NSF-Sponsored Workshop:

Accelerating NSF Research in Additive Manufacturing toward Industrial Applications

August 17-18, 2017

The University Club of the University of Pittsburgh,
123 University Pl, Pittsburgh, PA 15260

Workshop is organized in collaboration with America Makes
More information: http://www.engineering.pitt.edu/NSF-workshop-additive/

Organizing Committee:

Dr. Wei Xiong (weixiong@pitt.edu), University of Pittsburgh (Chair)

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Mr. Ralph L. Resnick, NCDMM and America Makes (Chair)

Dr. Howard A. Kuhn, University of Pittsburgh

Dr. Albert To, University of Pittsburgh

Dr. Zhijian Pei, Texas A&M University

Agenda

Thursday, August 17th, 2017

17:00 – 18:00 Registration

18:00 – 18:15 Welcome and Opening Remarks
Wei Xiong (Chair, Organizing Committee)

18:15 – 18:30 Overview of America Makes
Ralph L. Resnick (Founding Director, America Makes)

18:30 – 18:45 Overview of NSF-Funded Research
Mary Toney (Program Manager, NSF)

18:45 – 19:45 Poster Session
Light refreshments will be provided

Friday, August 18th, 2017

7:30 – 8:15 Registration and Continental Breakfast

8:15 – 8:30 Presentation on AM Industry Trends/Needs
John Wilczynski (Deputy Director, Technology Development, America Makes)
Rob Gorham (Executive Director, America Makes)

8:30 – 9:45 Session I: Additive Manufacturing Processes
Session Chair: Mostafa Bedewy (Co-Chair, Organizing Committee)

8:30 – 8:45 Additive Manufacturing by Electrochemical Deposition
Murali Sundaram, University of Cincinnati

8:45 – 9:00 3D Printing of Metals at Room Temperature
Michael D. Dickey, NC State University

9:00 – 9:15 Layer-to-Layer Control in Laser Metal Deposition
Douglas A. Bristow, Missouri University of Science and Technology

9:15 – 9:30 Modeling and Closed Loop Control for Jet-based 3D Printing
Sandipan Mishra, Rensselaer Polytechnic Institute

9:30 – 9:45 Automatic Finishing of Metal AM Components via DASH Manufacturing
Ola L. A. Harrysson, North Carolina State University

9:45 – 10:15 Break and Networking

10:15 – 11:30 Session II: Value Chain and Applications of Additive Manufacturing
Session Chair: Alaa Elwany (Member, Organizing Committee)

10:15 – 10:30 From Novel Materials to Cyber Security: Research Across the Additive Manufacturing Process Chain
Christopher Bryant Williams, Virginia Tech

10:30 – 10:45 Analytic Certification for Additively Manufacturing Parts and Processes under Uncertainty
Seung-Kyum Choi, Georgia Institute of Technology

10:45 – 11:00 Laser-Ultrasound and Acoustic In-Line Monitoring of 3D Metal Printing
Timothy A Bigelow, Iowa State University

11:00 – 11:15 3D Printing: A New Promising Avenue for Concrete and the Construction Industry
Joseph J. Biernacki, Tennessee Technological University

11:15 – 11:30 Additive Manufacturing of Batteries
Heng Pan, Missouri University of Science and Technology

11:30 – 13:00 Lunch

13:00 – 14:15 Session III: Materials in Additive Manufacturing
Session Chair: Wei Xiong (Chair, Organizing Committee)

13:00 – 13:15 Processing-Microstructure-Mechanical Property Relationships in Additive Manufacturing of Metals
Allison M. Beese, Pennsylvania State University

13:15 – 13:30 Additive Manufacturing of Multiphase Functionally Gradient Materials
Salil Desai, North Carolina A&T State University

13:30 – 13:45 Modeling Grain Texture and Yield Behavior of Laser Additive Manufactured Metals
Albert C. To, University of Pittsburgh

13:45 – 14:00 Synthesis and Evaluation of Metal Matrix Nanocomposites by Selective Laser Melting
Jing Shi, University of Cincinnati

14:00 – 14:15 Functional 3D Printing - Material, Processing and Design Perspective
Yong Chen, University of Southern California

14:15 – 14:45 Break and Networking

14:45 – 16:00 Session IV: Design in Additive Manufacturing
Session Chair: Alaa Elwany (Chair, Organizing Committee)

14:45 – 15:00 Topology Optimization of Additively Manufactured Materials and Components
James Guest, Johns Hopkins University

15:00 – 15:15 Topology Optimization for Additive Manufacturing
Krishnan Suresh, University of Wisconsin

15:15 – 15:30 Process Understanding of Powder-Bed Metal AM Technologies: Toward Effective Support Designs and Pore Defect Mitigations
Kevin Chou, University of Louisville

15:30 – 15:45 Predictive Model Building Across Different Process Conditions and Shapes in Additive Manufacturing
Arman Sabbaghi, Purdue University

15:45 – 16:00 Projection Stereolithography (SL) Process Planning and System Design for Fast Production and Multi-material Printing
Yayue Pan, University of Illinois at Chicago

16:00 – 16:30 Break and Networking

16:30 – 16:45 Closing Remarks
Mostafa Bedewy (Co-Chair, Organizing Committee)

Session I: Additive Manufacturing Processes

8:30 – 8:45 AM on 8/18/2017

Additive Manufacturing by Electrochemical Deposition

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Electrochemical Additive Manufacturing (ECAM) is a novel manufacturing method that is capable of producing complex shaped functional metal parts layer-by-layer / voxel-by-voxel directly from computer generated 3D CAD models. ECAM process has the potential to mitigate or overcome several of the limitations of traditional AM techniques, such as limited material choice, anisotropy, porosity, strength, scalability, support structure, and internal stresses. ECAM uses electrochemical deposition, a nonthermal process that uses the principles of electrolysis to deposit ions onto a surface. The process has considerably lower residual stresses, and the addition of material is atom by atom resulting in excellent microstructural properties which can be controlled in process. ECAM is capable of depositing conductive multi materials such as metals, metal alloys, and conducting polymers. This presentation will include an overview of the ECAM process, research updates, challenges and opportunities.

8:45 – 9:00 AM on 8/18/2017

3D Printing of Metals at Room Temperature

Michael D. Dickey
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This talk will discuss methods to directly print a micromoldable liquid metal into 3D structures at room temperature and embed it in functional polymers to create conductors that are soft, self-healing, and ultra-stretchable. The metal is a gallium-based metal alloy that is a low-viscosity liquid at room temperature with low toxicity and negligible volatility. Despite the large surface tension of the metal, it can be molded, patterned and printed into non-spherical shapes due to the presence of an ultra-thin surface oxide skin. We have harnessed these properties to form a number of electronic devices encased in polymer matrices. We have also utilized the ability to withdraw the metal from 3D printed structures as a sacrificial, fugitive ink to create microvasculature in polymer monoliths.

9:00 – 9:15 AM on 8/18/2017

Layer-to-Layer Control in Laser Metal Deposition

Douglas A. Bristow
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In order to achieve widespread industry adoption of Additive Manufacturing (AM), new methods of process control are needed to improve reliability. At the same time, many of the part defeats and process failures in AM begin small, at tolerable levels, but amplify as they propagate from layer to layer. In this presentation, we consider laser metal deposition (LMD), a direct energy deposition process in which metal powder is blown into a melt pool heated by a laser. The process is known to have geometric instabilities wherein the part may stop growing with increasing layers or ripples in the surface profile may form. Control-oriented dynamic models of this process, incorporating in-layer dynamic evolution and layer-to-layer dynamic propagation, are presented. Instability mechanisms in this process are illuminated and multi-dimensional dynamic system theory tools are used to establish rigorous stability constraints. Finally, stabilizing control algorithms that operate in a layer-by-layer fashion, that is by collecting geometric information of a complete layer after it has printed and generating the complete control correction for the subsequent layer prior to the start of that layer, are presented. Simulation and experimental results demonstrate strong potential for layer-to-layer control methods to provide robustly stability, improving process reliability.

9:15 – 9:30 AM on 8/18/2017

Modeling and Closed Loop Control for Jet-based 3D Printing

Sandipan Mishra
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This talk will focus on modeling and model-based feedback control design for additive manufacturing. Specifically, as a case study, we will discuss the development of a closed-loop control approach for ink-jet 3D printing that uses measurement of the height profile to do layer-to-layer control. The control design strategy is based on a distributed model predictive control scheme, which can handle constraints (such as droplet volume) as well as the typical large-scale nature of the control problem. We first propose and experimentally validate a graph-based height evolution model that can capture the liquid spreading dynamics. Then, based on this model, we design a scalable closed-loop control algorithm. The performance and efficiency of the algorithm

are shown to outperform open-loop printing and closed-loop printing with existing model-based methods.

9:30 – 9:45 AM on 8/18/2017

Automatic Finishing of Metal AM Components via DASH Manufacturing

Ola L. A. Harrysson
Edward P. Fitts Distinguished Professor
Edward P. Fitts Department of Industrial and Systems Engineering
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Finishing of metal AM components to achieve required tolerances and surface finish is often an issue when producing small lots. To design and fabricate the required fixtures and jigs can take weeks followed by the toolpath generation. To resolve this issue a software solution has been developed that seamlessly combine additive manufacturing and subtractive manufacturing in to a hybrid automatic solution (Direct Additive and Subtractive Hybrid (DASH) Manufacturing). The software analyses the component and add machining allowances based on the tolerance requirements and adds fixturing features used in the subtractive stage. The size and location of these fixturing features are determined automatically based on a visibility algorithm. The pre-planning software exports a file that can be used in any AM machine. The AM fabricated part is located in a four axis CNC machine and a laser scanner is used to determine the exact location and the amount of material that needs to be removed. In the last step the software will generate the toolpath automatically and select the optimal tool for each operation. The early research work was funded by NSF and the development of the software solution was funded by America Makes.

Session II: Value Chain and Applications of Additive Manufacturing

10:15 – 10:30 AM on 8/18/2017

From Novel Materials to Cyber Security: Research Across the Additive Manufacturing Process Chain

Christopher Bryant Williams
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Using Additive Manufacturing (AM), a designer has the power to selectively place (multi)material only where it is needed, and thus is afforded the opportunity to realize products that satisfy multiple functions and design objectives. However, to realize the full potential of this added capability, AM processes are in need of further advancements in material selection, process capability, design methodologies, and quality assurance techniques. To help fulfill AM's potential as a feasible means for producing end-use artifacts, researchers in the Virginia Tech DREAMS Lab have been engaged in fundamental research across the entire AM process chain. In this presentation, Williams will highlight the major outcomes from several research projects that have been sponsored by the National Science Foundation, including (i) Binder Jetting nanosuspensions to create fully dense copper parts, (ii) 3D sand printing cores for fabricating composite cellular structures, (iii) using impedance-based actuators for non-destructive evaluation of AM parts, and (iv) cyber-physical security methods for AM processes.

10:30 – 10:45 AM on 8/18/2017

Analytic Certification for Additively Manufacturing Parts and Processes under Uncertainty

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Advances in additive manufacturing (AM) enable virtually unlimited design complexity and thus require far more design decisions. The increased complexity in a system adds significant amounts of uncertainty associated with a large number of design variables. Successful product innovation cannot be achieved without adequate tools to analyze and manage these complexities and uncertainties. It is critical to incorporate the effect from these complexities and uncertainties in the design process of future engineering systems to regulate their safety and security. There are increasing pressures to require the certification of AM-fabricated parts by analysis without conducting customized testing of printed parts. To address this requirement, the proposed research developed a framework which can achieve analytical certification of additively manufactured parts by utilizing a new stochastic upscaling procedure.

Dr. Choi's research group at Georgia Tech developed a framework which can analytically certify additively manufactured parts with the consideration of uncertainty. Multi-scale modeling methods, effective probabilistic approaches, and design methods for additive manufacturing are utilized to create innovations in the fabrication process of complex engineering systems. Various experimental works on AM fabricated parts are conducted and the full characteristics and manufacturing constraints of these parts are integrated into the developed framework. The developed design and certification process can be applicable to most current AM fabrication technologies. The developed framework demonstrates how the certification of AM parts can be achieved with practical engineering examples.

10:45 – 11:00 AM on 8/18/2017

Laser-Ultrasound and Acoustic In-Line Monitoring of 3D Metal Printing

Timothy A Bigelow, Hossein Taheri, Lucas Koester, Peter Collins, and Leonard J. Bond
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The use of 3D printing to manufacture finished metal parts is poised to revolutionize the manufacturing industry. However, in-line monitoring during fabrication is critical as parts fabricated under identical conditions can have varying numbers and severity of defects. Two promising techniques for in-line monitoring during additive manufacturing are acoustic emissions and laser-based ultrasound. Acoustic emission (AE) systems are relatively low cost and will not increase the build times for 3D printing as they are passive systems. AE has also demonstrated potential for detecting changes in laser power and powder feed rate for a LENS Optomec Directed Energy Deposition System. However, AE may lack the sensitivity and specificity to detect smaller defects during the build. Laser-Based ultrasound (LUS) has the advantage of identifying individual defects ~100 μm provided they are relatively close to the surface, and it may be possible to detect smaller defects as well as quantify variations in the elastic moduli and residual stress of the materials. However, LUS may increase the build times. Therefore, both potential techniques need to be explored, and perhaps combined, in the future to achieve optimal in-line monitoring.

11:00 – 11:15 AM on 8/18/2017

3D Printing: A New Promising Avenue for Concrete and the Construction Industry

Florence Sanchez [1], Joseph J. Biernacki[2], Jan Olek[3] Jeffrey P.Youngblood[4], and Pablo Zavattieri[3]
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Portland cement concrete is the most used man-made materials on earth with some seven billion tons being placed annually. Though ancient in origin, 21st Century concrete is a distinctive blend of antiquity, modern material science, and chemistry. Concrete is now recognized as a complex, random, multi-scale material and research in the past two decades has focused on molecular modeling, nano-particle interactions and hydration studies – taking advantage of nano-technology. Utilizing this bottom-up understanding of the interactions between calcium-silicate-hydrate (C-S-H) and other constituents at the nano-scale, the next revolution appears to be motivated by a grand macroscopic vision of automated construction that will shape city landscapes and alter the fundamental nature of how constructed infrastructure is built. Additive manufacturing (AM) of concrete structures, while still in its infancy, is rapidly emerging as a research frontier and is positioned to revolutionize construction and to be a transformative economic factor in the global construction economy. While AM of concrete has the appearance of nothing more than a robotics challenge at the macroscopic scale, nothing can be further from the truth. And, while automation challenges exist, numerous materials issues across concrete's nine-fold length-scales must be addressed if AM is to be realized as a pervasive construction paradigm for 21st Century construction.

11:15 – 11:30 AM on 8/18/2017

Additive Manufacturing of Batteries

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Batteries play an essential role in enabling energy storage for applications ranging from portable electronics, electric vehicles to grid stabilization as well as renewable energy storage. Current cost of Li-ion battery (~$400/kWh) has been one of the major factors preventing the wide adoption of hybrid and electric vehicles. Advanced manufacturing of batteries aiming at reducing

manufacturing cost and increasing specific energy capacity is critical in enabling proliferation of electric vehicles and various portable electronics in the near future.

Currently, the electrodes for commercial Li-ion batteries are manufactured by the slurry process. Solvent and its associated cost in slurry-based electrode manufacturing contribute much of battery cost. A new powder-based additive manufacturing process has been discovered for manufacturing Li-ion batteries. In the process, solvents are no longer used and battery materials are printed layer-by-layer in the dry form for manufacturing Li-ion batteries. The technology can be used to manufacture Li-ion batteries at lower cost with high energy density, industrial scale throughput, and desired/engineered electrode structures. In the presentation, the current progress on the additive manufacturing characteristics, battery performance as well as commercialization plan will be presented.

Session III: Materials in Additive Manufacturing

13:00 – 13:15 on 8/18/2017

Processing-Microstructure-Mechanical Property Relationships in Additive Manufacturing of Metals

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Adoption of additive manufacturing (AM) for the production of metallic parts to be used in structural applications requires that the mechanical performance of additively manufactured components be reliable and predictable. This necessitates an understanding of the quantitative processing-structure-mechanical property relationships in AM. Complicating the elucidation of these relationships is the complex thermal history in AM, in which every location within a component undergoes rapid solidification followed by rapid heating and cooling cycles with subsequent laser passes adding material adjacent to or above the location. As a result, the microstructure, and thus properties, are heterogeneous and anisotropic. Here, we will present our efforts toward uncovering quantitative relationships among the processing, which dictates thermal history, microstructure, and resulting mechanical properties in both Ti-6Al-4V and 304L stainless steel. We will present the connection between salient microstructural features and macroscopic mechanical properties in AM of these alloys.

13:15 – 13:30 on 8/18/2017

Additive Manufacturing of Multiphase Functionally Gradient Materials

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Additive manufacturing (AM) of functional electronic components defines the next generation of miniaturized devices. Additive manufacturing of conductive traces can eliminate several post-processing operations in traditional manufacturing methods such as photolithography, tape casting, and screen printing. In this research our team employs a hybrid additive manufacturing technology which combines microextrusion and pico-jetting. Conductive slurries and colloidal inks were optimized for their rheological properties to assist with precision deposition on substrates. The deposition was performed on both rigid (glass) and flexible (kapton) substrates. The conductive traces were fabricated using carbon slurry and nickel ink using microextrusion and pico-jet units, respectively. *In situ* infiltration of media was implemented for manipulation of

the electrical properties. Further, multiphase materials which included a homogenous slurry of carbon, nickel, and silver components were deposited for multilayer structures. The effect of laser sintering parameters on conductivity values was contrasted against furnace curing mechanism. The 3D printed structures were characterized using scanning electron microscopy and energy dispersive x-ray spectroscopy. This research lays the foundation for the fabrication of 3D electronic components using a hybrid additive manufacturing technology.

13:30 – 13:45 on 8/18/2017

Modeling Grain Texture and Yield Behavior of Laser Additive Manufactured Metals

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In this talk, we will present our efforts on modeling the process-microstructure-property relationship between the grain texture and yield behavior in laser additive manufactured (AM) metals. First, we will discuss a quantitative semi-empirical method to predict the texture of the epitaxial columnar grains grown from single crystal and polycrystal substrates. Combined with the melt pool prediction by the Rosenthal solution, the processing and microstructure are linked together quantitatively. The proposed method is used to estimate the texture of different AM metals found in the literature. Next, we will present a mean field polycrystal plasticity modeling framework to predict mechanical properties (strength and anisotropy) from the microstructure features (texture, grain size, shape) of AM metals. Three case studies were performed on general FCC metals with three different ideal microstructures to demonstrate the coupled effect of grain size, shape and texture in the proposed polycrystal plasticity model. Finally, model validation and parameter calibration were performed for AlSi10Mg printed using the EOS DMLS (direct metal laser sintering) system.

13:45 – 14:00 on 8/18/2017

Synthesis and Evaluation of Metal Matrix Nanocomposites by Selective Laser Melting

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Additive manufacturing processes have potentials for fabricating high strength structural components. To enhance the mechanical properties of additive metal components, nano particles could be introduced to the metal matrix for reinforcing effects. The research group of Professor

Shi at the University of Cincinnati has fabricated a variety of metal matrix nanocomposites (MMNCs) by using the technique of selective laser melting (SLM).

Specifically, nano reinforcement materials in the forms of particulate and platelet such as ceramic nanoparticles and graphene are adopted to strengthen various metal matrix materials such as Inconel and aluminum alloys. Meanwhile, heat treatments and surface treatments are applied to the as-built MMNCs to investigate the effects of post-processing techniques. MMNCs are characterized to study the microstructure evolution, precipitates formation, and the incorporated second phase particles. Static mechanical properties (such as tensile and wear), fatigue performance, as well as failure mechanisms, are also evaluated.

In most cases, various degrees of improvement in mechanical properties have been observed. On the other hand, outstanding fundamental issues in this area, including effects of nano particles on non-equilibrium solidification, strengthening mechanisms of nano particles, optimal dispersion of nano particles, call for further research.

14:00 – 14:15 on 8/18/2017

Functional 3D Printing - Material, Processing and Design Perspective

Dr. Yong Chen
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Department of Aerospace and Mechanical Engineering (courtesy)
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Current 3D printing systems are designed to use a single material and a single size scale to fabricate parts mainly for structural purpose. A new generation of 3D printing technologies are starting to emerge in which (a) multiple materials can be digitally controlled to produce parts with heterogeneous properties, and (b) the deposited materials can serve more than just structural functions, e.g. electrical, thermal, optical, magnetic, chemical, or other functions. This talk will report our recent work on developing new multi-scale, multi-material and multi-functional additive manufacturing processes and related modeling and control methods, including (1) a functional ceramics 3D printing process to fabricate novel piezoelectric sensors, (2) a nanocomposite-based additive manufacturing process to fabricate bio-inspired structures with highly impact resistant architectures, (3) a general reverse compensation framework for shape compensation control in additive manufacturing, and (4) a multi-material modeling and design method with some novel applications. The talk will conclude with remarks and thoughts on future 3D printing developments.

Session IV: Design in Additive Manufacturing

14:45 – 15:00 on 8/18/2017

Topology Optimization of Additively Manufactured Materials and Components

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In order to fully leverage recent advancements in additive manufacturing, engineers must open up the design space and re-imagine design solutions. Topology optimization offers a computational, systematic approach to exploring the expanded design space provided by additive manufacturing and has a demonstrated capability of identifying novel, high performance design solutions. This talk will discuss a topology optimization approach known as Projection Methods where manufacturing capabilities and constraints are directly embedded in the topology optimization formulation. Together with rigorous integration of the governing physics, this means that designs are optimized for actual as-built conditions without the need for manual post-processing to satisfy manufacturing or end-use constraints. Ultimately, the approach has the potential to reduce design cycle times and produce components with dramatically improved, robust performance.

Multiple design examples will be presented illustrating topology optimization considering different manufacturing process constraints and design objectives, including structural, fluidic, and thermal properties. Considered manufacturing constraints include overhang angles in direct metal (anchorless printing), various forms of length scale constraints, multi-material polymer printing, and consideration of manufacturing uncertainties. Both component level design and the design of architected materials will be presented.

15:00 – 15:15 on 8/18/2017

Topology Optimization for Additive Manufacturing

Krishnan Suresh
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This talk will present two independent research topics that are currently being pursued in our group towards integrating topology optimization (TO) and additive manufacturing (AM).

Support structure constraint: For several AM processes, such as FDM and SLM, extraneous support structures are often needed. Support structures directly add to the build-time and material cost. Indeed, the largest percentage cost for metal AM, besides the machine cost that is amortized, is material cost (18%). Further, support structures can be hard to remove, leading to *post-fabrication (clean-up) cost*. The objective here to develop a TO methodology for limiting the support structure volume, thereby leading to high-performance designs that are also AM friendly.

Material anisotropy: It is well established that parts fabricated through some AM technologies are anisotropic. This induced anisotropy can have a negative impact on functionality of the part, and must be considered during optimization. We present a strength-based topology optimization method for structures with anisotropic materials. A new topological sensitivity formulation based on strength ratio of non-homogeneous failure criteria, such as Tsai-Wu will be discussed. The effectiveness of the proposed method is demonstrated through numerical and experimental tests.

15:15 – 15:30 on 8/18/2017

Process Understanding of Powder-Bed Metal AM Technologies: Toward Effective Support Designs and Pore Defect Mitigations

Kevin Chou

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To fully exploit the potential of metal additive manufacturing (AM) technologies, challenges related to part certification and process qualification must first be overcome in order for end-users to embrace metal AM implementations in the industry. Funded by NSF, AM research at University of Louisville has been heavily focused on metal powder-bed fusion processes, aiming at fundamental knowledge that sheds powerful light and can, moreover, lead to successful metal AM applications. In particular, process modeling assisted with experiments including thermography has been pursued to address two key problems: support structures for part overhangs and formation mechanisms of pore defects. For support structure designs, the contact-free thermal support has been demonstrated; in addition, based on thermomechanical process simulations and a minimum-energy approach, a design methodology is proposed to attempt optimal support structures with least material usage and distortions. For the pore formation study, advanced computational techniques of multi-physics, multi-scale nature including smoothed particle hydrodynamics are under development. Micro-scale computed tomography will be employed for pore measurements and analysis to validate the pore formation models. Porosity variability in AM builds due to powder variations, process parameter deviations, and different geometric features will be investigated to delineate the operative ranges for mitigating pore defects.

15:30 – 15:45 on 8/18/2017

Predictive Model Building Across Different Process Conditions and Shapes in Additive Manufacturing

Arman Sabbaghi
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Predictive models for geometric shape deformation constitute an important component in quality control for additive manufacturing. However, model building is made difficult by the wide variety of possible process conditions and shapes. A methodology that can make full use of data collected on different shapes and conditions, and reduce the haphazard aspect of traditional statistical model building techniques, is necessary in this context. We develop a new Bayesian procedure based on the effect equivalence and modular deformation features concepts that incorporates all available data for the systematic construction of predictive deformation models. Our method is applied to dramatically facilitate modeling of the multiple deformation profiles that exist in flat cylinders with different types of cavities. Ultimately, our Bayesian methodology connects different process conditions and shapes to provide a unified framework for quality control in additive manufacturing.

15:45 – 16:00 on 8/18/2017

Projection Stereolithography (SL) Process Planning and System Design for Fast Production and Multi-material Printing

Yayue Pan
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Projection Stereolithography (SL) is an Additive Manufacturing technique that uses light energy to solidify photosensitive polymer resin, usually one layer a time, to form a 3D object. It has been applied in many fields, ranging from the medical field to the consumer markets. Despite those advances, challenges still exist in fabricating objects with wide solid cross sections, due to the over-large separation force during printing processes. In addition, the application of Projection SL in manufacturing end-use products has been significantly limited by its limited material choices. In this talk, I will first present our recent research on projection SL machine design, for fabricating objects with wide solid cross sections. In this research, a Projection SL system with a textured constrained surface was investigated. It was found that proper constrained surface texture is capable of reducing the separation force greatly, and hence allows for stable printing of objects with wide solid cross sections. Besides, I will also present our recent research on multi-material polymer composite fabrication in Projection SL. A novel acoustic-field assisted Projection SL system and a multi-material printing process will be presented. Particle-polymer smart composites tested in this study will be demonstrated and discussed.

Poster Session

Electrohydrodynamic (EHD) 3D Printing for High-Resolution Additive Manufacturing

Jingyan Dong
Department of Industrial and Systems Engineering
North Carolina State University, Raleigh, NC

High-resolution additive manufacturing is critical for many emerging applications. Many high precision industrial parts require micron-scale part accuracy and high quality surface finish, so as to effectively reduce the time and cost in post-processing. In biomedical applications (e.g. tissue engineering scaffolds), micron-scale structures with their dimension similar to the size of the cells provide advanced functions to regulate cell responses to the scaffold, such as cell alignment and cell contact guidance. Traditional additive manufacturing (AM) have resolution no better than 50 µm, and the resolution is difficult to improve. Our group investigates high-resolution (micron-scale) electro-hydrodynamic (EHD) 3D printing process with a variety of structural materials (e.g. thermoplastic materials and low melting point alloys) to achieve high precision additive manufacturing of complex objects, which overcome the resolution barrier of most existing additive manufacturing approaches and significantly improve the accuracy and surface finish of the produced parts. Theoretical and empirical process models are investigated for the analysis of the melt electrohydrodynamic printing process with respect to material properties and process parameters. We integrate process development, process modeling, and a novel manufacturing system into a new framework that enables high-resolution 3D printing of complex structures.

Additive Manufacturing of Transparent Glass

Edward C. Kinzel
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Glass has significant scientific and engineering applications including optics, communications, electronics. Additive manufacturing provides transformational capabilities for creating parts with complicated geometries and low production volumes. It also opens up new possibilities for creating functionally graded materials. This poster describes ongoing work on depositing optically transparent glass components using a laser-heated filament-fed process. In this process, a CO_2 laser is used to locally melt continuously fed, small-diameter glass rods and fiber. 3D shapes are constructed by moving a CNC stage relative to the intersection of the filament and the laser beam. Material consolidated by the melting process, solidifies out of the melt pool as the part translates relative to the laser beam. The 10.6 µm laser energy is well absorbed by the glass and the build platform is heated to minimize thermal stresses during deposition. Starting with fulling dense feedstock and smoothly melting it allows deposition of glass with transparency approaching furnace cast pieces. Preliminary work printing lenses is presented. The AM process allows volumetric variation of the material composition which facilitates the deposition of Gradient Index (GRIN) optics. In addition, the AM approach is useful for printing integrated photonics and depositing hermetic seals.

Beyond Complex Shapes: Performance Driven Additive Manufacturing of Metallic Materials

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Additive manufacturing (AM) of metal parts is at a juncture where multiple technologies have established their domain and a critical set of questions/issues have emerged. With any advanced manufacturing process, the cost of implementation has to be justified by gains in performance. Among the fusion AM technologies, laser based powder bed technologies (LBPBT) have become very popular because of the extraordinary design advantages. Topological optimization of a component based on the stress analysis can lead to significant weight saving. While design of complex shapes with intricate lattice structures and process optimization to accomplish such parts have advanced significantly, the location specific metallurgical process-microstructure-properties correlations have lagged behind. Ultimately, structural components are qualified based on properties and reliability. It is critical to link the probabilistic nature of the process with microstructural distribution that result in property variation. Another glaring gap is the availability of suitable alloys for high structural performance. For example, only a few aluminum alloys are available for LBPBT and this is true for most alloy categories. On the other hand, a few solid state AM technologies are in early stages of development. Among these, friction stir additive manufacturing (FSAM) results in excellent properties but is limited to simple geometries. In this presentation, a few key aspects related to (a) need for alloy design for LBPBT, (b) development of site specific process-microstructure-property correlations, and (c) design domain for solid state techniques like FSAM will be discussed.

Understanding Transport Phenomena in Scalable Additive Manufacturing

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The Complex Fluids and Multiphase Transport Lab at Drexel University focuses on applying fundamental thermo-fluid and interfacial sciences to enable scalable additive manufacturing. Environmentally-benign roll-to-roll electronics fabrication using inkjet printing on flexible substrates is an enabling technology that will provide desired high-volume, low-cost production of flexible electronics. We combine multi-scale modeling and experimental efforts to better understand transport processes in evaporation-driven self-assembly of colloidal drops containing functional materials for printable electronics fabrication. We also extend the roll-to-roll printing process into the 3rd dimension with robust deposition controls, from complete or partial filling of nanoporous substrates to deposition of highly repeatable nanoscale arrays. Drop-on-demand printing inside nanoporous substrates enables encapsulation of multi-functional therapeutic materials for drug delivery with precisely controlled release and localized delivery of growth factors for tissue regeneration. Nanotemplated printing allows for large-area deposition of nanoarrays for rapid screening of biomolecules and efficient chemical detections. By tuning ink-substrate interactions, high-throughput production of highly ordered 3D nanostructures is achieved.

Properties and Microstructure in Thick Plate Inconel 718 Produced by Electron Beam Wire Feed

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Electron beam wire feed can be used to build up structures rapidly, compared to power bed fusion methods. A circular thick plate structure was fabricated from Inconel 718, then specimens were cut at different orientations with respect to the build direction. Tensile properties varied significantly depending on the location and orientation of the specimens removed from the plate. Electron backscatter diffraction (EBSD) was used to provide texture measurements of the plate material in each location. EBSD was also used to estimate local residual stresses and void content, based on novel methods of post-processing of scan data, for each location where specimens were extracted. Microstructure/property relationships will be discussed with respect to specimen orientation.

Multi-scale, Vat-free Photopolymerization

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A multi-scale, vat-free photopolymerization is being developed. The system takes an advantage of a liquid bridge, which does not require a vat, resulting in enabling fabrication with a small amount of the material. A liquid bridge can be easily found in nature after rain comes. The liquid bridge was first introduced into the digital micromirror device (DMD)-based microstereolithography (MSL) process by replacing a vat, allowing the entire fabrication process to occur within the liquid bridge. The liquid bridge has been investigated theoretically and experimentally to achieve a stable equilibrium shape and the relationship between the height and the volume of the liquid bridge. Using the liquid bridge MSL (LBMSL) process, the fabrication layer thickness of 0.5 µm was achieved. This could not be easily achieved in the vat-based MSL due to the oxygen inhibition to the photopolymer. Photopolymers with a viscosity range of 3000 cP or higher were tested and significant results were obtained. In addition, the multi-scale fabrication capability is being investigated by synchronizing DMD image modulation and continuous projection in the xy plane, targeting the fabrication of micron features in a large area such as several cm by cm.

Additive Manufacturing of Lightweight Composite Lattices to Achieve Extreme Thermomechanical Properties

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Cellular structures are porous solids with solid edges or faces packed together to fill the 3D space. Examples of cellular structures widely exist in Nature, such as wood, cork, coral, sponge, trabecular bone and plant parenchyma. These materials, after decades of natural evolution, feature superior mechanical properties with ultralow densities. Inspired from Nature, researchers have fabricated a number of man-made cellular structures in various tailored architectures from 2D to 3D, and various material constituents from polymers, metals to ceramics. These man-made cellular structures, with extraordinary properties including lightweight, high mechanical efficiency (stiffness/strength per unit density), high damping and high porosity, have shown great potential for diverse applications in structural panels, flow cooling, impact absorption and acoustic damping. Despite the prosperous studies in single-material lightweight cellular structures, the study of multi-material lightweight cellular structures is at the beginning stage. The primary hurdle is the difficulty in additive manufacturing of complex 3D cellular structures with multiple material components. Here, we present a home-built multi-material stereolithography system to additively manufacture lightweight lattice structures with multiple material components in single structures. We show that the integration of multiple material components can enable unprecedented extreme mechanical properties. We experimentally fabricate lightweight multimaterial lattices that exhibit significant negative thermal expansion (NTE) in three directions and over a temperature range of 170 degrees. Such NTE is induced by the structural interaction of material components with distinct thermal expansion coefficients. The NTE can be tuned over a large range by varying the thermal expansion coefficient difference between constituent beams and geometrical arrangements. Our experimental results match qualitatively with a simple scaling law and quantitatively with computational models.

Additive Manufacturing for Optical Applications

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Additive manufacturing can find potential applications in optics, such as illumination, sensing, display, and communication. In this research, we first investigated a multiphase printing method for biconvex micro optics. Monomer droplets were deposited on an immiscible liquid surface, and biconvex lenses were formed at the interface of the air and the liquid. The mechanism of the lens shape forming was studied using multi phase force equilibrium. A numerical method was used to investigate the shape of the lens. The numerical method was developed based on the consideration of Young-Laplace equation, simplified Navier-Stoke equation, mass conservation and force equilibrium equations. The influence of interface tension, droplet volume to the biconvex lens shape was investigated, and the numerical results showed good agreement with the experimental results.

In addition to making individual optics, we also investigated fabrication of affordable biosensing platforms by using additive manufacturing. By using additive manufacturing, customized freeform optics can be fabricated at a low cost and with a short manufacturing lead time. Integrated with smartphone technology, these opto-sensing platforms can be used for rapid, high accurate, and low-cost biomarker detection for remote areas and resource-limited areas.

Nanoparticle electrospray laser deposition for additive manufacturing of microlayers on flexible substrates

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Nanoparticles of various materials are known to possess excellent mechanical, chemical, electrical, and optical properties. However, it is difficult to deposit and transform nanoparticles into large two-dimensional and three-dimensional structures in a controlled manner. A laser-based new additive manufacturing process is presented for depositing nanoparticles using an electrospray technology. This process is versatile and scalable, and uses less materials and energy. In this process, aqueous microdrops of nanoparticle suspension are injected into a hollow laser beam that vaporizes the water, sinters the nanoparticles and deposits nanoparticles on rigid or flexible substrates. Each droplet serves as both a nanoparticle carrier, and a superlens that focuses the laser beam to subwavelength diameters for depositing extremely small nanodots or very thin lines. Nanoparticles of different semiconductor materials such as Si, SiC and ZnO have been deposited on a flexible substrate, kapton, and high precision deposition has been observed to occur under a particular microfluidic regime called microdripping mode. This process can promote roll-to-roll manufacturing of a variety of energy and electronic devices such as conformal solar cells, sensors, and actuators. It can also be used to fabricate masks for nanolithography, nanopillar arrays for photonic crystals, and nanodot arrays for plasmonic surfaces.

Dissolvable Metal Supports for 3D Printed Metals

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This presentation details our dissolvable metal support technologies for Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) printed metals. These self-terminating support dissolution processes are designed to integrate seamlessly with existing build processes and require no change to build materials or parameters. For PBF processes, a sensitizing agent introduced during the normal stress-relieving step decreases the chemical stability of the top 50 – 100 µm of the component surface while completely sensitizing the thin support structures used in PBF. The sensitized region is then selectively etched to completely remove the supports while the base component only looses 50 – 100 µm of sensitized material off of its surface. Unlike traditional chem-milling processes, our process is self-terminates once the sensitized region is consumed.

Support scaffolding and structures are an inconvenient necessity in metals additive manufacturing and can account for 70% of the cost of the final, printed part. Our dissolvable support technology dramatically reduces these unwanted costs while enabling support removal of complete build platforms in a single batch. It replaces hundreds of hours of manual labor with simple chemical processes that selectively remove the supports and only the supports while also reducing surface roughness across the entire part.