregularity of solidified tracks could be predicted. The predictions were validated by the experiments. It was demonstrated that the proposed method was able to distinguish the proper fabrication parameters avoiding flow distortions and balling.

**9:00-9:20 Performance Metrics for Powder Feeder Systems in Additive Manufacturing**

*V.S. Bitragunta, T. Sparks, F. Liou, Missouri University of Science and Technology*

In direct metal deposition processes, a single powder feeder is typically used. While working with different powders, multiple powder feeders with varying powder compositions are a convenient solution. Various parameters like powder flow fluctuation, laser scan speed, transportation medium, powder shape & size and apparent & tap density are considered. When integrating a multiple feeder system into a laser deposition system, laser scan speed & powder flow rate must be scaled appropriately to maintain good deposition quality. This work focuses on generating an algorithm that would determine operating range of the above parameters for a given powder feeder system in an additive manufacturing process. Each powder feeder system is given a performance metric that would determine its working parameters. Based on these metrics, a feeder system can be chosen for a particular application, such as FGM production.

**9:20-9:40 Feedforward Control for Polymer Laser Sintering Process using Part Geometry**

*M. Abdelrahman, T. Starr, University of Louisville*

For the polymer laser sintering process, achieving optimum mechanical properties requires that every volume element of a part experience a temperature history sufficient to reach full density. This history must include a peak temperature high enough to fully melt, but not degrade, the polymer and a cool-down period that ensures elimination of porosity, interlayer bonding and relaxation of stress. Real-time thermal monitoring of the laser sintering process has shown that this temperature history depends on the geometries of both the current and prior layers. In this paper we demonstrate a feed-forward control system that improves uniformity of the temperature history for parts with variable cross-sections. The control algorithm for this system will utilize information from layerwise geometry models for parts in a multi-part build. The cross-sectional area for every layer will be used at run-time for feed forward control the laser scan parameters. The results confirmed maintaining constant peak temperature throughout the part. This control system ensures optimized sintering for parts with complex geometries.

**9:40-10:10 BREAK**

**10:10-10:30 Selective Laser Melting of Ceramic**

*T. Liu<sup>ab</sup>, C. Zhang<sup>a</sup>, K. Zhang<sup>a</sup>, <sup>a</sup>Nanjing University of Science and Technology, <sup>b</sup>The University of Texas at Austin*

Some ceramic samples having good surface and quality are obtained by optimizing SLM (Selective Laser Melting) process parameters without preheating condition. But deformations and cracks can be found in these samples, which suggest that low laser power may create better samples and cracks can not be avoided under no preheating situation. To fundamentally resolve cracks and deformation, a series of experiments under high temperature preheating are carried out. The experiment results show that the preheating improves sample quality and no crack sample can be produced. Moreover, the results show SLM scanning strategy is also an important factor. The snake pattern scanning is beneficial to the uniform melting of ceramic powders, help to balance thermal stress in materials, avoid deformation and ensure continuity between each scanning line.

### **10:30-10:50 Characterization of Bulk to Thin Wall Mechanical Response Transition in Powder Bed AM**

*B. Brown, J. Dinardo, W. Everhart*, Department of Energy's National Security Campus Managed by Honeywell FM&T

In the development of powder bed AM process parameters, the characterization of mechanical properties is generally performed through relatively large mechanical test samples that represent a bulk response. This provides an accurate representation of mechanical properties for equivalently sized or larger parts. However as feature size is reduced, mechanical properties transition from a standard bulk response to a thin wall response where lower power border scans and surface roughness have a larger effect. This study identifies this threshold between bulk and thin wall for 304L SS on the Selective Laser Melting (SLM) platform and Ti-6Al-4V on the Electron Beam Melting (EBM) platform. A possible method for improving those properties and shifting the transition from bulk to thin wall response to smaller wall thicknesses was investigated. Mechanical testing and fractography was performed on samples to characterize the effect of wall thickness.

### **10:50-11:10 Mass Finishing of Laser Sintered Parts**

*P. Delfs, Z. Li, H.-J. Schmid*, University of Paderborn

Laser sintered (LS) part surfaces are quite rough textured by the layered structure and adherence of incomplete molten powder particles. Different post-treatments can help to smoothen these surfaces. In this work we investigated the mass finishing method with a disc finishing machine. The aim was to quantify the influences of different process parameters on roughness values and rounding of edges. Therefore different geometries and material of abrasive media were used. Further the intensity was varied by changing the rotational speed and duration of the finishing process. Analysis was done with a 3D optical microscope to get profile and areal roughness parameters as well as radii of edges. LS part surfaces with build angles from 0° to 180° in 15° steps were evaluated. The results show that depending on the used abrasive media roughness values can be reduced to about 15 % of its initial value in a few hours of finishing.

### **11:10-11:30 Development of Powder Bed Fusion Additive Manufacturing Test Bed for Enhanced Real Time Process Control**

*M. Vlasea, B. Lane, F. Lopez, S. Mekhontsev, A. Donmez*, National Institute of Standards and Technology

Laser powder bed fusion (PBF) is emerging as the most popular additive manufacturing (AM) method for producing metallic components based on the flexibility in accommodating for a wide range of materials with resulting mechanical properties similar to bulk machined counterparts, as well as based on in-class fabrication speed. Although this approach is advantageous, the current limitations in achieving predictable and repeatable material and structural properties, geometric and surface roughness characteristics, and the occurrence of deformations due to residual stresses result in significant variations in part quality and reliability. Therefore, a better understanding and control of PBF AM processes is needed. The National Institute of Standards and Technology (NIST) is developing a testbed to assess in-process and process-intermittent metrology methods, real-time process control algorithms, and to establish foundations for traceable radiance-based temperature measurements that support high-fidelity process modeling efforts. The paper will discuss functional requirements and design solutions to meet these distinct objectives.

**11:30-11:50 Material Properties of Laser Sintered Polyamide 12 as Function of Build Cycles using Low Refresh Rates**

*S. Josupeit<sup>a</sup>, J. Lohn<sup>ab</sup>, E. Hermann<sup>b</sup>, M. Gessler<sup>c</sup>, S. Tenbrink<sup>c</sup>, H.-J. Schmid<sup>a</sup>*, <sup>a</sup>University of Paderborn, <sup>b</sup>Phoenix Contact, <sup>c</sup>EOS Electro Optical Systems GmbH

Due to long process times at high temperatures, unmolten polyamide 12 material ages during the manufacturing process. Hence, it needs to be refreshed with new material for further build cycles. In application, refresh rates of about 50 % are commonly used. In this work, the recycling optimized material PA 2221 from EOS is analyzed along a series of 13 build and refresh cycles using a reduced refresh rate of 32 %. Before and after every build, the powder is analyzed regarding melt properties determined by MVR and DSC measurements. Thereby, in-process ageing effects are investigated and the steady-state conditions are determined accordingly. In addition, powder properties are directly linked to resulting mechanical and geometrical part properties. Key findings are a robust DSC measurement method for polyamide 12 powder, constant “circulated” material properties after three build/refresh cycles and robust tensile properties along the whole tested powder life cycle. As a result, process conditions of PA 2221 using reduced refresh rates can be derived from this work.

**11:50-1:00 LUNCH**

## Wednesday PM

### **Applications V: Biomedical**

Room 202

Session Chair: Patrick Delfs, DMRC/University of Paderborn

#### **1:00-1:20 In situ Printing - An Alternative Three Dimensional Laden Structure Fabrication Method**

*Y. Liu, W. Sun*, Drexel University

Recapitulating a structure that mimics the anatomic geometries and intratissue cell distribution as in live organism is a major challenge of tissue engineering nowadays. Solid free-form fabrication (SFF) has been demonstrated as an efficient tool for this purpose. In the paper we presented a SFF based in situ printing method that is free of fabrication time frame and fabrication environment constrains. The fabrication parameters on strut formability, fabricated structural stability against gentle fluidic disturbance, and the integrity of the fabricated structure in cell culture environment were studied to assess the potential of the fabrication method on biomedical application. Based on the results, controlled strut formability can be achieved in an appropriate cross-linking deposition range. Alginate composition is the main parameter that dominates the stability and integrity of the fabricated structure. A parameter set that can produce a stable scaffold with the ability to maintain its structure in cell culture environment for at least 15 days was optimized.

#### **1:20-1:40 Inkjet Printing of Materials with Resistance to Bacterial Attachment**

*B. Begines, A. Hook, R. Wildman, C. Tuck, M. Alexander*, University of Nottingham

Biofilm formation on the surface of medical devices is a major source of health-care associated infections. The discovery of new materials that inherently avoid formation of such biofilms on their surface points the way to the fabrication of biofilm resistant devices, with the consequent reduction in the incidence rate of device centred infections and therefore a reduction in suffering and costs for health-care systems. Drop on Demand (DOD) Three Dimensional (3D) Inkjet Printing presents higher versatility than common techniques for printing biomaterials. One of the main representations of this enhanced versatility is polymerisation post-jetting, which provides a great range of printable polymers. The combination of such materials with inkjet printing could revolutionise the biomedical industry.

In this paper, the printability of four acrylates with resistance to bacterial attachment was assessed using the printability indicator or Z parameter. Three of the materials showed a value of Z within the printability range. The remainder displayed a Z value higher than the maximum suggested. However, this material was ejected with stability using a complex waveform designed for low viscosity inks. Drop spacing was optimised for each ink using PET and glass as substrates. The combination of printability optimisation together with ideal drop spacing allowed the construction of 3D structures of three of the four inks that were tested.

#### **1:40-2:00 Optimal Process Parameters for 3D Printing of Dental Porcelain Structures**

*H. Miyajima, S. Zhang, A. Zandinejad, L. Yang, A. Lassell*, University of Louisville

Dental porcelain material is a typical glass ceramic material that is widely used in dental restoration applications. However, there still exists limited knowledge about the fabrication of this type of materials using binder jetting additive manufacturing process. There exist several

important factors such as saturation level, power level, drying time as well as spread speed, which would potentially affect the accuracy and strength of the printed parts before and after sintering. Therefore, in this research an extensive experimental study was performed to obtain the optimal process parameters for the dental porcelain materials fabricated via ExOne binder jetting system. The results also provide general design guidelines for the fabrication of glass ceramic materials.

### **2:00-2:20 Stem Cell Printing and Process Regulated Cell Properties**

*J. Snyder, A.R. Son, C. Wang, Q. Hamid, W. Sun, Drexel University*

Immunomodulatory, pluripotent mesenchymal stem cell address several major challenges in regenerative medicine today. As does bottom-up tissue engineering enabled by advanced biomanufacturing techniques to build 3-dimensional hetero-cellular constructs embedded with mathematically defined porosity. Integrating mechanically sensitive mesenchymal stem cells into the physical process of bioprinting requires additional consideration of mechano-regulatory theories, which induce differentiation. In this review, we present mesenchymal stem cell mechanotransduction in response to strain, shear flow, substrate stiffness, and damage-directed differentiation caused by apoptotic and neurotic cells. The cell's experience during printing is presented as a derived process window of standardized duration and intensity, generated by controllable process parameters; principally the dispensing pressure. Preliminary results identify that the minimum stress condition of the bioprinter preserves cell viability, while the maximum hemodynamic stress condition increases heterogeneity of cell response, induces inelastic ultra-structural distortion of the cell membrane and chromatin, increases exit cell cycle sub-populations post-printing and consequently up-regulates osteogenic specific biomarker expression after 5 days. The review of mechano-regulatory theories and preliminary results identify bioprinting as a controllable physical process for consciously preserving cell viability and stemness or prescriptively stimulating the printed cells to direct differentiation post-printing via process-regulated inelastic strain on individual cells and tunable volume fractions of damaged cell sub-populations.

### **2:20-2:40 Polymer Particle Formation using Inkjet Printing**

*A. Hüsler, M. Alexander, R. Wildman, University of Nottingham*

Exciting advances have been made in biomaterials research, through both hypotheses relating material properties to cell response, and discovery of new materials via high throughput screening. This area of research is still hindered though by the paucity of information on the physicochemical parameters governing the response of all cell types of interest to a broad range of materials. Herein, a combinatorial library of biodegradable and photocrosslinkable polymers is used to identify candidate biomaterials which are then fabricated using additive manufacturing (inkjet printing) to result in single and multiple polymer structured micro-particles. Materials screening will be used to identify candidates for cellular support. Specifically, the effect of microspheres with different polymer chemistries on cellular attachment and control of stem cell differentiation will be brought together in this work. The vision is to mature this effort for applications such as cell carriers in regenerative medicine strategies to engineer cell function.

### **2:40-3:00 Freeform Extrusion Fabrication of Titanium Fiber Reinforced Bioactive Glass Scaffolds**

*A. Thomas, K. Kolan, M. Leu, G. Hilmas*, Missouri University of Science and Technology

Although implants made with bioactive glass have shown promising results for bone repair, their application in repairing load-bearing long bones is limited due to their low fracture toughness and fairly fast degradation response *in vivo*. In this paper, we describe our investigation of freeform extrusion fabrication of silicate based 13-93 bioactive glass scaffolds reinforced with titanium fibers. A composite paste was prepared with 13-93 bioactive glass filled with titanium fibers (~16  $\mu\text{m}$  in diameter and aspect ratio of ~250) having volume fraction from 0.1 to 0.4 vol. % of the bioactive glass scaffold. This paste was then extruded to fabricate scaffolds with an extrudate diameter of about ~0.8 mm. The sintered scaffolds, with and without titanium fibers, had measured pore sizes ranging from 400 to 800  $\mu\text{m}$  and a porosity of ~50%. Scaffolds produced with 0.4 vol. % titanium fibers were measured to have a fracture toughness of ~0.8  $\text{MPa}\cdot\text{m}^{1/2}$  and a flexural strength of ~15 MPa. Bioactive glass scaffolds without titanium fibers had a toughness of ~0.5  $\text{MPa}\cdot\text{m}^{1/2}$  and strength of ~10 MPa. The addition of titanium fibers increased the fracture toughness of the scaffolds by ~70% and flexural strength by ~40%. The scaffolds' biocompatibility and their degradation in mechanical properties, *in vitro* were assessed by immersing the scaffolds in a simulated body fluid over a period of one to four weeks.

### **3:00-3:20 Maskless Fabrication of Cell-laden Microfluidic Chips with Localized Surface Functionalization for the Co-culture of Cancer Cells**

*Q. Hamid, C. Wang, J. Snyder, S. Williams, W. Sun*, Drexel University

The utilization of the microfabrication technique to fabricate advanced computing chips has exponentially increased in the last few decades. Needless to say, this fabrication technique offers some unique advantages to develop micro-systems. Though many conventional microfabrication techniques today uses very harsh chemicals, the authors believe that the manipulation of system components and fabrication methods may aid in the utilization of the microfabrication techniques used in fabricating computer chips to develop advanced biological microfluidic systems. Presented in this paper is a fabrication approach in which popular fabrication methods and techniques are coupled together to develop an integrated system that aids in the fabrication of cell-laden microfluidic systems. This system aims to reduce the uses of harsh chemicals and decreases the lengthy fabrication time. Additionally, this integrated system will enable the printing of cells as the microfluidic chip is being fabricated. To demonstrate the unique capabilities of the integrated system, an advanced microfluidic chip is being fabricated and investigated. The advanced chip will feature the investigation of cancer cells in a co-cultured microfluidic environment. The investigations presented demonstrate co-cultures in a microfluidic chip, advanced cell printing with localized surface enhancement, cell integration, and full additive fabrication of a microfluidic chip.



## **Applications VI: Various**

Room 203

Session Chair: Ian Maskery, University of Nottingham

### **1:00-1:20 Transition to Social Manufacturing: Applications of Additive Manufacturing in Consumer Products**

*B. Mohajeri, T. Nyberg, M. Hämäläinen, Aalto University*

The Economist's special report (2012) mentions additive manufacturing (AM) as the foundation of the third industrial revolution. This report highlights how AM can reshape the typical structure of manufacturing, shifting it toward a collaborative manufacturing model. Currently, the AM of end products is only a small and niche market. However, many start-ups enter this market every day, and the market opportunities and applications grows rapidly. On the other hand, price of machines and materials is decreasing constantly. Since, it might be possible to democratize the process of manufacturing in the future. This will lead to a new manufacturing paradigm called "Social Manufacturing". In this paper, we study opportunities and challenges in using AM to reach social manufacturing. Applications of AM in consumer products are investigated and based on the analysis, a path is proposed for transition to social manufacturing.

### **1:20-1:40 Improving Car Climate Control with SLS**

*M. Vetterli<sup>a</sup>, R. Schmid<sup>b</sup>, M. Schmid<sup>b</sup>, S. Harke<sup>c</sup>, T. Durand<sup>d</sup>, K. Wegener<sup>a</sup>, <sup>a</sup>IWF MAVT ETHZ, <sup>b</sup>inspire AG, <sup>c</sup>Weidplas GmbH, <sup>d</sup>Automotive Powertrain Technologies Laboratory*

In Europe, passenger cars are responsible for 12% of CO<sub>2</sub> emissions. The European Commission established new regulations to drastically reduce the emissions from 130g to 95g CO<sub>2</sub> per km between 2015 and 2021. While the automobile industry is looking at different ways to meet those criteria, the presented industry-driven project aims at reducing energy consumption by up to 30% of air-conditioning (AC) in passenger cars with the introduction of a novel system. The current systems reduce the fuel economy to up to 20% for gas motors and even more for electric cars. Through Selective Laser Sintering (SLS) design freedom and short production cycles; the design of the AC casing was drastically optimized to increase its contact area with incoming air. To further increase the heat exchange throughout the system, the thermal conductivity of SLS material was improved by incorporation of mineral fillers. The successful implementation of both optimizations led to a CO<sub>2</sub> emission reduction of around 50% for the climate control of passenger cars.

### **1:40-2:00 Investigation of Vapourised Solvent Attack on Additive Manufacturing Part Surface**

*M.W.M. Cunico<sup>ab</sup>, J. de Carvalho<sup>a</sup>, <sup>a</sup>University of São Paulo, <sup>b</sup>Puc-PR/Concep3D*

The additive manufacturing technologies have been facing an extraordinary growth during the last years, mainly as consequence of the increase of low cost FDM technologies into the marketing. In contrast with that, one of the main disadvantages of this sort of equipment is the final object finishing. For that reason, the main goal of this work is to present and characterise the post-processing which was introduced in the marketing as smoothing. In addition, a concise overview about the theory beneath this process is presented besides an experimental study that evaluates the impact of this process for the main mechanical properties of object.

### **2:00-2:20 Thermal Performance and Surface Characterization of a Selective Laser Melted Flat-plate Oscillating Heat Pipe**

*J.G. Monroe<sup>a</sup>, O.T. Ibrahim<sup>a</sup>, S.M. Thompson<sup>a</sup>, N. Shamsaei<sup>a</sup>, L. Bian<sup>a</sup>, A. Elwany<sup>b</sup>*, <sup>a</sup>Mississippi State University, <sup>b</sup>Texas A&M University

A titanium alloy (Ti-6Al-4V) flat-plate oscillating heat pipe (FP-OHP) was fabricated using Selective Laser Melting (SLM). The 50.8 x 38.1 x 15.75 mm<sup>3</sup> FP-OHP consisted of four integral layers of capillary-sized, circular mini-channels (1.52 mm in diameter). The post-SLM prototype was de-powdered using pressurized air and a novel layer-by-layer, plug-and-pressurize design/approach. A vacuum-grade port was threaded into the FP-OHP, and the heat pipe was charged with acetone (~70% by volume) then hermetically sealed. Experiments were conducted to characterize the thermal performance and functionality of the multi-layered FP-OHP. Results indicate that the acetone-filled FP-OHP operates and can provide for an 800% increase in effective thermal conductivity relative to pure Ti-6Al-4V. The build integrity of the FP-OHP was investigated by shearing along its width to inspect the channel-area surface using field emission scanning electron microscopy (SEM) and laser triangulation for channel topography. The mean surface roughness was found to be approximately 45 micrometers and characterized by partially-melted, abraded particles. This study demonstrates the appeal of additive manufacturing for fabrication of customized heat transfer media traditionally challenging to realize.

### **2:20-2:40 Further Study of the Electropolishing of Ti6Al4V Parts Made via Electron Beam Melting**

*L. Yang, A. Lassell, G. Paiva*, University of Louisville

In this study, the effect of various parameters including the voltage, current, polishing time, temperature and electrode spacing on the electropolishing quality of Ti6Al4V samples made via electron beam melting was investigated systematically. Through surface characterization and mechanical testing, the relationships between these process parameters and the surface roughness of the parts were established, and the relationship between the surface roughness and the mechanical properties of the samples was also studied.

### **2:40-3:00 Thermal Aspects of Selective Laser Sintered PMMA+ $\beta$ -TCP Composites**

*R. Velu, S. Singamneni*, AUT University

Biocompatible and osteoconductive attributes essential of materials used for bone grafting applications allowed to identify Polymethyl Methacrylate (PMMA) and  $\beta$ -Tri Calcium Phosphate ( $\beta$ -TCP) combinations to be potential biopolymer composite options. Combined with additive manufacturing methods like selective laser sintering, these materials will allow to bring critical biological characteristics and the benefits of free form fabrication together. Earlier research with PMMA+ $\beta$ -TCP composites experimentally proved the combination to be suitable for laser sintering. However, the inter-particle and inter-layer coalescence and consolidation varied with varying amounts of  $\beta$ -TCP plausibly due to differential thermal attributes of the constituents. An evaluation of the thermal fields and identification of the critical roles of varying process conditions and  $\beta$ -TCP contents will become essential to fully understand the system. The current research attempts this and presents results of numerical and experimental work carried out investigating the thermal fields of laser sintered PMMA+ $\beta$ -TCP composites.

### **3:00-3:20 Direct Selective Laser Sintering of Reaction Bonded Silicon Carbide**

*S. Meyers, J. Vleugels, J.-P. Kruth, KU Leuven*

Three-dimensional reaction bonded silicon carbide (SiSiC or RBSC) parts have been produced by direct selective laser sintering (SLS). Unlike previously investigated processing routes, which make use of a sacrificial polymer binder to form green parts, the parts in this work are built by scanning subsequent layers composed of a mixture of silicon and silicon carbide powders. A fibre laser is used to selectively melt the silicon under an inert argon atmosphere, resulting in porous preforms of sufficient strength for further handling and processing. After impregnation with a graphite suspension and infiltration with liquid silicon at 1450°C, highly dense reaction bonded silicon carbide parts are obtained.

### **3:20-3:40 Construction by Contour Crafting using Sulfur Concrete with Planetary Applications**

*B. Khoshnevis, X. Yuan, B. Zahiri, B. Xia, University of Southern California*

This paper reports on the experiments with the Contour Crafting Automated Construction process using sulfur concrete as the choice of construction material. Sulfur concrete has numerous terrestrial applications and is potentially an ideal construction material for planetary construction. On Mars, sulfur can be found in abundance and the range of temperature variation on the planet is within the safe zone for the structures to be built and survive over reasonable length of time with sulfur concrete. Several experiments have been performed at centimeter and meter scales. A FEA simulation model for the behavior of sulfur concrete based structures has been developed. Experimental results were compared with the results of simulation.

### **3:40-4:00 Additive Manufacturing of Physical Assets by using Ceramic Multicomponent Extra-terrestrial Materials**

*A. Goulas, R. Harris, R. Friel, Loughborough University*

Thermal Fusion based Additive Manufacturing (TFAM) is a range of advanced manufacturing technologies that can fabricate three-dimensional assets directly from CAD data, on a successive layer-by-layer strategy by using thermal energy, typically from a laser source, to irradiate and fuse particles within a powder bed. The aim of this paper was to investigate the application of this advanced manufacturing technique to process ceramic multicomponent materials into 3D layered structures. The materials used matched those found on the Lunar and Martian surface. The indigenous extra-terrestrial Lunar and Martian materials could potentially be used for manufacturing physical assets onsite (i.e. off World) on future planetary exploration missions and could cover a range of potential applications including: infrastructure, radiation shielding, thermal storage, etc.

Two different simulants of the mineralogical and basic properties of Lunar and Martian indigenous materials were used for the purpose of this study and processed with commercially available laser additive manufacturing equipment. The results of the laser processing were investigated and quantified through mechanical hardness testing, optical and scanning electron microscopy, energy dispersive x-ray spectroscopy, thermo-gravimetric analysis spectrometry, and finally x-ray diffraction.

The research resulted in the identification of a range of process parameters that resulted in the successful manufacture of three-dimensional components from Lunar and Martian ceramic multicomponent simulant materials. The feasibility of using thermal based additive manufacturing with multi-component ceramic materials has therefore been established, which

represents a potential solution to off-world bulk structure manufacture for future human space exploration.

## **Materials VII: Copper, Silicon, Nickel**

Salon AB

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

### **1:00-1:20 Effect of Bimodal Powder Mixture on Powder Packing Density and Sintered Density in Binder Jetting of Metals**

*Y. Bai, C.B. Williams, G. Wagner, Virginia Tech*

The Binder Jetting Additive Manufacturing process provides an economical and scalable means of fabricating complex metal parts from a wide variety of materials. However, the performance metrics of the resulting sintered parts (e.g., thermal, electrical, and mechanical properties) are typically lower than traditionally manufactured counterparts due to challenges in achieving full theoretical density. This can be attributed to an imposed constraint on particle size and its deleterious effects on powder bed packing density and green part density. To address this issue, the authors explore the use of bimodal powder mixtures to improve the sintered density and material properties within the context of copper parts fabricated by Binder Jetting. The effectiveness of using bimodal powder mixtures in an effort to improve sintered density is studied in terms of particle size distribution and powder packing density.

### **1:20-1:40 $\mu$ -SLS of Metals: Physical and Thermal Characterization of Cu-nanopowders**

*N.K. Roy, A. Yuksel, M. Cullinan, University of Texas at Austin*

Microscale selective laser sintering ( $\mu$ -SLS) requires the use of nanopowders since the particle size needs to be an order of magnitude smaller than the melt pool in order to accurately sinter particles together to form a part. Most properties of nanopowders are dependent upon size and thus, an exhaustive study of the physical and thermal properties of these nanopowders is required in order to successfully model and simulate the sintering process. In this paper we will present particle size characterization using SEM, density measurements using He pycnometry, specific heat capacity measurement using Differential Scanning Calorimetry and surface area analysis using BET, that were carried out to characterize the nanopowders. Two samples of Cu nanopowders of different average particle sizes (40nm and 100nm- from US Research Nanomaterials, Inc) were used for these experiments and the results have been discussed along with further scope of work for fully characterizing the particles.

### **1:40-2:00 Laser Metal Deposition of Functionally Gradient Copper-Nickel using Elemental Powders**

*S. Karnati<sup>a</sup>, T.E. Sparks<sup>a</sup>, F.W. Liou<sup>a</sup>, J.W. Newkirk<sup>a</sup>, K.M.B. Taminger<sup>b</sup>, W.J. Seufzer<sup>b</sup>, <sup>a</sup>Missouri University of Science and Technology, <sup>b</sup>NASA Langley Research Center*

This work deals with the planning and fabrication of a functionally gradient copper-nickel composition via Laser Metal Deposition (LMD). Various compositions of copper and nickel were made by blending different weight percentages which were then sequentially deposited to fabricate functionally gradient copper-nickel thin-wall structures. Analyses were performed by sectioning the thin-wall samples for metallographic, hardness, X-ray diffraction (XRD) and

Energy Dispersive X-ray Spectroscopy (EDS) studies. The fabrication was studied for identifying and corroborating the deposited compositions and their corresponding gradients. XRD analyses were performed to identify the crystal structure of the deposit. EDS analysis was instrumental in identifying the variation in composition and realizing the gradient in between compositions. Consequences of using different laser beam intensity profiles and varying laser power duty cycles were realized by analyzing the copper-nickel concentration trends obtained from EDS analyses. Hardness testing was successful in capturing the decreasing trends in strength with decreasing nickel concentration.

### **2:00-2:20 Selective Laser Melting of Doped Silicon Powder**

*A. El Desouky<sup>a</sup>, A. Elwany<sup>b</sup>, X. Gao<sup>b</sup>, S. LeBlanc<sup>a</sup>*, <sup>a</sup>George Washington University, <sup>b</sup>Texas A&M University

Selective laser melting (SLM) is an advantageous additive manufacturing technique as it enables faster processing of complex shapes at low cost. Although SLM has been applied to material systems such as polymers, metals and ceramics, its feasibility for semiconductors is unknown. This work describes SLM processing of silicon powder as a standard semiconductor material. High energy ball milling was used to make a fine silicon powder (<45 μm) from boron-doped silicon wafers. Particle size distribution and flowability of the milled powder were investigated to ensure suitability for layer-by-layer deposition in a Phenix-ProX 100 Laser system. Preliminary experimental results on the effect of laser power and scan speed on the mechanical and electrical properties of 3D laser sintered semiconductors are discussed. The success of SLM of silicon enables the processing of complex 3D electronic components which would have major implications on the semiconductor industry.

### **2:20-2:40 Processing of ODS Modified IN625 using Selective Laser Melting**

*A. Spierings<sup>a</sup>, T. Bauer<sup>a</sup>, K. Dawson<sup>b</sup>, A. Colella<sup>c</sup>, K. Wegener<sup>a</sup>*, <sup>a</sup>Inspire AG, <sup>b</sup>University of Liverpool, <sup>c</sup>MBN nanomaterialia s.p.a

Increasing the operating temperatures of power plant turbine generators is a universal method to increase the efficiency of steam and gas turbines. However, operating a plant at higher temperatures poses extreme challenges to the materials used, especially regarding oxidation, creep, thermal fatigue- and stress-corrosion cracking. The EU-OXIGEN project addresses these issues by the development of novel processing routes for ODS-modified materials, as this class of materials offers exceptionally high temperature strength, oxidation and corrosion resistance at temperatures exceeding 900°C. Additive manufacturing processes such as Selective Laser Melting are considered to enable their successful processing. First results on density of SLM-processed, mechanically alloyed ODS-modified Inconel-625 superalloy powders, are presented and compared to the processing conditions and results of gas atomized conventional Inconel-625 powders.

### **2:40-3:00 Microstructure and Mechanical Characterisation of SLM Processed Haynes 230**

*T. Bauer<sup>a</sup>, K. Dawson<sup>b</sup>, A.B. Spierings<sup>a</sup>, K. Wegener<sup>a</sup>*, <sup>a</sup>Inspire AG, <sup>b</sup>University of Liverpool

Selective Laser Melting (SLM) enables the production of complex near-net-shaped parts possibly reducing costs and lead times. Especially difficult to machine Nickel based alloys like Haynes<sup>®</sup> 230<sup>®</sup> used in high temperature applications such as turbines or industrial furnaces can profit from the technologies advantages. However, exact knowledge of the SLM processing

windows and the corresponding mechanical properties is essential for a target-oriented part design as well as post process planning. Especially the high cooling rate of the small weld pool characterizes the SLM process and is known to cause material microstructures different to standard wrought or cast material.

Samples are built with different heat input levels and are analysed for their density, pore- and crack sizes. Optical and scanning electron microscope (SEM) and electron backscatter diffraction (EBSD) are used to characterize the material microstructure. Static tensile test samples were built in either 0° or 90° orientation for the evaluation of mechanical properties at room temperature and anisotropy as well as the influence of the different heat input levels are assessed.

It is shown that the alloy itself is well suited for the SLM process allowing the consolidation of nearly defect free material with improved mechanical properties with regards of yield and ultimate tensile strength compared to cast as well as wrought material.

### **3:00-3:20 Effect of Scan Pattern on Microstructure and Mechanical Properties of Inconel 625 Fabricated by Selective Laser Melting**

*Md.A. Anam<sup>a</sup>, J.J.S. Dilip<sup>a</sup>, B. Stucker<sup>b</sup>*, <sup>a</sup>University of Louisville, <sup>b</sup>3DSIM

Selective laser melting (SLM) involves highly localized heat input and directional solidification, which enables novel microstructure control through the development of scanning strategies and related process variables. Thus, a careful study of scan pattern is important to understand microstructural evolution during SLM. In this study, various types of scanning strategies were used to build Inconel 625 samples for microstructure and mechanical properties. Microstructure of as-deposited Inconel 625 showed  $\gamma$  columnar grains which grow preferentially in the build direction, but there were also clear effects of grain orientation differences due to scan direction effects. The difference in grain orientation due to scan pattern variation was found to have significant effect on part properties.

### **3:20-3:40 Microstructural Characterization of Inconel 625 Components Fabricated by Selective Laser Melting**

*J.S.D. Jangam<sup>a</sup>, Md.A. Anam<sup>a</sup>, B. Stucker<sup>b</sup>*, <sup>a</sup>University of Louisville, <sup>b</sup>3DSIM

Nickel based superalloy Inconel 625 has excellent corrosion resistance and high strength at elevated temperatures. The alloy is used in aerospace and power plant industries. In the present study, microstructural evolution of Inconel 625 processed using selective laser melting (SLM) was investigated. Microstructural characterization was carried out using optical microscopy, SEM, EBSD, XRD and TEM. As-deposited Inconel 625 microstructure mainly consisted of coarse  $\gamma$  columnar grains directionally growing along the deposition direction. The columnar grains (with a large aspect ratio) were found to span multiple melt pools, indicating epitaxial growth during layer deposition. The columnar grains when further examined at higher magnification revealed fine cellular/dendritic substructure ( $<1 \mu\text{m}$ ) with inter cell/dendritic segregation. Interestingly, the columnar grains showed (EBSD) gradual change in the misorientation angle within the grain. The present investigation suggests that Inconel 625 SLM deposits are strongly anisotropic, which significantly can affect the part properties based on build orientation.

### **3:40-4:00 Effect of Si on the SLM Processability of IN738LC**

*R. Engeli<sup>ab</sup>, T. Etter<sup>a</sup>, F. Geiger<sup>a</sup>, A. Stankowski<sup>a</sup>, K. Wegener<sup>b</sup>*, <sup>a</sup>Alstom Ltd, <sup>b</sup>ETH Zürich  
Selective laser melting of high gamma-prime strengthened superalloys such as IN738LC is of interest in stationary gas turbine applications. Differences have been obtained for the hot cracking susceptibility of different powder batches during SLM processing and indications were found that also minor elements influence the SLM processability. By processing a specific powder batch blended by different amounts of pure silicon, the detrimental effect of this element during SLM could be shown. Therefore, the control of this minor element is crucial to decrease the hot cracking tendency and can extend the SLM processing window of this alloy.

## **Process Development VII: Metals**

Salon D

Session Chair: Abdalla Nassar, Pennsylvania State University Applied Research Laboratory

### **1:00-1:20 Investigation of Residual Stresses in Selective Laser Melting of Ti-6Al-4V**

*D. Brackett, I. Ashcroft, R. Wildman*, University of Nottingham

One of the most significant barriers to wider industrial adoption of selective laser melting (SLM) is the generation of residual stresses during part build which causes component distortion and potential build failure. The ability to predict susceptible areas prone to excessive levels of residual stress will improve current mitigation strategies, in particular in-efficient placement of support structures. A coupled thermo-mechanical finite element simulation has been developed for SLM of Ti-6Al-4V with various techniques being explored for addressing the modeling challenges encountered. Current capability enables a multi-layer analysis for predicting the residual stress distribution of different laser scan strategies in macro scale regions. The results obtained from the analysis are evaluated to propose steps towards optimising the process.

### **1:20-1:40 Elevated Region Area Measurement for Quantitative Analysis of Laser Beam Melting Process Stability**

*J. zur Jacobsmühlen<sup>a</sup>, S. Kleszczynski<sup>b</sup>, G. Witt<sup>b</sup>, D. Merhof<sup>a</sup>*, <sup>a</sup>RWTH Aachen University, <sup>b</sup>University of Duisburg-Essen

Laser beam melting (LBM) processes enable layer-based production of geometrically complex metallic parts with very good mechanical properties for Rapid Manufacturing. Collisions between powder coating mechanism and elevated part regions pose a major risk to process stability, which is crucial for industrial application. Minimizing elevated region area usually involves parameter tuning in a trial-and-error approach, as the process outcome is the only measure of stability. One published approach to quantifying elevated region area utilizes an imaging system, which acquires layer images of the powder bed after powder deposition and detects elevated regions using image analysis. We extend the image-based analysis to each part region, create quantitative visualizations of elevated region area for quick assessment/comparison and compute a figure of merit. In experimental build jobs with overhanging structures and different support junction parameters we gain insight into problematic part regions, which can be used as feedback in job design. The presented method helps to improve LBM process stability, which is strongly linked to process efficiency.

**1:40-2:00 Investigation of Support Structures for Direct Metal Laser Sintering (DMLS) of IN625 Parts**

*O. Poyraz, E. Yasa, G. Akbulut, A. Orhangul, S. Pilatin, Tusas Engine Industries, Inc.*

Along with the increased application of additive manufacturing (AM) in the aerospace industry, a better understanding of different aspects for the technique has become necessary to fulfill the high demands of reliability and robustness. The ability to introduce very complex, even internal, features into part design with AM appeals everyday many design engineers to this new group of technologies. In this respect, new design rules for AM are being researched, developed and updated day-to-day. Although, it is commonly stated that AM offers limitless geometrical complexity, there are some limits of the technology. For Direct Metal Laser Sintering (DMLS), a metal powder fusion AM process, one of the major limitations in the geometrical freedom offered by AM is the overhang surfaces which necessitates melting on loose powder and lead to dross formation, distortions, curling, etc. Support structures to be built together with the target part thus become necessary and critical to avoid such undesired results and moreover to facilitate a uniform heat dissipation. Design of the support structures which are easy to apply and remove is therefore among the important research topics in AM. The compromise in the design of support structures roots from the fact that the support structures must be strong enough to connect the part to provide resistance for curling up and they are desired to be loose enough to be easily removed. In addition, redundant use of support structures increases the amount of material spent, production time as well as post-processing efforts. This paper presents an investigation of different support structure designs; applied onto a thin-walled IN625 part, manufactured using DMLS.

**2:00-2:20 In-situ Synthesis of Titanium Aluminides in Additive Manufacture**

*A. Gasper, S. Catchpole-Smith, A. Clare, University of Nottingham*

This study explores the capabilities of several methods for in-situ synthesis of titanium aluminides using the direct metal deposition process. This allows for the functional grading of components which will be required for next generation aerospace components. The feasibility of three techniques are explored here, firstly, a new process of powder preparation (satelliting) for AM in which a larger parent powder is coated with a smaller powder, this study uses satellite  $\text{TiO}_2$  on a parent Al powder to produce an intermetallic matrix composite with  $\text{Al}_2\text{O}_3$  particulates. The satelliting procedure has potential to increase capability and mixing of in situ synthesis. Secondly, combined wire and powder feeding is explored through the use of Ti wire and Al powder to create Ti-50Al. Finally, a combination of wire and loose mixed powders is explored to produce the commercially used Ti-48Al-2Cr-2Nb. The simultaneous wire and powder delivery is designed to overcome issues encountered when processing with single powder or wire feedstocks. Comparison of these methodologies reveals the merits of each and hybrid approaches between these are proposed. Characterisation of the tracks and microstructures produced, through LOM, SEM, and EDS, reveals the influences of key processing parameters and provides a meaningful basis for comparison between the techniques. Results show that it is possible to produce  $\alpha_2+\gamma$  two-phase microstructures consistent with previous studies which have relied upon more expensive and harder to obtain pre-alloyed feedstocks.



## **2:20-2:40 Flaw Formation in Powder-Bed Additive Manufacturing of Metals- A Review**

*M. Jamshidinia, S. Kelly, E. Todorov, EWI*

In-situ monitoring of powder-bed fusion (PBF) additive manufacturing (AM) as well as non-destructive inspection (NDI) of AM components are two of the current challenges ahead of the full utilization of AM in industries. Generation of different types of flaw in PBF could be used to advance both of the NDI and in-situ monitoring techniques. For this purpose, a thorough understanding of the mechanisms of flaw formation in PBF-AM has to be developed. This study provides a comprehensive review of the different types of flaw form during laser powder-bed fusion (L-PBF) and electron beam powder-bed fusion (EB-PBF) processes. The influence of manufacturing processes on the formation of flaws was studied. Heat source characteristics, machine setup, powder properties, and contamination are among the factors that could result in the fabrication of defective parts. In addition, the influence of flaws on mechanical properties of additively manufactured components was reviewed.

## **2:40-3:00 Thermographic Measurements of the Commercial Laser Powder Bed Fusion Process at NIST**

*B. Lane, S. Moylan, E. Whiteman, L. Ma, National Institute of Standards and Technology*  
Measurement of the high-temperature melt pool region in the laser powder bed fusion (L-PBF) process is a primary focus of researchers to further understand the dynamic physics of the heating, melting, adhesion, and cooling which define this commercially popular additive manufacturing process. This paper will detail the design, execution, and results of high speed, high magnification in-situ thermographic measurements conducted at NIST focusing on the melt pool region of a commercial L-PBF process. Multiple phenomena are observed including plasma plume and hot particle ejection from the melt region. The thermographic measurement process will be detailed with emphasis on the ‘measurability’ of observed phenomena and the sources of measurement uncertainty. Further discussion will relate these thermographic results to other efforts at NIST towards L-PBF process finite element simulation and development of in-situ sensing and control methodologies.

## **3:00-3:20 System Identification and Feedback Control for Directed-Energy, Metal-based Additive Manufacturing**

*D. Seltzer, X. Wang, A. Nassar, J. Schiano, E. Reutzel, Pennsylvania State University*  
Additive manufacturing of metal parts is a complex process where many variables determine part quality. In addition to manipulated process variables, such as travel speed, feedstock flow pattern, and energy distribution, other exogenous inputs also determine part quality. For example, changing build geometry and a growing global temperature. In addition, there are random external disturbances such as spatter on a cover lens. Both manipulated process variables and exogenous inputs affect dimensional tolerance, microstructure, and other properties that determine the final part quality. Our long term aim is to improve part quality through real-time regulation of measurable process variables using vision-based feedback control. As a starting point, we present a process model that relates scanning speed and laser power to build height and melt pool width. These results demonstrate the necessity for using multi-input multi-output feedback control techniques and provide information for refining the frame rate and spectral sensitivity of the imaging system.

### **3:20-3:40 Femtosecond Fiber Laser Additive Manufacturing**

*B. Nie, H. Huang, L. Yang, S. Bai, P. Yang, J. Liu, Polaronyx, Inc*

Due to the unique ultra-short pulse duration and high peak power, femtosecond (fs) laser has emerged as a powerful tool for subtractive material processing such as high-precision drilling and cutting with almost no-limited material properties. However, fs laser has rarely been studied for additive manufacturing. Extremely high local temperature generated by fs laser irradiation has been reported in both simulations and experiments. We believe that this feature can make fs laser a great tool for additive manufacturing as well. In this paper, additive manufacturing based on both powder and bulk materials is demonstrated for the first time using high energy and high repetition rate fs fiber lasers. Fully melting of various powder materials with melting point as high as 3400°C is achieved. 3D parts with shapes like ring and cube are fabricated with metal powders such as iron and tungsten. Mechanical properties and micro-structures of the fabricated parts are investigated and compared to those fabricated using a continuous wave laser. Also, melting and mixing of dissimilar bulk materials result in a uniform and strong welding joint with over 210 MPa tensile strength. Not only does this study explore the feasibility of additive manufacturing using fs lasers, but also lays out a solid foundation for 3D printing of complex structure with designed compositions, microstructures and properties. It opens up new scenarios and opportunities for 3D printing for a wide range of materials, especially those with high melting temperature. This can greatly benefit the applications in automobile, aerospace and biomedical industries, by producing parts like nozzles, engines and miniaturized biomedical devices.

### **Process Development VIII: New and Hybrid Processes**

Salon E

Session Chair: Anne Mertens, University of Liege

### **1:00-1:20 Support-less Horizontal Filament-stacking by Layer-less FDM**

*Y. Kanada, Dasyn.com*

When using conventional additive manufacturing (AM) methods, material is stacked vertically and layer-by-layer. These methods cause two problems; that is, an object with overhang or skewed stacking structure is difficult to be created by these methods without support material and “seams” are easily generated when transiting between layers. This paper proposes a layer-less fused-deposition-modeling (FDM) method, which enables mostly horizontal stacking of filament without support material and which can avoid seams easily. Such filament-stacking is enabled by increasing the height of the print head gradually, i.e., without layer transitions that make horizontal stacking difficult. The proposed method also supports techniques for controlling printing directions and various printing-direction-dependent expressions, such as fiber-like textures or brilliance, and “deformation” and “modulation” techniques, which enables generation of various shapes and textures. These techniques make AM products attractive as arts or as final products for consumers. Objects to be printed by the proposed method can be modeled as directed solid models designed by a component-based method (i.e., a new CAD based method) or a generative method, which are completely different from conventional CAD based methods. (See <http://bit.ly/1JCenA3> for product photos.)

### **1:20-1:40 Selective Separation Sintering (SSS) --A New Layer Based Additive Manufacturing Approach for Metals and Ceramics**

*J. Zhang, B. Khoshnevis*, University of Southern California

Selective Separation Sintering (SSS) is a new layer based Additive Manufacturing approach. SSS can fabricate high temperature ceramic and metallic parts at comparatively lower cost with high quality. In this printing process a dry powder of higher sintering temperature is deposited into the base material which makes up the part. The inserted powder defines the boundary of the part and separates the part from its surroundings. When printing of all layers is completed the deposited dry powder serves as a separation coating which defines the shape of the part. In the sintering process the base material is sintered into a solid part while the separation coating remains as loose powder. The part is then separated from the surrounding area at the separation coating surfaces, and is post processed if necessary. Preliminary results have proven the capability of SSS in successfully printing ceramic and metallic parts. Future experiments are planned for improving the process resolution.

### **1:40-2:00 Understanding the Dynamics of Ultrasonic Additive Manufacturing**

*Q. Mao<sup>a</sup>, N. Coutris<sup>a</sup>, J. Gibert<sup>b</sup>, G. Fadel<sup>a</sup>*, <sup>a</sup>Clemson University, <sup>b</sup>Clarkson University

Ultrasonic Additive Manufacturing (UAM) is an additive manufacturing technique that uses ultrasound to merge metal foils (150  $\mu\text{m}$  thick, 24 mm wide) layer by layer to fabricate three-dimensional bodies. As new layers are deposited and the height-to-width ratio of the built feature changes, the dynamics of UAM changes accordingly. Prior research suggested the existence of a limit for the height-to-width ratio. Above this limit, additional layers fail to bond because the built feature reached its resonance frequency. Specifically, it is found that the bond failure is affected by the lack of plastic shear deformation between two foils which is essential to the generation of true metallic bonds. As the height-to-width ratio falls in the critical range, the built feature becomes resonant under the high-frequency excitations (20 kHz) of the sonotrode, leading to large-amplitude oscillations matching those of the sonotrode, and resulting in reduction of differential motion and therefore plastic shear deformation between the foils. In order to quantify this reduction, 2-D and 3-D lumped parameter models consisting of mass-spring networks are proposed to examine the dynamics of the built feature. The models are established such that they preserve the modal parameters of the built feature in free vibration. The lumped parameter models are validated by comparing their modal predictions with those from 2-D and 3-D finite element models. This model will be coupled with a 3-D finite element model to describe an elasto-plastic bonding layer and introduce friction and thermal aspects of UAM. By examining the deformation of the bonding layer under the combined effects of the excitation of the sonotrode and the vibration of the built feature, the bond failure due to geometry change of the built feature will be better understood and quantified in the future.

### **2:00-2:20 A Review of Hybrid Manufacturing**

*K. Lorenz<sup>ab</sup>, J. Jones<sup>c</sup>, D. Wimpenny<sup>a</sup>, M. Jackson<sup>b</sup>*, <sup>a</sup>Manufacturing Technology Centre,

<sup>b</sup>Loughborough University, <sup>c</sup>Hybrid Manufacturing Technologies

In recent years the combination of laser-based additive and subtractive manufacturing has become increasingly popular, with several machine tool manufacturers exhibiting products based on different machine tool configurations. This technology, widely known as hybrid manufacturing, typically exploits high-rate Directed Energy Deposition (DED) processes based typically of wire or powder feedstock which is fed into a melt pool created by a laser or other

heat source. Although DED methods predate (at least in terms of coating and repair applications) powder bed fusion techniques commercialization of hybrid DED methods is still very much in its infancy. However, there is clear advantages with the hybrid DED approach, offering a combination of high deposition rate together with the accuracy and surface finish associated with machining. This paper presents the history of the development of hybrid approaches dating back from work undertaken in the late 1980s through to the present day. The relative merits of different machine tool configurations and material deposition approaches are compared and some of the key technical challenges which remain are highlighted.

### **2:20-2:40      Integration of Subtractive Machining into Additive Manufacturing of Thermoplastics**

*S. Bhatia, R. Aman*, Rochester Institute of Technology

Filament extrusion additive manufacturing processes are relatively slow as compared to material removal via CNC milling, however the geometric complexity afforded by additive manufacturing, reduced waste and simplified process planning make these processes very appealing. Integration of subtractive manufacturing processes such Computer Numerical Controlled (CNC) milling into additive manufacturing technologies is appealing to capitalize on the advantages of each. Here we present a detailed analysis of material interface strength between bulk ABS material and deposited ABS material at different temperatures, material conditions, and processing parameters. Additionally we present a tool developed to determine the optimal starting stock size based on a maximum error threshold, machine tool access and a process cost model.

### **2:40-3:00      Dynamic Printing of Cells and Microbeads for Custom Microfluidic Assays**

*C.R. Oliver, N. Spielberg, L. Chin, F. Sun, A.J. Hart*, Massachusetts Institute of Technology

High-resolution digitally defined patterns of cells and microbeads can be used for screening of drug compounds, fundamental studies of cell and tissue growth, and as building blocks for large artificial tissues. Widespread research has focused on the use of physical traps and chemical templates to anchor micro-scale objects introduced by flow; however, it would be highly useful to have a template-free method to build arbitrary patterns of multiple object types in 2D, and eventually 3D. We present a platform for on-demand printing of cells and microparticles onto glass and PDMS substrates. This method combines a diffraction-limited maskless photopatterning system with machine vision algorithms that enable identification, tracking, and anchoring of flowing objects into user-defined patterns on the substrate. We discuss the hardware and software architecture of the system and demonstrate its capability to build arrays of individual cells and polymer beads within microfluidic devices. Finally, we address the speed limits of the method, and the tradeoff between speed and accuracy as mediated by the performance of the hardware and software, and the material properties.

### **3:00-3:20      Development of an Combinatorial High Throughput (CHT) Alloy Synthesis Technique for Additive Manufacturing using Dry Powder Printing and Controlled Laser Melting**

*A. Dotsenko<sup>a</sup>, J. Garofano<sup>b</sup>, J. Beals<sup>b</sup>, S. Das<sup>a</sup>*, <sup>a</sup>Georgia Tech, <sup>b</sup>United Technologies Research Center

This talk describes the development of a combinatorial high throughput (CHT) alloy synthesis technique for Additive Manufacturing (AM) that combines experimental and analytical

components tailored to advance the understanding of process-microstructure and microstructure-property relationships. The experimental component includes precision dry powder printing (DPP) for alloy composition control and Controlled Laser Melting (CLM) for consolidation to create a large set of physical alloy samples of unique composition under controlled processing conditions. The analytical component includes quantitative microstructural analysis and material property measurements of the fabricated samples. Together, these components form the basis of a powerful tool for rapid screening of microstructure-property-processing relationships as a function of alloy composition. The DPP and CLM techniques are presented along with a demonstration of the CHT technique on a family of aluminum alloys. The presented technique has the potential to serve as a valuable tool in advanced alloy development for AM as well as for streamlining process parameter optimization.

### **3:20-3:40 Selective Heat Sintering versus Laser Sintering: Comparison of Deposition Rate, Process Energy Consumption and Cost Performance**

*M. Baumann, C. Tuck, R. Hague, University of Nottingham*

The Selective Heat Sintering (SHS) process has become available as a low cost alternative to Laser Sintering (LS) for the additive deposition of polymer objects. While both processes belong to the powder bed fusion variant of Additive Manufacturing (AM) technology, their operating principles vary significantly: SHS employs a thermal print head to selectively fuse material powder, whereas the LS approach utilizes a laser beam coupled with a galvanometer. Based on a series of build experiments, this research compares these technology variants along three dimensions of process efficiency: deposition rate (measured in  $\text{cm}^3/\text{h}$ ), specific process energy consumption ( $\text{MJ}/\text{kg}$ ) and specific cost ( $\$/\text{cm}^3$ ). To ensure that both platforms are assessed under the condition of efficient technology utilization, an automatic build volume packing algorithm is employed to configure a subset of build experiments. Beyond reporting absolute and relative process performance, this paper additionally investigates how sensitive the compared processes are to a variation in the degree of capacity utilization and discusses the application of different levels of indirect cost in models of low cost AM.

### **3:40-4:00 Solid Freeform Fabrication of Transparent Fused Quartz using a Filament Fed Process**

*J. Luo<sup>a</sup>, L. Gilbert<sup>a</sup>, R. Landers<sup>a</sup>, C. Qu<sup>a</sup>, B. Morrow<sup>a</sup>, D. Bristow<sup>a</sup>, J. Goldstein<sup>b</sup>, A. Urbas<sup>b</sup>, E. Kinzel<sup>a</sup>, <sup>a</sup>Missouri University of Science and Technology, <sup>b</sup>Air Force Research Laboratory*

Glass is a critical material for many scientific and engineering applications including optics, communications, electronics, and hermetic seals. Despite this technological relevance, there has been minimal research toward Additive Manufacturing (AM) of glass, particularly optically transparent glass. Additive Manufacturing of transparent glass offers potential advantages for lower processing costs for small production volumes, increased design freedom, and the ability to locally vary the optical properties of the part. This paper presents a study of additive manufacturing of transparent fused quartz by a filament fed process. A CW  $\text{CO}_2$  laser ( $10.6 \mu\text{m}$ ) is used to melt glass filaments layer by layer. The laser couples to phononic modes in the glass and is well absorbed. The beam and melt pool are stationary while the work piece is scanned using a standard lab motion system. Representative parts are built to explore the effects of variable laser power on the properties of printed fused quartz. During printing the incandescent emission from the melt pool is measured using a spectrometer. This permits process monitoring and identifies potential chemical changes in the glass during printing. After deposition, the

printed parts are polished and the transmission measured to calculate the absorption/scattering coefficient. Finally, a low-order thermal analysis is presented and correlated to experimental results, including an energy balance and finite volume analysis using Fluent. These results suggest that optical quality fused quartz parts with low absorption and high index of refraction uniformity may be printed using the filament-fed process.