
August 12–14, 2019
Hilton Austin • Austin, Texas, USA

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

Sponsored by:

sffsymposium.engr.utexas.edu
## SCHEDULE AT-A-GLANCE

### Sunday, August 11

<table>
<thead>
<tr>
<th>Time</th>
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<tbody>
<tr>
<td>2:00 pm - 5:00 pm</td>
<td>Salon H Foyer</td>
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<tr>
<td>Pre-Conference Social Event*</td>
<td>Buffalo Billiards</td>
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### Monday, August 12

<table>
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<tbody>
<tr>
<td>7:00 a.m. to 5:00 p.m.</td>
<td>Salon H Foyer</td>
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<tr>
<td>Opening Remarks</td>
<td>Salon HJK</td>
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<tr>
<td>Plenary Session</td>
<td>Salon HJK</td>
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<tr>
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<tr>
<td>Lunch</td>
<td>On Your Own</td>
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<tr>
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<td>See Technical Program</td>
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<tr>
<td>Break</td>
<td>Salon HJK Foyer</td>
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<tr>
<td>Welcome Reception</td>
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<td>11th Annual Awards Program &amp; Banquet</td>
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### Tuesday, August 13

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<tr>
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### Wednesday, August 14

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<tr>
<td>Technical Sessions</td>
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<tr>
<td>Break</td>
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<tr>
<td>Lunch</td>
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<tr>
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*Must be 21 or older; Photo ID required

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2019 Annual International Solid Freeform Fabrication Symposium
ABOUT THE SYMPOSIUM & VENUE

REGISTRATION

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

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

The daily registration rate includes the following:

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

Registration Hours

The registration desk will be located in the Salon H Foyer of the Hilton Austin during the following hours:

**Sunday, August 11:** 2:00 p.m. to 5:00 p.m.
**Monday, August 12:** 7:00 a.m. to 5:00 p.m.
**Tuesday, August 13:** 7:00 a.m. to 5:00 p.m.
**Wednesday, August 14:** 7:00 a.m. to 5:00 p.m.

Internet Access

Complimentary wireless internet is for attendees in the Hilton Austin meeting spaces. To access the wireless internet, open the wireless menu on your device and choose the network "Hilton Meetings" and enter the access code “SFF2019.”

Technical Sessions

All technical and poster presentations will be located at the Hilton Austin. See the Technical Program on pages 24-123 for locations.

Luggage Storage

Luggage storage will be available at no cost to attendees on Wednesday, August 14, from 7:00 a.m. to 6:00 p.m. in room 612 at the Hilton Austin. Please note that this room will not be secured and any items left for storage will be at the attendee’s own risk. TMS and/or the SFF conference are not responsible for lost, stolen, or damaged items left in the room.

ABOUT THE VENUE

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

Self-parking ($32) and valet parking ($41) are both available at the hotel. Visit the Hilton Austin website for more details.

SOCIAL AND NETWORKING EVENTS

PRE-CONFERENCE SOCIAL EVENT

**6:00 p.m. to 8:30 p.m. • Sunday, August 11**

**Buffalo Billiards**

Come and meet old friends and make new ones before the “business” starts Monday! Enjoy a BBQ buffet at Buffalo Billiards, 201 East 6th Street in downtown Austin. The restaurant is only 0.3 mi (0.5 km) from the Hilton Austin. There is no additional charge to attend for conference registrants. No transportation will be provided. Guests must be 21 years or older to attend; photo ID will be required to enter Buffalo Billiards.

**About Buffalo Billiards**

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

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

AWARDS BANQUET

Monday, August 12 • Hilton Austin Salon HJK

6:00 p.m.  Reception
6:30 p.m.  Welcome Remarks
6:40 p.m.  Dinner & Wine Service
7:45 p.m.  The FAME Awards

International Outstanding Young Researcher in Freeform and Additive Manufacturing Award: Dr. Xiaoyu (Rayne) Zheng, Virginia Tech University
International Freeform and Additive Manufacturing Excellence Award: Dr. Olaf Diegel, University of Auckland

9:00 p.m.  Event Concludes

CONFERENCE LUNCH EVENT

General Lunch
12:05 p.m. to 1:40 p.m. • Tuesday, August 13

An informal networking lunch will be provided near the meeting rooms in Salon H at the Hilton Austin at the lunch break on Tuesday. The cost is included in the conference registration fee. There is no organized Tuesday evening social event this year.

Student Lunch and Panel Discussion
12:05 p.m. to 1:40 p.m. • Tuesday, August 13

For registered students, lunch will be provided in Salon G of the Hilton Austin at 12:05 PM on Tuesday. Cost is included in the registration fee. A panel discussion will focus on navigating the transition into career positions in the AM field, and students will have ample opportunities to ask questions. The panel will feature these four recent PhD graduates in academia, industry, and a national lab.

David Espalin
Dr. David Espalin is an Assistant Professor of Mechanical Engineering at the University of Texas at El Paso and serves as the Director of Research at the W.M. Keck Center for 3D Innovation – a multi-disciplinary center focused on the advancement and adoption of additive manufacturing (or more commonly known as 3D Printing) through activities in education, research, outreach, technology development and commercialization, and industrial partnerships. His current research is in the area of hybrid additive manufacturing, large area additive manufacturing, 3D electronics fabrication, and design software development. Through the development of custom machines at UTEP, Dr. Espalin has enabled multi-technology manufacturing that allows not only depositing thermoplastic materials, but also the use of wire embedding, machining, foil application, and robotic component placement to achieve the fabrication of multi-functional devices.

Ben Fulcher
Ben received his BS and MS degrees in Mechanical Engineering from UT Austin. He gained exposure to selective laser sintering as a graduate student, operating the SLS equipment at UT to build prototypes for his research project. He began his career as a manufacturing engineer at Harvest Technologies in 2012, where he started an additive metals department, built up a machine shop, and focused on process improvements and material development for both metal & polymer PBF. Upon Stratasys’ acquisition of Harvest in 2014, Ben led a team of engineers within Stratasys to develop a new metal powder bed fusion product. He continued this effort as Stratasys spun the team off into a new company called Vulcan Labs, which was acquired in 2018 by EOS. Ben now works as the engineering manager at EOS, where he continues to focus on new product development for powder bed fusion systems.

Brian Gierra
Brian Giera, PhD, is Principle Investigator at Lawrence Livermore National Laboratory’s Exploratory Research Project “Rapid Closed-Loop Control of Advanced Manufacturing with Machine Learning.” More broadly, Giera’s research focus is to develop and apply traditional (molecular dynamics & continuum/theory) and data driven (machine learning & computer vision) models to address materials processing and characterization problems within advanced manufacturing systems.

Joy Gockel
Dr. Joy Gockel is an Assistant Professor in Mechanical and Materials Engineering at Wright State University where her research focuses on integrating additive manufacturing, mechanics, materials and design. Prior to joining Wright State University, she was a Lead Engineer in research and development at GE Aviation’s Additive Technology Center. Joy completed her Ph.D. in Mechanical Engineering in 2014 from Carnegie Mellon University where she researched the relationships between additive manufacturing processing parameters and microstructure. She earned her bachelor’s degree in 2009 and master’s degree in 2010 from Wright State University where she formulated analytical models for additive manufacturing edge effects.
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Badges
All attendees are encouraged to wear SFF Symposium registration badges at all times during the conference to ensure admission to events included in the paid fee such as technical sessions, exhibition, and receptions.

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

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

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

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

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

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

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

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

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

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

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

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

The National Science Foundation for providing meeting support (Grant Number CMMI-1934397).

The Office of Naval Research for providing meeting support.

Professor Guha Manogharan from Penn State University for serving as this year’s coordinator for the NSF graduate student registration fee waiver program.

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

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

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International SFF Symposium Organizing Committee

Dave Bourell, Chair, The University of Texas at Austin
Joe Beaman, The University of Texas at Austin
Rich Crawford, The University of Texas at Austin
Carolyn Seepersad, The University of Texas at Austin
Scott Fish, The University of Texas at Austin
Desi Kovar, The University of Texas at Austin

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Adam Clare, University of Nottingham
April Cooke, Trumpf, Inc.
Nathan Crane, University of Southern Florida
Tom Starr, University of Louisville

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Brent Stucker, ANSYS
Wei Sun, Drexel and Tsinghua Universities
Ralph Wachter, National Science Foundation
Ryan Wicker, University of Texas at El Paso
PROGRAM HIGHLIGHTS: SPECIAL SESSIONS

Plenary Session (Monday AM)
Organized by the SFF 2019 Committee

Special Session: Binder Jet Additive Manufacturing: Materials, Modeling, and Experiments
Session Organizer: C. Fred Higgs III, Rice University; Zachary C. Cordero, Rice University
1. Process-structure Relations (Tuesday AM)
2. Applications (Tuesday PM)
3. Binder-powder Interactions (Wednesday AM)

Special Session: Data Analytics in AM
Session Organizer: Prahalada Rao, University of Nebraska at Lincoln; Brian Giera, Lawrence Livermore National Laboratory
1. Digital Twins; Machine Learning and Artificial Intelligence for In-process Defect Detection (Monday PM)
2. Machine Learning and Artificial Intelligence for In-process Defect Detection; Sensing for Quality Assurance (Tuesday AM)
3. Sensing for Quality Assurance (Tuesday PM)

Special Session: Design Methodologies for Tailoring Performance of Additively Manufactured Parts for Naval Applications
Session Organizer: John Michopoulos, Naval Research Lab; Ajit Achuthan, Clarkson University; Amit Bagchi, Naval Research Laboratory
1. General Design and Modeling (Tuesday AM)
2. Materials (Tuesday PM)

Special Session: Hybrid AM Processes
Session Organizer: Michael Sealy, University of Nebraska-Lincoln; Brett Conner, Youngstown State University; Frank Liou, Missouri University of Science and Technology; Guha Manoharan, Penn State; Ola Harrysson, NC State University; Iris V. Rivero, Rochester Institute of Technology
1. Strategies (Tuesday AM)
2. Additive-subtractive (Tuesday PM)
3. Materials, Structures, Function (Wednesday AM)

Special Session: Spray AM - Direct Writing by Aerosol Deposition (Monday PM)
Session Organizer: Desiderio Kovar, University of Texas at Austin

Special Session: Design for AM (Wednesday AM)
Session Organizer: Carolyn Seepersad, University of Texas at Austin
<table>
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<tr>
<th>Day/Time</th>
<th>Monday AM</th>
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<td>8:00 AM to 12:00 PM</td>
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<td>Special Session: Hybrid AM I - Strategies</td>
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<td>Special Session: Hybrid AM II - Additive-subtractive</td>
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<td>Design, Production &amp; Lifecycle Considerations</td>
<td>Page 43</td>
<td>Education and the Future of AM</td>
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<td>Special Session: Binder Jetting I - Process-structure Relations</td>
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<td>Special Session: Binder Jetting II - Applications</td>
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<td>Applications: Lattices and Cellular I - Mechanical Properties</td>
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<td>Topology Optimization</td>
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<td>Special Session: Data Analytics I - Digital Twins; Machine Learning and Artificial Intelligence for II process Defect Detection</td>
<td>Page 42</td>
<td>Special Session: Data Analytics II - Machine Learning and Artificial Intelligence for In-process Defect Detection; Sensing for Quality Assurance</td>
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<td>Applications: General I - Novel Materials and Processing</td>
<td>Page 49</td>
<td>Applications: General II</td>
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<td>Plenary Session</td>
<td>Salon HJK</td>
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<td>Page 24</td>
<td>Salon A</td>
<td>Sixth Floor</td>
<td>Page 117</td>
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<td>Salon A</td>
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<td>Materials: Ceramics, Glasses, Other I</td>
<td>Page 29</td>
<td>Materials: Ceramics, Glasses, Other II</td>
<td>Page 47</td>
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<td>Special Session: Design for Naval Applications I - General Design and Modeling</td>
<td>Page 26</td>
<td>Special Session: Design for Naval Applications II - Materials</td>
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<td>Process Development I - Sensors, Measurement and Controls A</td>
<td>Page 38</td>
<td>Process Development II - Sensors, Measurement and Controls B</td>
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<td>Process Development VI - Novel Methods and Processes</td>
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<td>Process Development VII - Deposition A</td>
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<td>Materials: Composites III</td>
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<td>Poster Session</td>
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<td>Materials: Ceramics, Glasses, Other I</td>
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<td>Applications: General IV - Materials: Polymers III - Processing</td>
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<td>Process Development VII - Deposition A</td>
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<td>Introductory Comments</td>
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<td>30 Years of Additive Manufacturing and the Solid Freeform Fabrication Symposium:</td>
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<td>David Bourell, University of Texas</td>
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<td>Then, Now, and What’s Ahead: Terry Wohlers, Wohlers Associates Inc</td>
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<td>An Open-architecture Multi-laser Research Platform for Acceleration of Large-scale</td>
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<td>Additive Manufacturing (ALSAM): William Carter, GE Research</td>
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<td>Funding Opportunities for Advanced Manufacturing at the National Science Foundation:</td>
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<td>Robert Landers, Missouri S&amp;T University</td>
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<td>Achieving More with Less: Design and Additive Manufacturing of Functionalities and</td>
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<td>Micro-architectures: Xiaoyu Zheng, Virginia Polytechnic Institute and State University</td>
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<td>Design for AM – The Key to the Industrialization of Additive Manufacturing: Olaf Diegel, University of Auckland</td>
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<td><strong>Session 3: Spray AM - Direct Writing</strong></td>
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<td>Direct-writing Sc with Micro-cold Spray: Velocity Dependence on Film Density</td>
<td>Enhancing the Predictability of the Mechanical Performance of Additively Manufactured Film</td>
<td>Jeremiah Alcock &amp; Albert To, University of Texas at Austin</td>
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<td>Direct-writing Vs Cold Spray: Film Dynamics</td>
<td>Predicting and Controlling the Thermal Effect in Powder Bed Fusion Using Neural Networks</td>
<td>Raghav Sharma, Arizona State University</td>
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<td><strong>Session 4: Advanced Materials: Scalable Direct Writing</strong></td>
<td>Concluding the Break down Approach on Additive Manufacturing Processes - A Machine Learning Approach</td>
<td>Janos Plocher, Imperial College London</td>
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<td>2:10 PM</td>
<td><strong>Session 5: Particle Trajectories, Focusing, and Fragmentation</strong></td>
<td>Influence of Impacting Particle Size and Stacking Fault Energy on Ag Films Deposited by Direct Writing</td>
<td>Rinoj Polyurethane Reinforcement: Rinoj Polyurethane Reinforcement, University of Memphis</td>
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<td><strong>Session 6: Additive Cold Spraying for Advanced Materials</strong></td>
<td>Enhancing the Predictability of the Mechanical Performance of Additively Manufactured Conformal Negative Sintered Honeycomb Structures</td>
<td>Christopher Hogan, University of Memphis</td>
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<td><strong>Session 7: Superionic Cold Spraying</strong></td>
<td>Additional Response of Strain Induced Austenite Structure with Polyurethane Reinforcement: Wally Gutierrez, Nanyang Technological University</td>
<td>Christopher Hogan, University of Memphis</td>
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<td>3:10 PM</td>
<td><strong>Session 8: Focus</strong></td>
<td>A Computational and Experimental Investigation into Mechanical Properties of Laser-Induced Lattice Structures - a Novel Approach to Science and Engineering</td>
<td>B. M. Keck Center for 3D Printing and Manufacturing</td>
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<td><strong>Session 9: Dimensional Analysis</strong></td>
<td>The Effects of Spatial Energy Distribution on Defects and Fracture of LPBF 316L Stainless Steel Produced by Wire Arc Additive Manufacturing with Interlayer Cooling</td>
<td>Josephine Jost, Texas A&amp;M University</td>
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<td>4:00 PM</td>
<td><strong>Session 10: Metal Additive Manufacturing</strong></td>
<td>The Effects of Spatial Energy Distribution on Defects and Fracture of LPBF 316L Stainless Steel Produced by Wire Arc Additive Manufacturing with Interlayer Cooling</td>
<td>Josephine Jost, Texas A&amp;M University</td>
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<td><strong>Session 11: Direct-writing by Micro-cold Spray</strong></td>
<td>A Versatile, Multi-mode Liquid Metal Printing Platform for Microstructural Studies</td>
<td>Kevin Firouzian, University of Southern Mississippi</td>
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**TECHNICAL SESSION GRID - MONDAY PM**
<p>| Session A |  | Session B |  | Session C |  | Session D |  | Session E |  | Session F |  | Session G |  | Session H |  | Session I |  | Session J |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Saniya Leblanc, George Washington University | Scott Thompson, Auburn University | Tavia Mayberry, Raytheon | Robert Landers, Missouri S&amp;T University | Abdalla Naouri, Applied Research Lab At Penn State | Christopher Williams, Virginia Tech | Dennis Corrigan, Rochester Institute of Technology | Chair |
| Structural Modification Induced by Laser Processing of Thermoelectric Materials: Saniya Leblanc, George Washington University | | | | | 1:30 PM | | |
| Relative Significance of Heat Loss through Radiation and Convection of Dual Energy Based Additive Manufacturing: Jie Xiong, Iowa State University | New Opportunities for Additive Manufacturing by Selective Electron Beam Melting: Christoph Wangermann, Baker Hughes, a GE Company | Measurement of Energy Transfer and Balance in Laser Induced Melting: David Deanham, National Institute of Standards and Technology | Wire Co-extrusion with Big Area Additive Manufacturing: Celeste Alexos, Oak Ridge National Laboratory | Tensile and Compression Test for Specimens Developed Using an Algorithm of Path Optimization: Apollinaire Dupas, Université d’Aix-Marseille | Improving the Strength of Additively Manufactured Concrete Structures via Intra- and Inter-layer Fiber Reinforcement: Carolina Sepulveda, University of Texas at Austin | 2:10 PM |
| Additive Manufacturing of Metallic Glasses: Challenges and Opportunities: Xiaoping Li, University of Auburn South Wales | Modeling Thermal Expansion of a Large Area Extreme Deposition Additively Manufactured Parts Using a Non-homogenized Approach: Dylan Kokkinis, University of Nebraska-Lincoln | Effects of Particle Size Distribution on Surface Roughness of Additively Manufactured Inconel 625 Channels: Scott Thompson, Korea State University | Out-of-plane Printing with Big Area Additive Manufacturing: Tyler Smith, ORAU | Impact Strength of 3D Printed Polyetheretherketone (PEEK): Hanyan Gao, Georgia Southern University | Towards a Micrometeorite Model for Fiber Composite 3D Printed Parts: Adrian Rebolleda, Arizona State University | 2:50 PM |
| A Time-efficient Analytical Model of Laser Directed Energy Deposition Process for Functionally Graded Materials Fabrication: Yuan Huang, University of Washington | A Design Method to Explicit Synergies Between Fiber Reinforcement Composites and Additively Manufactured Processes: David Ross, Georgia Institute of Technology | Characterization of Metal powder Composites for In Situ Direct Ink Writing Applications: Xiayu Wang, Lawrence Livermore National Laboratory | Large-Scale Additive Manufacturing of Concrete Using a Six-axis Robotic Arm for Autonomous Habitat Construction: Nathan Watson, The Pennsylvania State University | Characterizing the Influence of Print Parameters on Porosity and Mechanical Performance: James Brandt, University of Tennessee Knoxville | A Part-Strength Calculation Method for Additively Manufactured Parts Produced by Material Extrusion AM: Joseph DiSalvo, The Pennsylvania State University | 5:00 PM |
|--------------|----------------------------------------|--------------------------------------------|-------------------------------------------------|-------------------|------------------------------------------------|--------------------------------|--------------------------------------|
| 8:00 AM      | Chair                                   | C. Fred Higgins, Rice University           | Panos Damianou, University of Cambridge          | Brian Glenn, Lawrence Livermore National Laboratory, Inc. | Scott Graham, Pennsylvania State University | Large Kansas Grind, Penn State University | Creed - Lincoln, University of Illinois |
| 9:15 AM      | Break                                   | Break                                       | Break                                           | Break             | Break                                           | Break                          | Break |</p>
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<td>Laser Powder Bed Fusion of IN718/Inconel with Nickel Porous Marin disturbs / 10/10</td>
<td>Michael Juhasz, Missouri University of Science and Technology</td>
<td>Robert Saunders, U.S. Naval Research Laboratory</td>
<td>Nicole Allen, University of Michigan</td>
<td>Ruikai Liu, University of Waterloo</td>
<td>Scott Seibert, U.S. Naval Research Laboratory</td>
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<td>Additive Manufacturing of Aluminum Alloys by Laser Post-Processing: Cao-Kang Jiang, Missouri University of Science &amp; Technology</td>
<td>Tiffany Turner, Turner University</td>
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<td>In-situ Residual Stress Determination in Laser Powder Bed Fusion Using a Residual Stress Dynamometer: Ian Antion, Georgia Institute of Technology</td>
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<td>Bindjet 3D Printing: Opportunities and Challenges: Anti-Mottafar, Carnegie Mellon University</td>
<td>University of Waterloo</td>
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<td>Residual Stress Induced Fracture of Additive Manufactured Parts Based on Modified Inherent Strain Method: Ha Tran, University of Pittsburgh</td>
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<td>In-situ Process Monitoring: Shaw Feng, NIST</td>
<td>Bishal Silwal, Georgia Institute of Technology</td>
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**Chair:** Brett Conner, Youngstown State University

**Tech-education of Stainless Steel & Additive Manufactured Al5Si Alloy:** Shuai Zhang, Huazhong University of Science and Technology

**Manufacturing Process:** Xinyi Xiao, Carleton University

**In-situ Residual Stress Determination in Laser Powder Bed Fusion Using a Residual Stress Dynamometer:** Ian Antion, Georgia Institute of Technology

**Bindjet 3D Printing: Opportunities and Challenges:** Anti-Mottafar, Carnegie Mellon University

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**In-situ Process Monitoring:** Shaw Feng, NIST

**Bishal Silwal, Georgia Institute of Technology**
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<th>Materials: Polymers II - Powder Bed Processing</th>
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<td>Effect of Unit Cell Size on the Mechanical Performance of Additive Manufactured Lattices Structures: Akash Sahdeva, Auburn University</td>
<td>Laser Sintering of Polymeric Lattices: Ian Ho, University of Washington - Seattle</td>
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<td>9:40 AM</td>
<td>Hybrid AM: Masaaki Suzuki, University of Tokyo</td>
<td>Laser Sintering: Andreas Wörz, Institute of Polymer Technology</td>
<td>Relationship Between Powder Bed Fusion Temperature and Microstructure of Laser Sintered Polyamide 12: Tatsuo Figure, Tokyo Metallurgical Tech Research Inst</td>
<td>Additive Manufactured Stainless Steel Nanocomposites with Uniform Dispersion of Nanoparticles: Magdy El-Sayed, University of Science and Technology</td>
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<td>Hybrid AM: Masaaki Suzuki, University of Tokyo</td>
<td>Laser Sintering: Andreas Wörz, Institute of Polymer Technology</td>
<td>Effects of Layer Dependent Properties in Laser Sintering of PA22: Andreas Wörz, Institute of Polymer Technology</td>
<td>Additive Manufactured Stainless Steel Nanocomposites with Uniform Dispersion of Nanoparticles: Magdy El-Sayed, University of Science and Technology</td>
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<td>Hybrid AM: Masaaki Suzuki, University of Tokyo</td>
<td>Laser Sintering of Pine/Polyurethane Composite: Xiuhong Ren, University of Wisconsin-Platteville</td>
<td>Relationship Between Powder Bed Fusion Temperature and Microstructure of Laser Sintered Polyamide 12: Tatsuo Figure, Tokyo Metallurgical Tech Research Inst</td>
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<td>Effect of Heat Input on the Microstructure and Mechanical Properties of Magnesium Alloys Fabricated by Wire and Arc Additive Manufacturing: Huw Hsiung, K.S. Vidyasagar University</td>
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<td>The porosity and mechanical properties of W/42%Ni processed by high-speed laser metal melting: Tatsuo Nagayama, ITG Corporation</td>
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<td>The Porosity and Mechanical Properties of W/42%Ni processed by high-speed laser metal melting: Tatsuo Nagayama, ITG Corporation</td>
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<td>Path Planning for Wire and Arc Additive Manufacturing of Inconel 600: Suraj Doshi, University of Pittsburgh</td>
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<td>3D Printing of Polymers with Xenon Gas: Lincoln P. Ryan, The University of Texas at Austin</td>
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<td>The Tribological Performance of 316L Stainless Steel under Dry Friction: Goran Meyer, Imperial College London</td>
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<td>Heat Transfer Characteristics of Polymers Used in 3D-Printed Fused Deposition</td>
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<td>Xiaoqing Wang, Jacksonville State University</td>
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<td>Özgür Ethem, Arizona State University</td>
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<td>Self-powered Hydrophone with Broadband Frequency and Rationally Designed Directivity Pattern via 3D Printing Using Piezoelectric Metamaterials: Huachen Cui, Virginia Polytechnic Institute and State University</td>
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<td>Glass to Metal Seals by Additive Manufacturing: Catalina Young, Florida</td>
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<td>Mills, Clark Atlanta University</td>
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<td>Fiber Fed Laser Heated Additive Manufacturing of Glass: Pedro Mireles,</td>
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<td>304L Stainless Steel Parts Fabricated by Laser-foilprinting Process: Allen</td>
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<td>Glass Laser Additive Manufacturing Start and Stop Investigation: Cameron</td>
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<td>Assurance Criterion: Nicholas Altese, Missouri University of Science and</td>
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<td>In-Situ Ultrasonic Quality Inspection for Metallic Additive Manufacturing:</td>
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<td>Aerosol Jet Printing: Leticia Mercado, University of New Mexico</td>
<td>Adam Wachtor, Los Alamos National Laboratory</td>
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<td>Local Microstructure and Mechanical Properties Analysis of SLM 304L</td>
<td>Acoustic Monitoring for Defect Detection in Metal Powder-bed Laser Sintering:</td>
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<td>Stainless Steel: Ezekiel Buck, Missouri University of Science and Technology</td>
<td>Adam Wachtor, Los Alamos National Laboratory</td>
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Plenary

Monday AM  Room: Salon HJK
August 12, 2019  Location: Hilton Austin

Session Chair: David Rosen, Georgia Institute of Technology

8:00 AM Introductory Comments

8:15 AM Plenary
30 Years of Additive Manufacturing and the Solid Freeform Fabrication Symposium: David Bourell; ’The University of Texas at Austin

It is fitting on the 30th anniversary of the SFF Symposium to step back and consider developments in the additive manufacturing (AM) research community over the last three decades. A short description of the creation of the SFF Symposium will be presented. Its formation in the context of AM in the 1980s will be presented. Some AM highlights and milestones along the way will be reviewed.

8:45 AM Plenary
Then, Now, and What’s Ahead: Terry Wohlers; ’Wohlers Associates

Participating in the first 30+ years of the AM industry has been a privilege. The research, commercial, and government sectors have learned a lot over this period. Fortunately, only two significant downturns in revenue growth occurred. The first was during the dot-com collapse (2001-2002) and second during the Great Recession (2008-2009). It’s difficult to name another industry that has grown by nearly 27% annually, on average, over a period of three decades. For many, today’s AM industry is more interesting than its past. Currently, AM represents an extraordinary range of research projects, startup companies, and new products and services—much of which was not considered previously. The possibilities for what’s ahead are especially intriguing. To have any chance of predicting it, one must have a good grasp of the current state of AM. What we know about AM is fascinating, but what we don’t know is even more exciting.

9:15 AM Plenary
An Open-architecture Multi-laser Research Platform for Acceleration of Large-scale Additive Manufacturing (ALSAM): William Carter; Michael Tucker; Michael Mahony; David Toledano; Robert Butler; Subhrajit Roychowdhury; Abdalla Nasser; David Corbin; Mark Benedict; Adam Hicks; ’GE Research; ’Penn State; ’United States Air Force

As Powder Bed Fusion Additive Manufacturing (PBFAM) technology matures, researchers and engineers responsible for transitioning the technology from rapid prototyping into manufacturing are gaining a better understanding of the opportunities with this revolutionary technology. A step in accelerating solutions is to allow researchers complete access to all aspects of the process for experimentation. As part of an AFRL-sponsored program with America Makes, a production-grade PBFAM machine (a Concept Laser M2) will be enhanced to allow operation with either the OEM controls and scan path generation or an open-source set of software developed under prior America Makes programs. This machine will be referred to as the ALSAM Platform and will be delivered to the Air Force along with the source code for the open scan path generation software (written in C++) and the open machine controller (written in LabVIEW).

9:45 AM Plenary
Funding Opportunities for Advanced Manufacturing at the National Science Foundation: Robert Landers; ’Missouri S&T University

This presentation will provide an overview of the National Science Foundation (NSF) and funding opportunities offered by the Division of Civil, Mechanical and Manufacturing Innovation (CMMI) within its various disciplinary programs and through NSF crosscutting initiatives. There will be a discussion of new initiatives at NSF and the effect of the Engineering Directorate’s decision to remove deadlines for all unsolicited proposals. The talk will describe opportunities that are relevant to the manufacturing community, with a focus on the Advanced Manufacturing (AM) program within CMMI, including industry-relevant programs at NSF. The presentation will also describe programs targeted toward junior investigators and supplemental programs, as well as guidelines for NSF’s Intellectual Merit and Broader Impacts criteria.

10:15 AM Break

10:45 AM Plenary
Achieving More with Less: Design and Additive Manufacturing of Functionalities and Micro-architectures: Xiaoyu Zheng; Huachen Cui; Ryan Hensleigh; Desheng Yao; Chansoo Ha; Zhenpeng Xu; Ruthvik Kadam; Daniel Elkins; Amanda Wei; Michael Hemminger; Dominic LoPinto; ’Virginia Tech

Creating materials with tailorable properties are often constrained by the intrinsic material and manufacturing processes available. While additive manufacturing processes hold the promise for creating arbitrary topologies which impart material properties, they are often limited by the trade-off between the ease of processing, controllable feature size spans and processible materials. In this talk I will discuss a suite of scalable additive micro- and nano manufacturing processes for creating materials with controlled micro-architectures and functionalities. This enables the rapid production of architectural materials with feature size control over 7 orders of magnitude, unleashing the design freedom for unusual, fully tailorable mechanical properties and behaviors. Attention is focused on how additive manufacturing techniques will enable processing the unprocessable, from structural to multi-functional materials. Next, I will discuss a suite of new applications: from assembly free devices to intelligent infrastructures with time and spatially resolved energy transduction capabilities.

11:15 AM Plenary
Design for AM – The Key to the Industrialization of Additive Manufacturing: Olaf Diegel; ’University of Auckland

Many industries approach additive manufacturing (AM) as a drop-in replacement for conventional manufacturing technologies. This approach, however, does not fully utilize the unique possibilities that additive processes offer. For over thirty years, AM has been extensively used as a rapid prototyping technology. When using the technologies for manufacturing, however, it should be noted that AM does not remove all manufacturing restrictions. It, instead, replaces them with a different set of design considerations that designers must take into account if they wish to successfully use the technologies to add value to their products. Otherwise AM can easily become a slow and uneconomical way of manufacturing products or parts. It is also of great importance to understand that, despite much of the marketing hype over the past few decades, AM is not an “easy” technology that can make absolutely anything. It requires a good understanding of the different technologies and how to design for them. In fact, printing parts in metal, for example, can be downright hard, and the use of AM to manufacture metal parts should only be considered if the process truly adds value to the product. This talk attempts to impart some practical guidance on the thought process required to design parts that gain the maximum benefit from what AM can offer, and on some simple design strategies that can be utilized to drastically reduce AM part costs.
Applications: Biomedical I - Novel Processes and Properties

Monday PM  Room: 415 AB  Location: Hilton Austin
August 12, 2019

Session Chair: Guha Manogharan, Pennsylvania State University

1:30 PM  Manufacturing Process and Parameters Development for Water-atomized Zinc Powder for Selective Laser Melting Fabrication: Bryan Ruvalcaba1; Edel Arrieta1; Ryan Wicker1; Francisco Medina1; W.M. Keck Center for 3D Innovation

Biodegradability of metals is a desirable characteristic for medical implants. Metals like Fe, Mg, Zn and their alloys are usually preferred for this application, as their degradation rate has been shown to work on medical implants. The fast degradation rate of Mg may early compromise its structural performance for these components; while the slower degradation rate of Fe may also become a disadvantage. This leaves Zn’s degradation rate more suitable for this application. Vaporization temperatures make zinc a challenging material to use in conventional additive manufacturing systems. In this work, the process of developing parameters to print water-atomized zinc powder is presented. This process was performed in a commercial SLM system, implying inconveniences for a powder not optimized for AM. Optical analysis of water-atomized powder was conducted for size and shapes measurement of precursor powder. This work includes density and microstructure analysis, followed up by conclusion and remarks.

1:50 PM  Antibacterial Properties of 3D-printed Surfaces with Silver Coating: Jia Deng1; Ali Khoshkhoo1; Laura Cook1; Binghamton University

3D printing is gradually being adopted in various medical applications such as surgeries and implantations. However, infections and inflammation, caused by bacteria that may be introduced immediately after or develop later, remain a serious complication. In order to develop a surface that increases the lifetime of medical implants, factors that reduce colonization by bacteria must be considered. This paper investigates the antibacterial effects of two factors; surface patterns, and silver coating. Circular protrusions and grooves, have been designed, 3D printed, and then coated with both silver films and nanoparticles to fabricate functional substrates. To quantify the antibacterial effects, Escherichia coli and Staphylococcus aureus will be cultivated on different surface functional substrates. To quantify the antibacterial effects, Escherichia coli and Staphylococcus aureus will be cultivated on different surface functional substrates. In this work, the process of developing parameters to print water-atomized zinc powder is presented. This process was performed in a commercial SLM system, implying inconveniences for a powder not optimized for AM. Optical analysis of water-atomized powder was conducted for size and shapes measurement of precursor powder. This work includes density and microstructure analysis, followed up by conclusion and remarks.

2:00 PM  Guided Cell Migration on a Substrate with Graded Micropillars: Srikumar Krishnamoorthy1; Zhengyi Zhang1; Changle Xu1; Texas Tech University; Huazhong University of Science and Technology

Cell migration is facilitated by the interaction of living cells and the extracellular matrix (ECM). Living cells are capable to detect and respond to different ECM topographic surfaces, such as geometry and stiffness. However, the natural ECM is a complex meshwork featuring multiple scales of size and organization. A convenient approach to mimic and study the ECM topographies is to use a quasi-3D, micro-patterned surface with graded pillars. In this study, a dynamic mask photolithography technique has been utilized to fabricate a surface with graded micropillars mimicking the vivo geometry and size of large ECM fibers. It has been shown that the seeded cells are successfully guided to migrate from the sparse zone to the dense zone. Moreover, the effects of the micropillar diameter and the gradient of micropillar spacing have been investigated in terms of cell migration speed and cellular alignment.

2:30 PM  An Image-Guided Intrascaffold Cell Assembly Technique for Accurate Printing of Heterogeneous Tissue Constructs: Kevin Firouzian1; Ting Zhang1; Hefeng Zhang1; Yu Song1; Xiaolei Su1; Feng Lin1; Tsinghua University

Creating thick and heterogeneous scaffold-based tissue constructs requires deep and precise multicellular deposition, which is still a challenge using traditional seeding strategies. This study presents a novel and modular 3D intra scaffold bioassembly technique for cells and biomaterials. A series of image processing operations locate scaffold macropore centroids, which are later transformed to machine coordinates using a camera calibration algorithm. Intrascaffold assembly parameter optimization and complex structure assembly were studied. Path planning and cell assembly experiments were also demonstrated using NIH3T3- cell-laden hydrogels and collagen-coated PLGA scaffolds. CellTracker monitoring, live/dead, and phalloidin-F-actin/DAPI immunostaining showed accurate cell distribution and positioning and high cell viability (>93%). PrestoBlue assay showed obvious cell proliferation over seven culture days in vitro. Results suggest a valuable tool to facilitate direct spatial organization and hierarchical 3D assembly of cells/drugs within scaffolds for further studies and clinical applications. Acknowledgments to the National Natural Science Foundation of China (NSFC, 81571420; 31771108).

2:50 PM  A Multi-scale Computational Model to predict the performance of Cell Seeded Scaffolds with Triply Periodic Minimal Surface Geometries: Eric Lehder1; Laura Ruiz Cantu1; Ian Maskery1; Ian Ashcroft1; Ricky Wildman1; Centre for Additive Manufacturing

Bone scaffolds are required to replace the painful and dangerous process of bone grafting, currently the gold standard for treating open bone fractures. Tissue engineering scaffolds work best when there is a high amount of surface area for biological cells to attach. Triply Periodic Minimal Surface (TPMS) geometries offer high ratios of surface area per volume. However, it is not yet clear which TPMS cell type would yield the fastest bone growth rate. In this study, we used a three-dimensional multi-scale model to predict the performance of scaffolds with four TPMS unit cell types (Primitive, Gyroid, Diamond and Lidinoid). At the micro-scale, the model simulates curvature-dependent tissue growth, while at the macro-scale the model uses FEA to ensure the construct stiffness is acceptable. The Lidinoid unit cell type was found to yield the most bone growth after 40 days while also ensuring an acceptable scaffold stiffness.

3:10 PM  Break

3:40 PM  3D Printed Advanced Individualized Hearing Protection Devices for Sound Localization and Externalization Preservation: Alejandra Belmont1; Carlos Acosta Carrasco2; Vidya Krull2; Andrew Dittbrenner2; Ryan Wicker2; Department of Biomedical Engineering, The University of Texas at El Paso; 2Department of Mechanical Engineering, The University of Texas at El Paso

3D printing enables fabrication of complex objects such as the human ear. The visible part of the ear (pinna) serves as a funnel, and a natural filter for incoming sound. In an attempt to preserve spectral cues normally processed through the pinna, custom-designed hearing devices with externally located individualized pinna were fabricated. A CAD model of a standard pinna was generated using CT and 3D laser scanning. Multiple 3D printing technologies (desktop and industrial) were used to fabricate test samples, investigating different material options, dimensional accuracies, and acoustic performance. A CAD model of a hearing protection device integrated with the standard pinna to filter the incoming sound was designed, printed, and subjected to acoustic testing. Results from this work will be described, and hopefully lead to improved circumaural hearing devices with applications on the battlefield, in emergency response situations, and providing improved experiences for children with sensitive hearing.
26 2019 Annual International Solid Freeform Fabrication Symposium

Applications: General I

Monday PM  Room: 602  Location: Hilton Austin
August 12, 2019  Session Chair: Travis Mayberry, Raytheon

1:30 PM
Optimization of the Additive Manufacturing Process for Acoustic Metamaterials: Timur Mukhametkalyiev1; Matias Clasing Villanueva2; Tom Craeghs3; Claus Claeyts4; Elke Deckers5; Wim Desmet5; 1Materialise NV; 2KU Leuven, Department of Mechanical Engineering; 3Materialise A pilot-study performed at KU Leuven provided a proof-of-concept for locally resonant meta-materials manufactured with Laser Sintering (LS). However, the manufacturing process revealed a scatter on both geometrical accuracy and material parameters which overall lead to differences in resonance frequencies of the locally added resonators, also altering the predicted vibro-acoustic performance. In this work, a holistic engineering approach was used to improve the LS process of locally resonant vibro-acoustic metamaterials fabrication. It is shown that unequal energy density distribution within the printing layers is one of the main causes of such deviations. The goal of this research is to optimize the production parameters for locally resonant meta-materials made with LS to reduce the variation in vibro-acoustic behaviour of the final parts.

1:50 PM
New Opportunities for Additive Manufacturing by Selective Electron Beam Melting: Matthias Gieseke1; Anne Rathje1; Madison Burns1; Christoph Wagnerheim1; 1Baker Hughes, a GE company Selective Electron Beam Melting (SEBM) is an emerging additive manufacturing technology for metals. Although most metal parts are made using Selective Laser Melting (SLM), SEBM offers unique opportunities for specialized applications and materials. However, the use of this process in production is rare. The higher investment costs for the devices and the advanced complexity of the process compared to SLM might prevent companies from using SEBM. However, recent developments are now pushing the industrial use of this technology, and unique opportunities for additive manufacturing arise. This contribution shares experiences in using SEBM in an industrial production environment in regards to new and standard materials. After introducing the SEBM process with its opportunities and challenges, case studies are presented to show SEBM can contribute to an industrial additive manufacturing production.

2:10 PM
Influence of Contour Procedures on Surface Improvement of Additive Manufactured Components: Shaik Hoosain1; Lerato Tshabalala1; 1CSIR The current study, selective laser melting was used to investigate and generate the process for enhancing surface finish by enhancing the contour parameters during manufacturing. The Aeroswift, a custom built selective laser melting platform was used for the part building. The control parameters that were evaluated include laser power, speeds for the contours, and hatch contour spacings (hatch contour overlap) were varied for evaluation. The research aimed to recognise the critical factors in laser additive manufacturing process for reducing surface roughness. The responses analysed included density, porosity, and surface roughness using micro X-ray tomography, Archimedes, and surface profilometry for comparison. Results show that the best surface finishes are obtained using higher scan speeds. Higher spacings between the hatch and contour gave better surface finishes however at the expense of increased porosity below the surface.

4:00 PM
Surface Conditioning for Additively Manufactured Titanium Implants for Temporary Insertion in the Oral and Maxillofacial Surgery: Jakob Schneider1; Antje Petzold2; Kiriaki Papadopoulos3; Ute Botzenhart4; André Seidel5; Elena Lopez6; Frank Brueckner7; Christoph Leyens5; 1Fraunhofer IWS; 2Technical University Dresden
Especially within oral and maxillofacial areas human hard-tissue structures are featured by an extensive intra-individual variability. Hence, for an adequate osteosynthesis of bone defects or distraction osteogenesis the fitting accuracy of the implants is of essential importance. Consequently, the usage of patient specific medical devices manufactured via Additive Manufacturing technologies is highly beneficial. Within the scope of this manuscript, post processing routines for laser powder bed manufactured Ti6Al4V free form surfaces for a temporary integration in the human body were investigated. Vibratory finishing, electro and plasma polishing were indicated as appropriate technologies. Process characteristics like achievable surface roughness, dimensional changes and the influence of the surface chemistry were comparatively analyzed by tactile, optical and spectroscopic measurements. Generally, each technology enabled the adjustment of proper surface conditions for temporary implanted medical devices. However, the quantitative and qualitative appearance of the finished surfaces strongly differed between the technologies used for post processing.

4:20 PM
Selective Laser Melted Functionally Graded Biodegradable Porous Iron: Yageong Li1; Holger Jahn2; Prathyusha Pavanram3; Françoise Bobbert1; Umberto Puggi4; Xiangyu Zhang5; Behdad Pouran6; Marius Leeflang7; Harrie Weinans5; Jie Zhou8; Amir Zadpoor9; 1Deft University of Technology; 2University Hospital RWTH Aachen; 3D Systems - LayerWise NV; 4Tsinghua University; 5University Medical Center Utrecht
Selective laser melted (SLM) biodegradable topologically ordered porous iron has just appeared recently. However, the highly ordered micro-architecture is not consistent with highly graded human bone structure and thus may not meet the contradictory requirements of high permeability and mechanical strength at the same time. Here, we directly printed functionally graded biodegradable porous iron using SLM and aim to evaluate the biodegradation behaviour, permeability, and mechanical behaviour of functionally graded specimens by using both computational and experimental approaches. Consequently, the topological design could control the biodegradation behavior of AM porous iron scaffolds. Our results suggest that topological design in general and functional gradients in particular can be used as an effective tool for adjusting the biodegradation behavior of AM porous metallic biomaterials, while the mechanical property of porous iron are kept in the range of values reported for trabecular bone.

4:40 PM
Design and Development of Low-cost Prosthetic Hand Using Additive Manufacturing with Arduino Control: Santosh Kumar Malvaya1; Akshay Simha1; 1Acharya Institute of Technology
Additive Manufacturing (AM) is one of the latest and customized manufacturing processes, which is best suitable in case of custom Prosthetics. The aim of current work is to analyze the four versions of prosthetic hands and to identify the best one. Till today there are many AM prosthetic hands are readily available in open source, but most of them does not have any electronics included or works on mechanical moment. In the current work the moment of fingers are provided through DC motors and Servo motors, which are controlled by ARDUINO UNO microcontroller which is a budget-oriented microcontroller. The major features of the prosthetic hand is to control it through muscle sensor or with audio commands. The best version of prosthetic hand is customized according to the amputated person. The cost of developed prosthetic hand is less than hundred dollars and provides almost all basic functionalities of normal hand.

Session Chair:
August 12, 2019  Room: 202  Location: Hilton Austin

4:00 PM
Influence of Contour Procedures on Surface Improvement of Additive Manufactured Components: Shaik Hoosain1; Lerato Tshabalala1; 1CSIR
In the current study, selective laser melting was used to investigate and generate the process for enhancing surface finish by enhancing the contour parameters during manufacturing. The Aeroswift, a custom built selective laser melting platform was used for the part building. The control parameters that were evaluated include laser power, speeds for the contours, and hatch contour spacings (hatch contour overlap) were varied for evaluation. The research aimed to recognise the critical factors in laser additive manufacturing process for reducing surface roughness. The responses analysed included density, porosity, and surface roughness using micro X-ray tomography, Archimedes, and surface profilometry for comparison. Results show that the best surface finishes are obtained using higher scan speeds. Higher spacings between the hatch and contour gave better surface finishes however at the expense of increased porosity below the surface.
Effects of Particle Size Distribution on Surface Finish of Selective Laser Melting Parts: Jia Hao Lim; 1Advanced Remanufacturing and Technology Centre

Metal parts produced by Selective Laser Melting (SLM) usually exhibits poor surface finish compared to conventional manufacturing processes. There is a growing need for parts to have good surface quality in the as-built condition to minimize post-processing costs and reduce lead time. There are many studies done on the effects of processing parameters on surface finish but very little on the influence of powder characteristics. This study aims to investigate the effects of Particle Size Distribution (PSD) on surface finish of AM parts by printing coupons with Inconel 625 powders of varying PSD. It was found that roughness of internal surfaces were mainly caused by the presence of partially sintered particles. Whilst a smaller particle mean size and wider particle size range are preferred for better surface finish, a powder that is too fine may result in poor flowability affecting its processibility in terms of layering and powder bed quality.

2:50 PM
Effects of Chemical Polishing on Surface Roughness of Additively Manufactured Inconel 625 Channels: Zane Oligee1; Scott Thompson2; Bart Prorok1; 1Auburn University; 2Kansas State University

Chemical polishing, or ‘chempolishing’, can be an effective means for reducing the surface roughness of additively manufactured (AM) metallic parts. Via chempolishing, a heated solvent dissolves ‘overgrown’ surfaces within/along a submerged part for achieving better surface roughness and tolerances. Chempolishing can be used to reduce the roughness of hard-to-reach channels embedded within AM parts which cannot be easily polished — and this is important for realizing next-generation, compact heat exchangers fabricated via AM. In this work, experiments are performed to determine the effectiveness of chempolishing for smoothing long internal, mini-channels and micro-channels with internal bends/ellbows. Inconel 625 specimens with various channel cross-sections and lengths were fabricated using the laser-powder bed fusion (L-PBF) AM method. All pre/post-treated surfaces were inspected using scanning electron microscopy for quantifying surface roughnesses. Experimental results provide appropriate flow rates and submersion times for effectively smoothening various-sized L-PBF Inconel 625 channels.

3:10 PM Break

3:40 PM
Effect of Position and Orientation on Surface Topography in Laser Powder Bed Fusion of Nickel Superalloy 625: Jason Fox1; Saadat Razvi1; 1National Institute of Standards and Technology

As parts built through additive manufacturing (AM) increase in complexity, a strong understanding of the effect the as-built surface has on performance will be required. Currently, however, limited correlations between the as-build AM surface finish and part performance exist. This scarcity may stem not only from the complex AM build process, which leads to difficulty in isolating surface finish as a variable in functional correlation studies, but also from an inadequate consideration of surface characterization methods. In this work, a set of artifacts was built using a commercially available laser powder bed fusion system in nickel superalloy 625. From these artifacts, 648 unique surfaces were measured using a focus variation microscope. Surface height data was then characterized using the areal parameters and advanced filtering techniques available in the ISO and ASME standards and machine learning techniques were applied to identify correlations to surface position and orientation within the build chamber.

4:00 PM
An Automated Method for Geometrical Surface Characterization for Fatigue Analysis of Additive Manufactured Parts: Behnam Rasoolian1; Jonathan Pegues2; Nima Shamsaei1; Daniel Silva1; 1Auburn University

Additive manufacturing is becoming a popular fabrication technique for effectively smoothening various-sized L-PBF Inconel 625 channels. Experimental results provide appropriate flow rates and submersion times for effectively smoothening various-sized L-PBF Inconel 625 channels.

4:20 PM
Replicate, Adapt, Optimize: A Crawl, Walk, Run Approach to Design for Additive Manufacturing: Tim Simpson1; 1Penn State University

A pattern is emerging among companies adopting metal-based additive manufacturing (AM). In the first stage, they use AM to replicate an existing part to understand the technology's costs and capabilities. This starts to give them insight into the process and helps them transition into the second stage wherein they adapt their designs for AM to reap more of its benefits—leveraging the design and material freedoms that AM affords. Finally, companies will shift to optimizing for AM as they gain confidence in the process while learning how to capitalize on AM to its full potential. These three stages provide a crawl, walk, run approach to design for AM, but only if expectations are carefully managed at each stage. Automotive, aerospace, and consumer product examples from Penn State's Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D) are presented to illustrate the benefits and drawbacks of each stage.

4:40 PM
A Design Method to Exploit Synergies Between Fiber-Reinforce Composites and Additive Manufactured Processes: David Rosen1; Vahid Hassani2; Ethan Goh3; Sufiyen Sarwan4; Florian Doetzer1; 1Georgia Institute of Technology; 2University of Exeter; 3Composites Cluster Singapore

This paper proposes a design method for devices composed of long fiber-reinforced composites (FRC) and additive manufactured (AM) parts. Both FRC and AM processes have similar application characteristics: suitable for small production volumes, additive in nature, and capable of being highly automated. On the other hand, the classes have distinct characteristics. FRC components tend to be large with simple shapes, while AM components tend to be small with highly complex geometry. Their combination has the potential for significant synergies, while mitigating their individual limitations. A decision guide is proposed, in the form of a series of questions, to guide the designer to determine if their application is a good candidate for FRC-AM. The decision guide is reformulated into a proposed design process that guides the designer to advantageously benefit from AM and FRC characteristics. The tools are illustrated with an example of a composite pressure vessel with integrated pressure reducer.
Applications: Lattices and Cellular I - Mechanical Properties

Monday PM  Room: 410  Location: Hilton Austin

Session Chair: Albert To, University of Pittsburgh

1:30 PM  
Compressive and Bending Performance of Selectively Laser Melted AlSi10Mg Structures: David Murphy1; Okamisope Fashani2; Myranda Spratt1; Joseph Newkirk1; K Chandrashekhara1; Heath Misak1; Daniel Klenosky1; 1Missouri University of Science and Technology; 2Spirit AeroSystems  
Cellular structures are commonly used as structural support in lightweight structures. Selective laser melting (SLM) is a widely used additive manufacturing technique that effectively manufactures these structures. However, challenges such as anisotropy and mechanical property variation are commonly found due to process parameters. In a bid to utilize this method for the commercial production of cellular structures, it is important to understand the behavior of a material under different loading conditions. In this work, the behavior of additively manufactured AlSi10Mg is investigated in compression and bending. Compression and bending specimens were manufactured using a Renishaw AM 250 SLM machine. Process parameter effects on the mechanical performance of AlSi10Mg are reported.

1:50 PM  
Influence of the Process Parameters and Feature Geometries on Material Characteristics of Ti-6Al-4V Thin Strut Features Fabricated by Laser Powder Bed Fusion Additive Manufacturing: Shanshan Zhang1; Li Yang1; 1University of Louisville  
Lightweight cellular structures with thin strut features fabricated by laser powder bed fusion (LPBF) additive manufacturing exhibit unique material properties that are yet not well understood. This work investigated the material characteristics of Ti-6Al-4V thin strut features fabricated by LPBF-AM under different process parameters and geometry design conditions. The objective was to identify potential effects of feature dimensions on the material characteristics of structured manufactured by LPBF-AM. Through the investigation on the porosity, microstructure, and microhardness of features of various dimensions, it was found that the process-material characteristics of the thin features are significantly different from the bulk features, and exhibit significant dependency on not only the process parameters but also strut dimensions and orientations.
A Computational and Experimental Investigation into Mechanical Characterizations of Strut-based Lattice Structures: Mohammad Reza Vaziri Sereshk1; Kevin Triplett1; Christopher St. John1; Keith Martin1; Shira Gorin1; Alec Avery1; Eric Byer2; Conner St Pierre2; Arash Soltani-Tehrani1; Nima Shamsaei1; 1National Center for Additive Manufacturing Excellence; 2Auburn University

Strut-based lattices are widely used in structural components for lightweighting. Additive manufacturing has provided a unique opportunity to fabricate such complex geometries. In addition to the unit cell type, the strut size and shape can significantly affect the mechanical properties achieved. Therefore, furnishing a lattice structure library may help in selecting appropriate combination of lattice types and dimensions for a targeted mechanical performance for a particular application. This study presents a method for determination of mechanical properties, including strength and stiffness, for lattice structures. Finite element (FE) simulations are used as the main tool and the results of which are to be verified by mechanical testing of samples fabricated using the laser beam powder bed fusion (LB-PBF) process. The proposed procedure can be used for other unit cells of interest due to its generality.

The Effect of Cell Size and Surface Roughness on the Compressive Properties of ABS Lattice Structures Fabricated by Fused Deposition Modeling: Leah Mason1; Ming Leu1; 1Missouri University of Science and Technology

Researchers looking to improve the surface roughness of acrylonitrile butadiene styrene (ABS) parts fabricated by fused deposition modeling (FDM) have determined that acetone smoothing not only achieves improved surface roughness but increases compressive strength as well. However, the sensitivity of ABS parts to acetone smoothing has not been explored. In this study we investigated FDM-fabricated ABS lattice structures of various cell sizes subjected to cold acetone vapor smoothing to determine the combined effect of cell size and acetone smoothing on the compressive properties of the lattice structures. The acetone-smoothed specimens performed better than the as-built specimens in both compression modulus and maximum load, and there was a decrease in those compressive properties with decreasing cell size. The difference between as-built and acetone-smoothed specimens was found to increase with decreasing cell size for the maximum load.

An Investigation into the Stiffness Response of Lattice Shapes under Various Loading Conditions: Raghav Sharma1; D Bhat1; 1Arizona State University

One of the fundamental aspects of cellular material design for maximizing stiffness-to-weight ratios is cell shape selection. Of particular interest is how this selection can be made in the context of a realistic three-dimensional structure. Towards this goal, this work studied the stiffness response of periodic and stochastic lattice structures for the loading conditions of bending, torsion and tension/compression using commercially available lattice design optimization software. The goal of this computational study was to identify a ranking order for enabling cell selection. A study of stochastic shapes with different seeds was also performed. Experimental compression testing was also performed to validate a sample space of the simulations as well as study the failure modes of the lattices. The findings of this study suggest that under certain circumstances, stochastic shapes have the potential to generate the highest stiffness-to-weight ratio in the test environments considered.

Materials: Ceramics, Glasses, Other I

Monday PM
August 12, 2019
Room: Salon A
Location: Hilton Austin

Session Chair: Saniya Leblanc, George Washington University

Structural Modification Induced by Laser Processing of Thermoelectric Materials: Haidong Zhang1; Ryan Welch1; Saniya Leblanc1; 1George Washington University

Thermoelectric materials convert thermal energy to electrical energy (and vice versa) in solid state. They can be used for thermometry, localized heat pumping, and power generation. Our prior work demonstrated results for laser powder bed fusion of semiconductor thermoelectric materials (bismuth telluride, zirconium nickel stannide, and magnesium silicide). The temperature-dependent electrical transport properties and Seebeck coefficient were characterized from room temperature to 500°C, and the results showed variation in transport properties when the material is laser processed versus traditional hot pressing. In this work, we report on the structural modifications induced by laser processing which give rise to the varied carrier transport behavior. Using electron microscopy, X-ray diffraction, and Raman spectroscopy, we investigate both microstructure and phase to find the structural heterogeneity which impacts carrier transport. The results provide a fundamental understanding of the relationship between laser processing, microstructure, and carrier transport properties for both doped and undoped bismuth telluride.

Exploring the Process Structure Relationship for Laser Powder Bed Fusion of Bismuth Telluride: Ryan Welch1; Saniya Leblanc1; 1George Washington University

Thermoelectric devices are used in waste heat recovery and thermal management applications. The manufacturing methods currently used are labor intensive which restricts their widespread use in society. To address this issue, laser powder bed fusion, an additive manufacturing technique, is being used to determine the process-structure relationship between laser processing and thermoelectric materials. In this experiment, laser powder bed fusion is applied to create ingots of n and p-type bismuth telluride. After laser processing, the micro- and meso-structure was analyzed using optical and scanning electron microscopy. The grain structure and layer interfaces were observed to determine the relationship between processing parameters and processed material. The Seebeck coefficient of the processed material was also determined and compared to traditionally manufactured bismuth telluride. The results show the relationship between the selected laser parameters and the micro- and meso-scale structure of the processed material.
2:10 PM  
Rapid Stereolithography of Polymer-derived SiCN Ceramics: Li Wang; 1Xi’an Jiaotong University/National Institute Corporation of Additive Manufacturing

2:30 PM  
Additive Manufacturing of Metallic Glasses: Challenges and Opportunities: Xiaopeng Li; 1University of New South Wales

Bulk metallic glasses (BMGs) are important multi-component alloys with novel microstructures and unique physical and chemical properties which make them promising for applications in many industries, e.g., aerospace, energy, healthcare and etc. However, certain hindrances have been identified in the fabrication of BMGs by conventional techniques due to the intrinsic requirements of BMGs. With the advent of metal additive manufacturing such as laser powder-bed fusion (LPBF) techniques, new opportunities have been perceived to fabricate geometrically complex BMGs with tailorable microstructure theoretically at any site within the specimen, which are difficult to achieve using conventional fabrication techniques. After providing some background and introducing the conventional fabrication techniques for various BMGs, this presentation will focus on the current status, development, and challenges in metal additive manufacturing of BMGs including different additive manufacturing techniques being used, microstructure design and evolution, as well as properties of the fabricated BMGs. A few successful and pioneering examples will be given and discussed. A future outlook of metal additive manufacturing of BMGs will also be provided at the end.

2:50 PM  
Study on the Formability, Microstructures and Mechanical Properties of AlCrCuFeNiX High-entropy Alloys Prepared by Selective Laser Melting: Shuncun Luo; Zemin Wang; Xiaoyan Zeng; 1Huazhong University of Science and Technology

Preparing dual-phase high-entropy alloys (DP-HEAs) through selective laser melting (SLM) has hardly been achieved owing to easy cracking induced by rapid solidification. Here we reasonably design new DP-HEAs specific to SLM according to HEA definition and solid solutions formation criterion. Results show that Ni addition favors the formation of FCC phase and facilitates the columnar-to-equiaxed transition, thus improving the formability of AlCrCuFeNiX (2.0 = x = 3.0) HEAs. The SLMed AlCrCuFeNi3.0 HEA exhibits remarkably heterogeneous microstructures, such as modulated nanoscale lamellar or cellular dual-phase structures, and possesses the best combination of ultimate tensile strength (~ 957 MPa) and ductility (~ 14.3%). Also, high densities of Cr-enriched nano-precipitates embedded in the ordered BCC(B2) phase are discovered. Finally, the underlying strengthening mechanisms are analyzed for the SLMed AlCrCuFeNi3.0 HEA. This study demonstrates the potential of additive manufacturing technology to develop FCC + BCC DP-HEAs with excellent performance for engineering application.

3:10 PM  
Break

3:40 PM  
Towards Volumetric Manufacturing of Ceramics via Microwave Holography: Athanasios Ilipoulos; John Michopoulos; Edward Gorzkowski; Benjamin Graber; Benjamin Rock; Eric Patterson; John Steuben; Luke Johnson; Andrew Birnbaum; 1U.S. Naval Research Laboratory

The increased interest in efficient and scalable manufacturing and processing methods has motivated the development of novel volumetric additive manufacturing techniques. Examples include mass accretion via resistive thermal fields and volumetric polymerization through light tomography. In order to extend the volumetric additive manufacturing concept to ceramics and to address certain issues associated with these techniques, we describe a volumetric manufacturing methodology that uses microwave beam shaping via the utilization of holographic principles. The basic principles of volumetric manufacturing will be presented first, followed by the underlying theoretical multiphysics considerations and associated models that demonstrate the feasibility of such approaches. We also present initial experimental results demonstrating the feasibility of using high energy microwave beams for the volumetric sintering of ceramic powders such as yttria-stabilized zirconia and barium titanate.

4:00 PM  
A Practical Approach to Determine Optimal Heat Treatment Conditions for Additively Manufactured Parts: Hossein Sheykh-Poor; Youssf Gaber; Jono Munday; 1Renishaw PLC

LPBF of a wide range of materials are increasingly being adopted by industry following a decade of process development, but in most cases subsequent heat treatments are inherited from standards for wrought / cast materials which have a different microstructure. This work addresses a pragmatic approach to identify optimal heat treatments which are driven by the required mechanical performance of the target application, specific to additively manufactured parts. A statistical model was built using tensile testing data which enabled the prediction of heat treatment conditions that can achieve specific strength or ductility levels with reasonable accuracy. This approach allows for achieving the required mechanical performance while considering heat treatment costs and commercially available equipment.

4:20 PM  
Extrusion-based 3D Printing of Biomass Materials for Construction: Abhinav Bhardwaj; Zhijian Pei; Na Zou; 1Texas A&M University

The construction industry is responsible for 40 % of annual global energy consumption and 30 % of energy related greenhouse gas emissions. 0.8 tons of CO2 is released for every ton of cement produced. The emergence of a new class of biomass-based building materials can help address these issues. These new materials use domestic agricultural waste products (such as corn stalks) and fungal and bacterium species to grow new cells (mycelia). These new cells act as resin to join the raw materials together into biomass-based composite building materials. Currently, molding is used to manufacture building blocks of various shapes using these materials. In this study, experiments are conducted to reveal the effects of printing parameters (such as print speed) and material compositions on the extrudability of biomass-based materials.
Thermal Analysis of Thermoplastic Materials Filled with Chopped Fiber for Large Area Printing: Kazi Md Masum Billah1; Fernando Rodriguez Lorenzana1; Ryan Wicker1; David Espalin1; 1University of Texas El Paso

Material extrusion in the context of large area fabrication requires thermally stable materials because of extrusion at room temperature and as such fillers are included to tailor the thermal behavior. This research investigated the thermophysical properties of ABS filled with chopped carbon fiber (CF) and glass fiber (GF). Thermogravimetric analysis, differential scanning calorimetry, and dynamic mechanical analysis were carried out to determine the thermophysical properties. The addition of CF (20 and 40 wt. %) and GF (20 wt. %) to an ABS matrix showed the glass transition temperature and thermal conductivity shifted with the variation of fiber content. Improvement of the thermal conductivity (ABS/CF) reduced the 1% decomposition onset temperature (DOT) while the ABS/GF increased the DOT (from 256 to 260° C). The dataset from the thermal analysis can be used to design optimized printing parameters for highly filled thermoplastics used in large area 3D printing machines.

Improving the Strength of Additively Manufactured Concrete Structures via Intra and Inter-layer Fiber Reinforcement: Ademola Oridate1; Oliver Uitz1; Aleem Ali1; Carolyn Seepersad2; Mitch Pryor1; Patricia Clayton1; 1University of Texas at Austin

Additive manufacturing of concrete structures (via an extrusion-based process) enables the construction of structures with more complex geometries than a traditional (casting) process would allow. Engineers and designers can take advantage of this possibility to design structures with more appealing aesthetics or better optimized for strength, thermal insulation and other desired properties while minimizing material use and weight. However, this process poses a number of challenges due to layering effects. One such challenge is the compromise in strength of structures due to insufficient reinforcement and inter-layer adhesion. This research seeks to minimize this effect by exploring the use of fibers as inclusions in the concrete mix and as reinforcement between layers. Both metal and polymer fibers are considered in this study. Four-point bending tests are used to test the flexural strength of specimens with and without reinforcement. Results show the fiber reinforcement contributed to significant increase in flexural strength of the specimens.

Nonlinear Model Predictive Control of UV-induced Curing Process of Thick Composite Parts: Shiferaw Beyene1; Ankit Agarwal1; Bhavya Arora1; Abhay Gahlot1; Immanuella Kankam1; Dhruv Bhate1; 1Arizona State University

In this paper, a nonlinear model predictive control (NMPC) of UV-induced curing process for manufacturing of thick composite parts is proposed. The process involves coupled PDE-ODE equations. First, the optimal curing time is determined from offline open-loop optimal control with the objective of uniform final cure distribution with constant UV input. Once the temperature trajectory and optimal cure time are found, the NMPC is implemented for online control. The optimal temperature profile then is taken as a reference for online NMPC control. To demonstrate the effectiveness of the proposed approach a 5 mm thick fiber-reinforced matrix is considered and results show a very good agreement between the temperature of the reference and NMPC.
fracture behavior. The influence of geometry and porosity on mechanical performance and fracture location are also explored and reported.

1:50 PM

Metallurgical and Mechanical Characterizations of AINSI 316L Parts Produced by WAAM and LWAM: Christophe Voitzi; Michel Déméssy; 'Cea

In the additive manufacturing fields the multi-layered wire deposit technologies have a particular place. These techniques can produce large low-cost large parts with average complexity and near 100% of the wire feedstock is used in the parts. We are interested in elaborating AINSI 316L stainless steel AM large parts using both wire arc additive manufacturing (WAAM) and laser wire additive manufacturing technics (LWAM). In order to evaluate these techniques, samples are machined from thick parts and walls. We present the results of metallurgical and mechanical characterization. We notice some different microstructural behavior relative to solidification microstructures, hardness measurements and ferrite content. In complement, investigations have been conducted with electron backscatter diffraction and dispersive energy spectrometry in order to explain such behaviors. To conclude, these results are discussed in terms of energy deposit for these two manufacturing techniques.

2:10 PM

Effect of Build Platform Preheating on Microstructure and Mechanical Properties of LB-PBF 316L Stainless Steel: Pooriya Dastanjary Nezhadfar1; Arash Soltani-Tehrani1; Nima Shamsaei1; 'Auburn University

This study aims to understand the effect of build platform preheating on the microstructural features and mechanical properties of 316L stainless steel (SS) fabricated via laser beam powder bed fusion (LB-PBF) process. Two sets of specimens were fabricated on a non-preheated build platform and the build platform preheated to 150 °C. Thermal simulations are carried out using ANSYS using additive manufacturing module to investigate the variation in thermal history experienced by the specimens in each condition. Microstructural features are analyzed via simulation, and the results are validated experimentally. In addition, the effect of preheating on the porosity size and distribution is evaluated using microscopy. Mechanical properties of specimens from each condition are further assessed and correlated to the variations in microstructure and defect size distributions.

2:30 PM

Characterisation of Austenitic 316Lsi Stainless Steel Produced by Wire Arc Additive Manufacturing with Interlayer Cooling: Chloe Cunningham; Jie Wang1; Vimal Dhokia1; Alborz Shokrani1; Stephen Newman1; 'University of Bath

Wire arc additive manufacturing (WAAM) expands the possibilities of cost effectively producing large-scale, complex metal objects at high deposition rates. However, the variation in the WAAM process parameters is not well understood, despite greatly affecting the materials properties, part functionality and the economics of WAAM production. Austenitic stainless steel is a commonly used material and has many applications in the marine and nuclear industry due to its high toughness and corrosion resistance. In this research, the effects of the interpass temperature and heat input process parameters on WAAM of austenitic AISI 316Lsi stainless steel are experimentally analysed and evaluated. It was found that the heat input and interpass temperature influences the cellular/ dendritic morphology and the formation of macro-scale grains within the microstructure. Additionally, use of higher heat input, resulted in a 28.7% improvement in average Young’s modulus compared to lower heat input, although this remained lower than provided by wrought annealed material.
Effects of Spatial Energy Distribution on Defects and Fracture of LPBF 316L Stainless Steel: Elliott Jost; John Miers; David Moore; Christopher Saldana; *Georgia Institute of Technology; **Sandia National Laboratories

Measures of energy input and spatial energy distribution during laser powder bed fusion additive manufacturing have significant implications for the build quality of parts, specifically relating to processing defect morphology and formation. In this study, scanning electron microscopy was leveraged to investigate the effects of these distributions on the mechanical response of parts manufactured using laser powder bed fusion as seen through the fracture surfaces resulting from uniaxial tensile testing. Variation in spatial energy density is shown to manifest in differences in defect morphology. Computed tomography and scanning electron microscopy inspections revealed significant evidence of porosity acting as failure mechanisms in printed parts. The results of this study contribute to the ability to safely implement and reliably manufacture 316L stainless steel components through an improved understanding of the effects of spatial energy distributions on mechanical performance.

How AM Parts Fail: Influence of Build Orientation and Post Machining: Michael Heiden; Dan Tung; David Saiz; Bradley Jared; *Sandia National Laboratories

Metal additive manufacturing (AM) tends to generate parts with extreme surface roughness and waviness, which can negatively influence its mechanical performance. In this study, electrical discharge machining (wire-EDM) was used to cut tensile samples out of blocks of 316L stainless steel, printed using laser-powder bed fusion (L-PBF). This significantly reduced surface microcracks, surface roughness, and increased strength. Another aspect investigated was how build orientation coupled with wire-EDM plays a role in the mechanical properties. This talk will discuss how the mechanisms of AM failure change when AM material is wire-EDMed. To support this, the fractography, grain size, EBSD texture, and hardness of these parts will all be presented. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Selective Laser Melted 316L Stainless Steel Processing and Microstructure Effects on Local and Bulk Thermal Conductivity: Jacob Simmons; Xiaobo Chen; Arad Aziz; Matthias Daemeler; Peter Zavali; Guangwen Zhou; Scott Schifres; SUNY Binghamton

The thermal conductivity of 316L stainless steel produced using selective laser melting with a varying laser scan rate is investigated in bulk via flash diffusivity and at the microscale via frequency-domain thermoreflectance mapping. A critical energy density was observed, below which the porosity started to rapidly increase and thermal conductivity reduced. The thermal conductivity trend versus porosity is not fully explained by porosity according to effective medium models. We identify amorphous inclusions in the selective laser melted stainless steel, which link to the lower than expected thermal conductivity. We identify the amorphous inclusions via tunneling electron microscopy, as well as a reduction in x-ray diffraction peak intensity. The thermal conductivity along the layers was also found to be higher than the conductivity through the layers when the energy density was reduced below a critical value due to thermal resistance between build layers.

Stress Corrosion Cracking of an Additively Manufactured Austenitic Stainless Steel: Jonathan Pegues; Michael Roach; R. Williamson; Nima Shamsaie; *Auburn University; **University of Mississippi Medical School

Additive manufacturing (AM) is becoming a more viable manufacturing process in the biomedical, aerospace, nuclear, and defense sectors as a means to fabricate near net shaped parts on demand. Austenitic stainless steels are gaining attention for AM of products for these applications due to their ease of fabrication, excellent corrosion resistance, and superior toughness. The performance of these alloys fabricated by AM techniques such as laser beam powder bed fusion has not been yet fully established. This research compares the microstructural characteristics and tensile stress corrosion cracking (SCC) of 316L stainless steel in dry nitrogen, distilled H2O, and salt water. One-way ANOVA analyses were used to determine significant differences in percent elongation or reduction of area between wrought and AM specimens as a function of test environment. Two-way ANOVA analyses were also utilized to determine if significant interaction effects between test environment and test temperature were shown for these specimens.
Influence of Build Temperature on LBM of Tungsten: Jakob Fischer; Very Jüchter; Andreas Bauereiss; Heraeus Additive Manufacturing GmbH

Additive manufacturing is a promising approach to realize complex parts of refractory metals. Typical properties of these materials are a high melting point and a high thermal conductivity, thus they are hard to process by conventional manufacturing techniques. E.g. tungsten requires a high energy input when using LBM as a 3d printing technology to realize functional parts. Due to the brittle material behaviour of tungsten at low temperatures, the high thermal gradients in the LBM process typically lead to cracks and deformation. To overcome these problems one approach is to use a higher build temperature during the LBM process by heating the substrate. As a negative side effect, tungsten increasingly absorbs oxygen at higher temperatures. The following paper investigates the influence of higher preheating temperatures on the density and crack formation of tungsten specimens. Furthermore, the oxygen content of the parts with higher preheating temperatures will be analyzed and discussed.

2:50 PM
A Study of Pore Formation During Single Layer and Multiple Layer Build by Selective Laser Melting: Subin Shrestha; Thomas Starr; Kevin Chou; University of Louisville

In this study, different hatch spacings were used to fabricate single layer and multiple layers, and its effect on porosity was investigated by using microcomputed tomography. The combination of laser power (100 W, 150 W, 175 W, and 195W) and scan speeds (600 mm/s, 800 mm/s, 1000 mm/s and 1200 mm/s) which resulted in the least number of pores were selected from the previous single-track experiment. Six levels of hatch spacings were selected based on the track width to form single and multiple layers: 60%, 70%, 80%, 90%, 120% and 150% of track widths. For the multilayer build, the variation in keyhole porosity within the given window of parameters were found to be attributed to the variation in the hatch spacing. In general, the pore number decreased with increase in hatch spacing from 60% to 90% but increased when hatch spacing further increased from 90% to 120%.

3:10 PM Break

3:40 PM
High-throughput Screening of Composite Formulations for Metal Additive Manufacturing by Combining Inkjet Printing with Point-wise Laser Melting: Bethany Lettieri; Jiyun Kang; Ryan Penny; Daniel Oropeza; Davig Griggs; C.Cem Tasan; A. John Hart; Department of Mechanical Engineering and Laboratory for Manufacturing and Productivity, Massachusetts Institute of Technology; Department of Materials Science and Engineering, Massachusetts Institute of Technology

Optimization of the selective laser melting (SLM) process is typically an exhaustive endeavor, especially when seeking to understand the relationship between a particular alloy composition, process parameters, and microstructure-determined mechanical properties. Here, we present a high-throughput strategy to screen composite material formulations for use in SLM. Gradient substrates are produced by inkjet printing of an additive onto a plate or a powder layer. Then, point-wise laser melting is performed, locally varying the power and dwell time. Each spot is then characterized ex situ by scanning electron microscopy (morphology), electron backscatter detection (microstructure), and indentation (hardness and modulus). Selected results from point-wise experiments are correlated to linear melt tracks, and finally to overlapping melt tracks representative of three-dimensional build conditions. To conclude, we discuss the suitability of to ultimately achieve gradient composition control in metal AM.

4:00 PM
Paste-based 3D Printing of Metallic Materials: Effect of Binders and Precursor Sizes: Richa Agrawal; Farsal Anantichaisilp; Gabriel Supe; Joaquin Tirano; Hugo Ramirez; Claudia Luhrs; Naval Postgraduate School; Universidad Nacional de Colombia

This work proposes a three-step approach toward 3D printing of metallic materials: (i) synthesis of a paste containing metal precursor powders and organic binders, (ii) layer-by-layer deposition of the pastes based on a computer-aided-design file, and (iii) post-processing aimed at removing the sacrificial binder and sintering the metallic particles. Two organic binders consisting of (i) paraffin and (ii) alcohol based gels were studied. The decomposition of the pastes was investigated using thermogravimetric analysis and compared with commercial metal-polymer specimens. The gel binder was found to be the most effective medium as it evaporated cleanly without altering the sample composition. Rheological analyses revealed that the nano-sized metallic particles in gel media behaved as shear thinning fluids as compared to micro-particles that provided adequate paste flow. Upon identification of the best suited metal particulate sizes and binder formulations, the 3D printed samples were thermally processed and characterized using XRD, SEM, and EDS.
4:20 PM Dimensional Analysis of Metal Powder Infused Filament - Low Cost Metal 3D Printing: Shane Terry; Ismail Fidan; Khalid Tantawi; 1Tennessee Technological University; 2Mottow State Community College

The process of Additive Manufacturing is the newest form of fabrication with the primary method being 3D printing. The most common form of 3D printing is Fused deposition Modeling (FDM) where material is sequentially deposited to produce a customized part. When compared to subtractive manufacturing the production of waste is greatly reduced. This method of additive production has troubles with widespread adoption due to an inability to produce metallic parts with strong mechanical properties. This article presents an analysis on a low-cost metal fabrication technique for FDM printing. By printing a PolyLactic Acid (PLA) metal powder composite filament, a part can be printed with approximately 90% metal composition and sintered. This sintering process removes the PLA bonding resulting in a 100% metal part fabricated on a FDM printer. This study provides the preliminary mechanical property results in the comparison of PLA, Acrylonitrile Butadiene Styrene (ABS), and traditionally metal fabricated parts.

4:40 PM A Versatile, Multi-mode Liquid Metal Printing Platform for Microstructural Studies: Nicholas Watkins; Victor Beck; Vaakov Idell; Ava Ashby; Andrew Pascall; Jason Jeffries; Lawrence Livermore National Laboratory

We have developed a versatile molten metal printer to understand the dynamics of metal droplet generation and the process-structure-properties relationship in metal jetting additive manufacturing. The pneumatically-actuated print head has the flexibility to operate in different printing modes based on application needs. In droplet on demand (DoD) mode, we can precisely deposit nanoliter volumes of tin with each discrete pulse. For high build rate needs, this tool may operate in the jetting regime under constant pressure, creating similarly-sized droplets with higher mass deposition rates. The constant pressure mode may also be used to extrude metal filaments under different ambient conditions. We compare the effects of printing mode on the resultant microstructure and properties. In addition, high speed imaging of droplet ejection is used to validate computational process models. Prepared by LLNL under Contract DE-AC52-07NA27344.

5:00 PM Using Machine Learning to Guide Alloy Design and Compatibility with Directed Energy Deposition: Jose Loi; Yining He; Amish Chovatiya; Bryan Webler; Zachary Ulissi; Jack Beuth; Maarten De Boer; Carnegie Mellon University

Multiple principle element alloys (MPEAs) are exceptional in wear resistance, creep resistance, and high temperature oxidation resistance. The development of new alloys is daunting due to the vast number of possible compositions. To narrow the composition space, CALPHAD and Bayesian optimization are used to predict candidate MPEAs. Initially, this process has been automated by logging CALPHAD data of 4 and 5 element equimolar combinations from a 12 element palette. The objective is to develop an MPEA with high temperature oxidation resistance and good printability in a directed energy deposition system. Equimolar alloys were ranked based on the objective constraints. Selected alloys are being arc-melted, characterized, and oxidized to assess the validity of CALPHAD. The experimental data will be used in a black-box optimization software to predict non-equimolar systems. A final alloy candidate will then be printed as a coating using multiple powders to test its oxidation behavior through additive manufacturing.

Materials: Polymers I - Processing and Mechanical Properties

Monday PM Room: Salon F
August 12, 2019 Location: Hilton Austin

Session Chair: Christopher Williams, Virginia Tech

1:30 PM The Impact of Thermal Processing Conditions on Mechanical Strength and Dimensional Accuracy for Fused Filament Fabrication of Ultem 1010: Callie Zawaski; Christopher Williams; Virginia Tech

Ultem 1010 is a high-performance polymer that is valued for its high-strength and high-temperature characteristics. This thermoplastic is processable using Fused Filament Fabrication (FFF) in order to create customized parts with complex geometries for aerospace and automotive applications. High-temperature thermal processing conditions, including nozzle temperature, environment temperature, and post-processing, generally promote higher chain-entanglement resulting in increased layer-bonding and stronger parts; however, there is a tradeoff that the material may retain some chain mobility and result in less dimensionally accurate parts. In this work, the authors use an inverted FFF machine with a temperature-controlled chamber to study the effects of the nozzle temperature, environment temperature, and controlled post-processing cooling on the mechanical properties and dimensional accuracy of Ultem 1010 parts. The results provide insight for the optimal thermal processing conditions for printing with Ultem 1010.

1:50 PM Tensile and Compression Test for Specimens Developed Using an Algorithm of Path Optimization: Julian Aguilar-Armendariz; Cesar Balderama-Armendariz; Juan Hernández-Arellano; Liliana Avelar; 1Universidad Autónoma de Baja California; 2Universidad Autónoma de Ciudad Juárez

The propose of this research is to determine the tensile properties and compressive properties in specimens designed with the route optimization algorithm printed with Fused Filament Fabrication technology. Two types of specimens have been developed, the type A using CURA® software and the type B, modifying the G code proposed by CURA® with the algorithm of Salesman Traveling Problem to optimize the path of the extruder. The manufacture of the specimens was carried out with 3D Cube equipment and PLA material. The tensile test was developed using ASM D638-14 method and ASTM D695-15 for a compression test. Results expose a reduction of 4.5% in the standard time of printing. No significant differences were found in tensile and compressive strength between type A and B specimens.

2:10 PM Investigation of Mechanical Properties and Dimensional Accuracy of an UV-curable Silicone Printed with DLP: Dong Sung Kim; Jakkrit Suriboot; Chin-Cheng Shih; Austin Cwiklik; Melissa Grunlan; Bruce Tai; Texas A&M University

Silicone 3D printing has been commonly achieved by extrusion-based processes while the printed parts are often anisotropic, dimensionally inaccurate due to shrinkage, and of poor surface finish due to the layering process. The research introduces a new type of UV-curable silicone featuring a unique functional group to eliminate shrinkage. To evaluate this silicone in digital light processing (DLP), this work is focused on determining the mechanical isotropy and dimensional accuracy of the printed parts compared with a molded counterpart. Mechanical strengths of parts with different orientations are measured by a tensile test. The dimensional accuracy is determined by high-definition images.
2:30 PM Process Parameter Optimization to Improve the Mechanical Properties of Arburg Plastic Freeformed Components: Andre Hirsch; Felix Hecker; Elmar Moritzer; Paderborn (KTP), Direct Manufacturing Research Center (DMRC)

The Arburg Plastic Freeforming (APF) is an additive manufacturing process that can produce three-dimensional, thermoplastic components layer by layer. The open control of the associated machine system allows adjustment of the process parameters and optimization for specific applications. The objective of the investigations is the optimization of the mechanical properties of APF components. Relevant process parameters are the nozzle and build chamber temperatures, the layer thickness, the form factor, the raster and delta angle and the overlap between the contour and the filling of the layers. The investigations are carried out with the material ABS. Using this procedure, the interactions and influencing parameters on the mechanical properties (tensile strength, elongation at break and modulus of elasticity) are analyzed and converted into mathematical models. The resulting guidelines are intended to support the users of APF technology in their specific process configuration for their own applications.

2:50 PM Impact Strength of 3D Printed Polyether-ether-ketone (PEEK): Haijun Gong; Xiaodong Xing; Jan Nel; Georgia Southern University; Harbin Engineering University

Polyether-ether-ketone (PEEK) is a high-performance thermoplastic with high heat-, high chemical-, high water-, and high wear-resistance. Its strength and durability also make it highly accepted for a range of applications. The recent developments in Additive Manufacturing Powder Bed Fusion (AF) technology. Our ultimate goal is to enhance the quality of 3D printed products. In the last thirty years, additive manufacturing has been increasingly commercialized, therefore, it is critical to understand the influence of different process parameters on mechanical properties of PLA to broaden the use of 3D printing. We utilize a Universal Tensile Machine and Quality Engineering to comprehend tensile strength characteristics of PLA. Tensile strength tests are performed on PLA specimens to analyze their resistance to breakage. Statistical analysis of the experimental data collected shows that temperature and infill rate affect tensile strength.

3:10 PM Break

3:40 PM Mechanical Performance of Laser Sintered Poly(ether ketone ketones) (PEKK): Luiza Benedetti; Benoit Brulé; Nadine Decraemer; Oana Ghita; University of Exeter; Arkema Cerdato

The developments in Additive Manufacturing Powder Bed Fusion systems are bound to attract uptake of new high-performance materials. The Poly(aryl ether ketone) (PAEK) family, Poly(ether ketone ketone) (PEKK) shows promising mechanical properties, comparable with the commercial laser sintering grade PEK HP3, whilst processed at significantly lower temperatures. Kepstan 6000 PEKK specimens were laser sintered in multiple orientations and a range of mechanical tests were used to assess overall performance. PEKK showed outstanding ultimate tensile strength ranging between 75 and 90 MPa in x-y direction whilst maintaining an elongation at break of 2.6%. Further investigation of the fracture shows a solid interior with localized plastic regions attributed to a better performance. The same plastic behaviour is observed during compression, in which PEKK showed remarkable deformation with no signs of breaking. The combination of properties offered by Kepstan PEKK parts manufactured at a lower processing temperature makes it a very attractive polymer for applications in the aerospace and automotive sectors.

4:00 PM Influence of Part Microstructure on Mechanical Properties of PA6x Laser Sintered Specimens: Christina Kummert; Hans-Joachim Schmidt; Wolfgang Diekmann; Direct Manufacturing Research Center; Paderborn University; Evonik Resource Efficiency GmbH

The influence of different process parameters on mechanical properties of selectively laser sintered (SLS) parts was investigated in various studies. Until now, the significant differences in mechanical characteristics depending on processing conditions are insufficiently explained but reasons may be found in part microstructure. For this reason, PA6x test specimens with different component properties were printed by changing laser exposure strategies and their microstructure was examined using for example thin sections or XCT-analysis. PA6x is a comparatively new SLS material which offers outstanding mechanical properties if adequate SLS processing parameters are used. In this study different SLS machines are used by EVONIK and the DMRC, Paderborn University to investigate the relationship between SLS-specific manufacturing conditions, the resulting components microstructure and finally the component properties. The knowledge gained can contribute to a deeper understanding of the process.

4:20 PM Optimizing the Tensile Strength for 3D Printed PLA Parts: Clara Novoa; Alejandra Flores; Texas State University

This research investigates on how temperature, infill rate and number of shells affect the tensile strength of three-dimensional polyactic acid (PLA) products manufactured with the Fused Deposition Model (FDM) technology. Our ultimate goal is to enhance the quality of 3D printed products. In the last thirty years, additive manufacturing has been increasingly commercialized, therefore, it is critical to understand the influence of different process parameters on mechanical properties of PLA to broaden the use of 3D printing. We utilize a Universal Tensile Machine and Quality Engineering to comprehend tensile strength characteristics of PLA. Tensile strength tests are performed on PLA specimens to analyze their resistance to breakage. Statistical analysis of the experimental data collected shows that temperature and infill rate affect tensile strength.

4:40 PM Characterizing the Influence of Print Parameters on Porosity and Mechanical Performance: James Brackett; Tyler Smith; Nidia Gallego; Vlastimil Kunc; Chad Duty; University of Tennessee Knoxville; Oak Ridge National Laboratory - Manufacturing Demonstration Facility

Extrusion deposition additive manufacturing produces parts with inherent porosity, which typically manifests as easily accessible voids between beads. This open porosity can also be accompanied by voids within the beads themselves, and both types can impact a part’s desired performance. Porosity is influenced by a variety of factors, including infill percentage, layer height, nozzle diameter, print speed, and raster orientation. While their influence on mechanical properties and porosity have been studied previously, there has been minimal work connecting print parameters to porosity and subsequently to mechanical performance. This study investigates the relationships between print parameters, volumetric porosity, and mechanical performance. In addition, this study measures both open and closed porosity through use of a helium pycnometer rather than image analysis of a cross-section. Thus, this study will identify correlations between the volumetric density of parts and the resulting mechanical performance as a function of print parameters.
It is well known that the interfaces between adjacent layers and extrudate are the weakest point of thermoplastic polymer Material Extrusion Additive Manufacturing (MEAM) parts. When tested in uniaxial tension, MEAM parts exhibit one of two possible failure modes: (1) failure along the weld interface or (2) failure along a cross-section perpendicular to the applied tensile load. Previous work has shown that the strength of the interfaces can be accurately calculated, but part strength calculations only considered weld interface fracture. We introduce and demonstrate a novel part strength calculation method that not only accounts for both possible failure modes, but also accurately predicts which failure mode will occur. This part strength calculation and failure mode prediction method is shown to be agnostic to toolpath orientation and material.

**Physical Modeling I - Thermal**

**Monday PM**

**Room: Salon B**

**August 12, 2019**

**Location: Hilton Austin**

**Session Chair:** Scott Thompson, Auburn University

**1:30 PM**

**Scan-by-scan Thermal Modeling for Defect Prediction at the Part Scale:** Terrence Moran; Derek Warner; Nam Phan; Cornell University; Naval Air Systems Command

The utility of superposition-based finite element modeling is demonstrated for defect prediction in additively manufactured components built by thermal processes. We address the challenge of the discrepancy in scale between the localized heat source and the part geometry by summing an analytic solution for a moving heat source in a semi-infinite medium with a correcting finite domain field computed with the finite element method. Through efficient implementation of the analytic solution and the use of a coarse finite element mesh away from surfaces, we demonstrate that scan-by-scan layer-by-layer part-scale thermal modeling is possible for aircraft components on a modest sized computer cluster. The part-scale thermal fields are used to identify regions that experience high or low temperatures during the build, due to interactions of the heat source with the part geometry. From single scan experiments, such deviations in temperature can be connected with the likelihood of defect formation.

**1:50 PM**

**Relative Significance of Heat Loss through Radiation and Convection in Extrusion Based Additive Manufacturing:** Jie Zhang; Brecht Van Hooreweder; Eleonora Ferraris; KU Leuven

Energy balance plays a key role in extrusion based additive manufacturing (AM) such as fused filament fabrication (FFF). Many research efforts have been devoted to modeling temperature variations and their patterns after polymer melts leave the nozzle. In most models, boundaries conditions were usually set to (equivalently) be convective, and inherently ignored the significance of radiation. Because common nozzle temperature used in FFF seems not to be high. However, with temporal temperature profiles, the ratio of energy loss through radiation to that through convection could be calculated (Conduction increase system energy globally). With common printing parameters, this ratio could reach 50%, and it would easily exceed 100% when FFF is performed using polymers of higher melting polymer (e.g. PEEK) with better temperature management. These results mean heat loss through radiation could be comparable as through convection, and thus bring new challenges for more accurate temperature modeling in extrusion based AM.
Effect of Part Topology on Local Heat Transfer during Laser-Powder Bed Fusion: Basil Paudel; Scott Thompson; Auburn University; Kansas State University
The current study focuses on the effect of part topology on local heat transfer during the laser-powder bed fusion (L-PBF) additive manufacturing (AM) process. The high heat flux diffusion (i.e. thermal spreading) is numerically modeled and investigated for the L-PBF of a thin-walled part with various negative draft angles (overhangs) and a thin wall of variable cross-sectional area. Scan-wise and layer-wise manufacturing effects on heat transfer are quantified via local temperature gradients, temperature time rates of change, and thermal shock. These thermal metrics are used to predict residual stress and surface roughness traits of stainless steel 316L, Inconel 625 and Ti-6Al-4V parts. Both powder effects and phase change within the melt pool are considered using approximate, reduced-complexity techniques. Results demonstrate that the temperature distribution along geometries with negative draft angles are significantly different from that of geometries with positive draft angles.

Explanatory Multiphysics Modelling of Generated Heat in Vat Photopolymerization: Mohammad Mahdi Emami; David William Rosser; Singapore University of Technology and Design (SUTD); George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology
A multiphysics explanatory simulation for a projection vat photopolymerization process has been developed. The aim is to predict the effects of generated heat and conduction heat transfer during polymerization on local temperature distributions. Based on the temperature gradient at the exposed layer, the simulation exhibits how thermal expansion and contraction and reaction rates affect a single layer. The model utilized COMSOL Multiphysics for chemical reaction simulation, heat generation, species diffusion, and heat transfer. The generated heat released from the reaction calculated was based on the number of reacting double bonds. The simulation revealed a sharp thermal gradient between the exposed and unexposed region in the process. Temperatures were recorded experimentally in the resin vat during illumination and dark reaction periods and were found to be consistent with the simulation. The model was applied to several examples to determine temperature effects on reaction rates, degrees of cure, and final part shapes.

Energy Absorption Measurement in Laser Deposition Additive Manufacturing: Zhichao Liu; Tao Lu; Hong-Chao Zhang; Weilong Cong; Texas Tech University; Dalian University of Technology
The amount of energy transmitted into the molten pool in laser deposition additive manufacturing (LDAM) is an important factor, and it will not only affect the powder efficiency but also the quality of the fabricated part. In this paper, the energy absorption by the powder stream during LDAM process is measured based on stepwise heating method. High-resolution infrared camera is used to measure the temperature of the powder stream after laser radiation. The results suggest that the energy absorption of the powders in LDAM process is not a constant value and it has a negative relationship with the laser power input.

A Time-efficient Analytical Model of Laser Directed Energy Deposition Process for Functionally Graded Materials Fabrication: Yuze Huang; Behrad Khamesee; Ehsan Toyserkani; University of Waterloo
Owing to improper process parameters settings, quantities of defects may occur during the fabrication of functionally graded materials (FGM) by laser directed energy deposition (LDED). In addition, some defects may not be avoided by using constant optimized processing parameters because of layer-variant material properties. Moreover, the accumulated heat of prior layers may induce excessive dilutions. Under this context, a fast process model of LDED for FGM fabrication was built. The mass flow of the powder stream was coupled with the laser heat source, where powder material properties were varied in a layer fashion. The accumulated heat in the prior layers was counted by an adaptive initial temperature. Subsequently, the thermal field was computed based on the transient Green's heat conduction solution. The built model is capable of providing time-efficient calculations of transient thermal and dimensional features (e.g., cooling rate, melt pool size) to achieve adaptive process optimization and control.
2:10 PM
Simultaneous high-speed IR thermal camera and X-ray imaging at the Advanced Photon Source allow for a better understanding of the thermal changes during the process and how fluctuations in the melt pool lead to porosity. Mapping thermal characteristics of the melt pool in real time can lead to an understanding of how thermal cycling during laser-matter interactions can result in porosity formation. Ultimately, this understanding can lead to real time process modification and characterization.

2:30 PM
The laser powder bed fusion (LPBF) additive manufacturing (AM) process is becoming a critical tool in the prototyping and production of components for the aerospace, military and general manufacturing sectors. To increase the throughput, systems are increasingly relying on the use of multiple lasers during the build. However, the material response and part defect generation mechanisms under this build condition are poorly understood and relatively unexplored. Here, high resolution in situ imaging and post processing metallography are used to determine the interaction of the build lasers with the generated vapor plume and material structural response in stainless steel under multi-beam build conditions. The results reveal that the build laser spot size fluctuates significantly on exposure to the vapor plume which can have detrimental effects on track quality. This information can be used to optimize multi-beam LPBF and ultimately improve the reliability of printed parts produced in this processing regime.

2:50 PM
How Powders Incorporate into the Melt Pool in Deposition: An In-situ Study on Powders Overcoming the Melt Pool Surface Tension: Sarah Wolff, Samantha Webster, Jennifer Bennett, Niranjan Parab, Cang Zhao, Kornel Ehmann, Jian Cao, Tao Sun, Aronne National Laboratory, Northwestern University.
In powder-blown processes, the final microstructure, properties, and performance of parts depend on how powder particles melt and solidify in a layer-by-layer fashion. In this study, high-speed X-ray imaging of up to 80 kHz at the Advanced Photon Source reveals flow behavior of in-flight Ti-6Al-4V and 316L SS powder particles. Flow behavior includes melting at the surface of the melt pool, deposition into the melt pool below the surface, porosity formation, laser attenuation, and how these measurements can inform on the changes of properties during melting and solidification during the process.

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Process monitoring instrumentation in laser powder bed fusion (LPBF) principally relies on measurement of the radiant energy emitted from the laser-induced melt pool. However, the extreme surface temperatures and gradients pose a serious challenge to any process monitoring instrumentation, in which significant measurement error can occur from improper design, assumptions, or signal processing. This paper demonstrates an inverse metrological approach, in which the output of the sensor systems is simulated based on an assumed real temperature field obtained from high-fidelity numerical simulations of the LPBF process. Through this procedure, various components of measurement error can be isolated and studied and deficiencies in the instrumentation or image processing identified. This method is demonstrated and compared to measurement results from co-axial melt pool monitoring and high-magnification thermographic imaging performed on an LPBF testbed. Additional discussion is provided regarding the practical application to measurement uncertainty quantification, simulation validation, or real-time process control.

4:00 PM
Development of In-line Surface Measuring Instruments for Additive Surface Finishing: Luis Folgar, Konstantin Rybalcenko, AMT Inc.
The productivity rate of a manufacturing process is limited by the speed of any measurement processes at the quality control stage. Fast and effective in-line measurements are required to overcome this limitation. Optical instruments are the most promising methods for in-line measurement because they are faster than tactile measurements, able to collect high-density data, can be highly flexible to access complex features and are free from the risk of surface damage. This work presents a methodology for the development of fast and effective in-line optical measuring instruments for the surfaces of parts with millimetre- to micrometre-size and its implementation is demonstrated on an industrial case study in additive manufacturing (AM). Definitions related to in-line measurement and barriers to implementing in-line optical measuring instruments for surface finishing AM applications are discussed.

4:20 PM
Development of a Standalone In-situ Monitoring System for Defect Detection in the Direct Metal Laser Sintering Process: Paul Quinn, Sinead O’Halloran, Caetirna Ryan, Andrew Parnell, Jim Lawlor, Ramesh Ragavendra, SEAM Research Centre, Department of Engineering Technology, Waterford Institute of Technology, Maynooth University Hamilton Institute, Maynooth University & I-Form Advanced Manufacturing Research Centre, Department of Engineering Technology, Waterford Institute of Technology, SEAM Research Centre, Department of Engineering Technology, Waterford Institute of Technology & I-Form Advanced Manufacturing Research Centre.
Direct metal laser sintering (DMLS) is a powder bed fusion (PBF) additive manufacturing process commonly used within the medical device and aerospace industries where regulations drive the requirement for stringent quality control. Using in-situ monitoring, the identification of defects as well as geometric and dimensional measurement of the layers throughout the build allows for greater quality control, as well as a reduction in the requirement for ex-situ measurement. Presented in this research, is a standalone monitoring system for the EOS M280 allowing for the build process to be monitored layer-by-layer. The system images the build area after powder deposition and after laser exposure allowing for inefficiencies in both the powder deposition and the laser exposure to be identified. The system has proven to be capable to identify in build defects and work is ongoing in developing an automated program to identify these defects and notify the operator in real time.
Characterization of Metal-polymer Composites for In Situ Direct Ink Write Sensing Applications: Jenny Wang1; Allan Chang2; Sarai Sherfield2; Steven Hunter3; Alexandra Golobic4; Eric Duoss5; Manyalibio Matthews1; 1Lawrence Livermore National Laboratory; 2Georgia Institute of Technology

Additive manufacturing of multi-material objects enables the design of complex 3D architectures such as printed electronics and devices. Detecting the composition of multi-material printed inks in real time is an enabling capability in many manufacturing sectors. In this study, dielectric properties of microscale embedded metal particles in a dielectric matrix have been measured and characterized as a function of particle size, shape, volume percentage and frequency. Measurements were found to agree with calculations based on an anisotropic Maxwell-Garnett dielectric function model. This resulting data can be used to generate a calibration curve correlating metal loading with impedance or capacitance. This calibration curve can be used with an in situ sensor for compositional measurements during extrusion-based 3D printing. We demonstrate how an in situ sensor can locally measure the composition of the ink, facilitating greater control over the resulting properties and functionality of printed materials. Prepared by LLNL under Contract DE-AC52-07NA27344.

Types of Spatters and Their Features and Formation Mechanisms in Laser Powder Bed Fusion Additive Manufacturing Process: Zachary Young1; Qilin Guo1; Cang Zhao2; Luis Escano3; Lianghua Xiong1; Wes Everhart2; Tao Sun1; Lianyi Chen1; 1Missouri University of Science and Technology; 2Advanced Photon Source, Argonne National Laboratory; 3Honeywell FM&T

Spatter causes defect formation, powder redistribution and contamination in the laser powder bed fusion (LPBF) additive manufacturing process. This work reports the features and formation mechanism of spatter during LPBF with the use of in-situ high-speed, high-energy x-ray imaging. Alterations of the laser power, scan speed, and ambient pressure and their relations to spatter production are analyzed. Spatter observed during LPBF testing was quantified by their speed, size, and spatter direction. Potential ways to reduce spatter during manufacturing are proposed by the alteration of physical parameters of the laser system and environment.

1:50 PM
Wire Co-extrusion with Big Area Additive Manufacturing: Celeste Atkins1; Jesse Heineman1; Phillip Chesser2; Alex Roschl1; Brian Post3; Lonnie Love1; Randall Lind1; Abigail Barnes1; 1Oak Ridge National Laboratory

Oak Ridge National Laboratory’s Manufacturing Demonstration Facility is developing a system that will deposit and embed conductive and resistive elements within a printed bead of material. The system will be implemented on a Big Area Additive Manufacturing (BAAM) system using a co-extruding nozzle. It has already been demonstrated that BAAM is useful for the tooling industry, but this could be a great improvement on an established application of BAAM parts. This system will provide the ability to control and monitor the surface of additively manufactured (AM) parts. It will also enable self-heating surfaces of AM parts, which is particularly useful in tooling applications. This system could even be used in the future for embedding other materials not found in pellet form in BAAM parts. This work will cover the development of the co-extrusion system and its integration with the dual-port nozzle and the BAAM system.

2:10 PM
Volumetric Sintering of a Selectively Doped, Functionally Graded Powder Bed: Jared Allison1; Ali Sohaib1; Carolyn Seepersad1; Christopher Tuck1; Richard Hague1; Joseph Beamman1; 1University of Texas at Austin

Volumetric sintering using radio frequency (RF) radiation is an additive manufacturing (AM) approach that seeks to improve the mechanical properties and process speed over other thermoplastic AM methods. The volumetric sintering strategy uses a single stage heating mechanism in favor of the layer wise heating and cooling cycles associated with selective laser sintering and fused deposition modeling. Heat is generated by selectively doping a polymer powder bed with electrically conductive material and subjecting the entire volume to electromagnetic radiation. A complex relationship exists between the part geometry and the absorbed electric field, resulting in uneven heating within the part. Computational design techniques are used to improve the heating uniformity by functionally grading the dopant concentration throughout the build envelope. The models are confirmed experimentally, such that parts created from the graded dopant distributions are shown to have higher geometric accuracy than analogous parts created from uniform dopant distributions.

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SkyBAAM Large Scale Fieldable Deposition Platform System Architecture: Phillip Chesser1; Brian Post1; Randall Lind1; Alex Roschl1; Celeste Atkins1; Alex Boulger1; Paritosh Mhatre1; Peter Lloyd1; Abigail Barnes1; 1Oak Ridge National Laboratory

Oak Ridge National Laboratory (ORNL) is currently developing a concrete deposition system for infrastructure-scale printed objects. This system, called SkyBAAM, uses a cable driven motion platform to manipulate the print head. The focus of this work includes general aspects of the system architecture, including arrangement of the cable driven platform, general high-level control methodology, and system accuracy. Concrete pumping, extruding, and the shaping scheme will also be presented together with potential reinforcing strategies. Results and demonstration prints will be shown.
2:50 PM
Out-of-plane Printing with Big Area Additive Manufacturing: Tyler Smith; Liam Page; Greg Gorman; Ahmed Hassen; Seokpum Kim; Christopher Hershey; John Lindahl; Dylan Settlemeier; Jordan Failla; Tom Flammang; Brent Compton; Vlastimil Kunc; 1ORAU; 2University of Tennessee; 3Oak Ridge National Laboratory

Large scale additive manufacturing has demonstrated the capability of printing large structures used for tooling and rapid prototyping at a much lower lead time and cost compared to regular manufacturing methods. However, large-scale structures suffer from poor print resolution and voids which require post-processing to achieve a usable surface finish. Structures made using Big Area Additive Manufacturing (BAAM) methods are post-machined on a 5-axis mill to obtain a smooth surface, however, waste material generated from milling, decreases the advantage of additive manufacturing. This paper introduces the concept of printing out-of-plane to create a smoother surface and reduce material waste during the printing and milling processes, respectively. We present several small printed geometries that test the various incline and raster angles that the BAAM system can achieve for out-of-plane printing. Analysis of print quality with various incline and raster angles were used to create a map of optimal out-of-plane print settings.

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Material Flow Control via Image Reconstruction in Concrete Additive Manufacturing: Michael Borish; Brian Post; Alex Roschli; Phillip Chesser; Lonnie Love; Abigail Barnes; 1Oak Ridge National Laboratory

Concrete additive manufacturing presents unique challenges compared to other types of materials. In typical polymer or metal-based systems, the additive manufacturing process occurs in a defined, static environment using materials with specific properties such as particle size. Our new system, SkyBAAM, presents a unique alternative and does not require a set volume or material. Because special material is not required, variation in material properties can occur. As a result, a vision-based system was developed in order to facilitate material control. This vision system is composed of several data streams comprising depth and color images. These images were used for bead identification and reconstruction. From these images, the system's material flow was controlled in order to facilitate a stable build process.

4:00 PM
Dynamic Build for Additive Manufacturing: Ismail Yigit; Ismail Lazoglu; 1Koc University

Compared to subtractive manufacturing, additive manufacturing generally has low material waste. However, models with large overhangs require manufacturing of support structures which ends up as waste material. This paper proposes the use of a dynamic build bed for reducing support structures. The bed consists of an array of actuated pins which move in the build orientation. Each pin can be individually moved to the correct height for supporting the given model. Two separate applications of the build bed are investigated. In the first application, the dynamic build bed is used as support structures in deposition-based AM methods. The pins individually raise out of the build bed to support the overhang geometry at the given deposition height. The second application is in powder-based AM methods. In the second application, the pins are used to fill the space of the powder where the geometry will not occupy. The pins are individually lowered in the build orientation to make space for a new powder layer. Thus, saving excessive deposition of powder.

4:20 PM
Effect of Infrared Preheating on the Mechanical Properties of Large Format 3D Printed Parts: Vidya Kishore; Andrzej Nycz; John Lindahl; Chad Duty; Charles Carnal; Vlastimil Kunc; 1Oak Ridge National Laboratory; 2University of Tennessee; 3Oak Ridge National Laboratory

Anisotropy of mechanical properties is characteristic of components printed using extrusion deposition additive manufacturing (EDAM) processes. This effect, influenced by the z-direction (print direction) bond strength, can be more pronounced for components with long layer times as the bottom layers can cool below the glass transition temperature (Tg) of the material, thereby restricting thermal fusion between the printed layers. The work discussed here builds on the previous work by the authors, demonstrating infrared preheating as a technique to actively control the bond temperature during printing to improve z-direction mechanical properties of parts printed on large-format EDAM system. The surface of each printed layer was IR preheated just prior to the deposition of the next layer to increase the surface temperature closer to Tg. The current study explores the effect of bead surface temperature variations prior to and after pre-heating (indicative of different layer times) on the mechanical properties in z-direction.

4:40 PM
Large-Scale Additive Manufacturing of Concrete Using a Six-axis Robotic Arm for Autonomous Habitat Construction: Nathan Watson; Sven Bilen; Nicholas Meisel; 1Pennsylvania State University

Layer-by-layer construction of concrete structures via additive manufacturing (AM) provides greater design freedom when compared to conventional form-work methods. However, AM of habitat-scale structures can present significant challenges, including accurately depositing material throughout a large build volume as well as requiring freedom of movement to deposit material and supports in a manner to gain the best mechanical and aesthetic properties. This paper demonstrates the use of a six-axis robotic arm for concrete AM to address these issues through the use of non-planar layers and the off-axis deposition of concrete. Additionally, a larger print volume is achieved by using extensions on the robotic arm in coordination with unused axes. Finally, the robot is also used as a multi-functional system to complete other tasks autonomously, which includes placing prefabricated components into a structure being printed. By using these concepts, the authors were able to produce large-scale concrete components and structures.

5:00 PM
Bead Characterization System (BCS) for Big Area Additive Manufacturing (BAAM): Phillip Chesser; Randal Lind; Brian Post; Chelsea Silberglied; Alex Roschli; Lonnie Love; Abigail Barnes; 1Oak Ridge National Laboratory; 2Georgia Institute of Technology

In extrusion-based additive manufacturing systems, control of material flow rate is a critical aspect of achieving good part quality. Depending on the extrusion method, the difficulty of controlling the flowrate varies. In addition, poor flow control is also magnified at large scales. Flow control is a significant issue in the Big Area Additive Manufacturing (BAAM) system at Oak Ridge National Laboratory (ORNL). The dynamics associated with the single-screw extruders used in BAAM, make control difficult, and the large scale of BAAM magnifies the defects caused by lack of control. In this paper a Bead Characterization System (BCS) is presented that is used to measure the dynamics of the extruder. From this, a transfer function can be found through system identification. This transfer function can then be used in feed-forward control of the extrusion process. This has been shown to significantly improve the consistency of the bead geometry.
Predicting and Controlling the Thermal Part History in Powder Bed Fusion Using Neural Networks: Holger Merschroth; Michael Kniepkamp; Matthias Weigold; "Institute of Production Management, Technology and Machine Tools, Technische Universität Darmstadt

Laser based powder bed fusion of metallic components is widely used in different branches of industry. Although there have been many investigations to improve the process stability, thermal history is rarely taken into account. The thermal history describes the parts thermal situation throughout the build process as a result of successive heating and cooling with each layer. This could lead to different microstructures due to different thermal boundary conditions. In this paper a methodology based on neural networks is developed to predict and control the parts temperature by adjusting the laser power. A thermal imaging system is used to monitor the thermal history and to generate a training dataset for the neural network. The trained network is then used to predict control the parts temperature. Finally tensile testing is conducted to investigate the influence of the adjusted process on the mechanical properties of the parts.

Prediction and Control of Melt Pool Geometry in Additive Manufacturing Processes: A Machine Learning Based Approach: Sudeepta Mondal; Asok Ray; Amrita Basak; "Pennsylvania State University

Prediction and control of melt pool geometry is critical for controlling the thermal gradient and therefore the resulting microstructure in additive manufacturing processes. During layer-by-layer deposition, as the components continue to heat up, the melt pool geometry undergoes substantial changes if the process parameters are not properly controlled. In order to alleviate this problem, a coupled analytical and machine learning (ML) assisted modeling and optimization framework was explored in this work. A Green's function based 2-dimensional analytical heat transfer model is employed for predicting the thermal distribution in a directed energy deposition process. Thereafter, a surrogate-assisted statistical learning and optimization architecture involving Gaussian Process-based modeling and Bayesian Optimization is employed for finding the optimal set of process parameters as the scan progresses. The results demonstrate that model-based optimization can be significantly augmented by using ML to generate reliable a-priori estimates of the optimal process parameter evolution for this problem.

Seeing the Temperature Inside the Part during the Powder Bed Fusion Process: Nathaniel Wood; David Hoelzel; "The Ohio State University

Powder Bed Fusion (PBF) is a type of Additive Manufacturing (AM) technology that builds parts in a layer-by-layer fashion out of a metal powder bed via the selective melting action of a laser or electron beam heat source. The technology has become widespread; however, current PBF sensors do not permit the measurement of internal part temperatures. If we had a complete spatiotemporal temperature history, we could improve process quality and validation, and better predict metallurgical phases within produced parts. This paper demonstrates the use of closed-loop state estimation of temperature fields within parts during the PBF build process using an Ensemble Kalman Filter (EnKF). We demonstrate that an EnKF produces temperature estimates that are approximately 2.5 times more accurate than the open loop predictive models in simulation. The paper concludes with prospects for experimental validation and the utility of these temperature history estimates for quality control and validation.

The Digital Twin in Metal Additive Manufacturing – A Paradigm Integrating Modeling, Sensing, and Machine Learning for Defect Prediction: Reza Yavari; Aniruddha Gaikwad; Mohammad Montazeri; Prahalad Rao; Kevin Cole; Linkan Bian; "University of Nebraska; "Mississippi State University

The goal of this work is to prevent occurrence of defects in parts made using metal additive manufacturing (AM) though closed-loop control and in-situ process correction. As a step towards this goal, the objective of this work is to develop and apply a theoretical model-based approach to track the thermal profile of parts made using the directed energy deposition (DED) metal AM process, and subsequently, use the model-derived thermal predictions in conjunction with in-process temperature measurements to detect occurrence of lack-of-fusion flaws. In other words, instantiate the digital twin concept to identify and isolate defects in the DED metal AM process. The central hypothesis of this work is that, a deviation in the observed melt pool temperature from its model-derived counterpart signifies a process drift, indicative of an impending fault. This approach presented herein is demonstrated to predict the occurrence of lack-of-fusion flaws with statistical fidelity approaching 90% F-score.

A Detection Method for Spatter Particles and Related Defects in Selective Laser Melting Process Using Neural Network on Images Produced by In-situ Monitoring: Truong Do; Li Yang; John Middendorf; John Van Oss; Kyle Ryan; Tung Hoang; "University of Louisville; "Universal Technology Corporation; "Universal Technology Corporation; "WeWork

In this work, a spatter-induced defect prediction model based on in-situ spatter detection was established and verified for the OPENSLM laser powder bed fusion system developed by Universal Technology Corporation. Utilizing the in-situ near-IR camera, the time-integrated light intensity images were converted into grayscale images and stitched together to form images of full-scan layers, which were consequently analyzed for spatter detection. The spatter particles were hypothesized to exhibit higher values of light intensity due to their repetitive heating history. A convolutional neural network (CNN) based machine learning algorithm was utilized for the recognition of the spatter defects with each full-scan layer, which was validated against both the micro-CT results and cross sectional optical microscopy with the fabricated samples. Based on the results, the effectiveness of the proposed model was analyzed, and the challenges of utilizing spatter-based defect detection was discussed.

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The Digital Twin in Metal Additive Manufacturing – A Paradigm Integrating Modeling, Sensing, and Machine Learning for Defect Prediction: Reza Yavari; Aniruddha Gaikwad; Mohammad Montazeri; Prahalad Rao; Kevin Cole; Linkan Bian; "University of Nebraska; "Mississippi State University

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3:10 PM Break

3:40 PM Machine learning tools for additively manufactured data streams: Christian Gobert; Andelle Kudzal; Brandon McWilliams; "Oak Ridge Institute for Science and Education; "US Army Combat Capabilities Development Command - Army Research Laboratory

Additive manufacturing (AM) process monitoring enabling sensors to capture real-time process signatures. Machine learning tools can leverage and process these AM data streams, enabling end-users to manage big data. Post-process X-ray computed tomography (XCT) is widely used in AM to obtain discrete analysis of internal material discontinuities. A U-Net inspired network was developed to segment porosity from XCT images of metallic AM specimens, enabling automatic processing of XCT data without user-intervention. A convolutional neural network was trained to detect process faults in metal PBF and polymer FDM AM builds monitored by optical sensors. A conditional generative adversarial network is demonstrated for in-situ AM data to predict in-situ data for future process inputs.
Designing for additive manufacturing (AM) challenges traditional design understanding by introducing new freedoms of complexity. Unfortunately, capitalizing on these complexities can involve time-consuming steps, such as analyzing manufacturability during iterative modeling. Machine learning can leverage design repositories, such as GrabCAD and Thingiverse, to automate some of these tedious tasks. However, determining the suitability of an AM design repository for use with machine learning is challenging. We provide an initial investigation towards a solution using artificial design repositories to test how altering dataset properties impacts trained neural network precision. For this experiment, we use a 3D convolutional neural network to estimate manufacturability using build metrics directly from voxel-based geometries. We focus on material extrusion AM and investigate three AM build metrics: part mass, support material mass, and build time. Our results suggest that training on repositories with less standardized positioning increased neural network accuracy and that estimating orientation-dependent metrics was hardest.

4:20 PM
Exploring the Use of Artificial Neural Network Machine Learning for Process Quality Evaluation of Powder Bed Fusion in Additive Manufacturing of Lightweight Structures: Yuan Zhang; Li Yang;
1University of Louisville
Compared to conventional processes, additive manufacturing (AM) is relatively new, and lacks an extensive knowledge base that enables quantitative process quality predictions. This issue is especially aggravated for powder bed fusion AM (PBF-AM) processes, in which the process quality is dependent on a large number of input process variables. In order to overcome of the issue of complexity with process development and to effectively develop process quality evaluation knowledge, in this study an artificial neural network (ANN) based machine learning method was adopted for the fabrication of Ti6Al4V thin wall features using laser PBF-AM. The effectiveness of the model setting was evaluated and partially optimized. The ANN model was then applied to establish the quality evaluation knowledge for the fabrication of the thin wall features, and further explored for the discovery of potentially significant process principles when coupled with clustering algorithms and physics-based analysis which is performed manually.

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In-situ Layer-wise Quality Control for Laser-based Additive Manufacturing Using Image Series Analysis: Mehrnaz Noroozi Esfahani; Linkan Bian; Wenmeng Tian; 1Mississippi State University
Quality assurance has been one of the major challenges in laser-based additive manufacturing (AM) processes. This study proposes a novel process modeling methodology for layer-wise in-situ quality control based on image series analysis. An image-based autoregressive (AR) model has been proposed based on the image registration function between consecutively observed thermal images. Image registration is used to extract melt pool location and orientation change between consecutive images, which contains sensing stability information. Gaussian Process is then used to characterize the spatial correlation within the error matrix. Finally, the extracted features from the aforementioned processes are jointly used for layer-wise quality control. A case study of a thin wall fabrication by a Directed Laser Deposition (DLD) process is used to demonstrate the effectiveness of the proposed methodology.

5:00 PM
1Oak Ridge National Laboratory
Production of additively-manufactured components for safety-critical applications requires quality assurance while the use of the technology for medium-scale production is only feasible with a lower part rejection rate than is possible with purely open-loop control schema. Here, the authors present a machine and camera agnostic algorithm for autonomous detection, classification, and localization of layer-wise powder bed anomalies. Using a novel Convolutional Neural Network architecture, the algorithm is able to return pixel-wise anomaly predictions at the native resolution of the imaging system. The algorithm also allows for the sharing of learned knowledge between different printing technologies – reducing the total amount of training data which must be annotated. Real-time analysis of layer-wise imaging data as well as real-time mitigation of several anomalies (based on algorithm detections) is demonstrated for a metal binder jetting technology. Analysis results for laser and electron beam powder bed fusion machines are briefly discussed.

Special Session: Spray AM - Direct Writing by Aerosol Deposition
Monday PM  Room: 404
August 12, 2019  Location: Hilton Austin
Session Chair: Desiderio Kovar, University of Texas at Austin
1:30 PM
Particle Trajectories, Focusing, and Fragmentation in Supersonic Aerosol Deposition: Christopher Hogan; 1University of Minnesota
Supersonic Aerosol Deposition (AD) is an additive manufacturing technique wherein particles, dispersed in a gas, are accelerated through a nozzle and impacted on a substrate at supersonic gas velocities (gas velocity Mach numbers often approaching 5). It is well established that AD can yield dense coatings from metal and ceramic particles with little-to-no substrate damage, and without the need to heat the substrate. However, little is actually known about particle trajectories in AD. The drastic reduction in pressure leads to particles experiencing drag in a unique Knudsen number-Mach number regime where the drag coefficient was previously unknown. This presentation will overview our groups work in (1) using direct simulation Monte Carlo (DSMC) to develop an appropriate drag coefficient for particles in AD processes, (2) utilizing this drag coefficient to examine particle trajectories in AD processes with a de Laval slit nozzle, and (3) demonstrating that the particle impact velocity correlates with the extent of particle fragmentation for SnO2 nanoaggregates impacting onto Al2O3 substrates. Trajectory simulations show that for any given nozzle geometry, there is a particle size of maximum velocity: larger particles are insufficiently accelerated, while smaller particles are decelerated by the shock at the substrate surface. This peak velocity is typically limited to ~500 m s⁻¹ using air and N2 as the process gas. We have also found that it is possible to inertially focus particles in AD, suggesting that highly monodisperse particles can be used to deposit with extremely narrow linewidths (on the order of the particle diameter).
Fabricating Thin Films of TiO2 on Glass: One-step, Direct Write Aerosol Impact Consolidation Method for a range of SFEs (22-125 mJ/m²). The films were patterned into lines impact velocity constant. This was done by selecting FCC metals with a supersonic flat-plate nozzle onto a substrate controlled by a mobile x-y stage. Deformation upon impaction and the resulting film microstructure is controlled by partial dislocation motion. To assess the influence of particle size on deformation, systematic experiments have been conducted by impacting silver particles at a range of sizes (20-100 nm) through the acceleration of nanoparticles through a aerosol jet, lines of material are deposited. The process is capable of thin film deposition with thicknesses from 1-100 μm on flat or curvilinear substrates. As compared to conventional cold spray deposition which is capable of depositing metallic or metal-matrix composite films, micro-cold spray has demonstrated the unique capability of also successfully depositing high quality ceramic films at room temperature. Impact velocity is one processing parameter that influences the quality and microstructure of the deposit. In this study, we perform experiments to determine how the nanoparticle velocity (approximately 500 to 1100 m/s) affects the relative density of SiC films while keeping other processing parameters, such as particle diameter (less than 80 nm), fixed.

Influence of Impacting Particle Size and Stacking Fault Energy on Ag Films Deposited by Direct Writing: Jeremiah McCallister; Michael Becker; John Keto; Desiderio Kovar; "The University of Texas at Austin The aerosol deposition method (ADM) produces patterned thick films (15-150 μm) through the acceleration of nanoparticles through a supersonic flat-plate nozzle onto a substrate controlled by a mobile x-y stage. Deformation upon impaction and the resulting film microstructure is controlled by partial dislocation motion. To assess the influence of particle size on deformation, systematic experiments have been conducted by impacting silver particles at a range of sizes (20-100 nm) onto alumina substrates while keeping the impacting velocity constant. A series of experiments were also conducted in which the stacking fault energy (SFE) of the impacting particle was varied by while keeping the impact velocity constant. This was done by selecting FCC metals with a range of SFEs (22-125 mJ/m²). The films were patterned into lines and then analyzed with optical profilometry and electron microscopy to determine their grain sizes and relative densities.

One-step, Direct Write Aerosol Impact Consolidation Method for Fabricating Thin Films of TiO2 on Glass: Rayhan Ahmed; Vikram Suresh; Li Li; Prashant Parajuli; Sanjay Mishra; Ranganathan Gopalakrishnan; "University of Memphis Thin films of photocatalytic TiO2 on transparent substrates have a wide range of applications, for example in photovoltaic and photochromatic devices. Conventional methods of fabricating TiO2 films employ high temperature sintering and/or harsh chemical solvents to and yet yield films of significantly low substrate to film bond strength. Aerosol impact consolidation method overcomes these limitations by promoting bonding via fragmentation and plastic deformation of impacted ceramic particles. This method offers a potential low-cost, high-volume additive manufacturing route to process thin film ceramic coatings but requires scale up to larger areas (~few sq. inches to a ~sq. ft). This study demonstrates thin films of TiO2 on glass substrates and explores the parametric space of particle velocity and size that lead to successful film formation upon impaction. The density of the produced films are seen to be strictly determined by the particle kinetic energy, morphology (degree of agglomeration). Ensuring proper powder size requires preprocessing of the powder materials such as multiple rounds of sintering followed by ball milling. The impact velocity is greatly determined by the gas dynamics in the nozzle used to accelerate the particle-laden gas flow and in the final moments of particle impact on the substrate. Lastly, uniformity in the coating is strongly influenced by the stability of the concentration of aerosol particles generated from commercial powders and injected into the deposition chamber. Micron-sized aerosols at concentrations ~10,000 #/cm³ using an ultrasonic feeding mechanism and the necessary particle kinetic energy was achieved by supersonic nozzles designed to produced particle speeds ~ 400 m/s prior to impact. SEM, AFM and XRD techniques were used to confirm the uniformity in thickness and roughness of the produced films. Preliminary measurements of the adhesion strength inferred using simple tension testing are also described.
4:20 PM
Direct-writing by Micro-cold Spray of Yttria (Y2O3) Films for Reactive Metal Casting: Aidan Moyers1; Desiderio Kovar1; 1University of Texas at Austin

The micro-cold spray process operates by accelerating aerosolized nanoparticles through a nozzle from atmosphere (760 Torr) to a vacuum (1-2 Torr). These nanoparticles, moving at 400-1100 m/s, impact a substrate mounted on an x-y-z stage to allow for the direct-writing of conformal films on complex surfaces. Unlike cold spray, a similar process using larger particles and higher pressure, micro-cold spray has the demonstrated capacity to deposit highly dense ceramic films at low temperature. Current methods for producing protective ceramic films for casting reactive metals require the use of binders and extensive post-processing, making the simplicity and high-purity of micro-cold spray films an attractive alternative. In this study, we performed experiments to determine how processing variables such as deposition velocity affected the density of yttria films made with 30-45 nm particles. Additional tests were performed to study the suitability of these films for reactive metal casting.

Applications: Biomedical II - Novel Materials and Processing

Tuesday AM  Room: 415 AB
August 13, 2019  Location: Hilton Austin

Session Chair: Jia Deng, Binghamton University SSIE

8:15 AM
Material-structure-property Optimization and In-process Monitoring of 3D Printed Bone Tissue: Samuel Gerdes; Azadeh Mostafavi; Srikanthan Ramesh; Ali Tamayol; Iris Rivero; Prahalad Rao; 1University of Nebraska; 2Rochester Institute of Technology

These composites were rheologically assessed and extrusion was first optimized one-dimensionally then through two-dimensional geometric modeling. With the addition of hydroxyapatite were utilized to target the formation of bone tissue. These biomaterials and composite materials feature favorable mechanical properties, cell adhesion, and biodegradability for the formation of biologically relevant additively manufactured tissues. With hydrogels and hard polymers targeting soft tissues, such as skin or muscle, and hard tissues such as bone, respectively, tissues of varying composition could be created. However, the process of biological additive manufacturing has yet to have a standardized approach for reproducible, optimized material printability. This study employs a bottom-up approach to optimizing printability using in-process sensor data for the linking of process parameters and print quality. Composites of thermoplastic poly-caprolactone polymer and biologically relevant hydroxyapatite were utilized to target the formation of bone tissue. These composites were rheologically assessed and extrusion was first optimized one-dimensionally then through two-dimensional geometric analysis. Furthermore, three-dimensional scaffolds were evaluated for cell viability.

8:35 AM
Effects of Printing Conditions on Cell Distribution within Microspheres during Inkjet Printing of Cell-laden Bioink: Heqi Xu; Changxue Xu; 1Texas Tech University

Inkjet-based bioprinting have been widely employed in a variety of applications in tissue engineering and drug screening and delivery. The typical bioink used in inkjet bioprinting consists of biological materials and living cells. During inkjet bioprinting, the cell-laden bioink is ejected out from the inkjet dispenser to form microspheres with cells encapsulated. The cell distribution within microspheres is defined as the distribution of cell number within the microspheres. The paper focuses on the effects of polymer concentration, excitation voltage, and cell concentration on the cell distribution within microspheres during inkjet printing of cell-laden bioink. The normal distribution was utilized to fit the experimental results to obtain the mean and standard deviation of the distribution. It is found that the cell distribution within the microspheres is significantly affected by the cell-laden droplet formation process during inkjet bioprinting.

8:55 AM
Multi-material Soft-matter Robotic Fabrication: A Proof of Concept in Patient-specific Neurosurgical Surrogates: Chih-Chiang Michael Chang; Thomas Angelini; Frank Bova; Scott Banks; 1University of Florida

Soft matter 3D printing provides the capability to fabricate 3D structures using granular gel as supporting material for depositing hydrogel inks. As such, it remains challenging to fabricate complex-shaped models with multiple materials in a timely fashion. The aim of this project is to introduce recent research of multi-material soft-matter extrusion and deposition for fast freeform fabrication of 3D structures that are further available for neurosurgical-anatomical models, and present a process to automate the fabrication of patient-specific models. A compact design of multi-material extrusion printhead is developed, which is capable of fabricating 3D structures from multiple inks. This provides a fast and efficient way to convert a virtual volumetric model into a physical extruded hydrogel structure using the multi-material soft-matter robotic fabrication system. It is hoped that future development of this system will likely be utilized in areas such as soft matter robotic fabrication, pharmaceutical testing, and extrusion-based bioprinting.

9:15 AM
PLLA-infused Citric Acid-based Biodegradable Vascular Scaffolds 3D Printed via microCLIP: Henry Oliver Ware; Banu Akar; 1University of Texas at Austin

Recent development of high-resolution micro-Continuous Liquid Interface Production (microCLIP, continuous projection microstereolithography) process has enabled 3D printing of biomedical devices with 10 micron-scale precision. 3D biodegradable vascular scaffolds (BVS) were printed using an antioxidant, photopolymerizable citric acid-based material (B-InkTM). Despite demonstrating BVS fabrication feasibility, challenges remained. According to literature, a vascular stent when placed in the body must be able to sustain a pressure loading between 10.67kPa and 13.34kPa of pressure loading. To be clinically relevant, BVS struts must possess very small thickness, 100um or below. To overcome material strength/stiffness challenges, a PLLA nanophase (2wt.%) was dissolved and secondary initiators were added to the photopolymer resin to improve post-process polymerization. This greatly improved bulk material stiffness and yielded BVSs with 100um strut thickness that could sustain necessary biological radial pressure loadings. This technology and material is a large step forward toward on-the-spot and on-demand fabrication of patient specific BVSs.

9:35 AM
Selection Considerations of Orthopedic Implants for Electron Beam Melting Production: Margaret Golz; Ola Harssysson; Russell King; Richard Wysk; 1IC State University

Over a million hip and knee replacement operations occur annually in the United States. When a joint replacement fails, a more painful, riskier, and more costly revision surgery is required. Typically, implants are produced in standard sizes. Prosthesis customization could improve patient outcomes beyond survivorship but unique implants are typically not economically feasible to produce with traditional manufacturing methods. Electron beam melting (EBM) technology can be used as an alternative production method for orthopedic implants, with the added benefit of prosthesis customization. Though customized joint replacements are the motivating case, it is possible to fabricate nearly any orthopedic implant, standard or custom, with EBM technology. This work outlines considerations for orthopedic implants that would be good candidates for EBM production and further determines types of implants that would benefit from volume customization. The criteria is applied to a short list of orthopedic implants to illustrate the selection process.
9:55 AM  Break

10:25 AM  Effect of Nb Content on the Corrosion Resistance and Passive Film Composition of Ti-Nb Alloys Fabricated by Selective Laser Melting: Danlei Zhao1; Qingsong Wei1; Jie Liu1; 1Huazhong University of Science & Technology

Ti-Nb (containing 15,25 and 45 at. % Nb) alloys were fabricated by Selective laser melting (SLM) to study the effect of Nb content on their corrosion behavior and passive film composition using electrochemical measurements (potentiodynamic polarization curves) in NaCl solution. The morphology of the corrosive surface was observed by SEM and the composition of the passivation film formed on the metal surface was analyzed by X-ray photoelectron spectroscopy. The results demonstrated that the increase of Nb content results in the increase of niobium oxide in the passivation film and the improvement of the corrosion resistance of Ti-Nb alloys. Ti-45Nb possesses the lowest corrosion rate and highest corrosion potential. The passivation film of CP-Ti is TiO2 and the passivation film of Ti-Nb alloy is mainly composed of TiO2 and Nb2O5. The research indicated that SLM could be used for improving the corrosion resistance of Ti-Nb alloy by adjusting Nb addition.

10:45 AM  Bioprinting with Stem Cells and Alginate-Gelatin Bioink Modified by Bioactive Glass: Krishna Kolari1; Julie Semon1; Bradley Bromet1; Delbert Day1; Ming Leu1; 1Missouri University of Science and Technology

Bioprinting research is focused on utilizing growth factors and a combination of cells to create clinically relevant 3D tissue models with primary cells. An alternative approach is to utilize dissolvable bioactive glasses and their ionic micronutrients in 3D cell cultures to enable appropriate stem cell behavior. In this study, we investigate incorporation of highly angiogenic borate bioactive glass (13-93B3) in different weight percentages (2.5% to 10%) to alginate-gelatin hydrogel. Adipose stem cells (ASCs) are uniformly mixed in this bioactive bioink at a concentration of 1x106 cells/mL and the specimens are evaluated in both static and dynamic culture conditions. Scaffolds measuring 10x10x1 mm3 are fabricated using the optimized glass concentration and investigated for ASCs viability and cytokine expressions. Despite initial decrease in cell viability with glass addition, longer culture (14 days) shows increased viability indicating that using small quantities in dynamic culture conditions enables bioprinting of stem cells with bioactive glass.

11:05 AM  Experimental Investigation of Effect of Alginate-Methylcellulose Hydrogel Composition on Profile Accuracy of Bioprinted Constructs: Ketan Thakare1; Xinjing Wei1; Hongmin Qin1; Zhijian Pei1; 1Texas A&M University

Bioprinting is 3D printing of cells and other biologics. Bioprinting technology has great potential in tissue engineering. In the field of tissue engineering, the scaffolds are constructed to mimic the native tissue architecture for them to be functional. To effectively biomimic the tissue, the scaffolds should have a precise and accurate scaffold profile. However, designed profile of a scaffold and its printed profile will have dissimilarities depending on factors like viscosity, extrusion pressure, extrusion temperature and so on which affect the profile of the bioprinted scaffolds. Composition of hydrogel is one of the important parameters which affects the profile of scaffolds. In this study, we have evaluated and analyzed the effect of alginate-methylcellulose hydrogel composition on profile accuracy of bioprinted scaffolds.

11:25 AM  Biodegradable Cellular Zinc Fabricated by Selective Laser Melting: Edel Arrieta1; Bryan Ruvalcaba1; Oscar Garcia1; Ryan Wicker1; Francisco Medina1; 1University of Texas El Paso

Biocompatibility and biodegradability are probably the most desirable properties after structural performance in medical implants. The selection of metals with these characteristics is in general limited to Fe, Mg, Zn and its alloys. Rapid degradation rate such as in Mg may structurally compromise implants, thus, Zinc has shown a more suitable balance among these metals, however, low melting and vaporization temperatures of Zinc may be challenging for appropriate printability. A process to fabricate cellular structures, normally used in implants to promote bone ingrowth, is presented herein. Cellular Zinc was fabricated from Zinc powder, not intended for Additive Manufacturing applications, in a commercial Selective Laser Melting system. The process addresses the parameter development for SLM Zinc, powder particle analysis, manufacturing process and geometric design and parameters for cellular structures. Mechanical performance test, discussion and remarks completes the work.

Design, Production & Lifecycle Considerations

Tuesday AM  Room: 404  Location: Hilton Austin

8:15 AM  Adaptive Production Planning for AM series applications: Tobias Stittgen1; Maximilian Liese1; 1RWTH Aachen Digital Additive Production DAP; 2University of California Los Angeles

Enabling economies of scale in an Additive Manufacturing production environment is one of the major challenges the automotive, aerospace and even general industries sector is facing these days. As many technological issues along the entire process chain have already been solved, the flawless integration, especially into existing production lines, is hindered by a lack of robust methods for AM production planning (PP). While build job compilation, nesting of parts and job scheduling has been widely discussed in the literature, there are no holistic approaches for an automated, fully AM-integrated PP process, taking into account enduser-specific input factors such as adherence to delivery dates, batch sizes and capacity planning. Therefore, the goal of the research work to be presented is to develop a software tool, enabling continuous, real-time optimization of a mass production scenario with regard to desired part quality, production time and/or cost.

8:35 AM  Applying Prediction Algorithms to Part Selection for Print Jobs and Production Floor Scheduling: Aleksander Ciszek1; Alexandre Donnadieu-Deray1; 1YOURMIND

Lean manufacturing has dramatically impacted production efficiency, but additive manufacturing presents a new set of challenges and opportunities. AM Machines need to switch from a low volume moderate variety to a high volume and large variety of parts produced. This trend requires industrial 3D printing services to deal with an exponential complexity of production workflows, with different kinds of production processes and complex costs structures. In this landscape, it is becoming essential to add tools like predictive scheduling, dynamic workflow management and real-time production planning. Understanding this challenge is crucial for companies who aspire to become the leaders of Agile Manufacturing. Prediction algorithms can be used to link the sales team, design engineers, scheduling, the production floor and the machines themselves to create a seamless digital factory. The presentation will include first applications and how these algorithms are shifting the production workflow and business models for producers. The need to balance predictive suggestions with the expertise of employees will be explored. A frame work will be proposed for developing a standardized data transfer method for additive manufacturing. Adding predictive software algorithms onto the production floor is the next large step for improving production efficiency and creating a more agile production environment for AM. This presentation provides the abstract concepts about production prediction that 3D print services need to the understanding in order to take full advantage of scheduling and management software in production.
8:55 AM
Design for Additive Manufacturing: Simplification of Product Architecture by Part Consolidation for the Lifecycle: Samyeeon Kim; David Rosen; Yunlong Tang; Singapore University of Technology and Design; Georgia Institute of Technology

AM printed parts are often redesigned to exploit unique AM capabilities. To configure a product, AM parts are typically assembled with other parts from conventional manufacturing. This research addresses the question: How can product architectures be designed to take advantage of AM’s advantages, while satisfying economic and lifecycle requirements? To address this issue, this study provides a design method to simplify product architecture by part consolidation from the viewpoint of the product lifecycle. Part candidates to be printed by AM are determined by AM potential and manufacturing cost, and uniqueness for customization. Based on these part candidates as a starting point of part consolidation, neighboring parts are consolidated to integrate functions, reduce assembly difficulty and cost, and consider maintenance. As a result, various simplified product architectures with consolidated parts for AM are generated that take into account product lifecycle considerations. A case study is performed to demonstrate the proposed method.

9:15 AM
A Modeling-based Study of the Use of Additive Manufacturing for the On-demand Spare Part Supply: Yuan Zhang; Li Yang; Lihui Bai; University of Louisville

Despite the widespread expectation that additive manufacturing (AM) will become a disruptive technology to transform the spare parts supply chain, very limited research has been devoted to the quantitative modeling and analysis on how AM could fulfill the on-demand spare parts supply. In this study, analysis based on a discrete event simulation was carried out for the use of AM in replacement of traditional warehouse inventory for several on-demand spare parts supply scenarios. The impact of both spare parts demand characteristics (e.g., part attributes, demand rates) and the AM operations characteristics (e.g., machine size and postponement strategy) on the AM spare part supply performance was studied. The simulation results show that in many cases the AM operation is not as cost competitive compared to the traditional warehouse-based spare parts supply operation, and that the spare parts characteristics could significantly affect the overall performance of the AM operations.

9:35 AM
Potentials of Artificial Intelligence in Additive Manufacturing: K. Tuschen; Matthias Habdank; R. Koch; University of Paderborn

Additive manufacturing processes are spreading on an industrially applied level. This leads to increasing demands regarding the reliability and repeatability of these. Applications addressing some of the requirements have already emerged from the trend topic of artificial intelligence. Artificial intelligence is a comprehensive term that covers a broad spectrum of possible applications. The potential is not yet nearly exhausted. The biggest challenge is to bring the two complex issues additive manufacturing and artificial intelligence together without wasting potential through misapplication. In this paper we research current applications of artificial intelligence in additive manufacturing. Therefore, potentials and impact in the wider industrial application of additive manufacturing are derived to highlight the benefits of artificial intelligence in additive manufacturing. In this context an application to detect defects in metallographies of additive manufactured specimen will be presented.

9:55 AM
Large-scale Identification of Parts Suitable for Additive Manufacturing: An Industry Perspective: Jacob Shepherd; Nicholas Meisel; Pennsylvania State University

Additive manufacturing has many potential benefits to the aerospace industry, especially when low production quantities are required. These benefits range from lightweight and complex geometries to reduced setup costs and lead time. One of the largest challenges to introducing AM into an existing aerospace vehicle is identifying which parts are candidates to be printed. This paper identifies a number of criteria that can be used to quickly filter parts into three categories: Printable As-Is, Easily Redesigned for Printing, and Not Recommended for Printing. The criteria are also broken into three tiers based on their impact on eliminating parts from the selection process. As a demonstration of these criteria, a case study is performed on a suborbital rocket, consisting of over a thousand parts. A flow chart is provided to guide the implementation of the filtering criteria, as well as methods to adapt the criteria to different industries.

Materials: Ceramics, Glasses, Other II

Tuesday AM
Room: Salon A
August 13, 2019
Location: Hilton Austin

Session Chair: Frank Brueckner, Fraunhofer IWS Dresden / TU Dresden / LTU Lulea

8:15 AM
Ceramic On-demand Extrusion of Low Temperature Co-fired Ceramics: Austin Martin; Wenbin Li; Jeremy Watts; Gregory Hilmas; Ming Leu; Tieshhu Huang; Missouri University of Science & Technology; Kansas City National Security Campus

Ceramic On-Demand Extrusion (CODE) is a direct-write additive manufacturing process which minimizes non-uniform drying for parts with large cross-sections. CODE also utilizes self-sealing augers which allow for precise deposition and complex tool path planning. Low temperature co-fired ceramic (LTCC) devices are an electronic packaging technology which provide desirable chemical resistance and temperature stability. Typical LTCC processing involves complex steps which require specialized equipment, such as via punching and filling, patterning, and lamination. Low temperature co-fired ceramics are an attractive application for CODE because it can consolidate many processing steps and allow for more complex structural integration. The current research is focused on the implementation of tool path planning software and materials development to print multiplayer co-fired circuits. Software implementations which are specific to circuitry and the feedstock materials will be discussed. The colloidal properties and rheology of CODE feedstocks will also be highlighted. Honeywell Federal Manufacturing & Technologies is operated for the United States Department of Energy under Contract Number DE-NA0002839.

8:35 AM
Freeform Extrusion Fabrication of Alumina and Zirconia Functionally Graded Materials: Wenbin Li; Austin Martin; Tieshhu Huang; Jeremy Watts; Gregory Hilmas; Ming Leu; Missouri University of Science and Technology; NNSA's Kansas City National Security Campus

Ceramic On-Demand Extrusion (CODE) is an extrusion-based additive manufacturing process capable of fabricating dense monolithic ceramic components. In this study, the CODE process was employed to fabricate Functionally Graded Materials (FGM). A dynamic mixing mechanism was utilized to blend constituent ceramic pastes before deposition. FGM specimens with compositions graded between Al2O3 and ZrO2 were fabricated and ultimately densified by sintering. Energy dispersive spectroscopy (EDS) was used to compare the final compositions to the original material designs, to validate the feasibility of fabricating FGM components by the CODE process. Based on experimental results, the challenging issue of obtaining FGM ceramic parts without severe deformation due to the mismatch of material properties including coefficient of thermal expansion, paste curing speed, and volume shrinkage during sintering is discussed and potential solutions proposed.
Aerosol Jet Printing of Inductor Devices for Power Electronics: Lok-kun Tsui; Ste-ven Kayser; Eric Langlois; Judith Lavin; University of New Mexico; Sandia National Laboratories
Aerosol Jet Printing (AJP) is an additive manufacturing technique used to deposit thin films of a wide range of insulators and metals. In AJP an ink mist is driven through a flow cell where a sheath gas confines the ink stream into a fine beam for deposition. We have used AJP to deposit fine Ag traces that make up the toroidal windings of inductors for power electronics. Optimization of the ink formulation, gas flow rates, toolpath generation algorithms, and post-process heat-treatment conditions resulted in trace line-widths as low as 10 microns, sub-micron thick films, conductivity of 17% of bulk Ag, and minimum overspray. Impedance spectroscopy to assess the inductive properties of additively manufactured inductors with AJP printed toroidal windings and extrusion printed magnetic cores is also performed. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525. SAND Number: SAND2019-4229 A.

Advanced Applications for Zirconia Produced by NanoParticle JettingTM: John Martin; Bhargavi Mummareddy; Pedro Cortes; Eric MacDonald; Brett Conner; Jason Walker; Youngstown State University
Nanojetting is a new form of material jetting involving the dispersion of nanoparticles, of either metal or ceramic, which are suspended in a liquid solution. Highly detailed parts can be created as the layer thickness is 10 microns and the jetting resolution is 1200 DPI (20 microns). The development of creating finely detailed 3D printed zirconia objects has opened many doors into new applications regarding high performance ceramics. This study focuses on exploring new applications as well as investigating the overall capabilities of this novel technology. Some applications being investigated include electromagnetic, where low loss and high dielectric permittivity are extremely advantageous, as well as custom protective thermal housings for sensors used in extremely high temperature conditions. The properties being tested involve strength features such as flexural, compression, and hardness in addition to shrinkage variations. Different sintering profiles are also being investigated to elucidate the effects on part quality.

Printing SiO2 Dielectrics Using Reactive Inks at Low Temperature: Subbarao Raikar; Avinash Mamidanna; Pengfei Yang; Kris Parker; Owen Hildreth; Colorado School of Mines
With the semiconductor industry beginning to adopt additive manufacturing techniques for wearables, sensors, and flexible electronics, there is a need to develop inks that print high-quality materials at low temperatures. This work shows that sol-gel based printed reactive SiO2 inks can have high density with good dielectric properties, even when printed at temperatures below 100°C. The impact of substrate temperature, solvent viscosity, solvent vapor pressure on the composition, morphology, mechanical properties, and dielectric properties of the printed SiO2 layers are detailed. The primary objective of this work is to study the kinetics, mechanical, and electrical properties of SiO2 dielectrics printed using reactive inks. A COMSOL Multiphysics model is developed to establish how the SiO2 hardens when ultra-thin layers are printed by understanding the relationship between evaporation, fluid flow, particle aggregation, and hydrolysis kinetics.

Production of Geometrically Complex Glass Parts Using Indirect Selective Laser Sintering: Deborah Hagen; Alex Chen; Joseph Beaman; Desiderio Kovar; University of Texas Austin
Current production of geometrically complex glass parts relies on traditional glass blowing, the use of molten glass with molds, or drawing techniques to produce the geometry required for a final product. This limits feature geometries and sizes that otherwise might improve performance. This research proposes a method for producing geometrically complex glass parts using indirect selective laser sintering. A polymer binder is mixed with glass particles, which allows a green part to be produced by selectively melting the binder. The green part can be extruded to further reduce the feature size possible in the final glass part. The part is then pyrolyzed to remove the polymer and then heated further to sinter the part.

Cellular Ceramics by Selective Laser Sintering: Doug Sassaman; Aaron Liao; J Beaman; D Kovar; University of Texas Austin
The inherent porosity in indirect Selective Laser Sintering (SLS) of ceramics lends itself to producing cellular ceramics, where high surface area and multiscale porosity are desired. This porosity was tailored by varying material composition and laser energy applied to the part. Material composition was altered by mixing various types of aluminum oxide with one of two different sacrificial binders, stearic acid and polyamide 12. Groups of rectangular prisms were built with laser energy applied simultaneously with furnace heating. Selective laser flash sintering (SLFS) uses a scanning laser as the only external heating source in combination with a high electric field. The SLFS technique can increase in sintering rate of ceramics, which is of great value in ceramic additive manufacturing, particularly in selective laser sintering of ceramics. In this work we present the effects of selective laser flash sintering on yttria-stabilized zirconia ceramic using a carbon dioxide laser. The effects of processing parameters on ceramic surface temperatures, electrical current flow through the ceramic, and microstructure will be presented.
11:25 AM  
Characterization of Laser Direct Deposited Magnesium Aluminate Spinel Ceramics: John Pappas1; Xiyang Dong1; 1Missouri University of Science and Technology

An additive manufacturing (AM) approach, via laser direct deposition, is investigated in printing transparent magnesium aluminate spinel (MAS) ceramics. Using AM, traditionally difficult or expensive to manufacture shapes, such as optical lenses, can be rapidly manufactured to near net shape, reducing time consuming and expensive post processing requirements. The transparency of MAS ceramics is highly dependent on the microstructure, with porosity and microcracking having the largest effect on the transparency of fabricated parts. With high localized heat inherent in the laser deposition process, the microstructure of ceramic parts can be controlled by adjusting processing parameters. In this study, thin wall MAS structures were fabricated by varying processing parameters. Processing parameters including laser scan speed and laser power showed a large influence on the part quality. To fabricate transparent magnesium aluminate spinel ceramics with high mechanical properties, the effects of processing parameters on part porosity, density, and microstructure were studied. Dense MAS parts were successfully fabricated through the laser direct deposition process. Low scan speed and high laser power showed the most promising results in fabricating MAS parts of low porosity. Using a low powder flow rates of 0.58 g/min, a relative density of nearly 98% was achieved. Directional cooling through the substrate and from the powder conveying gas led to columnar grain growth at a tilt angle from the build direction. The primary defects of fabricated MAS ceramics were found to be residual porosity and microcracking, which negatively affected part transparency and mechanical properties. Typical microcracking patterns included transverse and longitudinal cracking, with longitudinal cracks being more prevalent due to the existence of columnar grains and transgranular fracture mode. A preliminary study demonstrated that a certain degree of transparency was achieved in additively manufactured MAS ceramic parts via laser direct deposition.

11:45 AM  
Fabrication and Characterization of High-Purity Alumina Ceramics Doped with Zirconia via Laser Direct Deposition: Aditya Thakur1; John Pappas2; Xiyang Dong1; 1Missouri University of Science and Technology

Additive manufacturing of ceramics via laser direct deposition is particularly challenging owing to high thermal gradients and subsequently high tendency for thermally induced cracking. Therefore, it is necessary to have an improved understanding of the effects of processing conditions and material compositions on the quality of deposited ceramic parts. In this paper, thin wall structures of high purity ceramics were fabricated with commercially available alumina powder. The effects of zirconia dopants, varying from 0 wt.% to 10 wt.%, were studied. The microstructure and compositions of the manufactured specimens were characterized using scanning electron microscopy and energy dispersive x-ray spectroscopy. The obtained images were then used to study grain size, orientation, and distribution. Grain size distribution varied within the deposited ceramic parts due to the non-uniform temperature distribution during printing. The zirconia dopant was found to mainly accumulate within grain boundaries. An increasingly finer microstructure was observed with increased zirconia doping materials in the printed samples.

12:05 PM  
Formation of Nitride and Carbide Compounds via Laser Synthesis: Bradley Childs1; Aiden Martin1; Kiel Holliday1; Yaakov Idell1; Scott Simpson1; CHERIE SCHAEFFER-CUELLAR1; Ryan Stillwell1; Jason Jeffries1; 1Lawrence Livermore National Laboratory

High temperature synthesis with the use of lasers presents a new dynamic that allows for the synthesis of binary compounds. The increase in materials able to be produced by this technique would expand the capabilities of chemistry via laser synthesis and allow for fabrication of parts of increasing complexity. Here, the high temperature syntheses of nitride and carbide compounds under laser conditions is discussed. The production of nitride and carbides of titanium, silicon, and boron using this method enables rapid fabrication of ultrahard tooling components and chemically resistant surface coating. The material properties of nitride and carbide coating were characterized by energy-dispersive X-ray spectroscopy, residual gas analysis and X-ray diffraction to reveal material chemistry, structural quality and density. The findings detailed here enables realization of these ultrahard and chemically resistant coatings under SLM conditions enabling critical part properties. Prepared by LLNL under Contract DE-AC52-07NA27344, LDRD Project 18-SI-001.LLNL-ABS-772083.

Materials: Metals III - Nickel 718

Tuesday AM  
August 13, 2019  
Room: 416 AB  
Location: Hilton Austin  
Session Chair: Jorge Ramos-Grez, Pontificia Universidad Católica de Chile

8:15 AM  
Additive Manufacturing of High-Gamma Prime Nickel-Based Superalloys through Selective Laser Melting (SLM): Amrita Basak1; 1Pennsylvania State University

High-gamma prime nickel-based superalloys are abundantly used in the aerospace, marine, nuclear, and chemical industries where excellent corrosion and oxidation resistance, superior mechanical properties, and exceptional high-temperature performance are required. However, selective laser melting (SLM)-based additive manufacturing (AM) of high-gamma prime nickel-base superalloys pose significant challenges due to these alloys’ complex chemistry. With multiple alloying elements and high aluminum + titanium fraction, these materials when consolidated through AM form various secondary phases severely affecting the processability leading to the formation of cracks. The objective of this review is to summarize the progress made so far on SLM of high-gamma prime nickel-based superalloys with a special emphasis towards elucidating the relationships between processing, microstructures, and properties in this alloy system.

8:35 AM  
The Effect of Primary Process Parameters on Porosity Population Characteristics in Alloy 718: Luke Sheridan1; Joy Gockel1; Onome Scott-Emuakpor1; 1Air Force Research Laboratory; 2Wright State University

Laser powder bed fusion (LPBF) manufactured materials commonly exhibit voids and defects. Some applications leverage these defects for specific purposes while other applications seek to remove them. The literature has shown that several defect characteristics are controllable through process parameter manipulation, but the number of factors and complex interactions make determining optimal process parameters very expensive. To this end, an experiment was designed using several primary processing parameters known to control porosity in AM components. The purpose of this experiment was to explore a wider region of laser powder bed fusion process space, and to obtain several measurements to characterize porosity population attributes such as component density, porosity percentage, pore size, and shape. Then, multiple porosity prediction models from the literature were compared with the experimental data. This work informs the conversation concerning defects in AM components and provides insights into physical mechanisms that produce defects via LPBF.
Investigating the build consistency of a laser powder bed fused nickel-based superalloy, using the small punch technique: Benjamin Haigh; Robert Lancaster; Richard Johnston; Martin White; James Minshull; 1Swansea University; 2GKN

Inconel 718 is a nickel-based superalloy that possesses impressive corrosion resistance and high strength at elevated temperatures, making it an ideal choice for aerospace applications. However, with the continuous evolution of the jet engine, there is a strong desire to fabricate more intricate components with less stress-raising features. To overcome this, companies are looking at Additive Manufacturing (AM) as a potential solution. In this paper, uniaxial and small punch samples of Inconel 718 were manufactured using the AM process known as Laser Powder Bed Fusion (LPBF). A limitation of AM is the transient nature of the microstructure. It is difficult to produce representative scale mechanical test specimens that closely replicate the microstructure of the finished component. Therefore, it can be beneficial to utilise small-scale test methods, such as the Small Punch (SP) test, which can utilise specimens directly extracted from the cross section of the finished part.

Microstructure, Surface Roughness and Dimensional Accuracy for As-built Thin Wall Inconel 718 with Laser Powder Bed Fusion: Mandar Shinde; Paul Paradice; Cameron Noe; Dhruv Bhate; 1Arizona State University

Most functional parts made with metal Additive Manufacturing (AM) undergo Hot Isostatic Pressing and machining to reduce porosity, surface defects, and to meet tight critical dimensions. However, metal AM applications that involve thin walls or struts, often cannot be accessed for machining with the same degree of precision possible for thick-section components. The requirement for machining also drives up cost, and importantly, it restricts the design freedom that often makes AM an attractive proposition to begin with. For these reasons, this study focuses on as-built, thin wall structures made out of Inconel 718 using the Laser Powder Bed Fusion process. This study shows how morphological characteristics (porosity, surface finish, grain morphology) change as a function of size. As the thickness of components is reduced, changes in porosity distribution, dimensional accuracy, and surface finish are observed. The role of laser scan strategy in influencing these characteristics is also discussed.

End-to-end Study of Microstructural Evolution and Defect Distribution for L-PBF IN78: Parisa Farahmand; Vijay Jagdale; 1AM COE- United Technology

Additive Manufacturing technologies are being increasingly employed in aerospace systems and certified additive manufacturing (AM) process is one of the current gap. Adoption for critical applications is limited by incomplete understanding of process inputs and its responses, such as defects, microstructure, surface integrity and resultant static as well as dynamic properties. To develop a robust optimized repeatable AM process and products end-to-end process understating is critical. In this study, a systematic end-to-end study is undertaken for Laser Powder Bed Fusion (L-PBF) of IN 718 material. Single track depositions and representative bulk geometry specimen are studied in terms of the effect of process parameters and different post processing steps on microstructural evolution and defect distribution. Since post processing in AM parts plays a major role in final built part quality, in this study microstructural evolution and defect distribution after each post processing step has been analyzed and compared.

Mechanical Properties of Selective Laser Melting IN718 Subjected to Experimental Hot Isostatic Pressing Cycles: Jaime Varela; Christina Pickett; Ahmad Abu-Issa; Edel Arrieta; Ryan Wicker; Magnus Ahlors; Donald Godfrey; Francisco Medina; 1University of Texas El Paso; 2Quintus Technologies; 3Honeywell Aerospace

The process of Hot Isostatic Pressing (HIP) is used on metals to improve density, and heal micro defects. Applied heat and pressure induce plastic deformation and diffusion bonding. The process can provide critical relieve to the internal stress associated with laser based additive manufacturing. Inconel 718 is a Nickel based super alloy commonly used in aerospace applications due to its retention of mechanical properties at high temperatures and excellent oxidation and corrosion resistance. Experimental HIP cycles were applied to Selective Laser Melting parts from an EOS M290 Machine. The specimens were tested as per ASTM E8 Standard. Different cycles yield various effects on the porosity reduction as well as the growth of grain in the microstructure, consequently presented different mechanical performances. Specimens were therefore analyzed for density, microstructure and chemical composition. The results of the series of experiments were analyzed and compared with as built specimens.
Fatigue crack growth thresholds were measured in selective laser melted (SLM) nickel superalloy 718 in two orientations. Two heat treatments were tested, one of which included a hot isostatic pressing (HIP). At a load ratio of 0.1, all SLM conditions showed significantly lower thresholds than wrought material. HIP processed samples had higher thresholds than non-HIP processed samples. Much of the differences between conditions can be attributed to reduced magnitude of the fatigue crack closure mechanisms that are responsible for the high threshold in wrought material. Contributions from plasticity and roughness induced closure are discussed in a microstructural context. Contributions to crack closure from residual stresses are also discussed in the context of neutron diffraction residual stress measurements. Constant maximum stress intensity threshold tests were also conducted to generate high load ratio closure free thresholds. Differences between the SLM conditions and wrought material narrowed significantly in the absence of closure phenomena.

Fatigue Behavior of Laser Beam Directed Energy Deposited Inconel 718 at Elevated Temperature: Alexander Johnson; Rakish Shrestha; Pooriya Dastranjy Nehzadfar; Nima Shamsaei; TrVector Services Incorporation; Auburn University
Due to its superior mechanical properties at elevated service temperatures, nickel based super alloys such as Inconel 718 are being extensively used to manufacture turbine blades for jet engines. Furthermore, poor machinability associated with Inconel 718 also makes it an attractive material for additive manufacturing processes, which possess the capability to fabricate near net shaped parts. In this study, the fatigue behavior of Inconel 718 fabricated using laser beam directed energy deposition (LB-DED) is investigated under strain-controlled, fully-reversed conditions at an elevated temperature of 650°C. A thorough microstructural analysis was also conducted to determine the evolution of grain structure due to elevated test temperatures. In addition, fractography analysis was performed to determine the failure mechanisms for LB-DED Inconel 718 due to higher working temperatures.

Very High Cycle Fatigue Behavior of Laser Beam-powder Bed Fusion Inconel 718: Palmer Frye; Jutima Simsiriwong; University of North Florida
In this study, the very high cycle fatigue (VHCF) behavior of Inconel 718 manufactured via a Laser Beam-Powder Bed Fusion (LB-PBF) process is investigated, with emphasis on the effects of surface roughness. LB-PBF Inconel 718 specimens are fabricated in vertical direction with two surface finish conditions, as-built and machined, and subjected to post-processing heat treatment. The experiment is conducted utilizing an ultrasonic fatigue test system operating at 20 kHz under force-controlled fully reversed constant amplitude cyclic loading. Fractography analysis is performed using an optical microscope and a scanning electron microscope to identify microstructural features that initiate fatigue cracks in both as-built and machined specimens. Experimental results from LB-PBF Inconel 718 specimens are presented and compared to those of wrought Inconel 718.

Materials: Metals IV - Aluminum Alloys
Tuesday AM Room: 417 AB Location: Hilton Austin
Session Chair: David Espalin, UTEP - W.M. Keck Center for 3D Innovation

8:15 AM Laser Powder Bed Fusion of AISI10Mg Powders with Narrow Particle Size Distribution: Tiffany Turner; Maëva Chrzaszcz; Jose Muniz-Lermia; Jaskaranpal Dhillon; Eileen Espiritu; Mathieu Brochu;
McGill University
AISI10Mg alloys are of great interest in the aerospace industry due to their desirable machining and casting characteristics at relatively low costs. Here we have investigated the possibility of utilizing powder bed fusion additive manufacturing with powders having a very narrow PSD, with the aim to minimize fabrication defects. We characterized the powder properties and flow, and compare the gas atomized powders to the as-printed microstructures. We linked the effects of processing parameters on density, as-built microstructure and mechanical properties.

8:35 AM On the Influence of Process Interruptions during the SLM Process on the Fatigue Resistance of AISI12: Julia Richter; Thomas Niendorf;
University of Kassel, Institute of Materials Engineering - Metallic Materials
The process of laser powder bed fusion is characterized by building at relatively low rates. Particularly processing of larger parts is time consuming. During long-lasting build-jobs process instabilities may occur leading to an interruption of the build-job, e.g. induced by power blackout or issues in process gas supply. Then, a restart of the whole build-job seems to be necessary increasing the overall processing time significantly. Restart of the same build-job at given height would be economically more efficient. The current study investigates the influence of interruptions on the material properties of AISI12 processed by selective laser melting (SLM). The interruption considered here includes cooling down of the build-job, inlet of atmospheric air, floating with argon again and heating up to restart. The influence of the interruption on the microstructure as well as the properties under quasi-static and cyclic loading are investigated and compared to well-managed build-jobs of the same material.

8:55 AM Investigation of the Selective Laser Melting Process for AISI10Mg and AA6061 Fabricated at High Laser Power: Michael Pires; Tzung Shin Guo; Wojciech Misiolek; Lehigh University
Selective Laser Melting of AISI10Mg and AA6061 is challenging in producing sound parts due to low powder flowability and high thermal conductivity. 3-D printing in machines with higher laser powers creates new microstructures, which are not fully understood. This project investigates aluminum powders printed parts using laser ranging from 200 to 350 Watts. The research objective is to establish the relationship between laser power and the resulting microstructure obtain using Renishaw AM400 unit. 10 mm x 10 mm x 10 mm solid cube samples were printed from AISI10Mg and AA6061 powders with variation in laser power, point spacing, and dwell time. Density of each sample was determined using the Archimedes method and light optical microscopy. Metallographic analysis determined optimum build parameters and characterized the melt pool boundaries and porosity formed in the SLM process using light optical microscopy. Microhardness tests were performed to determine mechanical properties.
Post-processing Heat Treatments and Residual Stress Behavior of AlSi10Mg: Michael Juhaasz; Will Bevan; Jared Clark; Jason Walker; Brett Conner; Youngstown State University

Laser powder bed fusion (LPBF) produced AlSi10Mg parts are being explored as a potential method for replacement of castings made of alloys such as A356. Like their traditionally produced counterparts, additively manufactured parts raise concerns about post-process induced distortion. Transverse isotropy and “as-produced” dendritic microstructures also add to these concerns and are unique to LPBF parts. Here the results will be presented from a design of experiments examining the post processing conditions of hot isostatic pressing (HIP), quench rate, and the length and temperature of artificial aging against existing heat treatment schedules. It will be shown that hot-isostatic pressing (HIP) before heat treatment will be shown to boost tensile properties. Lastly, residual stress measurements for a complicated part geometry will be shown and compared to simulation results.

Surface Damage of an AM-AlSi10Mg Alloy Exposed to Corrosive Environments with Lack of Fusion Defects and Powder Contamination: Holly Martin; Daniel Bogen; Vathula De Silva Jayasekera; Brett Conner; Youngstown State University

Laser powder bed fusion additive manufacturing can be used to create aerospace replacement parts. However, rogue processing conditions can produce defects at or near the surface. Two processing conditions of concern in this research are 1.) laser processing parameters that produce lack of fusion defects and 2.) inadvertent powder contamination. Lack of fusion defects can lead to a concentration of corrosive ions and increased damage. Powder contamination, potentially occurring when changing metal powders, can lead to an increase in corrosion, by creating galvanic cells. Determining how the effect of these defects on the metal in corrosive environments is vital, especially for parts planned for critical or long-term applications. The research presented here will detail the effects of corrosive environments on baseline material, material containing lack of fusion defects, and powder contamination samples to determine the type and extent of corrosive damage, which could result in unacceptable performance.

Additive Manufacturing of Aluminum Alloys by Laser Foil Printing: Chia-Hung Hung; Yingqi Li; Xiangtuo Gong; Heng Pan; Ming C. Leu; Missouri University of Science & Technology

This study investigates the feasibility of using the newly developed laser-foil-printing (LFP) additive manufacturing process to fabricate aluminum alloy parts from 300 micron-thick Al-1100 foils. First, a set of feasible process parameters were found through a parametric study by using LFP of a single Al-1100 layer. These feasible parameters were able to generate sufficient penetration depth and a stable melt pool, resulting in the weld layer without pores or cracks. By using these parameters, Al-1100 parts were successfully built with only ~0.5% porosity. The mechanical properties of the fabricated parts were measured using tensile tests, and their crystal structures and grain distributions were characterized using X-ray diffraction (XRD) and electron-backscatter diffraction (EBSD), respectively.

Analysis of Fatigue Crack Evolution Using In-situ Testing: Hassan Alqahtani; Eric Keller; Asok Ray; Amrita Basak; Pennsylvania State University

Fatigue damage is one of the most ubiquitous sources of structural degradation during both nominal and off-nominal operations in engineering components. While model-based computational methods for assessing structural damage evolution are available, difficulty in achieving the required accuracy due to inadequacy in capturing the dynamical behavior of fatigue damage at the grain level makes them difficult to solely rely on. The objective of the current work is to investigate the evolution of fatigue failure in aluminum parts in real time. An in-situ fatigue testing setup integrated with ultrasonic transducers and a digital microscope allows for the systematic study of fatigue crack evolution in aluminum specimens. The resulting data from experimentation, characterization, and analysis are integrated to gain unprecedented insights into the evolution of fatigue failure in aluminum parts.

Selective Electron Beam Melting of Al-Cu-Mg Alloy: Microstructure Characterization and Mechanical Performance: Mohammad Saleh Kenevisi; Feng Lin; Tsinghua University

Additive manufacturing of aluminum parts has been widely taken into consideration in different industries in recent years, however there is a basic need to develop high-strength aluminum alloys to satisfy the industrial requirements. To date, fabricating high strength aluminum parts have not yet fully investigated, due to solidification cracking and porosity formation. In this study, Al2024 parts were fabricated by electron beam selective melting (EBSM) process. Density measurement and microstructural analysis revealed that full-dense and crack-free samples with fine and equiaxed grains can be achieved by optimizing the processing parameters. Microhardness results showed an almost uniform change of hardness values within the sample in both horizontal and vertical sections, ranges from 100 HV to 110 HV for as-built samples. Additionally, the tensile and yield strengths of as-built samples reached 314 MPa and 191 MPa, respectively which can be further increased by a proper heat treatment.

Drop on Demand Jetting of Molten 6061 Aluminum: Usama Rifat; Khushbu Zope; Paarth Mehta; Denis Cormier; Rochester Institute of Technology

Powder bed fusion metal AM processes have been successfully used to process aluminum-silicon alloys with excellent results. However, they are less commonly used with precipitation hardening 2024, 6061, and 7075 alloys due to heat cracking and other challenges. This paper will explore the microstructure and properties of 6061 aluminum that has been deposited via an on-demand liquid metal droplet jetting process. The effect of jetting conditions (i.e. melt temperature, jetting frequency, droplet spacing, etc.) on microstructure will be discussed. Specifically, the analysis will consider the presence or absence of microcracks, density/porosity, grain structure, and elemental homogeneity. Lastly, mechanical properties such as tensile strength and modulus for as-printed and heat treated 6061 aluminum will be compared with handbook values.

Process Parameter Induced Lack of Fusion Defects in AlSi10Mg: Vathulla De Silva Jayasekera; Jeremy McKnight; Youngstown State University

The combination of laser powder bed fusion process parameters such as laser power, scanning velocity, layer thickness, and hatch spacing can result in the formation of lack of fusion defects due to inadequate melt pool overlap. These defects can degrade the material properties and performance of the part. Here, results are presented from a design of experiments where each of these parameters are changed and specimens are fabricated from AlSi10Mg powder. Optical metallography and image analysis are used to evaluate the size, shape, and distribution density of defects for each of the process conditions. In-situ melt pool monitoring data is compared to the optical metallography results and a determination is made if defect detection is possible.
8:15 AM

**Experimental Validation**

**Powder Bed Fusion: Non-equilibrium Phase Field Modeling and Experimental Validation**

*Kubra Karayagiz*; **Raiyan Seede**; **Luke Johnson**; **Bing Zhang**; **Ibrahim Karaman**; **Alaa Elwany**; **Raymundo Arroyave**

In the present work, we developed a computational modeling framework, which couples a finite element thermal model to a non-equilibrium phase field model to investigate the rapid solidification microstructure of Ni – 3.2 at. % Nb during LPBF. The framework was utilized to predict the spatial variation in the morphology and size of single-track melt pools obtained under varying process conditions. A planar to cellular transition was predicted in the majority of keyhole mode melt pools, while a planar interface beyond the limit of absolute stability was predominant in the conduction mode melt pools with high growth rates. The predicted morphology and size in the single-track melt pools under varying process conditions were compared against those experimentally measured and a very good agreement was achieved. Finally, a solidification map demonstrating the variation in the microstructure as a function of laser power and laser speed was presented for future design purposes.

8:35 AM

**Melting Modes in Laser Powder Bed Fusion and their Application towards Recipe Development**

*Sagar Patel*; **Mihaela Vlasea**

Laser powder bed fusion (LPBF) has broadly two different operational regimes, conduction and keyhole mode. Heat conduction governs the melt pool morphology observed in conduction mode melting. In contrast, keyhole mode melting is observed when the morphology of the molten pool is controlled by thermo-capillary convection and recoil momentum pressure generated by vaporization of a given material. In this work, we describe another melting mode called transition mode wherein the dominance of conduction or convection depends on processing conditions. Additionally, we propose processing diagrams to visualize the three melting modes - conduction, transition, and keyhole mode, along with a temperature prediction model to predict melting mode thresholds in both continuous and modulated beam LPBF systems. The normalized processing diagrams obtained from this work are used for understanding the physical origins of defects in three-dimensional Ti-6Al-4V continuous LPBF parts and AlSi10Mg modulated LPBF parts.

8:55 AM

**Validated Computational Modelling Techniques for Simulating Melt Pool Ejecta in Laser Powder Bed Fusion Processing**

*Daniel Butcher*; **Steve Brown**; **Nick Lavery**

Industry currently require faster build rates from laser powder bed fusion processes. As such, higher power lasers and multi-laser systems are being explored. Due to instabilities in the melting process material is ejected from the melt pool, in the form of spatter and vapour. Previous work has shown that these ‘ejecta’ can result in: attenuation of the laser and redeposition of droplets onto the powder bed; which can lead to poor mechanical properties. ANSYS Fluent was used to create a CFD model which was validated against hot wire anemometry results from Renshaw’s RenAM 500Q. This was then coupled with a Discrete Phase Model (DPM) and a multiphase formulation to track the ejection of spatter and vapour from the melt pool through the chamber. This has led to a better understanding of the removal of ‘ejecta’, leading to increased mechanical properties and lower rates of build failure.

9:15 AM

**Numerical Simulation and Experimental Validation of Solidification Phenomena in Functionally Graded Ti-Al Composite Coatings Fabricated with Laser Metal Deposition**

*Sisa Pityana*; **Subas Rao**; **Eyiayo Olatunde Olakamnif**; **Gaamangwe, Matsagopane**; **Thataoye Lekang**; **Carlos Kakwana**; **Bajaki-Ntesang**; **Mompati Ngwako**; **Oboletswe, Mookelets**; **Nokuthula, Mswela**; **Shaik Hoosain**; **Monamme Tlotleng**

Thermodynamic consistent phase field (PF) and laser metal deposition (LMD) models were employed in elucidating the solidification phenomena of Ti2AlCx dendrites in functionally graded (FG) Ti-Al/TiC composite coatings fabricated with 20 J/mm2 and pre-heated at 800oC. Temporal and spatial temperature fields of the molten pool were analysed via the LMD model. PF model was employed in predicting the microstructural evolution of Ti2AlCx dendrites across the volume of the FG coatings. It was established that micro-segregation could be accounted for by the distribution of carbon over the dendrites where the dendrite tips had a higher carbon concentration as temperature decreases. Increased refinement of the dendrites of Ti2AlCx at an increased speed from the bottom to the top could be ascribed to increased undercooling. In conclusion, the predicted temperature history, deposition geometry as well as the morphology of polycrystalline Ti2AlCx dendrites were validated by experiments.
The Investigation of Process Parameters on the Structural Integrity of an Additively Manufactured Nickel-based Superalloy

Robert Lancaster1; Spencer Jeffs1; Dave Stapleton2; Gavin Baxter2; 1Swansea University; 2Rolls-Royce plc

Additive Layer Manufacturing (ALM) is a near net shape manufacturing technology that offers tremendous potential to a wide range of industrial sectors given its ability to produce highly intricate components with little material wastage. Subsequently the aerospace industry has become interested in utilising ALM as a means to manufacture nickel-based superalloys for high temperature applications within the gas turbine engine, which are traditionally fabricated through cast and wrought methodologies. As a result, a detailed understanding into the influence of key process variables on the structural integrity of the different experimental builds is required. A semi-empirical quantitative approach for melt track analysis has been conducted, with the impact on melt track sizing and defect forming mechanisms in the as built and heat treated condition being investigated. Furthermore, small punch creep (SPC) has been applied to these samples in order to effectively rank process parameters influence on high temperature mechanical performance.

Overview of In-situ Temperature Measurement for Metallic Additive Manufacturing: How and then What: Ruikai Liu1; Xiayun Zhao1; 1University of Pittsburgh

Additive manufacturing (AM) is important in industrial and economical domains but still lacking process accuracy. In-situ measurement and process control can offer an effective solution. In metallic AM, the temperature field of melting pool has critical impacts on phase transformation and mechanical properties. Researchers have developed various approaches to track real-time temperature during metal AM. Nevertheless, large temperature gradient around the energy source demands a capable measurement system and method due to the limitations of conventional infrared cameras and pyrometers. This study will explore the deficiency and improvement of the existing approaches with a focus on the cutting-edge methods of metallic AM process temperature measurement, along with a critical thinking about the follow-up usage of the collected data. Specifically, it will report the status and trends in employing various machine learning and advanced control techniques with the in-situ sensor data for process qualification purposes.

In-situ Local Part Qualification of SLM 304L Stainless Steel through Voxel Based Processing of SWIR Imaging Data: Cody Lough1; Xin Wang2; Robert Landers3; Douglas Bristow4; James Drallmeier5; Edward Kinzel6; 1Missouri University of Science and Technology; 2University of Notre Dame

This paper demonstrates the potential for local qualification of 304L stainless steel parts manufactured by Selective Laser Melting (SLM) through voxel based processing of SWIR imaging data measured in-situ. Thermal features are extracted from time-series data recorded from layer-to-layer to generate 3D point cloud reconstructions of parts. The voxel based data is indexed with localized measurements of SLM part properties (melt pool size, microhardness, µCT data) to demonstrate the correlations. Various features are extracted from the thermal history for comparison of their abilities to predict the resulting local part properties. The developed correlations are then used to discuss the capability of a voxel based framework using information from in-situ measurements of the thermal history to locally qualify parts manufactured by SLM. This work was funded by the Department of Energy’s Kansas City National Security Campus which is operated and managed by Honeywell Federal Manufacturing Technologies, LLC under contract number DE-NA0002839.

In-situ Full-field Mapping of Melt Flow Dynamics in Laser Metal Additive Manufacturing: Qilin Guo1; Cang Zhao2; Minglei Qu1; Lianghua Xiong1; Luis I. Escano3; S. Mohammad H. Hojatzadeh4; Niranjan D. Parab2; Kamel Fezzaa2; Tao Sun2; Lianyi Chen1; 1Missouri University of Science and Technology; 2Argonne National Laboratory

Melt flow plays a critical role in laser metal additive manufacturing, yet the detailed melt flow behavior within the melt pool had never been explicitly presented, largely due to the lack of direct experimental measurements. Here, we report in-situ characterization of melt flow dynamics in every location of the entire melt pool in laser additive manufacturing under both conduction-mode and depression-mode melting. The complex melt flow behavior is traced by populous and uniformly dispersed micro-tracers through synchrotron x-ray imaging. The location-specific flow patterns in different regions of the melt pool are revealed and quantified. The melt flow instability induced by powder/droplet impingement, depression-zone vibration, and surface wave are discovered. The major driving forces for melt flow and the dominating physical processes at different locations in the melt pool are identified.
9:35 AM

High-resolution Metal Printing by Discrete Ejection, Melting, and Deposition of Microparticles: Henry Merrow; Justin Beroz; Ulrich Muecke; Jiyun Kang; Cem Tasan; John Hart; Massachusetts Institute of Technology

Metal additive manufacturing is applicable to many diverse applications; however, each metal AM process has key capabilities and limitations that will define its industrial uses. Most commonly, metal AM of high-detail components involves layer-by-layer deposition and laser melting of metal powders. Metal printing by molten droplet deposition has also been explored and demonstrated, but long-term operation of a high temperature molten metal reservoir has proven challenging. Here, we present a high resolution direct metal printing method wherein individual metal microparticles are electrohydrodynamically ejected on-demand from a water meniscus [1] and laser-melted in-flight before landing and solidifying. We demonstrate printing of solder and platinum particles ranging in size from 30-150μm and explore the process parameter space as limited by the ejection conditions and the kinetics of melting, impact, and solidification. We further present metallurgical characterization of printed droplets and patterns. [1] Hart, A. J., Beroz, J. (2015). U.S. Patent 9,937,522.

9:55 AM Break

10:25 AM

Gaining New Insight into Metal Additive Manufacturing Processes Using Ontologies and Visualization: Byeong-Min Roh; Timothy Simpson; Soundar Kumara; Paul Witherell; The Pennsylvania State University; 1The Pennsylvania Institute of Standards and Technology

Metal additive Manufacturing (AM) processes like powder bed fusion and directed energy deposition involve numerous process parameters that have complicated relationships. These relationships must be understood and carefully controlled to ensure part quality. AM process models and simulations have been developed to identify many of these relationships; however, visualizing these relationships and synthesizing them into a broader understanding of an AM process remains a challenge. In this work, we present how an ontology for AM process models can be used to visualize important relationships between different process parameters and analytical results. We also demonstrate how it can be used to construct an AM dictionary that documents relationships between different pairs of process parameters. Several use cases are then discussed to demonstrate the value of these approaches and the utility of an AM process ontology.

10:45 AM

An Investigation of Selective Laser Melting at Elevated Atmospheric Pressure: Effects on Melt Track Morphology and Porosity: David Griggs; Jonathan Gibbs; A. Hart; Massachusetts Institute of Technology; 2U.S. Naval Academy

Selective laser melting (SLM) can achieve full density and near-net shape geometric accuracy, yet the dynamics of the melt pool and stability of the melt track upon cooling are critical to the microstructure, porosity, and properties of the solidified material. In particular, it is now well known that the extreme temperature gradients at the melt pool surface lead to rapid evaporation of molten metal, denudation, and spatter. This contributes to surface roughness, pore formation, and limits the overall energy efficiency of the SLM process. Here, using a custom built miniature SLM system with a high pressure build chamber, we evaluate a hypothesis that performing SLM at elevated ambient pressure can address the limitations imparted by melt pool dynamics. Using stainless steel as a model system, we perform parametric studies of the effect of pressure on isolated and hatched melt tracks, and quantify influences on surface quality, porosity, and microstructure.

11:05 AM

Spatter in Laser Powder Bed Fusion: The Good, the Bad and the Ugly: Paul Hooper; Imperial College London

Spatter from the laser-material interaction zone in powder bed fusion has a bad reputation. This is somewhat justified as when spatter lands back on the part surface it can shield the laser, causing insufficient melting and lack-of-fusion porosity. However, spatter also plays an important role in the process zone and acts an indicator for processing conditions. Too little spatter can be evidence of insufficient melting, whereas too much can indicate increased likelihood of keyhole porosity. This presentation will detail high-speed in-situ observations of spatter and show how common build scenarios and machine problems influence spatter and final part properties.

11:25 AM

New Scanning Strategies and Support Structures for Reduced Overheating on Down-facing Regions of Direct Metal Printed Parts: Umberto Paggi; Rajit Ranjan; Lore Thijs; Can Ayas; Matthijs Langelaar; Fred van Keulen; Brecht van Hooreweder; KU Leuven, Department of Mechanical Engineering, Leuven, Belgium; 3D Systems Leuven, Belgium; TU Delft, Department of Precision and Microsystems Engineering (PME), Delft, the Netherlands; 3D Systems Leuven, Belgium; KU Leuven, Department of Mechanical Engineering, Leuven, Belgium

In Direct Metal Printing (DMP), the downfacing surfaces usually have increased surface roughness and reduced dimensional accuracy due to local overheating. To partially overcome this different optimization strategies are attempted in this study. A first approach is to increase the heat dissipation by employing non-contact (or “thermal”) supports, which are planar blades parallel to the downfacing area that act as heat sinks. A second approach is to modify the scan strategy: new hatching patterns and laser parameters are tested to promote the heat flow from the downfacing area to the middle area, and to closely control the melt pool shape, dimension and position. In both cases the effectiveness is evaluated by measuring the surface roughness and the geometrical accuracy of the samples. Computer simulation is also employed to define the optimal distance for the thermal supports.

11:45 AM

The Development Status of the National Project by Technology Research Association for Future Additive Manufacturing (TRAFAM) in Japan: Hideki Kyogoku; Akihiko Chiba; Michiaki Hashitani; Takahisa Kimijima; Kindai University; Tohoku University; TRAFAM

The Ministry of Economy, Trade and Industry (METI) of Japan established Technology Research Association for Future Additive Manufacturing (TRAFAM) to develop AM technology in FY 2014. The members of TRAFAM include three academic institutions and 29 companies. The association’s mission is twofold; to develop metal Additive Manufacturing technology and to develop binder jetting-type machine for the rapid production of sand molds. The goal of TRAFAM project is the development of innovative metal AM systems that will meet the world’s highest standards and the development of AM technology for high value-added products for aerospace, medical, and transportation industries etc. In the presentation, the latest development status of the project, especially, the development status of the electron beam PBF type machines, the laser PBF type machine and the laser DED type machines is introduced. In addition, the simulation software for metal AM based on multi-scale and multi-physics model is introduced.
Process Development IV - Sensors, Measurement and Controls B

Tuesday AM  Room: 616 AB
August 13, 2019  Location: Hilton Austin

Session Chair: Jason Weaver, Brigham Young University

8:15 AM
Near-surface porosity affects the fatigue life of additively manufactured parts and hence it is important to address this for wide-spread use of additive manufacturing for cyclic loading applications in the aerospace and medical implant industries. A method to mitigate near-surface porosity is demonstrated in this work via finite element simulations and experimentation. Proposed methods are demonstrated for laser powder bed fusion of Inconel 718. Specifically, the contour (near-surface) melting parameters are designed to mitigate porosity resulting from keyholing or insufficient overlap with the hatch scans at the component surfaces. These customized contour parameters result in considerably lower near-surface porosity compared to the nominal contour parameters specified by the machine manufacturer. The method proposed in this work can be extended to different materials and powder bed fusion processes that allow the user to modify the contour processing parameters.

8:35 AM
A Sensor Fusion Approach for In-situ Measurement of Metal Laser Powder Bed Fusion: Andrew Dickins1; Taufiq Widjanarko1; Simon Lawes1; Richard Leach1; 1University of Nottingham
In-situ measurement for laser powder bed fusion is challenging due to the harsh environment within the build chamber and the short time frames available to capture a full powder bed measurement. This work proposes a non-contact measurement system that combines fringe projection, photogrammetry and photometric stereo to obtain a high resolution reconstruction of the top layer during a build process. A bench top test system has been built to the dimensions of a commercially available additive machine. Current testing of the system has shown that it is capable of identifying micron-scale features over a measurement volume comparable to an additive build area. Our intent is to integrate the system into an operating additive machine to perform process measurement and control on a layer-by-layer basis. Fusing the data from three different methods will provide a more reliable reconstruction than a single method measurement is capable of within the build chamber.

8:55 AM
Frequency Inspection of Additively Manufactured Parts for Layer Defect Identification: Aimee Allen1; Jason Blough1; Andrew Barnard2; Kevin Johnson3; Ben Brown2; Troy Hartwig2; David Soine3; Tristan Collum2; Edward Kinzel2; Douglas Bristow2; Robert Landers; 1Michigan Technological University; 2Kansas City National Security Campus managed by Honeywell; 3Missouri University of Science and Technology
Additive manufactured (AM) parts are produced at low volume or with complex geometries. Identifying internal defects is difficult as current testing techniques are not optimized for AM processes. The goal of this paper is to evaluate defects on multiple parts printed on the same build plate. The technique used was resonant frequency testing with the results verified through Finite Element Analysis. From these tests, it was found that the natural frequencies needed to detect the defects were higher than the excitation provided by a modal hammer. The deficiencies in this range led to the development of other excitation methods. Based on these results, traditional methods of resonant part inspection are not sufficient, but special methods can be developed for specific cases.

9:15 AM
High Rate Monitoring of Laser Motion and Melt Pool Dynamics during Laser-powder Bed Fusion: Bradley Jared1; Matthew Roach1; David Saiz1; Abdalla Nassar2; Jared Blecher1; 1Sandia National Laboratories; 2University of New Mexico; 3Penn State University; 43D Systems
Abstract: During the metal additive manufacturing (AM) process, many data signals can be collected and analyzed to identify process defects. Here, laser galvanometer position and melt pool intensity are being measured at a high rate, 100kHz, using an ARCS (Archive, Research, Control, Synchronization) system from 3D Systems. The intent is to monitor machine health and identify potential process defects without the need for post-process inspection. Managing and analyzing the large data sets inherent to high data rate monitoring will be discussed. Typical process signals and deviations will also be quantified and correlated to both normal and abnormal process conditions. Subsequent material structures will also be explored. By identifying and correlating these deviations to the existence of defects, the validation of AM parts can be done faster and with less resources. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

9:35 AM
Implementation of Spetropyrometry within Electron Beam Powder Bed Fusion for Accurate Surface Temperature Measurements: Alfonso Fernandez1; Cesar Terrazas1; Rayan Wicker2; 1W.M. Keck Center for 3D Innovation
Monitoring accurate surface temperatures within powder bed fusion systems remains difficult due to many reasons, not the least of which is widely varying emissivity values during processing that must be known to convert measured radiation to temperature. This variation is due to material morphology, temperature, and wavelength among other factors. However, having accurate surface temperatures during fabrication can contribute to improved process control, process repeatability and reproducibility, and predictable fabrication results; and thus, the motivation for this work was to explore a method to accurately measure surface temperatures within an electron beam powder bed fusion (EBPF) system. For the research, a spectropyrometer was used to measure single point surface temperatures of copper while the electron beam scanned the surface in an Arcam S12 EPBF system. The surface temperatures acquired were used to improve the fabrication of copper.

9:55 AM Break

10:25 AM
Multi-sensor Approach to Determine the Effect of Parameters and Geometry in Laser Powder Bed Fusion: Joe Walker1; Andrew Drieling1; Rachel Evans1; Cody Tulis1; Sabrina D’Alesandro1; John Middendorf2; Joy Gockel3; Nathan Klingbell3; 1Wright State University; 2Universal Technology Corporation
Laser powder bed fusion (LPBF) is an additive manufacturing technique used for making complex parts through a layer-by-layer process with fine feature resolution. However, the layer-by-layer process, with complex scanning patterns within each layer, introduces variability in thermal behavior leading to inconsistent microstructure and defects. The in-situ process monitoring approach in this work uses sensors including a high-speed visible camera, thermal camera, and spectrometer to evaluate each location in the LPBF process. Each sensor focuses on a different process phenomenon such as the melt pool or thermal behavior. A combined experimental and modeling approach is used to determine the influence of processing parameters and geometric changes on the defects and final microstructure of Alloy 718. The multi-sensor approach creates a comprehensive view of the material changes. Combining in-situ process monitoring with process control allows for the prediction of part quality and reliable material properties.
10:45 AM  Melt Pool Monitoring for Control and Data Analytics in Large-scale Metal Additive Manufacturing:  Brian Gibson1; Yashwanth Bandari1; Brad Richardson1; Alex Roschl1; Brian Post1; Michael Borish1; Aaron Thornton2; William Henry2; Matthew Lamsey2; Lonnie Love2; Abigail Barnes2; 1Oak Ridge National Laboratory; 2GKN Aerospace; 2University of Tennessee, Knoxville

Laser-wire based Directed Energy Deposition (DED) processes are being developed at Oak Ridge National Laboratory's Manufacturing Demonstration Facility, in collaboration with GKN Aerospace, for Big Area Additive Manufacturing (BAAM) of metallic structures. The technology has the potential to deliver reduced costs and lead times when compared to conventional methods of manufacturing in several industries. While complex structures are being produced with relatively high deposition rates and at near-net shape, issues persist with achieving consistent geometric accuracy and thermal stability. A significant research effort is focused on developing coordinated, multi-modal sensing and control for addressing these issues. An introduction to the metal-BAAM process will be provided, followed by investigations into real-time thermal monitoring capabilities that support control and data analytics frameworks. Studies focused on melt pool monitoring via infrared thermography, thermal and geometric effects on melt pool size measurement, and interactions between process variables and thermal monitoring metrics will be presented.

11:05 AM  In-situ Laser Excited Frequency Response of Additive Manufactured Parts:  Tristan Cullom1; Douglas Bristow1; Robert Landers1; Ben Brown2; Troy Hartwig1; David Soine2; Aimee Allen2; Kevin Johnson2; Andrew Barnard2; Jason Blough2; Edward Kinzel2; 1Missouri University of Science and Technology; 2Department of Energy's Kansas City National Security Campus; 2Department of Energy's Kansas City National Security Campus; 2Department of Energy's Kansas City National Security Campus; 2University of Notre Dame Fielding Additively Manufactured (AM) parts requires evaluating both the part’s geometry and material state, which affects the vibration response of the parts. Modal analysis has been shown to be effective for at least simple geometries using ex-situ methods (shaker table and impact hammer excitations). This paper investigates evaluation of the frequency response of metal parts inside the build chamber using the process laser to excite the parts during printing (Renishaw AM250). Part vibrations are measured with accelerometers inside the chamber and used to track the response during pauses between each layer. The laser is modulated at different frequencies and focused onto specific targets to extract the response from individual parts on the build plate and then compared to numerical models. This work was funded by the Department of Energy's Kansas City National Security Campus which is operated and managed by Honeywell Federal Manufacturing Technologies, LLC under contract number DE-NA0002839.

11:25 AM  Interrogation of Mid-build Internal Temperature Distributions within Parts Being Manufactured via the Powder Bed Fusion Process:  Nathaniel Wood1; Heimdall Mendoza2; Paul Boulware2; David Hoelzle1; 1The Ohio State University; 2Edison Welding Institute

This work experimentally interrogates the internal temperature distributions of parts being manufactured via the Powder Bed Fusion (PBF) process. Eight test coupons were machined from a piece of wrought 304 stainless steel (SS). Thermocouples were inserted into the test coupon interiors to sample internal thermal history. The coupons were then placed into the open source laser PBF machine housed in the Edison Welding Institute and covered to their uppermost surfaces with 316 SS powder. Three tests were executed: First, the laser scanned over the coupons without inducing melting. Second, the laser scanned over the coupons while melting the exposed faces. Lastly, five layers of 316 SS were built atop the coupons. During all tests, data was gathered from the embedded thermocouples, galvanometer encoders, laser power, and infrared imagery of the exposed coupon faces. This data is our main result, which we make fully available to the PBF community.

11:45 AM  Investigations on the Effect of Powder Bed Fusion Processing Parameters on Optical Emissions and Final Part Quality Based on Single Track Deposits:  Christopher Stutzman1; Abdalla Nassar2; 1The Pennsylvania State Department of Engineering Science and Mechanics; 2The Pennsylvania State University Applied Research Laboratory

Laser powder bed fusion processes involve hundreds if not thousands of individual laser material interactions. Each interaction results in melting, vaporization, and plume formation. This work investigates the relationship between processing parameters used to form nickel alloy 625 tracks, resulting cross-sectional geometries, and optical emissions. All experiments are conducted on a commercial EOS M280 machine with varying input powers, scan speeds, and layer thicknesses. Optical emissions are observed using a UV-VIS optical emissions spectrometer and a custom multi-spectral sensor sensitive to atomically-excited chromium line emissions. Track geometries are measured using high-resolution optical profilometry and cross-sectioning. Processing conditions and single-track geometries are show to relate to optical emissions generated during the building process. A path forward for the use of optical emission for monitoring and control will be presented.

12:05 PM  Reducing Computer Visualization Errors for In-process Monitoring of Additive Manufacturing Systems Using Smart Lighting and Colorization System:  Joshua Engle1; Richard Nguyen1; Kwame Buah1; Jason Weaver1; 1Brigham Young University

Computer vision systems used to monitor additive manufacturing processes are susceptible to producing false-positive errors for defects. Two of the main sources for these errors come from uncontrolled ambient lighting and insufficient visual contrast between prints and their backgrounds. This paper presents a method for controlling ambient lighting and increasing visual contrast for an in-process monitoring system for a 3D printer, using a light-filtering camera enclosure and a smart lighting and colorization system. A single-camera in-process monitoring system was developed and used to visually inspect a series of identical test prints that were made in 3 different colors. The false-positive error rate was tested and measured for the camera system, comparing the results of including a blackout enclosure and a smart lighting system against using the camera system alone. Recommendations for future development of lighting and colorization systems are suggested.
Improving the Strength of Binder Jetted Pharmaceutical Tablets

Binder jetting can become a viable method to additively manufacture pharmaceutical tablets as an inherently scalable manufacturing platform with a wide range of applications such as filters, bearings, electronics, and medical implants. However, tablets made from AM technology often suffer from poor strength due to the low-density prints. The goal of this work is to improve the strength of binder jetted tablets through the exploration of novel jettable polymeric binders and powders. Parameters to be investigated include binder properties, such as viscosity and surface tension, and the properties of the powder, such as flowability and particle size. By optimizing these parameters, it is possible to improve the mechanical properties of binder jetted pharmaceutical tablets, making them suitable for use in various applications.

Results show that velocity impacts the feasible parameter space. Primitives and capillary pressure. There is, however, limited experimental validation for these methods and they do not include the impact of droplet velocity and droplet spacing. This study incorporates the influences of drop velocity and droplet spacing on the saturation level of the part. Drop primitives of varying droplet velocity and droplet spacing were compared. Results show that velocity impacts the feasible parameter space.

Distortion Prevention/support Elimination during Sintering of 3D Printed Copper Parts: John Samuel Dilip Jangam; Thomas Anthony; Ben Pon; Lihua Zhao; HP Labs

Binder jetting process for additive manufacturing involves fabricating a green part layer-by-layer followed by a consolidation/sintering treatment at high temperature. The green parts from binder jetting can deform (bend, warp, curl or sag) in unsupported or overhanging regions during sintering treatment if left unaddressed. In order to prevent such distortion and build desired 3D parts, a chemical-thermomechanical shape retaining stimulus coating was developed and applied on surfaces of a 3D printed “green part” such that the mechanical forces produced during high-temperature sintering process oppose the gravitational forces to mitigate or eliminate distortion. Our experimental results demonstrate that copper parts with a thickness of 4.5 mm and a span up to 50 mm do not require auxiliary supports during sintering.

The Effect of Particle Size on Powder Flowability and Mechanical Behavior of Ceramic Samples fabricated by Binder Jetting Additive Manufacturing: Mohammadamin Moghadasi; Wenchao Du; Ming Li; Chao Ma; Zhijian Pei; Department of Materials Science and Engineering, Texas A&M University; Department of Engineering Technology and Industrial Distribution, Texas A&M University

Binder jetting is an attractive means for producing pharmaceutical tablets as an inherently scalable manufacturing platform that can process the same powdered raw material currently in use by tablet manufacturers. However, tablets made from AM technology often suffer from poor strength due to the low-density prints. The goal of this work is to improve the strength of binder jetted tablets through the exploration of novel jettable polymeric binders and powders. Parameters to be investigated include binder properties, such as viscosity and surface tension, and the properties of the powder, such as flowability and particle size. By optimizing these parameters, it is possible to improve the mechanical properties of binder jetted pharmaceutical tablets, making them suitable for use in various applications.
Binder jetting additive manufacturing is a promising technology to fabricate ceramic parts of complex shape. However, the relatively low density of the manufactured parts is limiting the wide-spread application of binder jetting. The low density comes from the contradictory requirements on the feedstock powder particle size: a large particle size is required to have a high flowability while a small size is required to have a high sinterability. This paper reports an attempt to address the contradictory requirements. Alumina nanopowder was spray-freeze-dried to form bigger granules that have higher flowability. The sinterability was maintained after the granule was crushed into nanoparticles during the powder spreading process. The alumina granule was printed with a binder jetting printer under different printing parameters. The relationship between the printing parameters and particle density is also discussed.

11:05 AM
Contact Angle Measurement Comparisons of Common Additive Materials and Processes: Holly Martin; Arthur Kasson; Daniel Bogen; Varhula De Silva Jayasekera; Brett Conner; Youngstown State University

The wettability and surface energy of materials is important to understand because it demonstrates the tendency of a liquid material to spread across solid surfaces. The more easily a liquid spreads across the solid, the higher the wettability and surface energy of that surface. This spreading of liquids is vitally important in the use of binder jet printing, where the metal powder is held together by a binder material. To ensure that the metal powder and binder material adhere together, the metal powders must be adequately wetted by the binder. The KRUSS Drop Shape Analyzer 100 allows for the examination of contact angles and surface energy for both solid surfaces and powder materials. Various particle size distributions of stainless steel powders will be examined with water and with the binder material used in binder jet printing to determine wettability, while the surface energy will be determined using water and diiodomethane.

Special Session: Data Analytics II - Machine Learning and Artificial Intelligence for In-process Defect Detection; Sensing for Quality Assurance

Tuesday AM
August 13, 2019
Room: 412
Location: Hilton Austin

Session Chairs: Brian Giera, Lawrence Livermore National Laboratory; Yan Lu, National Institute of Standards and Technology

8:15 AM
Machine Learning Based Monitoring of Advanced Manufacturing: Brian Giera; Lawrence Livermore National Laboratory

Supervised machine learning (ML) offers a route to convert additive manufacturing (AM) sensor data into real-time assessments. However, this requires a wealth of labeled sensor data that traditionally is too time-consuming and/or expensive to assemble. Here, we solve this critical issue in a variety of AM systems. We develop and implement algorithms for the purposes of automated quality assessment. We discuss ML-based algorithms capable of automated detection in a host of AM technologies. The common thread within these systems is that the data collected sensor data contains pertinent information about the state of the system that can be converted into actionable information in real-time via ML. Successful implementation of these machine learning algorithms will reduce time and cost during process by automating quality assessment and lead to process control. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
9:35 AM
Using Heterogeneous In-process Sensor Data To Detect Lack-of-fusion Defects In Directed Energy Deposition of Titanium Alloy (Ti-6Al-4V) Parts: Mohammad Montazeri; Abdalla Nassar; Christopher Stutzman; Prahalad Rao; University of Nebraska; Applied Research Laboratory, Pennsylvania State University

The objective of this work is to detect in situ the occurrence of lack-of-fusion defects in titanium alloy (Ti-6Al-4V) parts made using directed energy deposition (DED) additive manufacturing (AM). We use data from two types of in-process sensors, namely, a spectrometer and a camera filtered around 430 nm which are integrated into an Optomec MR-7 DED machine. Both sensors are focused on capturing the dynamic phenomena around the melt pool region. The spectrometer measures optical emissions from the melt pool and vapor/plasma plume above the melt pool, whilst the filtered, optical camera captures images of the plume. To detect lack-of-fusion defects, we fuse (combine) the data from the in-process sensors invoking the concept of Kronecker product of graphs. We show that the features that manifest from the combined sensor data in the Kronecker graph product domain classify the pore severity with statistical fidelity (F-score) close to 85%.

9:55 AM
Break

10:25 AM
Additive Manufacturing In-Situ Information Modeling for Data Sharing and Analytics: Yan Lu; Brandon Lane; Zhuo Yang; Shaw Feng; National Institute of Standards and Technology; University of Massachusetts at Amherst

In-situ monitoring for additive manufacturing is considered as a main enabler to understand AM processes, set the optimal AM process plan, and close control loops in real-time. Metadata, a description of data sets, is needed for in-situ data analysis, fusion and correlation for process monitoring, AM process-structure-property relationship identification or part qualification. This paper aims to identify a minimum set of information required to process, analyze and fuse various AM in-situ monitoring data. We also present a data model to represent that information and a data schema to capture it in an XML-based open database, where its links to the material, process and inspection information of the build are established. The open database complements existing AM research data sharing mechanisms, such as data.gov, and has a potential to enhance the shared in-situ data utilization. A software system is built to demonstrate the proposed information model for data sharing and analysis.

10:45 AM
Application of the Fog Computing Paradigm to Additive Manufacturing Process Monitoring and Control: Muhammad Adnan; Yan Lu; Al Jones; Fan-Tien Cheng; National Institute of Standards and Technology; National Cheng Kung University

Monitoring and controlling Additive Manufacturing (AM) processes play a critical role in enabling the production of quality parts. Different from the traditional manufacturing processes, AM processes generate large volumes of structured and unstructured in-situ measurement data. The ability to analyze this volume and variety of data in real-time is necessary for effective closed-loop control and decision-making. Existing control architectures are unable to handle this level of data volume and speed. This paper investigates the functional and computational requirements for real-time closed-loop AM process control. The paper uses those requirements to propose a function architecture for AM process monitoring and control. That architecture leads to a fog-computing solution to address the big data and real-time control challenges.

11:05 AM
High Definition Scanning for Build to Build Feedback in PBFAM: Subhranjit Roychowdhury; Xiaohu Ping; Alexander Chen; Justin Gambone; Rogier Blom; Randal Rausch; Florian Bechmann; GE Global Research Center; GE Aviation

Geometric rule-based segmentation is prevalent today in deriving scan strategies for PBFAM parts. This often leads to material debits in different section of the parts as a cookie-cutter approach is often insufficient to capture the thermal leakage variation in a complex part. Real time feedback has been demonstrated in the literature to alleviate the issue by changing power in real time. That, however, poses several roadblocks in terms of noise, accuracy achieved for complex parts and process qualification standards. In this work, a build to build feedback approach is demonstrated to achieve much finer control over the processusing a high definition scanning strategy. Cut-up results are presented to show the superior porosity/surface finish trade-off achieved in canonical geometries using this methodology in a standard M2 system.

11:25 AM
Investigation of PBFAM Flaw Formation through High-speed Video Monitoring: David Corbin; Abdalla Nassar; Edward Reutzell; Michael Krane; Ryan Overdorff; Pennsylvania State University Applied Research Laboratory; 3D Systems

To investigate the nature of defect generation in powder bed fusion processes, simple Ti-6Al-4V components were fabricated on a commercial 3D Systems ProX-320 machine while two high-speed video imaging systems monitored the process in situ. During processing, machine parameters were manipulated to produce conditions likely to induce stochastic internal defects associated with part failure. The Phantom V1212 video imaging systems were focused at the melt pool and plume emissions separately, monitoring the process from two angles for anomalous laser-material interactions at rates up to 25,000 frames per second, and revealing the mechanisms that contribute to the generation of process defects. Post-build CT scans of the components established a ground truth for defect locations to which the video data, coupled with the response of additional position- and time-synchronized sensors, were correlated.

11:45 AM
MMHT Based In-situ Process Monitoring and Fault Detection in Additive Manufacturing: Sarah Felix; Harry Mathews; Saikat Ray Majumder; Thomas Spears; Subhranjit Roychowdhury; GE Global Research Center; GE Aviation

A unique aspect of the additive process is that it forms both the material and the geometry at the same time. This poses significant challenges in validation of part quality at the conclusion of each build and typically relies on sacrificial parts, CT scanning and other test coupons. Given the multiple process failure modes that can impact the build over a variety of temporal and spatial scales the benefits of robust in-situ process monitoring for direct metal laser melting (DMLM) manufacturing process are manifold in number. To that end a Multiple Model Hypothesis Testing (MMHT) based analytical methodology has been developed and tested on DMLM additive manufacturing processes at GE. Leveraging the photodiode sensors in additive machines, multiple models were developed corresponding to nominal and different failure modes which was followed by a Bayesian approach to attribute new signals from the sensors to one of the nominal or defect states.
8:15 AM
Additive Manufacturing in Non-traditional Environments: Bryan Kessel; Nathan Desloover; *Naval Surface Warfare Center
Additive Manufacturing (AM) provides novel capabilities for increasing operational readiness of naval platforms through the production of obsolescent or long lead time items. Although deployment of AM systems at the point of need further enhances these capabilities, installations in forward-deployed locations require additional evaluations of the performance of equipment and materials in dynamic environments. To address these issues, targeted shipboard installations in addition to a robust research and development program have been established to assess and enhance the performance boundaries of various AM equipment. The results of these efforts inform Naval Sea Systems Command (NAVSSEA) guidance on the implementation of AM within the Department of the Navy.

8:35 AM
A Framework for the Performance Qualification of Additively Manufactured Parts under Multiaxial Loading Emulating In-service Conditions: John Michopoulos; Athanasios Illiopoulos; John Steuben; Nicole Apetre; Nguyen Trung; Nam Phan; *U.S. Naval Research Laboratory; **Naval Air Systems Command
A rapid functional qualification framework based on the concept of Performance Signature (PerSig) is presented. This framework can be used to qualify Additively Manufactured (AM) parts in a manner that accounts for process-induced imperfections without accounting explicitly for each of them. The PerSigs are defined for both prequalified conventionally manufactured parts and their AM-produced counterparts. Comparison measures are defined that enable the construction of differential PerSigs in a manner that captures the differential performance of the AM part vs. the prequalified CM one. This approach is extended for the case of multiaxial loading conditions reflecting actual in-service loading. Application of the methodology is presented for a wing bracket in the P-3C Orion aircraft platform and is based on synthetic data. The application of multiaxial loading emulating in-service loading conditions is proposed by the utilization of a custom-designed 6-DoF robotic testing system that will generate physical data.

8:55 AM
Additive Manufacturing of Bicontinuous Piezocomposites Based on Triply Periodic Cellular Micro-skeleton for Tailorable Hydrostatic Performance: Xuan Song; Li He; Wenhua Yang; Zhuo Wang; Lei Chen; *University of Iowa; **Mississippi State University
Bicontinuous piezoelectric composites, consisting of a continuous piezoelectric ceramic skeleton and a flexible polymer phase interconnected in three-dimension (3D), possess an excellent property combination of mechanical flexibility and piezoelectricity. The piezoelectric performances of these materials are dependent on the meso-scale geometry of the interface between the active piezoelectric ceramic phase and the passive polymer phase. In this research, we investigate the design and fabrication of bicontinuous piezocomposites with tailorable hydrostatic performance utilizing a suspension enveloped projection stereolithography process (SEPS). Triply periodic cellular structures are used to design the active piezoelectric ceramic phase, due to the large elastic constants with respect to their rod-connected counterparts. Post processes including debinding, sintering, poling and polymer infiltration are presented. Mechanical and piezoelectric properties of the achieved bicontinuous piezocomposites are analyzed through experimental characterization and finite element modeling.

9:15 AM
Design Optimization for Laser Metal 3D Printing: Vedant Chahal; Robert Taylor; *The University of Texas at Arlington
Selective Laser Melting (SLM) offers high resolution, high density, and expanded design freedom, making it an ideal technique for weight sensitive structural applications. However, specific geometries, such as overhang features, lattice structures, and hollow members, not only complicate the fabrication process but also compromise the structural integrity as these features are susceptible to subsurface porosity, residual stresses, and high deformations. Current design methods either lack the ability to control these defects or are computationally infeasible. This study aims to provide a Design of Experiments (DOE) based approach to design an aircraft engine bracket. The initial design process involves an analysis of the localized geometric features critical in determining the part quality. These features are included in a DOE study to obtain a response surface for the studied defects. Further size and shape optimizations are then performed to minimize the influence of SLM induced defects on the part quality.

9:35 AM
Selective Laser Melting Fabrication of Fully Dense Ultra-high Strength Martensitic Steel: Raiyan Seede; David Shoukri; Bing Zhang; Austin Whitt; Sean Gibbons; Philip Flater; Alaa Elwany; Raymundo Arroyave; Ibrahim Karaman; *Texas A&M University; **Air Force Research Laboratory
Ultra-high strength steels (UHSSs) have attracted increasing interest for their use in the automotive and aerospace industries, in mining equipment, and in defense applications due to their high yield strengths and reasonable ductility. The Air Force Research Laboratory recently developed a relatively inexpensive UHSS called AF9628. This work assesses the printability and properties of AF9628 using laser powder bed fusion additive manufacturing. In particular, a new protocol for determining processing windows in an accelerated fashion is first introduced. The protocol integrates an analytical thermal model with experimental characterization, then uses geometric criteria for determining processing parameters such that fully dense parts with minimal lack of fusion and keyholing porosity can be produced. Using this framework, fully dense samples were achieved over a range of processing parameters. Flexibility in processing parameter selection while maintaining full density parts opens up the possibility of local microstructural refinement through processing parameter variation.

9:55 AM Break

10:25 AM
Additive Manufacturing Simulation Comparison Using Commercial Tools: Charles Fisher; *John Michopoulos; Athanasios Illiopoulos; John Steuben; Andrew Birnbaum; Cynthia Waters; *Naval Surface Warfare Center - Carderock; **Naval Research Laboratory
The present study is part of an integrated computational materials engineering (ICME) thrust to expand the use of computational simulations for additive manufacturing (AM) components within shipbuilding. Finite element analysis (FEA)-based tools have been developed to simulate the entire build process, including distortion and residual stress. To address this, recently developed computational tools are under a validation investigation for laser powder-bed fusion (L-PBF) builds. The on-going investigation includes physical validation of various AM parts to understand how modification of the process can improve build efficiency and reduce instances of failed builds. Additionally, the thermal modeling of the build process will likely influence the developed microstructure, thereby giving insight into how to modify build processes in order to obtain designed alloy systems. The project goal is to validate the computational tools to determine best practices for insertion of computational AM simulation into fabrication.
10:45 AM
A Multi-fidelity Gaussian Process Model for Melt Pool Prediction in Laser Powder Bed Fusion: Robert Saunders1; Raymundo Arroyave2; Ibrahim Karaman1; Dimitris Lagoudas2; Amit Bagchi1; Alaa Elwany2; 1U.S. Naval Research Laboratory; 2Texas A&M University

There is a plethora of computational and analytical models for predicting melt pool characteristics in laser powder-bed fusion (L-PBF) metal-based additive manufacturing (AM) processes. Such models are essential for establishing relationships between processing parameters and properties of the fabricated part including defects, residual stress, and mechanical strength. However, most of these models fall are either fast but inaccurate (i.e. analytical solutions) or slow and accurate (e.g. finite element models). In this work, we establish a Gaussian process-based framework to fuse information from a set of models with varying levels of fidelity. The goal of this framework is to construct a surrogate predictive model that strikes a balance between computational cost and prediction accuracy through leveraging the benefits of different fidelity models. The proposed framework is demonstrated on a two model case to predict L-PBF melt pool dimensions of nickel titanium shape memory alloys (NiTi SMAs) as a model material.

11:05 AM
A Thermoelastoplastic Energy and Mass Deposition Simulator for the Prediction of Residual Fields from Additive Manufacturing: Athanasios Illopolous1; John Michopoulos1; Nicole Apetre1; Andrew Birnbaum1; John Steuben1; Benjamin Graber1; 1U.S. Naval Research Laboratory

The complexity in the modeling and simulation of Additive Manufacturing (AM) processes, often necessitates the adoption of various simplifying assumptions over multiple length-scales. Herein, a domain activation-based Finite Element Analysis approach that uses exact part geometry to model the layer by layer mass and energy deposition physics is presented. The model predicts macro-level distortions and associated stresses developed in AM-produced components. A sensitivity analysis with respect to the accuracy of various simplification approaches will be presented in order to investigate the aspects of modeling decisions that give reasonable simulation times and reasonably accurate results. Finally, the model results will be compared with experimentally measured, synchrotron-based residual elastic strains for model validation.

11:25 AM
Functionally-graded Lattice Infill Design Optimization for Laser Powder Bed Fusion: Lin Cheng1; Albert To2; 1University of Pittsburgh

This talk will present an efficient homogenization-based topology optimization method for optimizing the design of functionally-graded lattice infills in components processed by laser powder bed fusion. In the proposed method, homogenization is first performed to model the effective properties of lattice structures as a function of relative density. Then the homogenized model is employed directly in conventional density-based topology optimization algorithms to compute the optimal density distribution for the design component under consideration. The final step in this method is to reconstruct the CAD model for the optimized component with graded lattice infill from the optimized density distribution. The proposed optimization method has been validated by comparing results obtained by the homogenized model, direct numerical simulation, and experimental testing for different design scenarios involving stress constraints, natural frequency, convective cooling, and support structure design, which are of great interest to the Navy.

11:45 AM
Design of Optimal Support Structure of Additive Manufacturing Parts Using Surrogate Models: Nicole Apetre1; Athanasios Illopolous1; John Steuben1; John Michopoulos1; 1U.S. Naval Research Laboratory

Simulations of additive manufacturing (AM) processes are impractical for a number of applications due to high computational cost. One such application is the determination of optimal support structures in order to maximize AM thermomechanical performance functions related with part quality. Aiming at dealing with this issue, a support structure optimization framework that is based on a data-driven local surrogate model is proposed. This physics-agnostic surrogate model is trained on data produced by full order physics-informed models that can estimate residual fields such as residual deformations, strains and stresses. The feasibility of the proposed framework is demonstrated and a number of computational performance studies are presented, based on accurate geometry and residual deformation prediction via fully thermoelastoplastic simulations for a number of AM-produced parts. The results of the present study are compared to output from full order modeling computations, and are shown to offer several orders of magnitude higher performance.
Part Remanufacturing Using Hybrid Manufacturing Processes: Xinchang Zhang1; Frank Liou1; 1Missouri University of Science and Technology

Many users of high-performance metal parts, such as the aerospace industry, the mold/die casting industry, and heavy machinery manufacturers, extend the service of these damaged parts by employing remanufacturing technology. Additive manufacturing has unique capabilities, such as low heat input, a small heat-affected zone, free-form fabrication, and a near-net-shape. This paper summarizes the effort and the tested results to achieve a more automated remanufacturing process using hybrid additive manufacturing and CNC machining processes. It will enable the robust repair-on-demand to significantly increase operational availability to reduce sustainment costs, thus will lead to robust and quality remanufacturing that is critical for remanufacturing process qualification.

Energy Consumption and Mechanical Proprietaries of Hybrid Deposition and Micro Rolling: Cheng Huang1; Haiou Zhang1; Guilan Wang1; Runsheng Li1; 1Huazhong University of Science and Technology

Traditional forging process involves high energy consumption due to the giant equipment, long process, and low material utilization. Recently, metal additive manufacturing technology has developed rapidly with the advantage of high utilization. However, looseness and defects caused by anisotropy of layer forming would result in low mechanical properties and fatigue properties. The hybrid deposition and micro rolling (HDMR) combined in-situ rolling with additive manufacturing, which applies a forging force to the built part by a micro-roller. A comparison is carried out with conventional forging approach in terms of energy consumption and mechanical properties. It was found that HDMR parts showed a better strength performance with a lower energy consumption. Additionally, HDMR realizes integrated manufacture instead of the distributed manufacturing of large scale equipment in a lengthy process, which is an promising substitute of conventional forging.

Residual Stresses Measurements in Hybrid Additive Manufacturing: Gurucharan Madireddy1; Michael Sealy1; 1University of Nebraska-Lincoln

Coupling additive manufacturing with secondary processes, such as peening or rolling, enables complex residual stress fields to form and evolve during building. Further, thermo-mechanical interactions arising from different heat sources in 3D printing, such as directed energy deposition (DED) versus powder bed fusion (PBF), affects the cumulative residual stress fields. DED has a relatively large melt pool compared to PBF whereby thermal cancellation plays a more critical role in cumulative residual stress formation. This presentation examines experimental observations in residual stress formation across DED and PBF builds by hole drilling. Limitations of this approach and the need for alternative techniques, such as high-resolution neutron diffraction, will be discussed.

Linear Friction Welding of Additive Manufactured Parts: Rhodri Lewis1; Jenna Tong1; Andrew Wescott1; Anthony McAndrew2; Bertrand Flipo2; 1Renishaw Plc; TWI

Additive manufacturing has seen the growth in the ability to produce complex parts with minimum material use and machining. The combination of both linear friction welding and additive manufactured parts has the potential to expand the capabilities and possibilities of both technologies. It allows for the joining of complex geometries to parent structures which may only require traditional subtractive manufacturing. This work presents the feasibility of joining Ti6Al4V additive manufactured components created with Renishaw’s metal powder bed fusion technology to showcase the potential of the combination of both technologies.
Electron beam and laser hybrid preheating strategy for powder bed fusion process and applications: Hongxin Li1; Bin Zhou2; Jun Zhou1; Feng Lin1; Tsinghua University

Electron beam selective melting (EBSM) and selective laser melting (SLM) are two types of powder bed fusion process, which use electron beam or laser to melt powder materials to form three dimensional parts. In SFF 2017, we had demonstrated a custom-made electron beam and laser hybrid melting (EB-LHM) system, which shows better surface quality than EBSM process and higher efficiency than SLM process. In this research, an electron beam and laser hybrid preheating strategy (EB-LHPS) was proposed to control the powder bed temperature on a much wider scale compared with single heat source melting process. Moreover, sintering the powder bed by laser first to prevent powder “smoking” and preheating the powder bed by high current EB directly after that can increase the preheating efficiency greatly, compared with preheating the powder bed by increasing the EB current gradually in EBSM process.

Multi-material topology optimization with arbitrary volume constraints for additive manufacturing: Yeming Xian1; David Rosen2; 1Georgia Institute of Technology

A framework for multi-material compliance optimization in the context of continuum based topology optimization is adapted and applied to additive manufacturing. Two issues are addressed in regard to additive manufacturing, more specifically, 3D inkjet printing: feature size and support volume. This paper incorporates manufacturing related constraints into the ZPR design variable update scheme, so as to control the feature size and minimize support volume by optimizing the build orientations. The ZPR method handles an arbitrary number of candidate materials with flexible material properties, features freely specified material layers, and updates each volume constraint independently. The dual objective associated with the series of explicit convex (linear) approximations of the optimization problem is a separable function of the Lagrange multipliers and thus, the update of each design variable is dependent only on the Lagrange multiplier of its associated volume constraint. The key ideas presented herein are demonstrated through numerical examples.

Cellular and topology optimization of beams under bending: An experimental study: Arjun Gopal1; Gaurav Parihar1; McKay Holt1; Tanner Stinson1; Manasvi Sharma1; Dhruv Bhate1; 1Arizona State University

Design for additive manufacturing (AM) includes concepts such as cellular materials and topology optimization that combine the capabilities of advanced computational design with those of AM technologies that can realize them. There is limited experimental study of the relative benefits of these different approaches to design. This paper examines these two different approaches to maximizing the flexural rigidity of a beam under bending, while minimizing density. A total of 26 beams were designed using commercially available cellular design and topology optimization software. The Selective Laser Sintering (SLS) process was used to manufacture these beams, which were then tested per ASTM D790 three-point bend test standards. The effect of varying the size and shape of cells on the flexural rigidity was studied using 15 different cellular design strategies. These results were then compared to eight different topology optimized beam designs, as well as three solid and hollow baseline beams.
9:35 AM
An Experimental Study of Design Strategies for Stiffening Thin Plates under Compression: Irving Ramirez Chaves, Siddharth Israni, Shainil Jogani, Cameron Noe, Vigneshwaran Sekar, Dhruv Bhaté
Arizona State University

Increasing stiffness and failure loads while minimizing mass is useful in many engineering applications, including the design of thin plates and shells. In this paper, the performance of thin plates using a range of stiffening approaches was studied for the specific instance of compressive loading. Periodic, graded, stepped, “Voronoi” stochastic, and topologically optimized patterns were explored. These stiffening designs were realized using different software tools, and manufactured with the Selective Laser Sintering (SLS) process. These 3D printed specimens were tested under compression to assess their mechanical response. Videos of these tests were recorded to study the shape of the failure modes. This data was analyzed to determine the performance of the different stiffener designs, in comparison to the performance of baseline plates without any stiffening. The study concludes with a discussion of the results and their implications for stiffening thin plates.

9:55 AM Break

10:25 AM
Multi-Objective Topology Optimization of Additively Manufactured Heat Exchangers: Basil Paudel, Mohammad Masoomi, Scott Thompson, Auburn University; ANSYS, Inc.; Kansas State University

Thompson

The higher design flexibility offered by additive manufacturing (AM) allows for radical improvements in the design and functionality of legacy parts. In this study, a flat-plate heat exchanger is designed and optimized using the ANSYS topology optimization module. Unlike conventional numerical optimization tools, the current optimization approach employs multiple objective functions, including mass reduction and maximization of heat transfer efficiency. Two unique, initial designs were used for ‘seeding’ the multi-objective topology optimization routines and the results were compared and discussed. Topology design and operating (boundary condition) variables were varied to elucidate major design sensitivities. The predicted heat transfer within the topology-optimized parts was validated using separate numerical methods. Constraints related to flow pressure drops and additive manufacturability were enforced. In both cases, the optimal design performed significantly better than the conventional heat exchanger in terms of thermal efficiency.

10:45 AM
Effects of Discrete Print Paths on the Stiffness and Strength of Topologically Optimized Structures: Nadim Hmeidat, Bailey Brown, Natasha Vermaak, Brett Compton, University of Tennessee Knoxville; Lehigh University

Düchting

The design flexibility that additive manufacturing (AM) enables makes it an ideal route for the fabrication of topologically optimized structures. However, strong mechanical anisotropy is associated with AM that is not accounted for with standard topology optimization design tools. Anisotropy may result from orientation of molecules or reinforcements within the materials, or from weak interfaces and porosity that derive directly from discrete print paths and infill patterns that are a central feature of many AM methods, particularly extrusion-based technologies. This talk will investigate the effects of discrete print paths on the strength, stiffness, and failure modes of an optimized topology printed with Fused Filament Fabrication (FFF), compared to identical structures cut from monolithic material. Finite element analyses (FEA) are conducted in parallel to rationalize the relationships between observed failure modes, print path orientation, and mechanical anisotropy. Implications for the development of new design tools for AM will also be discussed.

11:05 AM
A Mold Insert Case Study on Topology Optimized Design for Additive Manufacturing: Mirko Sinico, Rajit Ranjan, Mandanah Moshiri, Can Ayas, Matthijs Langelaar, Ann Vitrouv, Fred van Keulen, Wim Dewull, KU Leuven; Delft University of Technology; Technical University of Denmark

The additive manufacturing (AM) of injection molding inserts has gained popularity during recent years primarily due to the reduced design-to-production time and form freedom offered by AM. In this paper, topology optimization (TO) is performed on a metallic mold insert which is to be produced by the selective laser melting technique. First, a commercially available TO software is used, to minimize the mass of the component while ensuring adequate mechanical response under a prescribed loading condition. The commercial TO tool adopts geometry-based AM constraints and achieves a mass reduction of ~50%. Furthermore, an in-house TO method has been developed which integrates a simplified AM process model within the standard TO algorithm for addressing the issue of local overheating during manufacturing. The two topology optimized designs are briefly compared, and the advantages of implementing manufacturing constraints into the TO algorithm are discussed.

11:25 AM
A Coupled Thermal-flow Topology Optimization Approach for High-temperature Applications: Songtao Xia, Tsz Ling Tang, Suraj Musuvathy, Yixing Li, Wentao Fu, Siemens Corporation Corporate Technology; Siemens Energy Inc.

Topology optimization is a computational method for generating freeform designs to achieve given objectives under the governing physics. In this work, a coupled thermal-flow topology optimization approach for generating design concepts of high temperature components is presented. The design is generated by distributing materials intelligently based on the sensitivity of the design objectives with respect to the design variables. Multiple objectives and constraints, including minimizing pressure drop, maximizing cooling efficiency and maintaining mass flow rate can be defined in the optimization framework. Both heat transfer and fluid dynamics governing equations are considered and solved using Simcenter STAR-CCM+. The discrete adjoint approach is used to compute the analytical sensitivity efficiently. Numerical examples demonstrate that the developed approach leads to successful topological optimization of the complex gas turbine combustion component under various objectives and constraints. This approach can also benefit the design of other high temperature components in automobile and aerospace applications.

11:45 AM
Development, Production and Post-processing of a Topology Optimized Aircraft Bracket: Helge Klippstein, Thomas Reimer, Anne Düchting, Dennis Menge, Hans-Joachim Schmid, Direct Manufacturing Research Center - Paderborn University; AMendate GmbH

Development parts for aviation have very high demands on the development and production process. Therefore, the entire process must be considered in order to produce high-quality AM metal parts. In this case study, a conventional part was selected to be optimized for AM. The process presented includes component selection, design improvement with a novel approach for topology optimization based on the AMendate software, component production on a SLM 250 HL and post-processing including heat treatment and surface smoothing. Especially for topology optimized parts, the challenges of post-processing have to be mastered in order to produce competitive parts. A weight reduction of more than 50% could be realized, whereby the stress distribution is more homogeneous. Furthermore, the challenges of support optimization and post-processing have been addressed, in order to produce competitive parts.
Large-scale Thermoset Pick and Place Testing and Implementation

Alex Boulger

2:20 PM

Preliminary Study on Hybrid Manufacturing of the Electrical-Mechanical Integrated Systems (EMIS) Assisted by the LCD Stereolithography Technology: Guanghui Fei; Tiwei Wei; Qimin Shi; Yongjian Guo; Herman Oprins; Shoufeng Yang; "'KU Leuven; 'IMEC Compared to limited complexity capacity in traditional fabrication and assembly techniques, Additive Manufacturing(AM)-based hybrid fabrication was widely used in the electronics industry for the advantages of fabricating complex structures and simplifying the assembly steps. In this study, the fabrication process of the Electrical-Mechanical Integrated Systems was preliminarily studied, the mechanical parts (gas/liquid chambers) were printed directly on the PCB (the carrier of electrical devices). A mixture of resin with silica was applied as the printing feedstock, to reduce the mismatch in the thermal expansion coefficient (CTE) between the part and PCB. The silica loading at 60% is appropriate to achieve a balance between the viscosity and the CTE. Adhesion forces between different chambers and PCBs were measured, showing a great association with the roughness between Chamber-PCB. Thermal cycling test indicated that the tailored chamber owned good CTE compatibility with the PCB. Consequently, AM-based hybrid manufacturing is capable of fabricating protective/functional bodies for electronics.

2:40 PM

Polymer Welding of 3D Printed Hybrid Flexible Electronics for Patient-specific Wearables and Orthotics: Eric MacDonald; Pedro Cortes; ‘Youngstown State University

The design freedom offered by 3D printing is transformative and has been leveraged to fabricate structural electronics in which the printing process is interrupted and components and conductive traces are introduced at arbitrary build layers. A novel approach to extend this concept is to print 3D jigsaw subsections with mortise and tenon mating features to build a structure. The superficial surfaces of the subsections can be populated with components, assembled, and then subsequently fused together through polymer welding or overmolding. By constructing a complex structure from multiple pieces, a diversity of materials (e.g. stiff and flexible) can also be leveraged in order to create new applications like shape-to-fit flexible wearables or patient-specific orthotics. The presentation will explore the mechanical performance of polymer welding and includes several demonstrations in the context of customized wearables and orthotics.
This paper characterizes engineering designers’ abilities to re-design a component for additive manufacturing, employing screen capture methods. Additive Manufacturing has garnered significant interest from a wide range of industries, academia and government stakeholders due to its potential to reform and disrupt traditional manufacturing processes. The technology offers unprecedented design freedom and customization along with its ability to process novel and high strength alloys in promising lead times. To harness the maximum potential of this technology, designers are often tasked with creating new products or re-design existing portfolios of traditionally manufactured parts to achieve lightweight designs with better performance. To date, few studies explore the correspondence between design behaviors and manufacturability of final product within an Additive Manufacturing context. This paper presents empirical data from the design processes of six graduate student engineering designers as they re-design a traditionally designed part. Behaviors through the design task are compared between the study participants with a quantitative measure of the manufacturability and quality of each design. Results indicate opportunities for further research and best practices in design for Additive manufacturing and engineering education practitioners across multiple disciplines.
Materials: Metals V - Less Common Metals

Tuesday PM Room: 416 AB
August 13, 2019 Location: Hilton Austin

Session Chair: Ismail Fidan, Tennessee Tech University

1:40 PM
Compatibility of Additively Manufactured Cobalt-based Superalloy with Alloy Steel Substrate: Interface Bond Behavior and Failure Mechanism: Hoyeol Kim1; Zhichao Liu1; Hong Chao Zhang1; 1Texas Tech University

The good interface between hardfacing and substrate is required for remanufacturing application in order to sustain the structural integrity and obtain desirable performance of the whole part. The proper interface involves good physical and chemical compatibility between coating and substrate. There has been very limited research on compatibility at the interface and no relevant literature has been found. Therefore, investigation on the interface will have significance of material selection guidance. As potential materials for surface coating and repair applications, Tribaloy alloys combine exceptional wear, corrosion, and oxidation resistance as well as good mechanical properties owing to their distinct chemical compositions. The objective of this study is to investigate compatibility of LENS-printed Tribaloy alloy with alloy steel substrate. To reveal the interface bond and fracture mechanism, the cross-sectional interface is characterized using scanning electron microscopy (SEM), energy dispense X-ray spectrometry (EDS), and electron backscatter diffraction (EBSD).

2:00 PM
Investigation of Aluminum Cerium Alloy Laser Melting Dynamics under Additive Manufacturing Conditions: Aiden Martin1; Nicholas Calta1; Joshua Hammoms2; Jianchao Ye3; Ryan Ott3; Scott McCall3; Trevor Willey3; Jonathan Lee3; 1Lawrence Livermore National Laboratory; 2Ames Laboratory

Al-Ce based alloys exhibit excellent thermal stability and is therefore of considerable interest for high temperature, weight-critical applications in automotive and aerospace applications. Laser powder bed fusion (LPBF) is an ideal process for additive manufacturing (AM) of Al-Ce parts however, the material response at laser processing speeds on the order of 1 – 2 m s⁻¹ has not been investigated. Here, high-speed in situ X-ray imaging, ex situ spectroscopy and hardness testing are used to determine the laser-induced heating dynamics and structural response in an Al-Ce alloy. The results reveal minimal pore formation under these conditions and the rapid melting of Ce-rich inclusions into the Al-rich phase which improves material quality. This information can be used to optimize the LPBF AM process in this novel Al-Ce alloy and develop strategies for improved printed part performance. Prepared by LLNL under Contract DE-AC52-07NA27344.

2:19 PM
An Aluminum-lithium Alloy Produced by Laser Powder Bed Fusion: Yang Qi1; Hu Zhang1; Haihong Zhu1; Xiaoia Nie1; Xiaoyan Zeng1; 1Huazhong University of Science and Technology

Aluminum-lithium (Al-Li) alloys are promising to replace traditional high-strength aluminum alloys in aerospace and military industries due to their low density, high specific strength, and excellent corrosion resistance. However, there is little research focused on the laser powder bed fusion (LPBF) of Al-Li alloys due to their poor weldability and high crack susceptibility. In this study, the feasibility of the Al-Li alloy fabricated by LPBF was investigated. The effect of the processing parameters on the densification and crack formation behavior was studied. Finally, after optimizing the processing parameters, crack-free and nearly fully dense 2195 Al-Li alloy 3D-printed samples were obtained. A relative density of 99.92% and a microhardness of 89.1 HV were achieved.

2:40 PM
Wire-arc Additive Manufacturing: Invar Deposition Characterization: Jacob Fowler1; Andrzej Nycz2; Mark Noakes3; Christopher Masuo1; Derek Vaughan1; Abigail Barnes1; 1Oak Ridge National Laboratory

This paper investigates and analyzes the characteristics of the deposition of a Nickel-Iron alloy (Invar) as it is relevant to Wire-Arc Additive Manufacturing performed by the Metal Big Area Additive Manufacturing (MBAAM) team. The Invar alloy is extremely valuable in a variety of fields for its thermal expansion properties. There is a possibility that these fields will gain financial benefits in the future by turning to additive manufacturing as the production technique for their Invar parts. As such, it will be necessary for AM research to become familiar with the characteristics of Invar deposition. One potential AM technique that has the ability to carry out this type of printing is Wire-Arc AM. The goal of this paper is to narrow down and identify the different welding parameters that optimize the characteristics of Invar deposition in the Wire-Arc AM technique.

Materials: Metals VI - Characterization

Tuesday PM Room: 417 AB
August 13, 2019 Location: Hilton Austin

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

1:40 PM
Expeditied Optimization of AM Materials Using Miniaturized Testing: Jonathan Torres1; Ali Gordon2; 1Bucknell University; 2University of Central Florida

The small punch test (SPT) has been developed for the purpose of characterizing materials which are scarce or costly by using reduced-size test samples. While limitations exist for utilizing the SPT for material characterization, the test economizes resources in optimizing processing parameters for additive manufacturing (AM). Several AM materials were tested under various conditions and in differing stages of processing. Parameters such as build orientation, post-processing variations, and testing conditions are shown to cause notable differences in sample responses. Conditions varied include test temperature, load level, load type, and control mode. Comparisons between tests are made to find the effects of each varied condition, and trends are correlated with traditional test results, showing the capabilities of the SPT. Fractography results are shown exploring fracture patterns which vary depending on test conditions such as load and control type and are shown to be dependent on manufacturing orientation and processing conditions.
2:00 PM
Additive Manufacturing Materials Tested by Miniature Tensile Specimens: Laura Cordova1; Ton Bor2; Andrea Garcia-Junceda1; Tiedo Tinga1; 1University of Twente; 2Indea Materials
This study compares the use of miniature specimens to ASTM tensile specimens. The aim is to evaluate the mechanical properties of metal Additive Manufacturing (AM) materials by means of micro-mechanical characterization. AM techniques, specifically the Laser Powder Bed Fusion (LPBF) process, enable the build of complex parts with small features. The suitability of using miniature specimens in comparison with ASTM specimens has been investigated with two differently sized Scalmalloy specimens that were manufactured through the LPBF process. The study convincingly shows the potential to reduce the testing material dimensions to evaluate the mechanical properties of AM materials without compromising the test results.

2:20 PM
The Effect of Laser Surface Treatment on the Fatigue Behavior of Additively Manufactured Metallic Materials: Zabihollah Ahmadi1; Seunggong Lee2; Masoud Mahjouri-Samani3; Nima Shamsaei1; 1Auburn University
Laser surface treatment of additive manufactured (AM) parts has attracted considerable interest in the last few years due to its superior flexibility, operation speed and capability for polishing more complex geometries as compared to conventional mechanical based methods. This study presents the influence of laser power and scanning speed on surface roughness of AM specimens. A tunable nanosecond infrared (IR) laser (1064 nm) and a continuous wave (CW) laser (1064 nm) are employed for controlled laser surface treatment. The effective absorptivity is plotted as a function of incident laser power for different scanning speeds. The laser parameters are tuned to minimize the detrimental effect of surface roughness on the fatigue behavior of AM parts. An attempt is also made to re-melt and close the pores within 50 μm of the surface to further enhance the fatigue strength of these specimens.

2:40 PM
Multiscale Fatigue Modeling of Additively Manufactured Metallic Materials: Aref Yadollahi1; 1Mississippi State University
Uncertainty in fatigue performance of parts fabricated via metal additive manufacturing (AM) is one of the main concerns must be addressed to fulfill the certification constraints for structural applications. Having the ability to predict the fatigue resistance, based on the resultant microstructural details, can address the issue of fatigue damage uncertainty, or reliability, of AM parts. In this study, microstructural features (i.e. grain size and orientation, etc.) and defect characteristics (i.e. size, distribution, etc.) were used to predict the fatigue life of several AM metallic alloys (e.g. titanium alloys, nickel-based alloys, stainless steels) via a microstructure-sensitive multistage fatigue (MSF) model. The results indicated that using the process-dependent microstructural details, the calibrated MSF model can appropriately capture the scattering of results and allow the quantitative predictions of fatigue strength of AM parts. They also demonstrated the potential to predict fatigue behavior of AM parts faster than the classic fatigue tests. Finally, this model was used to predict the fatigue behavior of AM parts using different laser power and scanning speed.

3:00 PM
Precipitation Hardening Behavior of Additively Manufactured Materials: Prashanth Konda Gokuldoos1; 1Tallinn University of Technology
Selective Laser Melting (SLM) is one of the additive manufacturing processes (AM) that has gained increasing attention because of its ability to process a wide spectrum of materials apart from producing parts with added functionality. Several precipitation hardenable alloys have been processed using SLM with the traditional idea of improving the mechanical property of these parts with natural aging or with artificial thermal treatment. However, not alloys show significant improvement in their mechanical properties with the aging/precipitation hardening treatments. The present talk will discuss the processing of age/precipitation hardenable alloys by SLM and their merit and demerits. In addition, the alloy systems that show a significant response to age/precipitation hardening will be highlighted and the scientific reasons behind this class of materials will be discussed in detail.

3:20 PM
Characterization of Wire-arc Additive Manufactured Hybrid Nickel Aluminum Bronze-stainless Steel Bi-metals: Dharmendra Chalasani1; Mohsen Mohammadi2; 1Marine Additive Manufacturing Centre of Excellence
Nickel aluminum bronze (NAB) alloys are valued for their high strength combined with good ductility, and high corrosion resistance especially in marine environments. One of the limitations with major additive processes is the maximum component size and corresponding low productivity. To avoid such size restrictions and making economically viable fabrication processes, hybrid manufacturing approach is gaining attention. In this work, hybrid bi-metals were fabricated by depositing NAB wire in cuboidal shape on a substrate of austenitic stainless steel using wire-arc additive manufacturing. This work describes an in-depth high-resolution microstructural characterization of NAB/stainless steel interface by using emerging tomographic 3D-Electron backscatter diffraction (EBSD) based on automated serial sectioning in FIB (focused ion beam)-SEM (scanning electron microscope). The 3D EBSD approach allowed the full crystallographic characterization of the interface including the morphology and the orientation of its crystal planes. Finally, innovative techniques regarding TEM sample preparations were practiced for further microstructural observations.
2:00 PM
Experimental Validation of the Thermal Distribution Predicted by the Graph Theory Approach: Application to Laser Powder Bed Fusion:
Paul Hooper; Reza Yavari; Prahalad Rao; Kevin Cole; 1Imperial College London; 2University of Nebraska
The objective of this paper is to experimentally validate the graph-based approach, advanced in our companion abstract, for predicting the thermal distribution in parts made using the laser powder bed fusion. The graph approach was used to predict the temperature on the top surface of two geometries, namely, an inverted cone and cylinder (stainless steel). Experimental data in the form thermal images were acquired using a calibrated staring-configuration shortwave infrared camera. The results show that the graph theory approach predicts the temperature at the top surface of the build within the time it takes to build the part with error within 10%. For instance, in the case of the inverted cone geometry (top diameter 20 mm, height 11.25 mm, 225 layers), the simulation time with graph theory was less than 20 minutes versus 50 minute build time.

2:20 AM
Analysis of Pressure Profile Within Big Area Additive Manufacturing Single Screw Extruder: Jake Dvorak; Chad Duty; Christine Ajinjeru; John Lindahl; Christopher Hershey; Vlastamil Kunc; 1University of Tennessee, Knoxville; 2Manufacturing Demonstration Facility
Pressure distributions within a single screw extruder are dependent on several factors, namely, processing parameters and flow geometry. The Big Area Additive Manufacturing (BAAM) system involves a complex flow geometry with multiple flow zones following the screw extruder. This study utilized finite element analysis (FEA) and experimental data to generate a pressure map across the single screw extruder and flow channels of the BAAM system. Several constitutive models were evaluated in the FEA code to determine the closest correlation with experimental data. The results of this work allow for further study of BAAM input parameters for optimal print quality, material properties, and print head geometric design.

2:40 PM
Tailoring Microstructure through Beam Shaping: Saad Khairallah; Rongpei Shi; Tien Roehling; Tae Wook Heo; Joel Berry; Joseph Mckeown; Manyalibo Matthews; 1Lawrence Livermore National Laboratory
Laser powder bed additive manufacturing is promising a new process capability, that of tailoring mechanical properties by locally controlling the microstructure. The thermal history produced in a raster scan already produces heterogeneous and spatially non-uniform structures and differ from conventional manufacturing. Understanding how these thermal profiles result in AM centric microstructure is crucial to controlling AM process parameters and final mechanical properties. We present a high-fidelity powder scale simulation model that is fully-coupled with cellular automata for grain growth. The model uses full laser ray tracing to accurately capture the thermal profiles imposed by different beam shapes at varied laser scan speeds. The model accounts for nucleation and epitaxial growth and shows that beam shaping is a strategy to control the columnar to equiaxed transition. Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344, Lawrence Livermore National Security, LLC.

3:00 PM
This work focuses on parameter development for a large-scale laser hot wire process. The laser hot wire process consists of a moving melt pool formed by a moving laser source and a moving “hot wire” fed into the melt pool at an elevated temperature. Parameter development for a large-scale hot wire feed additive manufacturing process was carried out with the use of analytical welding models and finite element analysis. Initial work consisted of mapping a single bead geometry with key mapping outputs including, melt pool cross sectional area, melt pool depth, melt pool width, melt pool length, and the length to with ratio. Parameter development is being extended to mapping parameter space for more complex geometries such single-layer pads, multi-layer cubes and thin walled T junctions.

3:20 PM
Numerical Simulation of Extrusion-based Additive Manufacturing for Process Parameter Planning in a Polymer Dispensing System: Haiyang He; Bo Cheng; Kaja Schmidt; Claudia Kruse; Charles Tuffile; 1Robert Bosch LLC; 2Robert Bosch GmbH
This paper establishes a computation fluid dynamics (CFD) model for the time-pressure polymer dispensing process. The developed model simulates the process of liquid being applied on a substrate and predicts critical performance index, such as strand width and height, of the dispensing system. A mesh sensitivity analysis has been performed to identify the element size for achieving satisfactory accuracy and efficient computation time. The influences of material properties, such as surface tension and viscosity, on the simulation results were investigated. In addition, the effect of flow rate and nozzle translational speed on strand width were studied. The simulation results were validated against experimental measurements, and the model was demonstrated to be effective in predicting the strand width. Based on the simulations, a process map was constructed for process parameter planning and optimization.

3:40 PM
Defining Design Parameters for Large-scale Extrusion Additive Manufacturing Systems by Estimation of Interlayer Cooling Rates: Rebecca Kurless; Lonnie Love; Gregory Dreibus; Brian Post; Alex Roschli; A. John Hart; Abigail Barnes; Massachusetts Institute of Technology; 2Oak Ridge National Laboratory
The interlayer strength of fused filament fabrication (FFF) components depends on the effective weld time between layers during printing. Insufficient weld time results in weak adhesion between layers. We develop a simplified thermal model of surface heat transfer and interlayer welding in FFF printing, and apply this model to dictate design criteria for big area extrusion additive manufacturing (BAAM) systems. The model is used to predict the maximum time permitted to print each layer for a prescribed print material, layer thickness, and bead geometry. This maximum time is established such that the underlying printed layer does not cool below a critical temperature, correlated to a minimum acceptable interlayer strength. This minimum time is then used to calculate the extruder flow rate and define design parameters for the BAAM system. We discuss limiting cases dictated by part and layer geometry and use in situ infrared imaging to validate our modeling assumptions.
Thermal Boundary Conditions in Finite Element Modeling of Laser Powder Bed Fusion: Chao Li1; Erik Denlinger1; Michael Gouge1; Jeff Irwin1; Pan Michaeleris1; Autodesk Inc.

This work was funded by the Department of Energy's Kansas City AM part evaluated in this work includes a common bracket evaluated and response locations are in order to find these frequency changes. The convection coefficient values, which predict similar thermal history as the powder model, are found to be a function of thermal conductivity of the deposited material and the cross-sectional thickness of the part feature.

Alternative Approach on an In-situ Analysis of the Thermal Progression during the LPBF-M Process Using Welded Thermocouples Embedded into the Substrate Plate: Norman Schnell1; Marvin Siewert2; Stefan Kleszczyński1; Gerd Witt1; Vasily Ploshikhin2; 1Universität Duisburg Essen; 2Universität Bremen

Laser powder bed fusion (LPBF-M) is a very potent technology for creating highly individual, complex and functional metal parts. One of the major influencing factors is the thermal progression significantly influencing size accuracy, microstructure and process stability. Therefore, creating an enhanced understanding of thermal phenomena through measurements and simulations is crucial to increase the reliability of the technology. Current research is mainly based on temperature measurements of the upper layer, leaving major leeway at the substrate-part-interface. Especially this area is of utmost technical importance serving as the main heat sink. Insufficient heat dissipation leads to accumulations of heat, deformations and process breakdowns. This contribution presents a simple and flexible method to analyze the thermal progression close to the part inside the substrate plate. The acquired data shows very high consistency. Additionally, the results are compared to a model created using an at ISEM developed FEM-Software leading to promising results for validation studies.

Dynamic Defect Detection in AM Parts Using FEA Simulation: Kevin Johnson1; Jason Blough1; Andrew Barnard1; Aimee Allen1; Ben Brown1; Troy Hartwig1; David Soine1; Tristan Cullom1; Edward Kinzel1; Douglas Bristow1; Robert Landers1; 1Michigan Technological University; 2Kansas City National Security Campus managed by Honeywell; 3Missouri University of Science and Technology; 4University of Notre Dame

The goal of this paper is to evaluate internal defects in AM parts using FEA simulation. The resonant frequencies of parts are determined by the stiffness and mass involved in the mode shape at each resonant frequency. Voids in AM parts will change the stiffness and mass therefore shift the resonant frequencies from nominal. This paper will investigate the use of FEA to determine how much a void size, shape, and location will change the resonant frequencies. Along with where the optimal input and response locations are in order to find these frequency changes. The AM part evaluated in this work includes a common bracket evaluated individually and as a set of parts that are still attached to the build plate. This work was funded by the Department of Energy's Kansas City National Security Campus which is operated and managed by Honeywell Federal Manufacturing Technologies, LLC under contract number DE-NA0002839.
Short fiber-filled polymers experience increasing applications in melt extrusion additive manufacturing. As the filled polymer is melted and extruded, the fiber-filled polymer suspension exhibits mutually dependent effects, such that flow kinematics influence fiber orientation while the fiber alignment affects the formation of melt flow. This paper presents a fully-coupled numerical scheme to characterize the mutually dependent effects between melt flow and fiber orientation in a non-Newtonian axisymmetric flow including a free surface using the Galerkin Finite Element Method. The power law fluid model is employed to characterize the shear thinning rheological behaviors of polymer melts. This approach is used to solve the fully-coupled flow velocity and the fiber orientation fields for the nozzle extrusion flow in a large-scale polymer deposition additive manufacturing process. Computed results obtained from both the weakly-coupled and fully-coupled schemes exhibit noticeable differences in the flow velocity, fiber orientation tensor fields, die swell of free extrudate, and predicted elastic constants.

Nicholas Calta, Lawrence Livermore National Laboratory

Tuesday PM Room: 615 AB
August 13, 2019 Location: Hilton Austin

Process Chair: Nicholas Calta, Lawrence Livermore National Laboratory

1:40 PM Quantitatively Revealing the Dynamics in Laser Additive Manufacturing Processes by High-speed Synchrotron X-ray Imaging and Diffraction: Lianyi Chen; Missouri University of Science and Technology

Understanding the dynamics of laser additive manufacturing processes is critical for establishing location-specific processing-microstructure-property relationships. The highly localized (tens of micrometers) and very short (tens of microseconds) interaction of a laser beam with powders/substrate pose a huge challenge to the characterization and understanding of this process. In this talk, I will give an overview of our research on characterizing the dynamics of powder spreading, powder sputtering, melt pool evolution, melt flow, defect formation and evolution, and solidification in laser additive manufacturing processes by using high-energy high-speed x-ray imaging and diffraction, with a focus on defect formation and evolution.

2:00 PM Pressure Dependence of the Laser-Material Interaction under High Speed Welding and Laser Powder Bed Fusion Conditions Probed by In Situ X-ray Imaging: Nicholas Calta; Aiden Martin; Joshua Hammans; Michael Nielsens; Manyalibo Matthews; Trevor Willey; Jonathan Lee; Lawrence Livermore National Laboratory

Pressure has been suggested as a process variable in laser powder bed fusion (LPBF). Many laser welding studies illustrate that reduced pressure can significantly increase weld penetration depth. These studies primarily rely on ex situ measurements, leaving gaps in understanding of how pressure changes process dynamics. While in situ measurements using optical imaging provide valuable insight, these techniques are only surface sensitive and therefore cannot provide direct information about subsurface behavior. Here we use high speed in situ X-ray imaging to probe the subsurface dynamics of the laser-metal interaction in LPBF conditions. The geometry and dynamics of the vapor-liquid interface at the melt pool surface change significantly as a function of ambient pressure. The physical mechanisms behind these changes will be discussed. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

2:20 PM Identifying the Formation of Laser Powder Bed Fusion Defects In-situ by Coupling High Speed X-ray and Infra-fed Imaging: Benjamin Gould; Sarah Wolff; Tao Sun; Niranjan Parab; Cang Zhao; Aaron Greco; Cinta Lorenzo-Martin; Argonne National Laboratory

Laser powder bed fusion has become increasingly popular over the past decade. However, the reproducibility of parts manufactured by this technique is still a problem, overcoming which requires the understanding of the keyhole and melt pool dynamics during the process. In this work, we synchronize the high-speed x-ray imaging with high-speed infra-red imaging to study the laser powder bed fusion processes in real time. Using this technique, we demonstrate the simultaneous multimodal observation of many dynamic physical phenomena that affect the quality of the additively manufactured parts. Additionally, the formation of observable print defects in the X-ray images were correlated to distinct features observable via high speed Infra-red imaging of the surface of the print.

2:40 PM Hydrothermal-assisted Powder Bed Fusion of Ceramics for Achieving High Green Density: Fan Fei; Li He; Baizhuang Zhou; Ziyang Xu; Xuan Song; University of Iowa

Ceramic additive manufacturing (AM) provides a freeform fabrication method for creating complex ceramic structures that have been extremely difficult to build by traditional manufacturing processes. However, ceramic structures made by AM processes usually exhibit a relatively low density, which is largely due to the use of a large amount of organic binder in shaping green bodies. In this research, we present a new ceramic AM process, named hydrothermal-assisted powder bed fusion (HPBF), which utilizes a water-based hydrothermal mechanism to fuse particles, eliminating the use of binders in forming green bodies. A prototype system for the proposed HPBF process is introduced. The effects of process parameters (such as layer thickness, printing passes, prepressing and final pressing pressure, temperature) on the properties of green green parts are investigated. Experimental results indicate that with optimized process parameters, HPBF can achieve 3D ceramic green parts with a high density up to 90%.

3:00 PM Examination of the LPBF Process by Means of Thermal Imaging for the Development of a Geometric-specific Process Control: Tobias Pichler; Johannes Schleifenbaum; Fraunhofer Institute for Laser Technology ILT; RWTH Aachen University, Chair for Digital Additive Production DAP

The development of process parameters for the Laser Powder Bed Fusion (LPBF) process is typically carried out by the manufacturing and metallurgical analysis of geometrically primitive test specimens (e.g. cubes). The process parameters identified in this way are used for the manufacturing of parts which are characterized by a high geometric complexity and a combination of solid and filigree component areas. Due to the discrepancy between the parameter development on primitive specimens and applications with complex parts, a geometric-specific process control is to be developed. In the context of this work different sample geometries are manufactured from Ti6Al4V by LPBF and the process is monitored by thermal imaging. The influence between component geometry and process parameters on the thermal behavior is shown. On the basis of this information, rules for adapting the process control to the specific component geometry are derived.
Corresponding results and studies on the interaction between investigating the influence of shielding gas flow conditions on single melt and particles with up to 10,568 fps. This arrangement allowed dynamics to analyze their influence on process stability. Therefore, a of this work comprises visualizing the convection processes and particle of particles from the process zone that emerge from the interaction with corresponding manufacturing system. The gas flow assures the removal process depends on the design of the shielding gas flow in the Ensuring a robust and reproducible Laser Powder Bed Fusion (L-PBF) Aachen University

Investigating Applicability of Surface Roughness Parameters in 1:40 PM Laboratory August 13, 2019 Location: Hilton Austin

Process Development VI - Metals B

Tuesday PM Room: 616 AB Location: Hilton Austin

Session Chair: Manyalibo Matthews, Lawrence Livermore National Laboratory

1:40 PM

Investigating Applicability of Surface Roughness Parameters in Describing the Metallic Additive Manufacturing Process: Samantha Taylor1; Bradley Jared2; Josh Koepke3; Eric Forrest1; Joseph Beam1; 1University of Texas Austin; 2Sandia National Laboratories Additive manufacturing (AM) is known for its large variance in mechanical properties. This is not only true for properties like strength, but also surface roughness. Build settings, which affect surface roughness, are often chosen to optimize strength or ductility. As part requirements change, build settings change, thereby changing resultant surface roughness. When describing surfaces, arithmetic roughness (Ra) is the most common parameter. However, it may not provide an adequate representation of surface topography for AM parts. Traditional surface roughness parameters for defining surface topography were well-established before the advent of AM, and a need has arisen to investigate applicability of these parameters to the unusual surfaces created through various AM technologies. This study demonstrates that Ra is not a suitable parameter in correlating surface topography to AM build parameters. Other existing parameters and combination of parameters will be investigated for their suitability in describing the AM process.

2:00 PM

Melt Pool Geometry Modeling and Monitoring via In-situ Vision System for Powder Fed Laser Fusion Process: Deniz Ertay1; Mihaela Vlasea2; 1University of Waterloo Powder fed laser fusion (PFFL) is a metal additive manufacturing process where modeling and monitoring the geometry of the process are necessary to improve accuracy and repeatability. In this work, an analytical lumped-parameter thermal and geometry models are presented, which predict the complex thermal behavior and the geometric features of the PFFL process. The melt pool is monitored by a high dynamic range (HDR) camera during the process, which has an advantage of higher pixel depth and is preferred in the monitoring of welding processes. Image processing techniques are used to detect the melt pool. The process signatures extracted with the HDR camera are used for the validation of the physics-based models and for the detection of process instability. The detected process instabilities will be used in planning post-processing in the future.

2:20 PM

Quantification of Metal Powder Layer Uniformity for Additive Manufacturing Using Transmission X-ray Imaging: Ryan Penny1; Marvin Ochsenius2; Christoph Meier3; Wolfgang Wall4; A. Hart5; 1Massachusetts Institute of Technology; 2Technical University of Munich Powder bed additive manufacturing (AM) requires consistent spreading of each powder layer to create dimensionally accurate and defect-free components. Attributes of the powder, such as diameter distribution, shape, and surface roughness, change flowability and therefore influence layer uniformity. Moreover, spreading may be affected by local boundary conditions including friction from the underlying part and constraint near the edge of the build area. Here, we show how X-ray absorbance can be used to map the local volume of powder deposited within layers typical to powder bed AM. First, a model is described estimating the sensitivity of this method, considering the materials in the X-ray beam path and the measurement noise, and is validated by measuring metal foils. This technique is then applied to characterize spatial layer uniformity as related to powder and layer properties. Our findings are compared to discrete element simulations that include adhesion and friction.

2:40 PM

Dynamic Measurement of Laser Beam Quality for Selective Laser Melting: Ivan Zhirnov1; Shawn Moylan1; Sergey Mekhontsev1; Brandon Lane2; Steven Grantham1; 1National Institute of Standards and Technology Recent studies of Laser Powder Bed Fusion show that the spatial variation of the beam profile in the working plane being processed leads to irregular geometry and asymmetry of single tracks. While there are several commercial devices to perform such a characterization, all of them require having an ability to have special access to operate the machine in the maintenance mode. In this research, we investigated the possibility of using this device in the common mode. This will make laser diagnostic easier before 3D build. A commercial-off-the-shelf beam sampler with several add-on features was used as a drop-in tool to allow evaluation of the laser spot distribution and total power during selective laser melting. This presentation describes a setup, experiment design and measurement results, including measurements in the static and dynamic modes. The proposed method can be used to diagnose the laser beam quality for both laboratory and industrial machine.
Defect Detection in Metal Additive Manufacturing through Application of In-situ Diagnostics: Bradley Jared; Manyalibo Matthews; John Carpenter; Ben Brown; Sarah Garlea; Sandia National Laboratories; Lawrence Livermore National Laboratory; Los Alamos National Laboratory; Kansas City National Security Campus; Y-12 National Security Complex

Coupling process-structure-property relationships is a significant challenge that must be overcome to facilitate the rapid, widescale adoption of metal additive manufacturing (AM) for high consequence applications. Research addressing this challenge has occurred during a multi-site collaboration effort within the National Nuclear Security Administration (NNSA). Metal AM process signatures have been monitored across different time and spatial scales for directed energy deposition and laser powder bed fusion processes using diverse optical, thermal and acoustic modalities. These signatures have been correlated to as-built material structures captured using metallography, computed tomography (CT) and X-ray tomography. Resulting process-structure-property correlations are probabilistic in nature, prompting the successful use of advanced data analytics and machine learning techniques in their quantification. Accomplishments and key take-aways will be discussed from the collaborative effort, tying their relevance to part qualification and production acceptance. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

A Direct Metal Laser Melting System Using a Continuously Rotating Powder Bed: William Carter; Michael Graham; Christopher Hayden; Yoonkoo Jeong; Justin Mamrak; Brian McCarthy; William Monaghan; Edward Nieters; Victor Ostroverkhov; Subhrajit Roychowdhury; Andrea Schmitz; Michael Tucker; GE Research; GE Additive

The aviation industry manufactures many metal parts of large diameter, but small cross sectional area. Designers of these parts are requiring increasingly complex geometries for improved aerodynamic efficiency and cooling. The combination of large diameter and complex geometric features inspired the development of a new DMLM architecture with a rotating powder bed. The system coordinates the rotational motion of a powder bed with an ascending laser scanner and recoater to build in a helical fashion. A single-point powder feeder delivers metal powder near the inner radius of an annular build volume, and the recoater spreads the powder to the outer radius in a "snow plow" fashion. The recoater and laser scanner are installed at different angular positions, they operate independently and simultaneously. A prototype system was built to demonstrate this concept for an aircraft engine combustor liner (600-mm dia. x 150-mm ht.) and showed continuous laser utilization exceeding 97%.

Residual Stress

Mitigating Residual Stress and Distortion in Additive Manufacturing by Topology Optimization of Latticed Support Structures: Jiadong Deng; Victor Oancea; Juan Hurtado; Claus Pedersen; Chris Woehler; Dassault Systemes Simulia Corp

Support structures are generally required in AM to satisfy the overhang constraint. However, residual stress accumulated in AM can fracture the support structures, leading to build failure or exaggerated distortion. Sacrificial support structures will also increase build time/cost. It is therefore essential to design support structures intelligently to ensure build success and reduce cost. In this work, latticed support structures will be introduced and topologically optimized to mitigate residual stress or distortion and reduce cost. Support structure is assumed to be composed of self-supporting lattice materials to circumvent the overhang issue, and its relative density distribution is optimized. To reduce computational cost, eigenstrain-based simulation in ABAQUS is employed. Numerical examples demonstrate the proposed method can successfully mitigate the residual stress level and reduce the support material usage simultaneously. The optimized latticed support structures obtained are further 3D printed, demonstrating that the computed lightweight support designs can successfully survive without cracking.

In-situ Residual Stress Determination in Laser Powder Bed Fusion Using a Residual Stress Dynamometer: Ian Ashton; Rodrigo Magana-Carranza; Joseph Robinson; Peter Fox; Chris Sutcliffe; University of Liverpool, School of Engineering

Although there has been adoption of Laser powder bed fusion (L-PBF) in mass manufacturing, there are limitations of the process due to residual stress generation. In certain geometries stress will cause deformation or cracking which cannot be remedied by post-process stress relief. Currently residual stresses in L-PBF parts are assessed via post-process techniques or expensive x-ray diffraction experiments. There is a lack of simple in-situ analytical approaches to understanding stresses evolution in components. In this study in-situ stress measurements for a variety of process parameters and build materials, have been performed with the use of a residual stress dynamometer. This methodology reveals information of stress generation, both intra and inter build layers. Absolute residual stress magnitude in Ti-6Al-4V has been found to depend on total energy per layer as opposed to scanning strategy. This in-situ process will enable optimisation of L-PBF components and therefore the widen uptake of the technology.

Residual Stress Induced Fracture of Additive Manufactured Parts Based on Modified Inherent Strain Method: Hai Tran; Qian Chen; Albert To; University of Pittsburgh

Residual stress is believed to be the main cause of cracking of a part during the build process of laser powder bed fusion. A systematic investigation on the residual stress-induced cracking issue is presented. Simulations based on modified inherent strain method and experiments were used to investigate the residual stress and fracture in Inconel 718 additively manufactured by a laser powder bed fusion system. The results show that the modified inherent strain method can accurately predict the residual stress and hence, together with J-integral approach, fracture can also be simulated. This model will also be applied to simulate crack delamination at the solid/support interface in additively manufactured parts. The results of this work may shed light on the cracking issue in components processed by laser powder bed fusion process.
Fused Deposition Modeling (FDM) Process

Estimation of Filament Temperature History and Part Distortion in Fused Deposition Modeling (FDM) Process: Thao Phan\(^1\); Ahmed El-Gizawy\(^1\); 1University of Missouri- Columbia

Fused Deposition Modeling (FDM) is an effective additive manufacturing technique because of its capacity for building complex structures at low cost compared with other AM methods. In FDM process, filament material is heated and extruded in semi-molten state to form beads and layers needed for building the required structure. Variation on the thermal and mechanical loading conditions during processing could lead to process-induced defects that could seriously affect the quality of the FDM built products. The present paper presents an integrated approach for modeling of the process-induced defects of FDM printed materials. The introduced approach would effectively predict the relation between time-dependence temperature distribution and the resulting distortion of the final product. Numerical modeling based on finite difference method is used in identifying temperature history during the printing process. A finite element technique is used to characterize the structure deformation and residual stresses resulting from temperature variations during processing.

X-ray Diffraction Stress Measurement and Comparison for Various Raster Path in Laser Powder Bed Fusion (LPBF): Amit Kumar\(^1\); Jose Lerma\(^1\); Xianglong Wang\(^1\); Oscar Mata\(^1\); Sila Atabay\(^1\); Mohammad Shandiz\(^1\); Mathieu Brochu\(^1\); McGill University

Laser powder bed fusion (LPBF) has become one of the most popular options for the fabrication of complex part because of the emerging variety of manufacturing options. Residual stress is the common problem in LPBF that is generated due from the intrinsic high-temperature heating and cooling cycles. Typical destructive residual stress measurement techniques are time-consuming. The Sin2 method (normal X-ray equipment) is also a well-known technique to measure the residual stress, but it involves a certain level of part cutting to fit within the hardware. To overcome this issue, the present study focused at comparing residual stress measurement using a μ-360 Pulsetec portable X-ray stress analyzer (Cos a method) to the values obtained with the normal X-ray equipment (Sin2 method). The residual stress response was measured on popular LPBF materials, including SS-316L and Inconels. Among the variables studied to influence the residual are raster paths and part shape. The Debye-Scherrer ring (D-S ring) plot is analyzed and discussed for all the raster paths.

A Modified Inherent Strain Method with the Consideration of Transformation Induced Plasticity for Metal Additive Manufacturing Process: Wen Dong\(^2\); Qian Chen\(^3\); Xuan Liang\(^3\); Albert To\(^4\); 1University of Alberta

A modified inherent strain method that takes the transformation induced plasticity (TRIP) into consideration is proposed to improve the accuracy of residual distortion and stress prediction for metal additive manufacturing (AM). In this work, details on the adoption of the TRIP in theory and its realization in the simulation are presented. The procedure to extract and apply the inherent strain is also illustrated. Additionally, the effect of geometrical parameters of the melt pool on the inherent strain values is investigated. Experiments and simulations for printing double cantilever beams and L-brackets are conducted to validate the availability of the proposed method. The predicted distortions and residual stresses have good agreements with the experimental data. This method shows a great potential application value in the design and production of metal AM field.

Topography Optimization of Support Structures Considering the Distortion Minimization in Laser Powder-bed Fusion Additive Manufacturing: Zhidong Zhang\(^1\); Osezuwa Ibadode\(^1\); Usman Ali\(^1\); Chinedu Francis Dibia\(^1\); Pouyan Rahnama\(^1\); Ali Bonakdar\(^1\); Ehsan Toysorkani\(^1\); 1University of Waterloo; 2Siemens Canada Limited

Laser Powder-Bed Fusion (LPBF) is an important additive manufacturing technique, with which complex metal parts can be realized. Well-designed support structures are critical in this process because they significantly influence the quality of the final products. The support structures should not only bear the gravity but also the high thermal loading caused by the fast-moving laser beam in LPBF. Topology optimization, a widely used technique to find high-performance structures, has been employed in the support structure design of additive manufacturing. However, there is still a gap that the distortion caused by LPBF is not considered in the support design, especially for LPBF. In this work, an innovative topology optimization model has been proposed that the distortion minimization of the printed part is integrated in the topology optimization based on the inherent strain method. The resulting support structures have been 3D printed and evaluated, showing the strength of the proposed model.

Binder-jet 3D-printing process: Opportunities and Challenges: Amir Mostaefa\(^1\); Anthony Rollett\(^1\); 1Carnegie Mellon University

Binder-jet 3D-printing (BJ3DP) is a non-beam-based additive manufacturing (AM) technique where a liquid binder is jetted on layers of powdered materials, selectively joined and then followed by densification process. To fabricate complex geometry, it is necessary to understand the physical processes during 3D-printing and the fundamental science of densification. Here, the effect of powder characteristics (e.g. morphology, mean size, and distribution), printing process parameters (e.g. layer thickness, print orientation, binder saturation, print speed, and drying time), sintering (e.g. temperature and holding time) and post-processing are addressed. With the rapid development of AM technologies, there are many potential opportunities to use the binder jetting technology. Nevertheless, there are challenges such as: powder packing defect formation and agglomeration during the printing process, non-linear shrinkage during densification step, and residual porosity, all of which can affect the properties of the final product.
Fabrication and Characterization of 3D Printing Induced Orthotropic Functional Ceramics: Luis Chavez; Bethany Wilburn; Ryan Wicker; Yirong Lin; "The University of Texas at El Paso
Barium titanate with high piezoelectric coupling coefficients was fabricated using binder jetting 3D printing. The 3D printed ceramic presented piezoelectric properties as high as 80% of theoretical value with only 36.77% of the theoretical density. The dielectric and piezoelectric properties were shown to be have a strong dependency in the printing direction. The dielectric property of the perpendicularly tested samples was 20% higher than those tested parallelly. The piezoelectric property of samples tested in perpendicular orientation was 35.1% higher than those tested in parallel orientation. The piezoelectric coupling coefficient obtained for the perpendicular samples was 152.7 pC/N. Therefore, it was shown that the printing orientation has a direct influence on the functional properties of additively manufactured ceramics. The findings in this study can lead to the development of more efficient sensing and energy harvesting devices that can be tuned to respond based on the direction of the loads applied.

Process Integrated Production of WC-Co Tools with Local Cobalt Gradient Fabricated by Binder Jetting: Maja Lehmann; Michael Zaeh; "TU Munich
Producing complex shaped tungsten carbide (WC) tools by classical technologies is difficult and often impossible due to their high hardness and brittle fracture behavior. Additive Manufacturing (AM) is a suitable technology for creating complex structures and simultaneously shortening ex-pensive machining processes. Binder Jetting is an innovative AM technology that offers several advantages over laser-based processes, e.g. low manufacturing costs and high build-up rates. Binders with nanoparticle additives have already proven to be effective in increasing the packing density of the powder bed and improving the sintering properties. Additionally, they offer the possibility to selectively change the material composition in the component. This paper demonstrates a concept for the use of WC nanoparticles to generate gradients in the green compact, which lead to a cobalt gradient in the component after sintering. The possibility to introduce par-ticles locally into complex structures allows a local adaption of material properties.

The Effect of Print Speed on Surface Roughness of Parts Produced Using Binder Jet 3D Printing: Kyle Myers; Andrew Klein; "ExOne
One of the main benefits of binder jetting is the ability to print fast compared to other metal additive manufacturing methods. As volumetric throughput values continue to increase, it is not widely understood the effect of printing faster. MIM powders are used to achieve optimal density and surface finish. Printing at slower speeds results in densities near 98% and surface roughness values as low as 3μm in the as-sintered condition. In this study, spread speeds were varied to understand the effect of print speed on surface roughness. 316L D90 -22μm powder is used to print with 5 different spread speeds, 2 different layer thicknesses, and 2 different printhead droplet sizes. Surface finish and density will be measured for the sintered parts.

Binder Jetting Additive Manufacturing of Copper/Diamond Composites: Ming Li; Mohammadamin Moghadasi; Michael Hurst; Zhijian Pei; Chao Ma; "Texas A&M University
This work aims to survey the feasibility of the processing of copper/diamond composites with binder jetting. The suitable sintering profile was first tested on copper/diamond composite powders at different volume fractions of copper. The copper/diamond composite was then printed using a commercial binder jetting machine with different processing parameters. The printed parts were finally sintered according to the results of the preliminary study on the sintering profile. The sintering-induced shrinkage was investigated. The microstructure of the initial powder, green parts, and sintered parts was analyzed using scanning electron microscope and optical microscope. The compositional evaluation and phase identification were carried out by an energy dispersive X-ray spectroscopy and X-ray diffraction analysis, respectively. The thermal conductivity of the resultant parts were also evaluated.

Special Session: Data Analytics III - Sensing for Quality Assurance
Tuesday PM  Room: 412  Location: Hilton Austin
Session Chairs: Subhrajit Roychowdhury, GE Global Research Center; John Mitchell, Sandia National Laboratories

Pyrometry Linked to Voids in Additively Manufactured Metals: SAND2019-4035 A: John Mitchell; Thomas Ivanoff; Jonathan Madison; Daryl Dagel; Bradley Jared; Joshua Koepke; David Saiz; "Sandia National Laboratories
Although studies have shown strong relationships between process parameters and porosity, monitoring strategies for defect detection and void formation are still needed. In this talk, instantaneous anomalous conditions are detected in pyrometry data collected during laser powder bed fusion additive manufacturing and correlated with voids observed from micro-ct scan data. Large two color pyrometry data sets collected were used to estimate instantaneous temperatures, melt pool orientations and aspect ratios; machine learning algorithms were applied to processed pyrometry data to detect outlier images and conditions. It is shown that outliers are good predictors of voids. Concepts and algorithms used to process pyrometer data for a powder bed AM process of stainless steel are presented. Sandia National Labs is managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a subsidiary of Honeywell International, Inc., for the U.S Dept. of Energy's National Nuclear Security Administration under contract DE-NA0003525.
2:00 PM
Scenario-based Approaches for In-Situ Process Monitoring: Shaw Feng; Saadia Razvi; Paul Witherell; Albert Jones; 1National Institute of Standards and Technology
Additive Manufacturing (AM) machines have been increasingly instrumented with nondestructive sensors that collect a variety of data for monitoring AM process and part quality. Aligning these sensors to the AM-part-build coordinates can be a major problem. This paper focuses on the data collected by those sensors and a data-rich environment, including both structured and unstructured data, for process monitoring. The quantity and quality of different data types are causing curation, organization, and administration problems that can impact data usages. The scope of this paper is within laser powder bed fusion (L-PBF) processes. The purpose of scenario-based approaches is to better understand those problems. Scenarios include the use of thermal and grayscale images, movies, acoustic signals, and acceleration signals to detect anomalies in the AM process. The goal is to improve process control for better part quality via sensor data organization, fusion, and analytics.

2:20 PM
Sensor Based Prediction of Material Defects: Xiaohu Ping; Lembit Salassoo; Subhrabaj Roychowdhury; Thomas Spears; Vipul Gupta; Justin Gambone; Xiaolei Shi; 1GE Global Research Center; 2GE Aviation
Minimization of material defects is one of the main objectives in metal additive manufacturing. In current practice, assessment of part defects is done either by optical micrographs from cut ups, CT scans, or by regular physical testing. In this paper, we propose a novel approach of using real-time sensor measurements of the melt-pool to detect and assess part defects. Particularly, we add an on-axis photodiode sensor to a standard commercial M2 machine with QMM3D system, collect the real-time photodiode intensity data, and use a machine learning model to predict the relationship between the melt-pool sensor data and the actual material defects. In conclusion, we find a high correlation between on-axis sensor data and material defects which will save significant time in post process inspection and pave the way to using in-situ monitoring as a robust NDE technique for part acceptance.

2:40 PM
Cyber Security through Side-channels: A Methodology for Implementing a Cyber-physical Hash on Additive Manufacturing Systems: Logan Sturm; Nathan Raeker-Jordan; Christopher Williams; 1Virginia Polytechnic Institute
Previous work has demonstrated the ability to detect cyber-physical attacks on additive manufacturing (AM) systems by transmitting information to an air-gapped side-channel measurement system using a secure cyber-physical hash. This was achieved by transmitting the hash information to a camera using a printed QR code. This work expands upon the previous work by demonstrating transmission of the cyber-physical hash through two new side-channels, acoustic (extrusion) and laser intensity/position (metal powder bed fusion). This work presents two case studies, the use of modified g-code to transmit information acoustically using the stepper motors and the use of laser melt pool tracking to detect build attacks and to transmit hash information. The work provides a methodology for selecting side-channels for the measurement system and discusses design considerations, such as bandwidth, signal-to-noise ratio, and transmission frequency, for the cyber-physical hash based on the type of side-channels selected.

3:00 PM
Experimental Investigation of Stratasys J750 PolyJet Printer: Predictive Modeling of Color Accuracy: Xingjian Wei; Li Zeng; Zhijian Pei; 1Texas A&M University
The J750 PolyJet printer from Stratasys is capable of printing full-color parts. However, little information is currently available about the color accuracy of parts printed by the process. In this study, multivariate multiple regression is used to predict the color accuracy of PolyJet printed parts. The actual colors are measured and quantified by a color sensor and used as training data. The validation of the predictive model is performed on testing data. These results would be valuable to researchers and practitioners who use the PolyJet printer.

3:20 PM
An Exploration of the Use of Archimedes Density Measurement for the Characterization of Spatial Density Distribution of Metal Additive Manufacturing Parts: Li Yang; Truong Do; 1University of Louisville
Archimedes density measurement method has been widely utilized for the estimation of overall density of parts in various applications. On the other hand, with many metal additive manufacturing (AM) parts, in addition to the overall density levels, the spatial characteristics of the density is also of interest for the characterization of the process qualities. In this study, the Archimedes method was utilized for the spatial density distribution characterization of metal parts fabricated by powder bed fusion (PBF) process, by utilizing a moving-volume method. The measurement device was setup to continuously move the sample into/out of the water solution, with weight information continuously recorded. The measurement results were compared with both the cross sectional imaging based porosity measurement and micro-CT scan results, and sensitivity analysis was carried out to evaluate the errors and the spatial resolution of this method as a possible low-cost alternative for spatial density distribution characterization.

3:40 PM
Towards Real-time NDT with Hyperspectral X-ray Data: Nicholas Polydorides; Dimitris Kamilis; Susanne Lee; Joseph Desjardins; 1University of Edinburgh; 2Harris Corporation
We present progress in fast, high-resolution imaging, material classification, and fault detection using hyperspectral X-ray measurements. Classical X-ray CT approaches rely on data from many projections, resulting in long acquisition and reconstruction times. Additionally, conventional CT cannot distinguish between materials with similar densities. However with 3D printing, the majority of materials are known a priori. This allows machine learning tools within the image reconstruction algorithms to vastly reduce the data collected and increase the accuracy of fault detection. We demonstrate simulation results of such machine learning using an algorithm that combines model-based inversion with unsupervised classification. Our approach entails acquiring hyperspectral data and resolving it into monochromatic data for each material in the sample. This results in a number of binary imaging problems that are much simpler to solve than classical CT, where no a priori material information is assumed. Additionally, we describe hardware that makes such hyperspectral imaging possible.
A Framework to Streamline New Materials Implementation in Additive Manufacturing: Bing Zhang; Raiyan Seede; Raymundo Arroyave; Ibrahim Karaman; Alaa Elwany; Texas A&M University

Many materials currently used in metal additive manufacturing (AM) were originally developed for traditional manufacturing methods. This results in challenges when attempting to process these materials using AM. To overcome these challenges, there is now emphasis on developing new materials specifically for AM that can take into consideration unique aspects of the process. However, determining the processing recipes for new materials that have not been previously investigated is typically expensive and time-consuming. In this study, we propose a new framework for determining windows of processing parameters for new AM metallic materials. The proposed framework integrates experimental design, modeling, simulation, uncertainty quantification, experimental material characterization, and detailed melt pool analysis. One important benefit is that it uses common analytical models, as opposed to specialized computational codes that might not be accessible to all stakeholders. We present several case studies using different model materials to illustrate the effectiveness of the proposed framework.

Fabrication of Three-dimensional Structured Ti-6Al-4V/TiN Metal Matrix Composite in Laser Powder Bed Fusion Using Selective Laser Nitriding: Philip Morton; Hunter Taylor; Andres Navarro; Cesar Terrazas; Lawrence Murr; Ryan Wicker; University of Texas El Paso

The laser powder bed fusion (LPBF) additive manufacturing process was utilized to fabricate a Ti-6Al-4V/titanium nitride (TiN) metal matrix composites (MMC). TiN was selectively precipitated during LPBF processing of Ti-6Al-4V and formed a dendritic microstructure observed with optical and electron microscopy. Additionally, x-ray diffraction was used to confirm the TiN crystal structure. Laser parameters and chamber atmosphere during the laser nitriding step were studied to control the resulting dendritic layer thickness, which ranged from 8 – 267 μm, and dendrite morphology (size and orientation). Microhardness of the TiN layer measured a maximum of 1,832 VHN, compared to ~450 VHN measured for the Ti-6Al-4V matrix. Single wavelength pyrometry and high-speed video recording were used to monitor the nitriding process. Process improvements are being further developed to enable full three-dimensional control of the TiN geometry and create a scalable manufacturing process for Ti-6Al-4V/TiN MMCs.

Tensile and Fatigue Properties of Ti6Al4V Fabricated Using a Renishaw's 500Q Powder Bed Fusion System: Ravi Aswathanarayana; George Rowlands; Youssef Gaber; Rhys Jones; Jono Munday; Marc Saunders; Renishaw Plc

In this study, the influence of various surface modification techniques and scanning strategies on the mechanical performance of Ti6Al4V was investigated. The test pieces were fabricated using a layer thickness of 60 μm on a Renishaw's 500Q multi-laser machine with one laser per part. Flat dog bone test pieces of varying thickness (1mm, 3mm and 5mm) were tensile tested and cylindrical test pieces of 6mm diameter were tested under high cycle fatigue (HCF). All samples were heat treated and the only variable was the surface condition which varied between as-built, bead blasted and machined. The tensile testing results obtained from the as built and bead blasted specimens were lower than machined test pieces. This drop off in performance was more prominent in specimens with wall thickness < 3mm, highlighting the importance of selecting the appropriate scan strategies for the respective part geometry.

Nested Size Effects Observed in Nanoindentation Studies of Additively Manufactured 316L Stainless Steel: Andrew Birnbaum; Heonjuje Ryoo; John Steuben; Athanasios Iliopoulos; Kathryn Wahl; John Michopoulos; US Naval Research Laboratory

Recent work has shown that the presence of cellular substructures in selectively laser melted (SLM) 316L is correlated with significant increases in yield stress and ultimate strength. These substructures have been associated with dislocation cell formation, with cell walls and cell interiors corresponding to regions of high and low dislocation densities, respectively. Motivated by this finding, this effort sought a more comprehensive understanding of this phenomenon through spatially resolved hardness mapping via nanoindentation. Initially it was assumed that a spatially varying “cellular” hardness pattern would emerge, corresponding to the geometry of the cell structure. However, due to multiple, simultaneously operating hierarchical size effects, the apparent hardness deviates from this anticipated behavior. These size effects are due to the indenter, characteristic sub-structural length, and grain size. Analysis of the load/displacement behavior enabled an observation of each of these size effects, independent of the local anisotropy due to crystal orientation.

The Influence of Cellular Sub-grain Microstructure on Mechanical Deformation: An Experimental Investigation: Janith Wanni; John Michopoulos; Amit Bagchi; Ajit Achuthan; Clarkson University

The microstructure in additively manufactured (AM) metals is rich with hierarchical sub-grain features such as dislocation networks, twinning boundaries, and segregated elements. These features play a dominant role in determining the plastic flow behavior of the metal. For instance, the dislocation network is expected to offer resistance to dislocation nucleation and motion. In this work, the role of this dislocation network in metals manufactured by laser engineered net shaping (LENS) process is studied. In-situ characterization of the local deformation at sub-grain length scale during the tensile testing of coupon samples are performed using a micro-tensile loading frame. The local deformation was captured using a microscope. The preliminary results show that the cellular sub-grain structure has a major influence on the local deformation. Results from the ongoing parametric study to relate various geometric characteristics and texture of the cellular sub-grain structure to their influence on local deformation will be presented.

Weighing the Evidence: Origins and Mechanisms of Cellular Substructure in Additively Manufactured 316L: Andrew Birnbaum; John Steuben; Erin Barrick; Athanasios Iliopoulos; John Michopoulos; US Naval Research Laboratory; Lehigh University

Driven by the prospect of transcending the so-called “strength-ductility trade-off,” significant effort has been devoted to characterizing, analyzing, and understanding the widely observed cellular substructure in selectively laser melted (SLM) 316L. Recent efforts correlated an apparent increase in strength with the presence of these features, while others sought to assess their impact on inelastic strain generation. Despite this sustained effort and interest, the origin of these cellular structures, and the mechanisms by which they form remain an open question. Several theories have been posed, though none so far is capable of reconciling the constellation of reported observations. By analyzing 316L SLM single-tracks, we present hitherto unseen behaviors with regard to microstructural evolution and microsegregation, and seek to resolve these inconsistencies. We identify a strong correlation between the presence of Sigma-3 twin boundaries and absence of local microsegregation, bringing into question the idea that directional re-growth proceeds via cellular solidification.
The Mechanism of Cellular Sub-grain Microstructure Formation in Additively Manufactured (AM) 316L Alloy: A Computational Study

Chamara Herath1; Andrew Birnbaum2; John Michopoulos3; Amit Bagchi1; Ajit Achuthan1
1 Clarkson University

The cellular sub-grain structure of appropriate dimensions has been attributed to be responsible for improved strength–ductility trade-off in some of the Additively Manufactured (AM) metals. The formation of this dislocation network has been reported to be as stress driven in recent experimental studies. To investigate the mechanism responsible for their formation, a computational study using a crystal plasticity based FEA model is performed by simulating the Selective Laser Melting (SLM) process of a single track of 316L alloy. The distribution of stress field is carefully analyzed to determine its specific characteristics that could lead to the cellular structure formation obtained experimentally. A mathematical model to predict cellular sub-structure formation as a function of local stress and temperature fields will be presented. It is anticipated that the insight gained from the study will be helpful to design materials with spatially tailorable properties by controlling their microstructure for advanced naval applications.

Special Session: Hybrid AM II - Additive-subtractive

Tuesday PM  Room: 400/402
August 13, 2019  Location: Hilton Austin

Session Chair: Brett Conner, Youngstown State University

Integrated Hardfacing of Stellite-6 Using Hybrid Manufacturing Process: Maxwell Praniewicz1; Thomas Feldhausen1; Samuel Kersten1; Elliott Jost1; Jaime Berez2; Thomas Kurfess2; Christopher Saldana2
1 Georgia Institute of Technology

Hybrid manufacturing systems provide a platform for integrated additive, subtractive and inspection methods on a single machine setup. The present work explores use of hybrid manufacturing for hardfacing of performance components for improving wear resistance. In this work, Stellite-6 was applied to a 410 stainless steel substrate using a hybrid manufacturing system incorporating multi-axis directed energy deposition and machining. Experimental testing was conducted to determine the effects of hybrid manufacturing parameters on internal porosity, surface porosity and microstructure in the cladded material, as well as on the roughness of the final machined surface. Correlation between porosity measurements made by x-ray tomography and surface dye-penetrant testing is presented and determination of ideal process parameters for hardfacing of components using hybrid manufacturing systems is briefly discussed.

In Situ Combination of Selective Laser Melting and Selective Laser Erosion for Edge Effect Removal: Jitka Metelkova1; Yannis Kinds2; Charlotte de Formanoir1; Ann Witvrouw1; Brecht Van Hooreweder1
1 KU Leuven, Member of Flanders Make

Selective Laser Melting (SLM) allows a high degree of design freedom, however in practice its geometrical accuracy stays limited. Among the most frequent issues are high surface roughness, distortion due to thermal stresses, the occurrence of elevated edges (“edge effect”) or the “staircase effect” when building inclined surfaces. Surface roughness can be reduced by multiple laser exposure (“Selective Laser Remelting”), but the excessive material from the edges needs to be removed. In order to avoid time consuming and expensive post-processing, a laser-based subtractive process can be implemented directly into the building phase. This paper presents first insights into in situ edge effect removal by “Selective Laser Erosion” using a novel hybrid setup developed at KU Leuven. This setup includes both a continuous wave and a nanosecond pulsed wave laser, and makes it possible to perform local geometrical corrections or even to create fine internal features directly during the SLM process.

Hybrid Manufacturing: Role of Contoured Geometries in Directed Energy Deposition of Stainless Steel 316L: Jakob Hamilton1; Samantha Sorondo1; Andrew Greeley1; Denis Cormier1; Iris Rivero1
1 Rochester Institute of Technology

In-envelope hybrid manufacturing is a promising solution for the production of near-net geometries with minimal setup changes. However, the technology combining directed energy deposition (DED) and machining operations have yet to be incorporated as standard manufacturing practice. For hybrid manufacturing to be feasible in an industrial production or repair setting, metal deposition must reliably produce components with isotropic strength properties regardless of substrate and deposition geometries. This study seeks to explain the challenges associated with DED of stainless steel 316L in contoured deposition geometries. Various applied laser energy densities were explored for achieving minimal porosity and preferable grain growth at distinct deposition orientations. Microstructural characteristics revealed bond integrity and machinability for DED structures. Optimal power intensities and scanning speeds for maximizing mechanical performance of as-deposited components were selected based on microhardness at distinct deposition locations. This study indicates preferable mechanical performance may be achieved through controlled energy application in DED.

Tensile Strength of Ti-6Al-4V from Interlayer Milling during LENS Deposition: Rakesh Karunakaran1; Sam Ortgies1; Michael Sealy1
1 University of Nebraska-Lincoln

Laser Engineered Net Shaping (LENS) is an additive process wherein a laser beam is focused at the surface of a substrate and powder is sprayed at the focal plane causing melting and fusion on the previous layer. Material is only deposited in required regions of each layer, thereby reducing the cost and increasing the speed of the process. LENS is often an inaccurate process in terms of layer thickness. By combining this process with face milling, control over layer thickness is achievable. In addition, mechanical properties, such as hardness and strength, are affected by adjusting intermittent milling parameters. The objective of this research was to enhance the properties of Ti-6Al-4V by coupling LENS and end milling on predefined layers. Result indicate multiple compressive residual stress hooks improved the mechanical strength of the alloy.
3:20 PM
3D Model Decomposition and Sequencing on 5-axis Hybrid Manufacturing Process: Xinyi Xiao; Sanjay Joshi; 1Penn State
5-axis hybrid manufacturing (HM) process has been described as two or more different processes that are combined into one process, including, Additive Manufacturing (AM), subtract manufacturing and welding. The HM process involves a large amount of effort in process planning, which contains decomposing the 3D model into an additively manufactured part and machined features, pre-processing the decomposition results into a feasible manufacturing sequence. NX hybrid version developed with DMG Mori for AM, welding, and milling in one machine. However, part decomposition and toolpath specification require specialists to plan. This paper aims to propose a feasible automatic decomposition and sequencing approach, combining additive processes into traditional subtractive processes in a hybrid modular loop, which integrates AM and subtractive machining into one stage.

3:40 PM
Microstructure and Tensile Properties of Hybrid Additive/subtractive Manufactured A1SiAlloy: Shuai Zhang; Ming Gao; 1Huazhong University of Science and Technology
A hybrid technique integrating wire arc additive manufacturing and high-speed milling of A1Si alloy was carried out. It was found that the milling made the layered structure characteristics more obvious. After the surface was milled to a plane, it helps to stabilize the next arc combustion and concentrate the arc heat distribution on the deposited surface well, so the area of bonding zone increased. Secondly, the fusion line spacing was reduced under the milling. So the fusion line was parallel and densely distributed in the vertical direction, which had a certain influence on the tensile properties. The tensile test results showed that the ultimate tensile strength (UTS) gradually becomes larger in the horizontal direction, but decreases in the vertical direction when the t increases. Relatively, the UTS in the vertical direction are smaller than those of the horizontal direction, and the difference of the UTS increases linearly with the t.

Applications: General III
Wednesday AM
Room: 602
August 14, 2019
Location: Hilton Austin
Session Chair: Filomeno Martina, Cranfield University

8:00 AM
Wet-chemical Support Removal for Additive Manufactured Metal Parts: Tobias Schmithüsen; Johannes Schleifenbaum; 1Fraunhofer-Institute for Laser technology ILT; 2RWTH Aachen University, Chair for Digital Additive Production
The additive manufacturing technology laser powder bed fusion (LPBF) offers great flexibility regarding the manufacturing of complex part structures. Due to the process, support structures have to be manufactured for overhanging part surfaces in order to guarantee dimensional accuracy and reduce distortion. However, these must be removed after manufacturing. Especially for internally supported part surfaces, removal is only possible by means of tool-free technologies. A promising approach for a tool-free support removal is the wet-chemical ablation, in which the support structures are removed by chemical dissolution. So far, the approach has been tested for a few materials (e.g. stainless steel). In order to extend the use of this automatable approach to further AM materials, the influence of different etching agents on different additive processible aluminum alloys with regard to material ablation and surface influence will be investigated. Finally, the applicability of the results to a supported part will be tested.

8:20 AM
Analysis of Powder Removal Methods for EBM Manufactured Ti-6Al-4V Parts: Amit Lopes; Luis Ramos; David Saenz; Philip Morton; Cesar Terrazas; Ahsan Choudhuri; Ryan Wicker; 1The University of Texas at El Paso
Additive Manufacturing (AM) allows the creation of complex geometries that are not achievable through subtractive manufacturing. Regardless of the advantages that 3D Printing offers, technology limitations put constraints on desired geometry. When fabricating Ti-6Al-4V parts in Electron Beam Powder Bed Fusion (EBPBF), the electron beam is used to preheat the powder bed to maintain the desired temperature gradient during the build. One disadvantage of EBPBF during the fabrication process is the trapped powder within internal channels gets sintered. This research analyzes different powder removal methods and compares their effectiveness removing the powder. This work will utilize two types of samples, both made of Ti-6Al-4V in EBPBF; with geometries that resemble typical features when designing a component. The target weight of each cylinder is calculated based on dimensions and effective density of the sample. The results summarizing the effectiveness of each method is presented.

8:40 AM
The Tribological Performance of SLM 316L Stainless Steel under Dry Sliding Conditions: M Bahshwan; Connor Myant; T Reddyhoff; 1University of Jeddah, Imperial College London; 2Imperial College London
Fricion and wear are key elements that predict system efficiencies and components’ lifespan in various applications (aerospace, automotive, and medical implants). This work presents a dry-sliding tribological investigation of austenitic 316L stainless steel manufactured by Selective Laser Melting (SLM) subject to various normal loads. Three build orientations were employed to alter the grain formation of the SLM parts and compare each of them against traditionally-manufactured (bulk) samples. Results showed that the bulk samples exhibited the highest friction coefficient under all normal loads. The wear volumes of the bulk specimens showed linear relationship with the applied load, while each SLM type exhibited distinct non-linearity. At lower loads, the wear volume of bulk specimens was the lowest, however, at greater loads SLM specimen T1’s wear volume was the lowest. The tribological behaviour of SLM specimens printed with altered build orientations seemed promising, though further investigation of their particular grain structure is required.

9:00 AM
Tensile Property Variation with Wall Thickness in Selective Laser Melted Parts: Shrivasan Raghavan; Norman Soh; Jia Hao Lim; Niaz Khan; Raguram Muthu; Jan Dzugan; 1Advanced Remanufacturing and Technology Center; 2COMTES FHT
3D printed parts with complex geometries have different section thickness which leads to non-uniform mechanical properties due to microstructure and defect distributions. Hence, it is essential to characterise the localised mechanical properties to obtain a better understanding of the variability. The tensile property variability is captured by testing miniature sized tensile coupons that are extracted from different part locations which is more representative, when compared to testing printed tensile coupons. In the current work a benchmark study was first carried out to correlate miniature tensile properties with ASTM standard tensile test for different wall thickness in SLM Maraging steels. Following this, tensile property variation at different locations in an AM fabricated impeller part was studied. It was observed the thin sections in the part exhibited large variability in the elongation values. The effect of heat treatment on the tensile properties in the impeller was also studied.
9:20 AM
Methodical Design of a 3D-Printable Orthosis for the Left Hand to Support Double Bass Perceptual Training: Detlev Borstell1; Nicholas Walker2; Sebastian Kurz3; 1Binghamton University; 2Ithaca College
The evolution of Additive Manufacturing in the past decades has opened up its use to a wide range of new applications where conventional manufacturing methods dominated. Orthoses are medical devices, mostly used on legs or arms after injuries or surgery. Amongst other functions, they limit the possible movement of limbs or joints to prevent excessive movements or loads during remobilization. Their manufacturing process is predominantly manual and conventional. Playing the acoustic double bass requires precise positioning of the left hand fingers on the fingerboard. Perception of the finger spacing is very important for good intonation. Different educational approaches have therefore been made to kinesthetic and perceptual training. Miniaturization and low forces allow applying additive manufacturing technology to a conventional device leading to a new perceptual training device for the left hand: an individually shaped orthosis, which is lightweight, low cost, and adjustable and which can be worn during instrument practice.

9:40 AM Break

10:10 AM
Direct Fabrication of AlSi10Mg Thermal Management Devices onto Silicon Substrate by Selective Laser Melting: Arad Azizi1; Matthias Daumer2; Scott Schiffres2; Binghamton University
Laser metal additive manufacturing onto silicon has important applications for cooling electronics. The heat generated by electronics has been rising exponentially and pose a significant barrier to microprocessor performance. In particular, the thermal interface materials (TIMs), the glue that thermally connects the electronic chip to the heat sink, is a bottleneck. We recently demonstrated that the high energy intensities provided by selective laser melting rapidly overcomes the energy barrier for Sn-3Ag-4Ti reacting with silicon to form titanium-silicide. In the current research, it is demonstrated how AlSi10Mg thermal management devices (e.g. micro-channels, vapor chamber evaporators and lattice-based heat sinks) can be directly fabricated via SLM onto silicon substrate using a Sn-3Ag-4Ti interlayer alloy. By employing this technology, low thermal conductivity TIMs can be eliminated from the electronic packaging and at current chip heat fluxes the chip can be kept about 20 °C cooler.

10:30 AM
Cause of Cantilever Structure Distortion via Selective Laser Melting: Inconsistent Shrinkage during Additive Manufacturing Process: Deqiao Xie1; Jianfeng Zhao1; Huixin Liang1; Lida Shen1; Zongjun Tian1; 1Nanjing University of Aeronautics and Astronautics
The distortion of cantilever structure via selective laser melting is hard to be avoid. The physical cause of distortion has been relatively unknown. In this paper, a physical model was established so as to illustrate the process and cause of distortion of cantilever structure via selective laser melting. The distortion of cantilever structure with different support densities, as well as with different sizes, were studied based on experimental results. It can be concluded that the inconsistent shrinkage between layers can occur when additive manufacturing the cantilever structure. After the support structure is removed, the inconsistent shrinkage between layers cause the distortion of cantilever structure.

10:50 AM
Additive Manufacturing of New Structures for Heat Exchange: Philip Depond1; Du Thai Nguyen1; Pratanu Roy1; Victor Beck1; Omer Dogan2; Dan Tortorelli1; Eric Duoss1; Manyalibo Matthews1; Josh Stolaroff1; 1Lawrence Livermore National Laboratory; 2The National Energy Technology Laboratory
Here we describe the modeling, development and testing of a heat exchanger for supercritical CO2 (sCO2) power cycles with radically improved material efficiency and higher temperature tolerance than current technology. Triply Periodic Minimal Surfaces (TPMS) are chosen as candidate structures as previous work shows potential for an order of magnitude improvement in heat transfer performance over tubes and flat plates. In this work, a prototype heat exchanger design is presented based on various TPMS geometries. The design is fabricated using laser powder bed fusion. The process development of 5 candidate nickel super alloys is described, along with ambient and high temperature mechanical testing results, and finally methods for printing the prototype heat exchanger. Bench scale measurements of heat transfer, pressure drop and device robustness are performed for comparison and to aid design of a viable process. Flow characteristics and temperature fields are modeled and compared with these measurements.

11:10 AM
3D Printed Materials and Their Effects on Quasi-optical Millimeter Wave Guide Lens Systems: Diana Foster1; Christopher Corey1; Christopher Fisher1; Caitlin Smith1; Arthur Paolella1; 1Harris Technology Laboratory
This study of 3D printed quasi-optical (Q-O) millimeter wave guide lens systems is presented in three phases: the characterization of 3D printed materials for radio frequency (RF) applications and systems; the development and demonstration of 3D printing technology for RF systems; and the design process, simulation, fabrication, and testing of RF lens systems. The first phase explores the ability to print high-quality materials with fine resolution and the determination of each material’s dielectric constant and loss tangent. The second phase details the development of dual biconvex shaped lens systems and the resulting test data. The third phase combines the former stages’ results to model, print, and test a set of lenses pre-aligned with an integrated support structure. These lens systems were tested up to 100 GHz with demonstrated focusing gain of 22.1 dB.

11:30 AM
Porosity analysis and pore tracking of metal AM tensile specimen by Micro-CT: Santosh Rauniyar1; Kevin Chou1; 1University of Louisville
In this research, the porosity of Ti64 Laser powder bed fusion (L-PBF) samples built by varying various process conditions (3 factors) is studied. The variation includes the energy density in fabrications (3 levels), the samples built by varying various process conditions (3 factors) is studied. In this research, the porosity of Ti64 Laser powder bed fusion (L-PBF) samples built by varying various process conditions (3 factors) is studied. The variation includes the energy density in fabrications (3 levels), the build orientation (2 levels) and the build location (3 levels) for a constant scan speed of 600 mm/s. The as-built specimens were scanned using a micro-CT system with a resolution of 6.1 μm. After that, the samples were tested in a tensile testing machine to obtain the mechanical properties. The fractured samples were again scanned at the same resolution with similar scan parameters. The porosity of the samples varied according to the energy density and the build direction while only slight effect of location change was observed. The fractured samples showed significant increase, more than nice percent in high energy case, in the pore volume as well as the porosity percentage.
Carbon Composite Engineered Lattice Structures Exhibiting Viscoelastic Behavior: Denis Cormier1; Pritam Poddar1; Rochester Institute of Technology
Layer based manufacturing of engineered lattice structures results in struts that are fabricated by depositing one "dot" of material on top of another. This approach typically results in brittle fracture of struts at relatively low loads during mechanical testing due to delamination and rough surface texture of the struts. In this paper, a carbon fiber + PA6 copolymer composite is used for additive manufacturing of lattice structures in which struts are continuously extruded such that embedded carbon fibers preferentially align with the strut axes. Using this approach, octet truss lattice structures have been produced. Closed cell plate lattice structures fabricated with this material are also presented. Compression testing of the open and closed cell lattice structures reveals an unusual visco-elastic response in which the lattice blocks return to their original dimensions after the load is removed. Test results are used to make design recommendations for energy absorption and other suitable applications.

Effective Elastic Properties of Additively Manufactured Metallic Lattice Structures: Unit-cell Modeling: Okamnise Fashanu1; David Murphy1; Myranda Spratt1; Joseph Newkirk1; K Chandrashekhara1; Ben Brown1; John Porter2; Rochester Institute of Technology; 1Department of Energy's Kansas City National Security Campus
Lattice structures are lightweight materials, which exhibit unique combination of properties such as air and water permeability, energy and acoustic absorption, low thermal conductivity, and electrical insulation. In this work, numerical modeling was used to predict the effective elastic moduli of octet-truss (OT) lattice structures manufactured using selective laser melting (SLM). OT structures were manufactured using a Renishaw AM 250 SLM machine with various relative densities. Compression was carried out at strain rate 5 × 10^{-4} s^{-1} using a MTS frame. Finite element analysis was used in the determination of the OT’s effective elastic properties. Results from the finite element analysis were compared against analytical models found in literature and validated using results of the experiments. This work was funded by the Department of Energy’s Kansas City National Security Campus which is operated and managed by Honeywell Federal Manufacturing Technologies, LLC under contract number DE-NA0002839.

Lattice Metamatel Design for Enhanced Stretchability and Energy Dissipation via Topology Optimization: Hao Deng1; Albert To2; University of Pittsburgh
Motivated by key advances in additive manufacturing techniques, the tailoring of materials to achieve unique properties such as stretchability or energy dissipation has been the focus of research over the past decade. However, it is challenging to derive optimization algorithms to design these metamaterials due to their highly non-linear nature. Also, existing density-based optimization methods often yield designs having non-smooth surfaces and a large number of small intricate features, which are difficult to manufacture even by AM. To overcome these difficulties, a new topology optimization method based on the Bezier curve is proposed. To demonstrate the ability of designing lattice metamaterials using the proposed method, two different metamaterial designs are presented, one design is to tailor lattice material to present super stretchability under large deformation with fully recoverable properties. The other design is to optimize buckling-induced energy dissipation lattice material to achieve desired energy dissipation capacity.

Impact Energy Absorption Ability of Thermoplastic Polyurethane (TPU) Cellular Structures Fabricated via Powder Bed Fusion: Yan Wu1; Leander Verbelen2; Li Yang3; University of Louisville; 1BASF
In this study, experimental based investigation was carried out with various cellular structure designs realized using a developmental thermoplastic polyurethane (TPU) fabricated by powder bed fusion process, in the attempt to evaluate the effectiveness of impact energy absorption design with cellular structures when combined with favorable materials. Various cellular designs including the re-entrant auxetic, double-arrow auxetic, octet-truss, BCC, octahedral, diamond and double bow-tie were designed and evaluated. Charpy-impact testing and drop-weight impact testing were carried out with each design, and the effective energy absorption capabilities of these designs were compared. The results from this study provide some initial insights into the design of TPU-based cellular structures for energy absorption applications that could benefit the future establishment of more comprehensive knowledge base in this area.

Permeability Analysis of Polymeric Porous Media Obtained by Material Extrusion Additive Manufacturing: Marcelo Shigueoka1; Silvio Junqueira1; Thiago Alves1; Neri Volpato1; 1Federal University of Technology - Paraná - UTFPR
Porous media (PM) are used in many applications, and their geometry and hydraulic properties are essential in flow analysis, especially in geology (oil and gas) and medical (tissue engineering) applications. Additive Manufacturing (AM) enables the production of planned porosity with many replicas, which is a relevant issue in geology. The material extrusion AM allows working with process parameters to produce lattice type geometries, without the need to model each filament. This work presents a preliminary study on the permeability of some PM designs obtained in PLA using an in-house process-planning software. Two main filling variations of the raster strategies were studied, one considering the displacement of staggered layers and the other involving a new joined filaments proposal. The permeability obtained experimentally is compared with numerical outputs. The results indicate that both filling strategies influence the PM permeability, but the joining filaments approach had a more significant effect on this property.

Effects of Unit Cell Size on the Mechanical Performance of Additive Manufactured Lattice Structures: Arash Soltani-Tehrani1; Seungjong Lee2; Mohammad Reza Vaziri Sereshk1; Nima Shamssaei1; 1Auburn University
Lattice structures are generated through the repetition of smaller structures, defined as unit cells. These structures are popular alternatives for bone implants due to the potential to adjust the stiffness. However, in some applications, there are volume and mass constraints that cannot be exceeded. Therefore, to match the lattice structure's stiffness to that of the natural bone, unit cell sizes should be altered. In this study, the effects of different unit cell sizes, on the compression behavior of lattice structures fabricated from 316L stainless steel (SS) via laser beam powder bed fusion (LB-PBF) are studied through finite element analysis (FEA) while the volume and mass are kept constant and results of which, are validated by experiments.
Mechanical Metamaterial Development for 3D Discriminatory Logic Systems: Usman Waheed; Connor Myant; "Imperial College London Mechanical metamaterials utilise the structuring of materials for novel applications, often exhibiting phenomena not found in nature. Properties such as topological protection and textured material response are advantageous to many industries. Through advancements in additive manufacturing, architected materials can be designed to respond in unique ways to actuation. These functional materials are programmable and open an exciting avenue into mechanical logic devices. Here we present the formation of AND, OR logic in a 3D mechanical metamaterial system through a multi-material approach, combining anisotropic structures with bistable mechanisms. This allows the formation of 3D structures that can perform mechanical logic in any planar direction. This system is particularly useful in discriminating mechanisms (nuclear code reading mechanisms) - through a combinatorial approach, these structures can be combined to perform 24-bit discriminatory logic in a truly 3-dimensional space.

Spatially Variant Structures: Unlocking the Full Potential of Additive Manufacturing: Jonathan Harris; Christian Thomsen; "nTopology Additively manufactured cellular materials (lattices, honeycombs, gyroids, etc.) have recently appeared in a variety of industrial applications, from structural lightweighting to medical implants to multifunctional heat exchangers, as they can offer unique combinations of mechanical properties. However, many use cases employ simple design rules such as uniform infill patterns, which in most cases are far from optimal and do not leverage the full potential of additive manufacturing. In this presentation, we will present two new techniques which aim to unlock this potential: Spatially Variant Structures (SVS) and implicit geometric modelling. With these, one can tailor cellular materials with total and precise control, free from the limitations of mesh-based or feature-based design tools. For example, unit cells of a cellular material can be continuously varied across any path (be it one, two, or three dimensional) and oriented to any vector field (derived analytically, from a simulation, or from a part's geometry).

Mechanical Behavior of Additively-manufactured Gyroid Lattice Structure under Different Heat Treatments: Mohammad Reza Vaziri Sereshki; Rakish Shrestha; Brandon Lessel; Nam Phan; Nima Shamsaei; "National Center for Additive Manufacturing Excellence; "Naval Air Systems Command (NAVAIR) Gyroid lattice structures, known for high stiffness and specific strength, are gaining attention for their energy absorption ability. However, energy absorption and strength of the Gyroids are two desired properties, which vary contradictory. While a particular post-processing heat treatment may improve one property, it may be detrimental to other ones. In this study, effect of different heat treatment procedures on compressive properties of 17-4 PH stainless steel Gyroid lattice structures fabricated using laser beam powder bed fusion (LB-PBF) method is investigated. Compressive properties such as crushing strength, densification strain, and plateau strength are determined and the trends in their variation are discussed. Based on the experimental results, an optimal heat treatment procedure that can exhibit high strength and good energy absorption ability will be proposed.

Fast and Simple Printing of Graded Auxetic Structures: Molly Carton; Mark Ganter; "University of Washington - Seattle One of the great promises of additive manufacturing is the ability to build parts with volumetrically graded parameters that would be difficult or impossible with traditional manufacturing. This paper presents a method of procedural generation and unsupported fabrication of 2.5D objects patterned with functionally graded auxetic (negative Poisson's ratio) cellular structures using commercially available FDM and direct-write printers. Several types of two-dimensional auxetic pattern are fabricated in different shapes and orientations. The resulting printed objects exhibit a graded response to load, deforming corresponding to local patterning. Deformation is studied using imaging of loaded structures and applications in several areas are considered.

Design for AM Special Session

Wednesday AM Room: 414
August 14, 2019 Location: Hilton Austin

8:00 AM
An Overview of Design for AM: Terry Wohlers; Olaf Diegel; Ray Huff; "Wohlers Associates, Inc.; "University of Auckland Design for additive manufacturing (DIAM) is arguably the most important consideration when using AM for series production. DIAM can impact the build and support materials, build speed, post-processing, part performance, and economics—all factors that determine whether AM is a good fit. Diegel, Huff, and Wohlers will each provide their thoughts and perspective on these and other elements influenced by design. The three presentations will serve as a warm-up to the 2.5-day DIAM course that begins the same afternoon and is conducted by the same three individuals.

9:40 AM Break

10:10 AM
An Interactive Exploration of Conceptual Design and Ideation for AM: Nicholas Meisel; "Pennsylvania State University Design for additive manufacturing (DIAM) considerations are, in many cases, in direct contrast to an engineer's intuitive understanding of what makes a design "manufacturable." However, to innovate with AM, engineers must learn to leverage the design opportunities that the technology offers. In this special session of SFF, attendees will learn about techniques for integrating DIAM considerations into their concept generation activities. They will also have the opportunity to participate in an interactive design "charrette," where they will practice applying DIAM to a product design challenge.
Materials: Composites II

Wednesday AM  Room: 415 AB  Location: Hilton Austin

Session Chair: John Obielodan, University of Wisconsin-Platteville

8:00 AM  Effect of Process Parameters on Selective Laser Melting Al2O3-Al Cermet Material: Haifong Liao; Haihong Zhu; Junjie Zhu; Shijie Chang; Xiaoyan Zeng; Huazhong University of Science and Technology; Shanghai Aerospace System Engineering Institute

The cermet composite material is one of the research focuses in the field of materials, for it can combine the toughness of metal and the hardness of ceramics. In this work, Al2O3-Al cermet composite with a mass ratio of 1:1 is fabricated by selective laser melting process. The effect of process parameters on the relative density and Al2O3 loss rate as well as the Al2O3 loss mechanism were investigated in detail. The results show that Al2O3 undergoes melt recrystallization and is significantly aggregated. The aggregated Al2O3 exhibits a network distribution in the metal matrix. The process parameters have a great influence on the relative density and the Al2O3 loss rate. As the scanning speed increases, the relative density and the loss rate will increase simultaneously. The loss mechanism is that the aluminum acts as a reducing agent, causing the Al2O3 becoming a gaseous substance Al2O during selective laser melting process.

8:20 AM  Additive Manufactured Stainless Steel Nanocomposites with Uniform Dispersion of Nanoparticles: Minglei Qu; Luis I. Escano; Khalid Hussain Solangi; Qilin Guo; Lianyi Chen; Missouri University of Science and Technology

Metal matrix nanocomposites (MMNCs) with uniform distribution of nanoscale ceramic particles can show dramatically improved mechanical properties as compared to the matrix materials. However, when the size of the nanoparticles is small and the volume fraction of nanoparticles is high, it is very difficult to disperse them uniformly in the metal matrix. Here we report the dense stainless steel nanocomposites with uniform distributed ceramic nanoparticles were successfully fabricated by ball milling and selective laser melting (SLM). Detailed microstructure characterization and analysis reveal that the dispersion of nanoparticles in the SLMed sample strongly depends on the dispersion of nanoparticles in the feedstock powders. Our research provides a promising approach to manufacture MMNCs with uniform dispersion of nanoparticles by additive manufacturing process. This work was funded by the Department of Energy’s Kansas City National Security Campus which is operated and managed by Honeywell Federal Manufacturing Technologies, LLC under contract number DE-NA0002839.

8:40 AM  Strengthening of 304L Stainless Steel by Addition of Yttrium Oxide and Grain Refinement during Selective Laser Melting: Milad Ghayoor; Kijoon Lee; Yujuan He; Chih-Hung Chang; Brian Paul; Somayeh Paseban; Oregon State University

This study investigates the role of submicron size yttrium oxide, added to a 304L stainless steel matrix, on the microstructural evolution and mechanical properties of selective laser melted 304L oxide dispersion strengthening (ODS) nanocomposite. 304L SS powder and a mixture of 304L SS powder and yttria particles were used as two feedstocks for fabricating parts using selective laser melting (SLM) process. Scanning electron microscopy and energy dispersive X-ray spectroscopy revealed a homogenous distribution of Si-Mn-O nanoparticles in the SLM 304L matrix and Y-Si-O nanoparticles in the SLM 304L ODS alloy. Electron backscatter diffraction images imply that the addition of yttria disrupts the formation of large columnar grains in SLM 304L, resulting in the formation of finer grains. The average microhardness values increased from 240 HV in SLM 304L to 350 HV in SLM 304L ODS alloy, due to the combined effects of grain refinement and dispersion hardening.

9:00 AM  Selective Laser Melting of Aluminum-ceramic Composites: Ethan Parsons; MIT Lincoln Laboratory

The mechanical and thermal properties of metal matrix composites (MMCs) are attractive for high performance defense and commercial applications, but fabrication with MMCs is presently difficult, costly, and limited to components with simple geometries. Processing particulate MMCs with selective laser melting (SLM) would be an ideal method, but the laser consolidation of these materials is not well understood and therefore has been largely unsuccessful in matching the properties of conventionally processed MMCs. Here, we modify a commercial SLM aluminum powder with ceramic particles and investigate the effect of the ceramic phase on laser consolidation. Our results and analysis identify conditions under which bulk MMCs can be successfully processed with SLM, potentially opening up many new applications for MMCs.

9:20 AM  Investigation of Influence of Various Process Parameters on Mechanical Characteristics of Laser Sintered Aluminum Reinforced Polyamide 12: Anna Tarasova; Andreas Wegner; Gerd Witt; Universitat Duisburg-Essen

Laser sintering is one of the most popular additive manufacturing techniques that uses thermoplastic polymer powders to generate layer by layer complex structures. Despite its broad application some limitations exist restricting its further development. One of such limitations is a narrow assortment of commercially available materials that would allow production of the parts with the desired mechanical characteristics, which is the case with the widely used Polyamide 12 (PA12). In order to achieve better mechanical characteristics, reinforcement of the initial polymer with metal particles is routinely performed. In our work, a PA12 system enhanced with 35 % volume ratio of aluminum was investigated. We examined parameter variation during the manufacturing process with respect to mechanical characteristics, e.g. elastic and flexural moduli. In addition, we tested a new methodology that would help determine the maximum packing volume fraction corresponding to the highest mechanical characteristics of a polymer-metal mixture.

9:40 AM  Effects of the Dissolution of the Reinforcements on the Microstructure and Fracture Toughness of Ni Al/WC Composite Coating Produced by Laser Cladding: Eyi Taylor Olatunde Olakanmi; Monamme Tlotleng; Carlos Kakuwa; Bajakoe-Ntesang; E. Mokelets; M. Nkuthula; M. Mswela; Botswana International University of Science & Technology; Council for Scientific & Industrial Research

The role of the dissolution of the reinforcing tungsten carbide (WC) particles in the microstructural evolution and fracture toughness of 65Ni-Al/35WC (wt.%) composite coating was explored as laser energy density (LED) was varied. The fracture toughness of the composite samples was evaluated with a Vickers diamond indenture under loading 50gf. To establish the nature of variation in brittleness distribution imparted by dissolution of WC particles in the Ni-Al matrix, measurements were carried out through a cross-section of the specimen. With increase in LED, the volume fraction of secondary compounds formed in the composite coating also increases as it deteriorates the fracture toughness. Evidence from micrographs indicates the presence of crack bridging and crack arrest near Ni-Al phase which resulted in the highest fracture toughness.
10:30 AM
Laser Sintering of Pine/Polylactic Acid Composites: Hui Zhang1; David Bourell2; Yanling Guo1; Jian Li1; Xiaodong Zhang1; Yu Zhuang1; Zhipeng Li1; 1Northeast Forestry University; 2The University of Texas at Austin
A new powder feedstock composed of sustainable and degradable biomass composite material was proposed for laser sintering technology in this research. This biomass mixture, abbreviated P-PLA, is made up of mechanically mixed polylactic acid (PLA) powder and pine powder. The proper processing parameters were determined based on the component thermal behavior and laser sintering testing: processing temperature 130-135 °C, laser power 20-24 W, scan spacing 0.1-0.2 mm, scan speed 1.6-2.2 m/s and layer thickness 0.2 mm. Laser-sintered P-PLA parts exhibited much better mechanical properties compared with pine/polyethersulfone copolyester (P-CoPES) wood-plastic composite, with tensile strength 34-200% higher and flexural strength 92-246% higher than values for lasersintered P-CoPES. Results reveal that pine powder loading can reduce the shrinkage and deformation of laser-sintered P-PLA parts. Shrinkage decreased from 4% to 0.31-2.27% in the XY plane and from 3.25% to 0.13-2.25% in the Z direction.

10:50 AM
Characterization of PLA/Lignin Biocomposite for 3D Printing: John Obielodan1; Kevin Vergenz1; Danyal Aqil1; 1University of Wisconsin-Platteville
A greater proportion of polymer-based three-dimensional (3D) printing materials are synthetic petroleum derivatives that are not biodegradable, contributing to environmental pollution and have potential adverse effects on human health. Polylactic acid (PLA) is currently the most widely used among the bio-based alternatives. This work explores alternative environmentally friendly bio-based polymers sourced from sustainable crop and forest biomass derivatives for 3D printing. Various blends of PLA/ Organosolv lignin were extruded for fused filament fabrication (FFF) 3D printing process. The processing parameters and results of mechanical and thermal properties of fabricated test specimens of the biocomposite with up to 40wt% lignin concentration are presented. Results indicates that lignin, a low-cost waste product of pulping for the paper industry and bioethanol fuel production could serve as a key component of new biocomposite polymers for 3D printing applications.

11:10 AM
Preparation of Ordered Perovskite Needle-like Crystal Films by Electric Field and Micro-droplet Jetting 3D Printing: Zhao Zhenhao1; Lin Feng1; 1Tsinghua
The crystallization of perovskite structure of organic and inorganic halide depends on its composition and environmental condition. The most convenient method for the preparation of perovskite films is the one-step method, which can produce disordered needle-like perovskite films with poor surface morphology. The electric polarity of perovskite needle-like crystals was used to arrange the perovskite needle-like crystals and prepare orderly perovskite needle-like crystal films to improve their surface morphology. A micro-drop-on-demand jetting 3D printing system that can simply add physical fields such as electric filed is used to print perovskite narrow line films, which helps to improve the anisotropy of perovskite films. At room temperature and under electric field, ordered needle-like perovskite crystal film can be obtained to improve the morphology and performance of perovskite film. This phenomenon is helpful for us to explore the influence and application of electrical polarity in the preparation of perovskite needle crystal films.
8:40 AM
Forming, Microstructure Evolution and Mechanical Properties of Wire Arc Additively Manufactured AZ80M Magnesium Alloy Using Gas Tungsten Arc Welding: Yangyang Guo1; Gaofeng Guan1; Houhong Pan1; 1Southwest Jiaotong University
Magnesium alloys have attracted great attention recently due to the low density, high specific strength and other superior performance. However, it is difficult to fabricate magnesium components with large scale and complex shape by conventional forging and casting methods. Wire arc additive manufacturing (WAAM) offers a potential approach to fabricate them with low cost and high efficiency. In this study, WAAM is applied to fabricate AZ80M magnesium alloy. Single-pass multilayer walls are successfully obtained. The results indicate that microstructural evolution occurred during the deposition process, and microstructure along deposition direction exhibits obvious inhomogeneity. Meanwhile, the heat accumulation has significant effect on the forming, microstructural evolution and mechanical properties. The tensile properties in the horizontal and vertical direction show an asymmetric characteristics, which is caused by the inhomogeneity of grain structure and the aggregation of micro-cracks at interlayer transition zone.

9:00 AM
Influence of Powder Particle Size Distribution on the Printability of Pure Copper for Selective Laser Melting: Mirko Sinico1; Giacomo Cogo2; Massimo Benettoni2; Irene Calliari2; Adriano Pepato3; 1KU Leuven; 2National Institute for Nuclear Physics; 3University of Padova
This work investigates the use of fine Cu powder, with ~20 vol% smaller than 15 μm size, for the selective laser melting process. Cubes reaching > 98 % density are produced at relative low laser output (175 W) and characterized. After the selection of a proper combination of laser scan parameters, the properties of fabricated parts are briefly studied through profilometry and tensile tests. Finally, a voluminous demo component for high-energy physics is manufactured to stress-test the employed SLM machine. Even though unmolten particles and lack of fusion defects are still present in the produced specimens, the investigated approach confirms that powder selection can have a huge influence on the processability of materials with high reflectivity towards near-infrared irradiation.

9:20 AM
Mechanical and Electrical Properties of Selective Laser Melted Carbon Mixed Copper and Copper-chromium Alloy: Suraj Dinkar Jadhav1; Sasan Dadbakhsh2; Jean-Pierre Kruth1; Jan Van Humbeeck1; Kim Vandevelde1; 1KU Leuven; 2Department of Production Engineering, KTH Royal Institute of Technology
SLM of copper is gaining interest because of its high electrical and thermal conductivity. However, additive production of crack-free and dense copper parts using a fiber laser is still limited because of the high optical reflectivity of copper at the fiber laser wavelength and very high thermal conductivity. Initially, 99.7% purity copper powder was mechanically mixed with 0.1wt% carbon nanoparticles to improve its laser absorption. Dense as-built parts showed poor mechanical properties due to carbon segregation along the grain boundaries and low electrical conductivity because of the impurity elements (P, O2) present in the virgin copper powder. Accordingly, a phosphorous free Cu-Cr powder was mixed with carbon as Cr is expected to react with carbon to form carbides. As such, no carbon segregation was observed after SLM, while crack-free, dense parts combining a tensile strength of 300 MPa and electrical conductivity of 87% IACS were obtained after heat treatment.

Laser powder bed fusion (LPBF) additive manufacturing (AM) allows for unprecedented levels of customization and design freedom; however, the process is currently only well established for a small subset of alloys and material structures. Copper heat pipes (HP) and vapor chambers (VC) are two-phase thermal management systems that exhibit excellent thermal conductivity. They consist of a porous wicking structure, which circulates a working fluid, and a solid shell housing. There are few published works on AM of pure copper or on AM of porous copper structures. This work seeks to take advantage of AM to produce custom vapor chambers for the thermal management of high-power-density converters. Nearly pure copper wicking structures are produced via partial sintering and via the formation of structured surfaces. The printability, porosity, and capillary performance of the wicking structures are assessed. Implications for the production of AM copper HPs and VCs are presented.

10:30 AM
3D Printing of Tungsten by Selective Laser Melting: Jianchi Huang1; Ming Li1; Zhijian Pei1; Peter McIntyre2; Jyhwen Wang3; Chao Ma4; 1Texas A&M University
An experimental research was conducted on the effect of substrate material and process parameters on the printing quality of pure tungsten by selective laser melting (SLM). Tungsten and stainless-steel substrates were evaluated to achieve good adhesion between the printed layers and the substrate. The stainless-steel substrate was preferred because of its lower melting temperature. Two laser scan parameters, hatch distance and point distance, were studied using a full-factorial design of experiment. Linear, areal, and volumetric energy density was calculated based on the process parameters to investigate their effects on the printing quality metrics, including relative bulk density, open porosity, closed porosity, and number of cracks. The results led to the development of optimal process parameter sets to have good print quality. The results also led to a more comprehensive criterion on the printing quality, including not only the relative bulk density but also the defects such as pores and cracks.

Materials: Metals VIII - Iron-based Alloys
Wednesday AM
Room: 417 AB
August 14, 2019
Location: Hilton Austin
Session Chair: Yashwanth Kumar Bandari, Oak Ridge National Laboratory

8:00 AM
Investigation of the Oxygen Content of Additively Manufactured Tool Steel 1.2344: Raik Dörfert1; Jun Zhang2; Brigitte Clausen2; Hannes Freiße1; Jens Schumacher1; Frank Vollertsen2; 1BIAS - Bremer Institut für angewandte Strahltechnik GmbH; 2Leibniz-Institut für Werkstofforientierte Technologien – IWT; 2BIAS – Bremer Institut für angewandte Strahltechnik GmbH and University of Bremen
Laser Beam Melting (LBm) offers a high design flexibility and the possibility to create complex metal parts in small batch sizes efficiently. However, several questions regarding the mechanical properties are still not conclusively clarified. In general, the remaining degree of porosity is regarded as major indicator on the parts properties. Other properties such as the resulting residual stresses, the oxygen contents and possible contaminants of the powder or the influence of humidity are less often taken into consideration and difficult to measure. In this work, the mechanical properties for LBm generated specimens out of tool steel 1.2344 are investigated and compared to conventionally fabricated material. The quasi-static properties are comparable to conventionally fabricated materials, whereas a significant impact on the fatigue strength was observed together with a high oxygen content of 570 ppm, but no significant oxygen peak can be allocated directly to the fractured area.
8:20 AM
The Porosity and Mechanical Properties of H13 Tool Steel Processed by High-speed Selective Laser Melting: Takaya Nagahama; Takashi Mizoguchi; Hideki Kyogoku; Makiko Yonehara; 1JTEKT Corporation; 2KINDAI University
Additive Manufacturing (AM) technology has advantages of complicated geometry fabrication and integration of multiple parts. On the other hand, selective laser melting (SLM), which is one of the AM Technology, generally takes longer time than other manufacturing methods. In this research, the process parameters, which can achieve high speed additive manufacturing of H13 tool steel, are investigated by a SLM machine with 1kW multi mode fiber laser. As a result, the optimal process window has been determined in the process map of the laser power and the scan speed. High laser power in the process window is estimated to increase the manufacturing speed by 50% of that with the conventional parameters. The specimen manufactured with the optimal parameters has a tensile strength of 1470 MPa, which is equivalent to the conventional manufacturing method.

8:40 AM
Realization of the P20 Tool Steel and Mild Steel for Building Composite Die through Hybrid Layered Manufacturing Process: Fissheha Gebre; 1Defence University, College of Engineering
One of the advantages of Rapid Tooling (RT) using HLM is production cost reduction. In composite die approach the whole die is manufactured using two metallic different materials by considering mild steel from inside and P20 tool steel from outside. The research is based on the reduction of P20 tool steel material cost by taking a significant amount of inside material with less cheap material like mild steel. In the composite metal deposition, the main concern is the intermetallic composition. To have a good intermetallic composition process parameter optimization was done to find proper deposition parameters. This optimization has been done thoroughly and characterization of intermetallic composition was studied using SEM.

9:00 AM
Manufacturing Development For Army Relevant Ultra-high Strength Steel: Andelle Kudzal; Brandon McWilliams; Josh Taggart-Scarf; Marko Knezevic; 1U.S. Army Research Laboratory; 2Survive; 3University of New Hampshire
The current commercial powder feedstocks available for powder bed fusion (PFM) additive manufacturing (AM) systems have a limited range of material properties. This makes it hard to transition commercial AM to the defense community due to the high strength and toughness requirements. In this work, an Air Force developed, low alloy, ultra-high strength steel is adapted to PBF. PBF processing parameters were successfully developed to form fully dense parts with tensile mechanical properties meeting those of the wrought form in the as built condition. Microstructure was examined using optical microscopy, scanning electron microscopy, and x-ray diffraction. Porosity was quantified using micro-computed-tomography and optical microscopy in order to measure the effect of laser processing parameters on defect formation. The effect of laser processing parameters on microstructure and defect formation is presented. Baseline mechanical properties including tensile, compression, hardness, and charpy impact was established for this material on multiple commercial AM machines.

9:20 AM
Study of Printing Direction, Post-processing Effects on Mechanical and Material Properties of EOS MS1 Maraging Steel: Nandhini Raju; David Rosen; 1Singapore University of Technology and Design
The objective of this paper is to investigate mechanical and material properties of EOS MS1 maraging steel (as-built, machined) samples, which were manufactured by the powder bed fusion process in different orientations in an EOS M280 machine. The MS1 material is well known for its high strength, ductility, machinability, and high fracture toughness. A literature review related to mechanical properties of printed EOS MS1 Steel found that there are no available studies of both building direction and further machining on mechanical and material properties of this material. To address this gap, mechanical property tests including tensile, hardness, Charpy impact, bending, and compression, as well as SEM analysis of microstructure, were performed to understand the influence of both build direction and post-processing effects. The results showed there was an impact of machining and build orientation over mechanical and material properties. Results are statistically analyzed to understand the confidence of level.

9:40 AM Break

10:10 AM
Environmental Impact of 3D-printed 18Ni-300 Maraging Steel: Troy Ansell; Joshua Ricks; Chantel Lavendar; Chanman Park; Claudia Luhrs; 1Naval Postgraduate School
In this study, we investigated the mechanical and microstructural properties and the corrosion resistance of 3D-printed maraging steel 300 (18Ni-300) parts. Surface roughness due to the printing process was identified. Microscopy revealed lack of fusion around the edge of specimens and related to surface roughness; however, these features did not have a measured impact on mechanical properties. Surface roughness also had a role in initiating cracks along the edge in as-printed samples during tensile testing. In contrast, tensile loads in sand blasted samples, produced the typical cup and cone features. The microstructural characteristics found in the specimens closely match the ones previously reported in the literature. After exposure of parts in a salt fog, heat-treated samples were shown to be more susceptible to corrosion as compared to the as-printed specimen. Comparisons between corrosion susceptibility in 3D printed specimens and those produced by CNC are included.

10:30 AM
Feasibility Analysis of Using Maraging Steel in a Wire Arc Additive Process for High-Strength Tooling Applications: Christopher Masou; Andrzej Nycz; Mark Noakes; Derek Vaughan; Niyanth Sridharan; Abigail Barnes; 1Oak Ridge National Laboratory
Traditional tool and die development requires skilled labor and long lead times. It is also very expensive. Metal Big Area Additive Manufacturing (mBAAM) is a wire-arc additive process that uses a metal inert gas (MIG) welding robot to print large-scale parts layer-by-layer. By using mBAAM, tooling is manufactured rapidly with significantly decreased costs. For cold work tooling applications, a high hardness level is desired to increase the lifetime of the tool. Maraging steel is known to have good weldability and desirable hardness levels. However, further testing must be conducted to ensure feasibility for printing using the mBAAM system. In this paper, initial process parameters were obtained by printing single bead walls. Multi-bead walls were then printed with some refinement of process parameters to construct homogenous outer features of the walls. Lastly, the walls were heat treated, and hardness data was gathered through Charpy tests.

10:50 AM
On the Heat Treatments of a Carbon Steel for Gear Applications: Charlie Poulat; 1Safran Transmission Systems
From now on, none of the LBM usual materials are able to withstand the high mechanical loads in aerospace bearings or gears. To achieve these high mechanical performances, 33CrMoV12, a common forged carbon aerospace steel with a nitriding treatment, has been argon-atomized for the first time and used in a DMLS machine. In this study, the initial microstructure is characterized to show a cellular pattern. This dual-phase microstructure has been characterized by nano-SIMS analysis to evidence micro-segregation. Several heat treatments are then tested to reach mechanical properties of the forged material: tempered, quenched / tempered, double-tempered and normalized / quenched / tempered. Each one is characterized by means of tensile tests, impact toughness and phase analysis. Very encouraging results have been obtained, paving the way for original heat treatments.
Materials: Polymers II - Powder Bed Processing

Wednesday AM  Room: 412  August 14, 2019  Location: Hilton Austin

Session Chair: Christopher Tuck, University of Nottingham

8:00 AM  Characterization of Polymer Powders for Selective Laser Sintering: Jochen Schmidt1; Maximilian Dechet1; Juan Gómez Bonilla1; Nicolas Hesse1; Andreas Bück1; Wolfgang Peukert1; 1Institute of Particle Technology

Flowability and packing properties are essential for powder spreading and resulting part properties in selective laser sintering (SLS). Within this contribution, powder requirements for SLS, structure-property relationships and appropriate methods for powder characterization will be discussed. Effects of particle size, particle shape and surface functionalization on flowability, packing density and tribo-charging will be addressed for commercial PA12 laser sintering powders (virgin vs. aged), polyolefin and polyester powders. The possibilities of dry particle coating as an efficient method to tailor powder flowability, bulk density and charging behavior are demonstrated. The capabilities of a Schulze ring shear tester, a powder tensile strength tester, a thermally controllable charging behavior are demonstrated. The performance of a Schulze ring shear tester, a powder tensile strength tester, a thermally controllable charging behavior will be discussed to assess SLS processability. Moreover, the effect of structural properties of the polymer on thermal and rheological properties, appropriate analytical methods for characterization and the resulting implications for SLS processability are addressed.

8:20 AM  Effect of Particle Rounding on the Processability of Polypropylene Powder and the Mechanical Properties of Selective Laser Sintered Produced Parts: Juan Gomez Bonilla1; Robin Keltcher1; Franz Lanyi2; Dirk W. Schubert1; Andreas Bück1; Jochen Schmidt1; Wolfgang Peukert1; 1Institute of Particle Technology; 2Institute of Polymer Materials

Common techniques for the production of polymer powders for Selective Laser sintering (SLS) involve the comminution of polymers. Comminution of polymers often results in powders made of irregular shaped particles with a low bulk density and a bad flow behavior. With the aim of improve the flowability of grinded powders, a thermal process for particle shape modification was developed. This has been applied successfully for a broad variety of polymers. In this contribution, an improved design of a rounding reactor with direct heating and optimized geometry is presented. The performance of the new design is assessed by the rounding of commercial available polypropylene powders. The influence of the rounding process on the packing density, particle size and shape distributions and flowability of the powders is investigated. Test specimens by SLS are also produced to assess the effect of the rounding process on the mechanical properties of the produced parts.

8:40 AM  Process Routes Towards Novel Polybutylene Terephthalate – Polycarbonate Blend Powders for Selective Laser Sintering: Jochen Schmidt1; Juan Gómez Bonilla1; Maximilian Dechet1; Andreas Bück1; Wolfgang Peukert1; 1Institute of Particle Technology

Additive manufacturing techniques, such as selective laser sintering (SLS) of plastics, generate components directly from a CAD data set without using a specific mould. The range of materials commercially available for SLS merely includes some semi-crystalline polymers, mainly polyamides. In this contribution two process chains to produce polybutylene terephthalate (PBT) – polycarbonate (PC) blend particles and the respective dependencies of product characteristics (e.g. particle size distribution, shape, flowability) on process parameters are addressed in this contribution. In the first recently proposed approach, blend powder systems are produced via co-comminution of PBT and PC and subsequent thermal rounding of the obtained comminution product.

The second approach to produce blend particles is spray agglomeration of suspensions of the respective polymers obtained by wet grinding or precipitation. The products obtained are thoroughly investigated with respect to their characteristics for SLS processability, like bulk density, powder flowability or thermal and rheological characteristics.

9:00 AM  Impact of Flow Aid on the Flowability and Coalescence Behavior of Polymer Laser Sintering Powder: Rob Kleijnen1; Manfred Schmid1; Konrad Wegener2; 1inspire AG; 2ETH Zurich

Small amounts of nanometer-sized flow aids are typically added to polymer powders for laser sintering to increase flowability. These additives reduce friction between particles by electrostatic repulsion, leading to better bed density and part properties. The same repulsion however also hinders particle coalescence in the melt, reducing part density. The amount of flow aid in a powder must strike the balance between packing density and particle consolidation. This study investigates the effect of different amounts of flow aid on flowability and coalescence. A polybutylene terephthalate powder with spherical morphology, specially designed for laser sintering, is used as a base and ideal model material. Its flowability is characterized with various techniques. The coalescence is monitored by hot-stage optical microscopy. This work establishes a workflow for an efficient determination of the effects of flow aid on powder behavior. It also aims to provide recommendations regarding the optimal amount of flow aid.

9:20 AM  Curing and Infiltration Behavior of UV-curing Thermosets for the Use in a Combined Selective Laser Sintering Process of Polymers: Katrin Wudy1; 1Institute of Polymer Technology

The investigations in this study addresses a new additive manufacturing process, which enables the production of multi-material parts consisting of thermosets and thermoplastics. The liquid thermoset resin will be applied with a micro value syringe in the selective laser sintering system. Thus, the liquid thermoset reacts parallel to the laser exposure of the thermoplastic powder. Therefore, in this study the UV curing and the infiltration behavior of the thermoset will be investigated under process relevant conditions. The investigations show a strong temperature dependent absorption of the liquid in the powder bed. Whereas, the surface tension of the liquid plays a minor role. Furthermore, the UV curing of the thermosets takes place at low interaction times and at lamp powers between 100 and 300 mW.

9:40 AM  Break

10:10 AM  Relationship Between Powder Bed Temperature and Microstructure of Laser Sintered PA12 Parts: Takashi Kigure1; Yuki Yamauchi1; Toshiki Niino1; 1Tokyo Metro Industrial Tech Research Inst; 2Institute of Industrial Science the University of Tokyo

The microstructure of semi-crystalline polymers used in a laser sintering have an effect on the mechanical properties of a parts. The microstructure of laser sintering parts depends on s powder bed temperature. If the powder bed temperature can be set in a wide range, it is also possible to control the microstructure of a part. The authors have been introducing a modified laser sintering process, namely low-temperature process. The process allows powder bed temperature being set wide range. In this research, relationship between microstructure of PA12 parts by low-temperature process and powder bed temperature is investigated. As a result, high strength and crystallinity were obtained in high powder bed temperature, and high ductility and low crystallinity were obtained in low powder bed temperature. This result indicates that parts having the desired mechanical properties can be obtained by controlling the powder bed temperature.
10:30 AM
Understanding the Influence of Energy-density on the Layer Dependent Part Properties in Laser-sintering of PA12: Andreas Wörz1; Katrin Wudy1; Dietmar Drummer1; 1Institute of Polymer Technology
As the demand for individualization and complex parts is continuously growing, laser-sintering of polymers is on the edge from a pure prototyping technology to manufacturing parts for applications in series production. The influence on the resulting parts and the layer dependent part properties are well known in the literature but the understanding of the interaction between process parameters and the layer dependent properties is missing and limiting the dimensioning. Within this study, tensile bars with different amounts of layers and energy-densities were produced and investigated for the resulting mechanical properties, roughness, density and the degree of particle melt. The results showed strong interaction between the energy density and amount of layers, which resulted in differences in the ductility of the breaking behavior as well as the mechanical properties. Therefore, the presented results enable the prediction of necessary part thickness for dimensioning thin parts with laser-sintering.

10:50 AM
Process Parameter Optimization in Powder Bed Fusion for Polyphenylene Sulfide through Design of Experiments: Ian Ho1; Camden Chatham2; Gary Pickrell3; Christopher Williams2; 1Virginia Tech; 2DREAMS Lab, Department of Mechanical Engineering, Virginia Tech; 3Nano-Bio Materials Lab, Department of Materials Science and Engineering, Virginia Tech
Polyphenylene sulfide (PPS) is a high-performance engineering thermoplastic with a melting temperature of 285°C and excellent resistance to solvents, abrasion, and sunlight enabling use in electrical, automotive, and aerospace applications. In prior work, the authors demonstrated printing PPS via powder bed fusion (PBF) with bed temperatures near 200°C, well below its melting temperature. To optimize final part properties, a statistical design of experiments analysis was performed to determine the influence of laser power, hatch spacing, and beam velocity on ultimate tensile strength and elongation for PBF-grade PPS. An L8 (23) Taguchi array was used for selecting experimental conditions, and enabling subsequent study of process variation due to laser processing parameters and their interactions. The interaction of all three investigated terms represents energy density, a commonly used metric for predicting process parameter settings. Results suggest builds at the same energy densities, but different constituent parameters, may not produce comparable mechanical properties.

11:10 AM
Recyclability of Polyphenylene Sulfide Powder in Laser Powder Bed Fusion: Camden Chatham1; Timothy Long1; Christopher Williams1; 1DREAMS Lab, Department of Mechanical Engineering, Virginia Tech; 2Long Research Group, Department of Chemistry, Virginia Tech
More material is wasted in polymer powder bed fusion (PBF) than other additive manufacturing (AM) processes because the material properties change with continued use. The polyamides typically used in PBF suffer from changing molecular weight due to chain-extension and chain-scission reactions during printing. The authors have been exploring a PBF-grade poly(phenylene sulfide) (PPS), a high-temperature polymer exhibiting high solvent resistance, specific strength, radiation resistance, and wear resistance. The goal of this study is to explore the recyclability of PPS powder by quantifying material property changes through a controlled aging study at two, process-relevant temperatures (200 °C and 278 °C) for up to 300 hours. Investigated properties correspond to powder recoating (e.g., Hausner ratio and avalanche angle), thermal transitions (e.g., Tm and Hm), flow behavior (e.g., melt flow index), and printed properties (e.g., E'). The results indicate greater changes in molecular weight and molecular architecture with increasing temperature and time.
10:30 AM
A Fully Automated Design Pipeline for Mass Customisation of Personal Equipment via Additive Manufacturing: Shinya Li1; Stylianos Ploumpis1; Stefanos Zafeiriou2; Connor Myant1; 1Imperial College London
Additive manufacturing (AM) has been identified as a key enabler for mass customisation due to its negligible tooling cost for producing one-off items. This is especially valuable for the medical industry where the ability to create patient-specific products can greatly improve performance and comfort. However, the use of AM so far has only been limited to previously custom-made devices, such as prostheses, due to the prohibitive design cost associated with a highly knowledge- and labour-intensive modelling process. This has often been over-looked and as yet no study has shown a completely automated design process. This paper presents a fully automated design pipeline to reduce or even eliminate this cost. The pipeline is applied onto several previously mass-produced personal equipment such as a medical breathing mask. Time and cost comparison made to mass production methods shows its potential at making AM more accessible for mass-customising previously mass-produced items.

11:10 AM
Framework for CAD to Part of Large Scale Additive Metals Manufacturing in Arbitrary Directions: James McNeil1; William Hamel1; 1University of Tennessee-Knoxville
The purpose of this research is to provide a framework for Large Scale Additive Metals Manufacturing (LSAMM) in arbitrary directions. Traditionally, slicing and path planning is done along the gravity-aligned direction of a part, causing more complex geometrical shapes to have unsupported overhangs. The overhangs can be tackled using a part positioner or a powder bed process, but to extend a different framework for slicing and building parts out of gravity alignment could improve current capabilities of LSAMM processes. The presented research focuses on segmenting more complex geometrical parts into gravity-aligned (GA), non-gravity aligned (NGA), and transition segments to help generate toolpaths. Initial research on segmenting and planning segments of complex geometrical shapes will be presented, as well as current results from builds completed at the University of Tennessee-Knoxville. The completed builds show that more consistent thermal evolution of a part based on the path sequence results in more successful builds.

11:30 AM
Path Planning for Wire and Arc Additive Manufacturing of an Underwater Thruster: Fusheng Dai1; Haiou Zhang1; Guilan Wang1; 1Huazhong University of Science and Technology
The fabrication of large components with complicated shape is challengeable via traditional manufacturing technologies like casting and forging because of high consumptions of materials, energy and production cycle. The underwater thruster, consisting of a pipe with varying thickness and a spindle with groups of blades around, is especially difficult to fabricate. In order to address this fabricating problem, methods of Wire and Arc Additive Manufacturing (WAAM) are proposed in this paper. We present an adaptive path planning method for varying thickness wall, and a path planning method for overhangs built on cylindrical or conical surface. With these methods, the deposition paths of the varying thickness pipe and the blades around the spindle are effectively generated. The methods prove to be applicable for the wire based additive manufacturing of the underwater thruster.
Physical Modeling V - Simulation and Part Quality

Wednesday AM  Room: Salon B
August 14, 2019  Location: Hilton Austin

Session Chair: Jack Beuth, Carnegie Mellon University

8:00 AM
Simulated Effect of Laser Beam Quality on the Robustness of Laser-based AM System: Aaron Flood1; Frank Liou1; 1Missouri University of Science and Technology
In many metal AM techniques, a laser is used as the heat source and in some applications, it can be advantageous to work off of the focal plane. When operating outside of focus, the beam quality of the laser can have drastic impacts on the ability to manufacture quality parts. This study will investigate the effect of beam quality and distance from the focal point on the manufacturability of thin wall samples in Ti-64, aluminum, and steel through the simulation of the blown powder process. The focus will be the fidelity of the thin wall built to its desired geometry and the sensitivity of the laser to being out of focus.

8:20 AM
Chemical Kinetics of Reactive Silver Inks: Avinash Mamidanna1; Carolina Galant1; Subbarao Raikar1; Kris Parker1; Pengfei Yang2; Owen Hildreth1; 1Colorado School of Mines
Reactive inks pave way for newer, low-temperature alternatives to traditional particle-based inks. Reactive silver inks can print silver films with resistivities within 0.2 μΩ-cm of bulk silver without the need for high temperature sintering steps. Our earlier studies showed that processing parameters, such as substrate temperature, and solvent properties have a direct impact on the morphology of printed metal films. This work connects the mass transport, heat transfer, and underlying reaction kinetics to the particle nucleation and growth distributions within the evaporating reactive ink droplets. Kinetics experiments were done to estimate the orders of reactant species and activation energy of the reaction. Next, high speed camera imaging was done on printed droplets to quantify the reaction timescales. Finally, the kinetics data was fed into a reactive ink droplet evolution model developed using COMSOL to predict printed morphologies for any given processing parameters.

8:40 AM
Investigating Transient Pressure Variations during Extrusion-based Additive Manufacturing: Christine Ajineru1; Jake Dvorak1; Vidya Kishore2; Christopher Hershey3; John Lindahl3; Vlastimil Kunc4; Chad Duty5; 1University of Tennessee Knoxville; 2Manufacturing Demonstration Facility
A challenge that arises when extruding molten polymers lies in controlling pressure transients. The start-and-stop process is necessary for additive manufacturing (AM) because it is not feasible to generate tool paths with continuous extrusion profiles. However, this requires that a pressure gradient is applied for arrested flow to resume and achieve steady-state pressure. This study predicts and models the pressure required to initiate flow of molten thermoplastics during a print. The start-up pressure was modeled as a ramp function to mimic the transient behavior of single screw extruders. Computational fluid dynamics simulations were made to predict start-up pressures in AM. Capillary rheometry measurements using dies of various diameters and length-to-diameter ratios were used to study the effect of isothermal compressibility and pressure transients over the range of shear rates observed in AM. These results were compared to the pressure output from AM systems such as Big Area Additive Manufacturing.

9:00 AM
Modeling of the Vapor Plume and Its Interaction with Ambient Gas and Powder in the PBF-LBM Process: Jan Frederik Hagen1; Stefanie Kohl1; Michael Schmidt1; 1University Erlangen-Nürnberg
The understanding of the powder bed fusion process has increased rapidly over the last couple of years due to advances in experimental and simulative setups. Through these, fast analytical models for the prediction of melt pool dimensions and the onset of deep penetration welding have been developed. We show an extension of our high fidelity melt pool model that also includes the vapor plume and the thereby induced gas flow over the powder bed and discuss the constitution of the plume. First results suggest, contrary to recent publications, temperatures not significantly above the boiling point of the material. With the help of this model we look at the correlation between processing parameters and the denudation effect and derive criteria which can be evaluated quickly to describe gas flow induced limits of the PBF-LBM process.

9:20 AM
A Strategy to Determine the Optimal Parameters for Producing High Density Part in Selective Laser Melting Process: Hong-Chuong Tran1; Yu-Lung Lo2; Trong-Nhan Le1; 1National Cheng Kung University
Finding the processing conditions which can produce high density components using Selective Laser Melting (SLM) technique based on trial-and-error is costly and time consuming. With a given SLM machine characteristics (e.g., laser power, scanning speed, laser spot size and laser type), powder material and powder size distribution, the present study proposes an approach to reduce the time and cost in searching optimal parameters for fabricating fully dense parts. The proposed method include several simulation models which are powder bed simulation, Monte Carlo ray tracing simulation, Finite Element Heat Transfer simulation and surrogate modeling. These simulation models are employed to find the viable processing parameters to produce high density component. The experimental results show that the proposed methods results in a maximum component density of 99.97%, an average component density of 99.89% and a maximum standard deviation of 0.03%.

9:40 AM Break

10:10 AM
Effective Moduli of Fused Filament Fabrication Material with Aligned Mesostructure: Ruqi Chen1; Debbie Senesky1; 1Stanford University
Fused filament fabrication (FFF) is one of the most common additive manufacturing techniques. However, use of FFF for mechanical structures is limited by the presence of inter-layer voids. To properly predict the mechanical response of FFF parts, the void shape and distributions must be accounted for. While possible to directly simulate a void-filled component, it is computationally expensive. Instead, it is more efficient to simulate a solid component with effective moduli that take the voids into account. We present analytical solutions for several in-plane effective moduli of an aligned mesostructure. The complex variable method is used to determine the stress and displacement fields in a representative volume element. Effective moduli values are then determined using elastic strain energy equivalence. The results are compared to several upper and lower bounds derived from composite theory, finite element simulations, and experiments on tensile specimens manufactured using FFF.
10:50 AM
Simulating Droplet Break-up in Liquid Metal Printing Processes: Avia Ashby; Victor Beck; Nicholas Watkins; Eric Elton; Luke Thorsley; Phillip Paul; Thomas Reeve; Andrew Pascall; Jason Jeffries; Lawrence Livermore National Laboratory
Droplet-on-demand jetting of liquid metals is emerging as a powerful technology for the additive manufacturing of metallic parts. The viability of this process hinges on overcoming several technological challenges. Principal among these is controlling the droplet jetting process to ensure single, uniform droplets upon ejection. To characterize and control this process we perform Volume-of-Fluid (VoF) simulations of model liquid metal droplet ejection from a single orifice. We develop an operational phase diagram mapping the physical and operational parameters, including the actuation mode, to the droplet break-up time and length at break-up. These results are compared to molten tin ejection experiments and used to elucidate the observed droplet break-up dynamics. We thus provide a systematic path toward developing a computational tool to provide guidance for jetting architectures and processing parameters. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.LLNL-ABS-772009

11:10 AM
Rheology and Applications of Particulate Composites in Additive Manufacturing: Bin Xia; Paul Krueger; Southern Methodist University
To provide different functionalities such as electrical conductivity or magnetism, particulate composites have been utilized widely in additive manufacturing. These materials are usually formulated as a blend of different functional particles and shear thinning non-Newtonian fluids such as polymer melts and silicone. The materials are viscous non-Newtonian suspensions during formulation and printing, and their rheology is the key factor in these processes. This investigation concentrates on suspensions with micron-sized particles, and investigates the rheology and overall flow behavior in capillaries scaled appropriately for additive manufacturing applications (around 1 mm ID). Micron size glass beads and shear thinning silicone are used to demonstrate the impact of particle volume fraction on the shear thinning behavior. The impact of particle and capillary size on viscosity and jamming conditions will be discussed. Previous models based on Newtonian fluids and free flowing conditions will also be reviewed and compared.
increased degree of fiber alignment with the load paths in the multi-axis relative to geometrically similar structures fabricated from the same carbon fiber-loaded ABS exhibited improved mechanical performance as a result of this novel process and workflow, structures fabricated from optimization and multi-axis depositions oriented along 3D load paths. As that optimizes both the part geometry and the toolpath through topology geometric flexibility. In this paper, the authors present a novel workflow existing multi-axis toolpath planning strategies are limited in terms of applied to the weak inter- and intra-layer bonds. Multi-axis ME is not insufficient for load-bearing applications, as load is often unavoidably due to the thermal characteristics of the material extrusion (ME) additive manufacturing process, which requires strong interlayer bonds due to inter-layer curing and minimizes thermal gradient induced warping/residual stresses via the absence of an external heating mechanism. A system utilizing this approach is created by pairing a thermoset metering system with a commercially available fused deposition desktop printer. Modifications are made to G-code generated for the printer to incorporate communication between the printer and the metering system as well as path planning modifications to account for the transient properties of the thermoset material. Parts are created with the composite system and tested for geometric accuracy, material properties, and isotropy.

9:00 AM Melt Flow Characterization of Filaments Used in Fused Filament Fabrication Additive Manufacturing: Jingdong Chen; Douglas Smith; ‘Baylor University Users of Fused Filament Fabrication (FFF) can choose from a wide variety of new materials as filament producers continue to introduce new filament into the market place. This paper describes a low-cost device (FFF-filament rheometer) capable of measuring the rheological properties of off-the-shelf polymer and polyamide composite filament. In this approach, measurements are taken during filament extrusion which are combined with a flow model based on simple shear flow within the FFF nozzle to compute viscosity model parameters for various Generalized-Newtonian-Fluid Models including the Power Law, Cross, and Carreau-Yasuda models. The applicability of our FFF-filament rheometer is demonstrated with six commercially available FFF filaments by comparing the results to those obtained from a commercial rotational rheometer. A melt characterization approach similar to Melt Flow Index is also proposed to assess the extrusion characteristics of materials specifically in FFF technique.

9:20 AM Fabricating Optimized Composite Structures via Multi-axis Material Extrusion: Joseph Kubalak; Alfred Wicks; Christopher Williams; ‘Virginia Tech Due to the thermal characteristics of the material extrusion (ME) additive manufacturing process, the typical layer-by-layer deposition process is insufficient for load-bearing applications, as load is often unavoidably applied to the weak inter- and intra-layer bonds. Multi-axis ME is not constrained to depositing material in layer-wise fashion, which enables significant freedom in the customization of mechanical properties, but existing multi-axis toolpath planning strategies are limited in terms of geometric flexibility. In this paper, the authors present a novel workflow that optimizes both the part geometry and the toolpath through topology optimization and multi-axis depositions oriented along 3D load paths. As a result of this novel process and workflow, structures fabricated from carbon fiber-loaded ABS exhibited improved mechanical performance relative to geometrically similar structures fabricated from the same material and XY-planar layers. This improvement is attributed to the increased degree of fiber alignment with the load paths in the multi-axis structures.
Enhancement of the Bonding Strength between Layers with Dissimilar Materials in Fused Filament Fabrication via Z-pinning Approach: Justin Condon; Tyler Smith; Seokpum Kim; John Lindahl; Jordan Failla; Chad Duty; Vlastimil Kunc; 1; ORAU; 2; Oak Ridge National Laboratory; 3; University of Tennessee

Additive manufacturing (AM) has been widely adopted for prototyping and tooling applications. Fused Filament Fabrication (FFF) is a common AM process where thermoplastics are deposited in layers that are bonded together to create a structure. This process creates structures that have anisotropic properties due to cooling, voids, and fiber alignment. AM structures utilizing multiple materials throughout the printing process can be used to optimize the mechanical properties and cost. However, incorporating different materials can be difficult due to differences in chemical and processing properties between polymers. These differences can lead to delamination across layers once a force is applied to the interface. This paper introduces the application of Z-pinning to reinforce two different materials along the z-axis. Samples of PA and PLA were created with and without pins to test the interface strength between the materials. Tested samples demonstrate the capability to significantly increase the interface strength between multiple materials.

Development of Functionally Graded Material Capabilities in Large-scale Extrusion Deposition Additive Manufacturing: James Brackett; Yongzhe Yan; Vidya Kishore; Haibin Ning; Vlastimil Kunc; Chad Duty; 1; University of Tennessee Knoxville; 2; University of Alabama - Birmingham; 3; Oak Ridge National Laboratory - ManufacturingDemonstration Facility

Additive manufacturing’s (AM) layer-by-layer nature is well-suited to the production of functionally graded materials (FGM) with discrete material boundaries. Extrusion deposition is especially advantageous since multiple nozzles easily accommodate the inclusion of additional materials. However, discrete interfaces and sudden composition changes can limit the functionality of a printed part through inherently weak bonding. Furthermore, same-layer transitions are not only difficult to execute, but also further amplify structural weaknesses by creating multiple discrete interfaces. Therefore, successfully implementing a blended, continuous gradient will greatly advance the applicability of FGM in additive manufacturing. The pellet-fed nature and integrated screw design of the Big Area Additive Manufacturing system enables material mixing needed for development of this capability. Using constituent content analysis, this study evaluates the transition behavior of a neat ABS/CF-ABS material pair and characterizes the repeatability of the mixing and printing process, which ultimately leads to control of site-specific material deposition and properties.

Process Development VIII - Novel Methods and Processes

Wednesday AM Room: 616 AB Location: Hilton Austin

Session Chair: Shanshan Zhang, University of Louisville

8:00 AM Refinement Technique for Robotically Path-planned Functional Gradients: Olga Elseeva; Tanner Kirk; Raymond Arroyave; Richard Malak; Alaa Elwany; Ibrahim Karaman; 1; Texas A&M University

Directed energy deposition (DED) is capable of fabricating functionally and compositionally graded metallic (FGMs) structures through simultaneously fusing multiple elemental or alloy powders in different ratios using multiple nozzles. In previous work by the authors, we had developed a robotic path-planning algorithm to enable the fabrication of functionally graded DED structures, while avoiding undesirable phases such as brittle intermetallics. Working in the ternary iron-chromium-nickel phase diagram and having as path end-points 316L stainless steel and pure chromium, we were able to minimize the existence of sigma phase even after heat treating the part. In this work, we will show how our proposed methodology can be used not only to successfully fabricate functionally graded structures without undesirable phases, but also to achieve desired properties, as well as to tailor their composition. We further show how, by applying error-correction techniques, it is possible to accurately replicate the paths designed by our path-planning algorithms.

8:20 AM Analysis of Porosity Formation and Meltpool Geometry in Directed Energy Deposition Using High-speed, In-situ Imaging: Samantha Webster; Sarah Wolff; Jennifer Bennett; Tao Sun; Jian Cao; Kornel Ehmann; 1; Northwestern University; 2; Argonne National Laboratory

Fundamental process understanding is paramount in laser-based metal additive manufacturing (AM). One of the state of the art approaches of metal AM process characterization is in situ observation. High-speed synchrotron imaging provides adequate spatial and temporal resolutions to capture critical phenomena such as melt-pool dynamics, powder entrainment, and defect formation. Previous studies have characterized these phenomena in laser powder bed fusion; however, they will be very different from those in directed energy deposition processes. In this study, the X-ray imaging technique at the Advanced Photon Source was used to observe dynamic phenomena in DED processes using a high-throughput setup. The set-up allowed the observation of melt-pool geometry and fluctuations, pore formation, and particle capture. Observations that relate the number of generated pores as a function of laser power and melt-pool geometry oscillations as a function of time, among others, will be discussed.

8:40 AM A Comparative Study Between 3-Axis and 5-Axis Additively Manufactured Samples and Their Ability to Resist Compressive Loading: Nathaniel Kail; Ian Campbell; Patrick Pradel; Guy Bingham; 1; Loughborough University; 2; De Montfort University

One of the main limitations of Material Extrusion (ME) components is their anisotropic mechanical behaviour. This behaviour limits the functionality of these components in multi-directional loading conditions. A critical factor for this mechanical behaviour is the poor bonding between layers. 5-axis ME has the capability to orientate the printed layers in order to limit the effect of poor inter-laminar bonding. Previous studies have investigated 5-axis ME, but not fully explored 5-axis capabilities of this manufacturing technique. To address this gap, this paper compares the mechanical behaviour of 3-axis and 5-axis ME samples when subjected to compressive loading. The results demonstrate how aligning deposited material in the same direction as the dominant stresses can improve a samples mechanical performance. 5-axis samples demonstrated improved isotropic behaviour when compared to 3-axis. This study indicates that 5-axis ME can reduce the inherent mechanical limitations of current ME components, enabling more isotropic behaviour.

9:00 AM Using Parallel Computing Techniques to Algorithmically Generate Voronoi Support and Infill Structures for 3D Printed Objects: Tyler Williams; Sarah Langehenning; Duane Storti; Mark Ganter; 1; University of Washington

Many methods of 3D printing rely on support and infill structures in order to produce quality parts. This paper formulates an algorithm that produces both support and infill structures based on Voronoi cells for objects described by a function or a closed triangulated mesh. This algorithm utilizes parallel techniques to speed up implementation, and the large number of parameters used to define the Voronoi structure allows for a high degree of customization for the user. The aforementioned method is novel because it uses Voronoi structures as supports and combines support and infill generation into a single process, displaying the flexibility of Voronoi cell structures in 3D printing applications. The primary focus is on the implementation of the algorithm itself and the customization opportunities provided by the Voronoi cells.
3D Printing of Polymers with Xenon Flash Lamp: Krzysztof Nauka; Lihua Zhao; Aja Hartman; 1HP Inc

High power Xenon flash lamp has been employed as an energy source for 3D polymer printing. Its radiation energy spans over the entire visible range with emission tails reaching into ultraviolet and near infrared. Emitted radiation can be tuned to desired power level and can be as high as tens of J/cm² per pulse with pulse lasting few tens of milliseconds. Customized mirror surrounding the lamp can provide large-area uniform irradiation comparable to the entire powder bed. Selectivity required for 3D printing can be achieved by ink-jetting agents that can either enhance or suppress absorption of the Xenon lamp radiation impinging on the powder's surface. Examples of 3D printing polymers with Xenon flash lamp will be provided, and advantages and challenges of this 3D printing process will be discussed.

A Framework for Enhancing Work Envelope of SFF Implements while Sustaining Dimensional Accuracy: Rajeev Dwivedi; Arpan Gupta; 1STEM and Robotics Academy

Form fit of a part manufactured by solid freeform fabrication equipment is limited by its work envelope. Additionally, the accuracy of work envelope of manufacturing equipment is limited by the positional accuracy of its drives and the end effector. For most of the Solid freeform equipment, the actual implements used to address the two intents are contrary to each other. A large work envelope, requires larger mechanical drives, that inherently are prone to accumulation of mechanical errors and tolerance errors. This paper provides a framework for manufacturing large parts with higher accuracy. By cascading two set of drives (1) that one can provide larger displacements and (2) second that can fabricate parts accurately, larger parts can be built while limiting the tolerance errors. The framework also suggests a unique approach of monitoring and correcting the errors.

A Framework for Manufacturerbility Assessment and Minimum-order-machine Classification of Parts Fabricated by Additive-subtractive Processes: Rajeev Dwivedi; 1STEM and Robotics Academy

Additive and subtractive manufacturing equipments require relative motion of additive and/or subtractive end effector tool with respect to the substrate. The relative motion is implemented with the help of mechanical drives. At the core of each mechanical drive is a rotary motor. This paper proposes a novel method to classify different types of parts on the basis of geometrical features, location of the geometrical features and relative location of the features. The manufacturability of any part, therefore, can be expressed in the context of a basic rotary machine. By expressing the geometry of a part in context of rotary machines, the manufacturing can be classified to follow a sequential topology or parallel topology. This approach leads to the classification of manufacturing implements and the minimum-order-machine needed for fabricating a part.

Advancing Additive Manufacturing with Robotics Beyond 2.5D: Andrzej Nycz; Mark Noakes; Christopher Masuo; Derek Vaughan; Jonathan Paul; Tommy Tucker; Abigail Barnes; 1Oak Ridge National Laboratory; 2Wolf Robotics; 3Tucker Innovations Incorporated

The typical additive manufacturing system consists of a three degree-of-freedom (DOF) gantry system with a deposition head mounted to it. Some direct energy deposition systems have extended the kinematics with a robotic arm or part positioner. However, the build process is still similar to a conventional 2.5D system where a single depositing head builds the part in a layer by layer manner. This work presents current results in creating parts in a true 3D manner using more than six DOF multiple robot arms, multi-DOF part positioners, and print heads capable of depositing multiple materials in the same parts. A recently printed, 1-m diameter marine propeller case study is presented showing the challenges and a path forward towards the use of high DOF multi-robot systems. MedUSA is a new large-scale multi-robot prototype system at Oak Ridge National Laboratory designed to demonstrate and use full 3D print capability.

Exploration of Scalable Build Spaces for Cable-driven 3D Printers: Jesse Heineman; Randall Lind; Brian Post; Phillip Chesser; Celeste Atkins; Alex Roschil; Lonnie Love; Abigail Barnes; 1Oak Ridge National Laboratory

Oak Ridge National Laboratory is currently developing a concrete deposition system for infrastructure-scale printed objects. This system, called SKYBAAM, utilizes cables to support and manipulate the print head within a build space. Compared to traditional gantry and robotic arm systems, this cable driven system has some unique differences that could prove to be advantageous for infrastructure scale applications. One key advantage is that the maximum build height can be increased by simply moving the apex point upward. This work will explore some scalable conceptual structures that would allow for an adjustable and increased apex point height while using cable driven 3D printing systems for printing tower like structures. This work will also explore some other non-cable-driven systems that could potentially be used for printing these structures.

Reduction Expansion Synthesis of Designed Metal Parts: Jonathan Phillips; Zachary Daniels; Troy Ansell; Claudia Luhrs; Wilson Rydalch; 1Naval Postgraduate School

Introducing Reduction Expansion Synthesis-Sintered Metal (RES-SM), a novel method to create green bodies of designed shape far below the metal melting temperature. The precursor to the metal part is a mixture of metal and metal oxide particles (e.g. nickel/ nickel oxide). It is postulated the metal oxide component is reduced via exposure to radical species produced via thermal decomposition of urea/organic solids. In the study performed the highest temperature required was 950 C, the longest duration of high temperature treatment was 1200 s, and in all cases the atmosphere was flowing nitrogen gas. The sintered body produced are fully self-supporting ~90 % dense 'green bodies', not as dense, hard, ductile, electrically or thermally conductive as a metal piece of the same size produced by casting from liquid metal. Scanning electron microscopy (SEM), reveals a microstructure of metal particles joined by necks. Post process HIP produces fully dense parts.
Numerical and Experimental Investigation of Interfacial Fluid-particle Flow in Binder Jet 3D Printing: Joshua Wagner; C. Fred Higgs III; Rice University

In binder jet 3D printing (BJ3DP), strongly coupled fluid-particle interaction is a primary factor governing the overall quality of the final part. Wide scale adoption of this method for demanding, mission-critical applications, such as high-performance aerospace components, requires improved mechanical properties and operating characteristics of the end use parts. This increased fidelity may be achieved with better understanding of the interfacial physics and complex fluid-particle flow that is fundamental to the BJ3DP process. In this work, we seek to elucidate the fluid and particle dynamics occurring upon impact of a liquid droplet onto a powder bed — effects of particle and fluid properties as well as process parameters (droplet size, impact velocity, jetting frequency, etc.) are studied. The investigation is carried out through numerical simulation with a multiphase computational fluid dynamics (CFD) framework. Furthermore, we employ high-speed, microscopic imaging of the droplet impact event for experimental validation.

Modelling of Binder-powder Interactions for the Improvement of Part Density in Binder Jet Printing: Joseph Roberts; Ian Ashton; Simon Mitchell; Richard Finch; University of Liverpool

To increase part density and reduce shrinkage in metallic binder jet printed components, some groups are using the addition of particles in binders, to fill the voids within the powder bed. To aid the development and further understanding of these new particle containing binders, a Monte-Carlo raindrop simulation has been created which generates loose-packed powder beds and infiltrates them with smaller particles. Using this simulation approach enables the determination of basic rules which govern the relationship between the size distribution of the bed particles and the likelihood of the binder particles causing blocking of channels and therefore hindering spreading and permeation of the binder into the powder-bed. The simulation will allow optimum powder bed and binder particle sizes to be determined and as a result improve part density and shrinkage of the printed components.

Imaging and Analysis of Binder-powder Interactions in Metallic Binder Jet Printing: Richard Finch; Joseph Roberts; Ian Ashton; Simon Mitchell; Kate Black; University of Liverpool

Insight into the synergies between the binder and powder in binder jet printing would enable greater control over density, accuracy and mechanical properties of printed components. High-speed cameras are used to investigate the effect of droplet speed and drop volume of the binder on the impact dynamics. The effect of altering bed temperature and powder-bed size distribution is also analysed. The influence of each of these process variables have been characterised in terms of the ability of the binder to wet and permeate into the powder-bed. Greater understanding of the interaction between binder and powder will aid in the determination of optimal print parameters. The output will yield improved part integrity which will drive the wider adoption of binder jet printing as a viable manufacturing tool for end-users in aerospace, automotive and medical sectors.
A concept for a hybrid process chain that combines additive electrodes with interdigitated structures of high geometrical complexity. This is only achievable with subtractive post-processing, such as laser processing, which allows for structures with high complexity and resolution. Conventional methods, like structured electrodes, surface design that promotes ion and electron flow promise to achieve more demanding performance characteristics. Electrodes with a structured surface or more secondary processes enable unique surface integrities to be imparted throughout an entire part volume rather than on external surfaces. For example, peening can be used to print a custom surface integrity on each layer. The idea of a layer-by-layer surface integrity is referred to as a glocal (i.e., local with global implications) integrity and presents new temporal and spatial manufacturing challenges. The goal of this talk is to introduce the concept of glocal integrity and discuss future research challenges.

8:20 AM
Hybrid Additive Manufacturing for Embedded Wire Interconnections in 3D Printed Thermoplastics: Jose Coronel1; Jose Motta1; Leonardo Gutierrez Sierra1; Emerson Armendariz2; Ryan Wicker1; David Espalin1; 1University of Texas El Paso
Employing supplementary functionality to additively manufactured parts often requires the introduction of complementary processes. The hybrid approach of embedding copper wires within 3D printed thermoplastics has allowed for functional printed electronics. Though traditional embedding processes allow for planar wire embedding, the development of techniques for interconnecting wires vertically would allow for compact circuitry design. Interconnections were tested as a means to transfer current to electronic components embedded within a thermoplastic substrate, at vertically differing locations within the printed part. Experiments were conducted on a custom system that allowed for the automated embedding of wire during a print interrupt, with the ability to resume thermoplastic deposition to fully encapsulate the wire along with electronic components. Results showed successful interconnections, with electrical continuity within separate planes of embedded wire. Optimization of the process would further improve the ability to fabricate compact printed electronics, extending their potential applications.

8:40 AM
Inkjet Printing of Geometrically Optimized Electrodes for Lithium-Ion Cells: Cara Greta Kolb1; Harish Mareddy1; Florian Guenter1; Michael Zaeh1; 1Technical University of Munich
Lithium-ion batteries have proven to be reliable energy storage devices for portable and stationary electric consumers because they possess a high energy and power density. Nevertheless, modern applications require more demanding performance characteristics. Electrodes with a structured surface design that promotes ion and electron flow promise to achieve the demanded cell characterististics. Conventionally, structured electrodes are produced by subtractive post-treatment, such as laser processing, which only allows structures with low complexity and resolution. This paper demonstrates a novel approach using inkjet printing to produce electrodes with interdigitated structures of high geometrical complexity. A concept for a hybrid process chain that combines the additive process with subtractive and further manufacturing technologies is presented. The hybrid process chain enables the creation of functional electrodes by multi-material processing of liquid and powdery raw materials.
Hybrid Material Extrusion with Multi-process Technologies: Jose Motta; Xavier Jimenez; Christopher Minjares; Jose Coronel; Chiyen Kim; Ryan Wicker; David Espalin; ‘University of Texas El Paso
The addition of processes such as wire embedding, robotic component placement, and machining to additive manufacturing (AM), allows for the generation of multi-functional 3D printed components that are able to perform beyond their mechanical function. Examples of this include embedded sensors, wire for structural reinforcement, and machining for fine features. A desktop 3D printer known as the “Compact Multi-Tool Fabricator” and an industrial “All-In-One Multi-3D” system allowed for fine features. A desktop 3D printer known as the “Compact Multi-

Connections?
Can Solderable Inks Increase Survivability for Resilient Electrical

Applications: General IV
Wednesday PM Room: 602 August 14, 2019 Location: Hilton Austin

Session Chair: Eric MacDonald, Youngstown State University

1:10 PM
Using Wax Filament Additive Manufacturing For Low-volume Investment Casting: Kevin Andrew; Jason Weaver; ‘Brigham Young University
Investment casting is a popular method of converting wax or polymer patterns into metal objects. For low-volumes, these patterns can be manufactured using additive manufacturing. However, burning out conventional additive thermoplastics like PLA can be more problematic than removing wax. Often, these plastics leave ash residue on the cavity surface, leading to defects in the final metal part. Possible solutions to this problem include using ash-free materials like wax or adjusting parameters to lessen ash buildup. With sufficient consistency in quality, investment casting can be an attractive alternative to metal additive processes. This paper will discuss using wax filament on a conventional desktop fused filament fabrication (FFF) additive machine, including discoveries, settings, and design guidelines leading to successful wax prints. The results wax filament castings are compared to identical castings produced from colored PLA and natural undyed PLA, and advantages and disadvantages of using wax filament are discussed.

1:30 PM
Fatigue Performance of Additively Manufactured Stainless Steel 316L for Nuclear Applications: William Beard; Robert Lancaster; Jack Adams; Dane Buller; ‘Swansea University; ‘Rolls-Royce plc
Additive manufacturing (AM) is a rapidly growing technology which is extending its influence into many industrial sectors such as aerospace, automotive and marine. Recently the nuclear sector has considered AM in the production of nuclear reactor components due to its possible advantages over conventional manufacturing routes. This includes considerable cost savings due to less material wastage, the ability to produce complex near net shape components that conventional manufacturing processes are unable to achieve and a reduced manufacturing time. Initially Stainless Steel 316L (SS316L) manufactured by laser powder bed fusion (LPBF) has been identified as a potential candidate. However, due to the transient nature of the microstructure it is now of fundamental importance to assess and understand the mechanical behaviour of the LPBF material. This paper will highlight some of the recent research at Swansea University in investigating the variation on the fatigue characteristics between wrought SS316L and LPBF processed SS316L material. This will include an extensive microstructural and fractographic investigation. As LPBF material looks to replace conventionally manufactured equivalents, an understanding of how build integrity and orientation affects the mechanical properties of AM material is critical. Wrought and vertical LPBF material are to be assessed to understand how the microstructure controls the fatigue performance of LPBF SS316L material.
1:50 PM  
Failure Detection of Fused Filament Fabrication via Deep Learning: Zhicheng Zhang1; Ismail Fidan1; "Tennessee Tech University  
Today, the utilization of AM, is growing sharply in almost every field of daily life, especially in the field of industry. Moreover, the development of new machines and materials are the hot spots of the current studies in the field of AM. There is a limited number of technical studies on the troubleshooting, maintenance and problem solving aspects of the AM processes. DL is an emerging machine learning type, which is widely used in several research studies lately. The research team believes that the application of DL could make the AM processes operation more smoothly and help the AM machines to print very accurate objects eventually. In this study, the research team proposes a newly developed DL application to avoid the waste of materials generated by the bad printing process. This study will report the nature of this newly developed DL application, and how it works in several failure cases.

2:10 PM  
3D Printing Card: Apisith Patana-anek1; "Acharya Institute of Technology  
The 3d printing card represent the feeling and emotion of the giver to the receiver. In the past decade, people used to send the card to the person they loved. But these day, people just send the E-card by the smart phone which does not mean anything to the receiver at all. 3d printing card can build better relationship between people. It is a touchable object and it will not faded away. This 3D card will be the sign of relationship which people in this generation needed. 3d card will be made of polymer by 3d printer and it will be design for all occasions. 3d card will pop up in 3d structure when someone open it.

2:30 PM  
Penetration Performance of Additively Manufactured Ultra High Strength Steel Fragment Simulating Projectiles: Brandon Mcwilliams2; Jian Yu1; Andelle Kudzal1; "CCDC Army Research Laboratory  
Current commercially available feedstocks for powder bed fusion (PBF) additive manufacturing (AM) processes typically have lower strength, hardness, and ductility than the high-strength steel alloys typically used in Army ground vehicle and munitions applications. In order to take full advantage of AM to improve performance, reduce weight, and decrease cost while addressing Army modernization priorities, it is critical to develop new feedstocks which meet high material demands in extreme loading conditions. In this presentation, fragment simulating projectiles (FSP) were produced using PBF of ultra high strength, high toughness, low alloy martensitic steel. This material, originally developed by the Air Force for castings and wrought applications, has recently been produced in powder form, optimized laser PBF parameters developed, and demonstrated to have remarkable toughness in the as-printed conditions. The penetration performance of these FSP against traditional metallic and polymeric targets are evaluated and compared to that of wrought.

2:50 PM  
Large Format Additive Manufacturing for Low-head Hydropower: Alex Roschil1; Phillip Chesser1; Jesse Heineman1; Brian Post1; Alex Boulger1; Celeste Atkins1; Lonnie Love1; Vito Gervasi1; Randal Mueller1; Abigail Barnes1; "Oak Ridge National Laboratory; Cadens  
Low-head hydropower is a relatively untapped resource for reliable power generation. The major barrier to entry is the cost of components needed to generate the power because each installation needs custom-made components for the turbine system. With additive manufacturing, parts can be custom made for each unique installation. These parts can be designed in such a way that they form a unique modular system, which saves time for future designs and iterations. The modular design, and use of additive manufacturing, will help to greatly reduce the cost and time to set up low-head hydropower plants. This paper will explore the use of large format additive manufacturing for the production of low-cost, end-use parts in the low-head hydropower industry.

3:40 PM  
Surface Roughness Characterization in Laser Powder Bed Fusion Additive Manufacturing: Wesley Eidt1; Eric-Paul Tatman1; Josiah McCarther1; Jared Kastner1; Sean Gunther1; Joy Gockel1; "Wright State University  
Rough surfaces are known to be a detriment to the fatigue performance of metallic materials and laser powder bed fusion additive manufacturing (AM) is known to produce surfaces with high roughness. Prior work has shown the relationship between surface roughness metrics and the fatigue performance of AM metals through extensive characterization. However, it is not always feasible to characterize the entire specimen, so a statistical understanding of the surface must be obtained. Characterized surfaces can then be used to predict the mechanical performance of the specimen using a variety of traditional methods. This approach is further extended to characterization of downward facing surfaces and the design of novel test specimens with structurally relevant as-built features. Understanding the surface roughness features through characterization and experimental fatigue testing will give insight to optimize processing parameters for improved AM mechanical performance and build tolerances.

4:00 PM  
Influence of 3D Sand-Printing Processing Conditions on Thermo-Mechanical Properties of Molds: Daniel Martinez2; Casey Bate1; Guha Manoharan1; "Pennsylvania State University  
A comprehensive study on the thermo-mechanical properties of 3D sand-printed molds and its effects on aluminum castings is performed on molds printed using a state-of-the-art VIRIDIS3D RAM system. The effect of changing furan binder content between 1 and 3% in silica sand is evaluated for the as-printed samples to determine changes in dimensional accuracy and density of the mold. Actual binder content is determined using loss on ignition test. Mechanical strength of the samples is established using three-point bending and tensile tests. Specific heat is measured using differential scanning calorimetry. Permeability and porosity measurements are carried out using AFS standard permeability test and mercury porosimetry. Micro-computer tomography is done on samples of each binder content to reconstruct a pore network via image analysis. To examine the effects of binder content in the mold on metal castings, solidification experiments are carried out determine solidification curves. Microstructural characteristics are observed via optical microscopy. Finally, mechanical properties are experimentally established using Rockwell hardness and three-point bending test. These results allow for optimum selection of binder content for adequate degassing capacity and mechanical strength and can be implemented in foundry conditions.
Applications: Layered and Cellular Optimized Structures

Wednesday PM  Room: 410
August 14, 2019  Location: Hilton Austin

Session Chair: Dhruv Bhatte, Arizona State University

Layered Assembly: Digital Fabrication of Voxel-based Multi-material Parts: Joni Mici1; Jared West1; Jeffrey Jaquith1; Hod Lipson1; 1Columbia University

Layered Assembly is a voxel-based digital manufacturing method which uses premanufactured voxels as feedstock to create multi-material parts. In Layered Assembly, voxels are grasped and positioned by electroadhesive grippers, which are low-power, solid-state-controlled, and epoxy-free grippers capable of selectively parallel pickup. Parallel grasping allows for much faster deposition rates, while electroadhesion enables the grasping of a wide range of materials. In the present work, a 4 x 4 array of electroadhesive grippers was used to achieve layer-by-layer manufacture of several multi-material electromechanical parts. The manufactured parts showcase the potential of Layered Assembly as a novel digital fabrication technique, capable of printing cellular, voxel-based, multi-material systems.

Compressive Properties Optimization of Bio-inspired Sandwich Structures Fabricated by Selective Laser Melting: Liang Meng1; Zemin Wang1; Xiaoyan Zeng1; 1Huazhong University of Science & Technology

Based on the microstructure of cybister elytra, the lightweight sandwich structure is designed. Response Surface Methodology (RSM) and Non-dominated Sorting Genetic Algorithm II (NSGA-II) are used to investigate multi-objective optimization of the bio-inspired structure. Multilayer bio-inspired structures of Ti6Al4V alloy are designed and fabricated by Selective Laser Melting. Results show that the optimization model can explain the relationship between the variables and the response well. Additionally, for the multilayer structures with parallel-arranged configurations, increasing the number of layers cannot effectively improve the energy absorption (EA) and specific energy absorption (SEA). Comparatively, increasing the layer numbers can absorb much more energy but weaken their SEA for multilayer structures with vertical-arranged configurations. For those structures with different core configurations, bio-inspired structures with vertical-arranged configurations have more excellent compressive properties than those of structures with parallel-arranged configurations. Finally, the simulation results are consistent with experimental results.

In-plane Pure Shear Deformation of Cellular Materials with Novel Grip Design: Kaitlynn Conway1; Shubhamkar Kulkarni1; Benjamin Smith1; Garrett Pataky1; Gregory Mocko1; Joshua Summers1; 1Clemson University

Cellular materials are popular due to their high specific strength, but their in-plane shear behavior is not well understood. Current experimental methods are limited due to the lack of pure shear loading as common arcane-style grips have not been adjusted for cellular materials. A significant concern is a mixture of shear loading with grip induced tension. While in bulk materials the tensile force can be assumed negligible, it is the driving force for failure in cellular materials. In this study, finite element modeling simulations were used to demonstrate that using a new floating grip design reduced the normal stress and the normal strain, demonstrating a significant reduction in induced tension. Experimental studies were performed on cellular materials with traditional and newly-developed grips to calculate and compare the shear strength, shear modulus, and ductility of cellular materials.

2:10 PM
Size Effect on the Fracture Characteristic of Cellular Structures under Tensile Load: Yan Wu1; Li Yang1; 1University of Louisville

In the unit cell based design of cellular structures, an important issue is the effect of the cellular pattern size (i.e. the number of unit cell numbers along different orientations) on their mechanical properties. Among these properties, the fracture properties are of great importance for a broad range of applications but have been rarely investigated. In this work the size effects on the fracture characteristic (including failure initiation, crack propagation and failure patterns) of the BCC, octet-truss and two types of auxetic structures under tensile loadings were analyzed based analytical models. It was found that for the fracture of the cellular structures there exist significant coupling effects between the unit cell topology and the cellular pattern size. The results also clearly suggested the importance of dedicating more design attentions to the boundaries of the cellular structures during their fracture designs. This study provides additional insights into the design considerations for the fracture properties of the cellular structures.

2:30 PM
Topology Optimization of Lattice Structure Unit Cell for Convective Heat Transfer Applications: Florian Dugast1; Albert To1; 1University of Pittsburgh

This talk aims to present the optimized lattice structure unit cell for convective heat transfer applications. A gradient-based method based on the Lattice Boltmann method (LBM) is used to find the optimal geometry. LBM has an explicit formulation and its algorithm is well suited for high-performance parallel computing. Added to that, LBM can treat in a simple way the boundary conditions, which is another interesting feature for topology optimization where the geometry can be complex. The numerical application is based on a 3D laminar flow with heat transfer. The computational domain is composed of 100*100*100 elements. The objective of the topology optimization problem is to increase the heat transfer efficiency of the unit cell. As the minimal surfaces are good candidate for heat transfer intensification due to their high surface area, a comparison between the optimal geometry and classical minimal surfaces (gyroid for example) is also presented.

2:50 PM Break

3:20 PM
Design, Modeling and Characterization of Triply Periodic Minimal Surface Heat Exchangers with Additive Manufacturing: Hao Peng1; 1TAMCO

Next-generation power plants will generate heated fluids at significantly higher temperatures than current-generation power plants, which challenges the state-of-the-art heat exchanger design. In this study minimal surfaces were combined with additive manufacturing for next-generation heat exchanger design. Minimal surfaces separate three-dimensional space into two interpenetrating channels, creating high surface area to volume ratios and low hydrodynamic resistance. Parametric design of minimal surface heat exchanger is straightforward because they are governed by simple implicit functions with parameters such as periodic length and offset parameter. In this study a software design platform was developed to streamline the design of minimal surface heat exchangers and a numerical model was developed to optimize minimal surface heat exchanger design for optimal performance. Finally, the optimized minimal surface heat exchanger was printed with EOS M290 DMLS machine and the performance was tested by experiment.
Two-photon polymerisation (TPP) is an additive manufacturing technique allowing the fabrication of arbitrary 3D geometries with sub-micron features. As such, TPP is a promising technique for fabricating optical metamaterials. The electromagnetic (EM) properties of metamaterials arise from their geometrical structure rather than their material constituents alone. By introducing variations across the unit cells of a metamaterial spatially varying EM properties can be created. In this way, gradient index (GRIN) optics can be produced which are useful for reducing coupling losses and creating compact optical systems. This work looks at modulating fabrication parameters to achieve geometrical variations. Line widths of IP-L 780 are measured on an array of lines fabricated at different laser powers and scan speeds. Proof of concept woodpile structures are also fabricated where laser power is changed for variations. Line widths of IP-L 780 are measured on an array of lines fabricated at different laser powers and scan speeds. Proof of concept woodpile structures are also fabricated where laser power is changed for individual lines in the structure resulting in geometrical changes. Changing fabrication parameters along a single scan line is also investigated.

Additive Manufactured Lightweight Vehicle Door Hinge with Hybrid Lattice Structure: Ismet Aydin; Ehran Akarşay; Omer Gümüş; Hümeysa Yelek; Can Engin; 1; Rollmehc Automotive San. ve Tic. A.S. Replacing body components to high-strength-low density cellular structures are promising candidate for design lightweight and complex parts especially for automotive industry. The goal of this research is to evaluate the limitations of additive manufacturing technology to produce vehicle door hinge with hybrid lattice structures to fulfill the safety criteria. Mechanical properties and anisotropy level of tensile specimens with different build directions, fabricated from maraging steel, using direct metal laser sintering have been investigated. A topology optimization software is optimized vehicle door hinge with lattice structure. However, prediction of the mechanical behaviour of the door hinge system remains a challenge, especially against the global technical regulation (ECE-11). This paper presents an approach to finite element analysis of regulation to simulate mechanical behaviour of the door hinge with hybrid lattice structures under the regulatory conditions. Moreover, acceptance criteria of the regulation for printed hinge designs are examined.

Build Orientation Optimization for Structural Performance Enhancement of Functionally Graded Conformal Lattice Structure Fabricated by Fused Deposition Modeling: Phong Nguyen; Young Choi; 1; Chung Ang University Lattice structures, classified as non-stochastic cellular structures, are well-known for their lightweight and the multifunctional characteristic is increasingly adopted in the industry for lightweight part design due to the advancement of additive manufacturing (AM). The conformal lattice structure (CLS) is a particular type of lattice structure in which lattice unit cell orientations are varied to match with design domain boundaries leading to the improvement in structures’ performance. However, since the part is fabricated by AM, additively manufactured CLSs hold some AM unique characteristics including its anisotropy in mechanical properties which could affect structures’ performance and highly depends on the parts’ build orientation. In this method, a working optimization of CLSs fabricated by fused deposit modeling, a common AM process, for the structure’s performance maximization is proposed. The optimum design method is validated through two test models by comparison with parts fabricated in different orientations.
The scope of this research is to evaluate the effects on electrostatic charge dissipation at different annealing temperatures of nanographene platelets (NGP) added in polyamide 6 (PA6) filaments. Previous research of polymers filled with NGP suggests that the improved electrical conductivity properties are ideal for the parts manufactured by fused filament fabrication (FFF) that require electrostatic discharge protection. In this study, NGP were blended into PA6 using a co-rotating twin screw extruder to compare electrical and mechanical properties and exfoliation of the nanoparticles. Scanning Electron Microscopy (SEM) was used to determine the degree of dispersion. Loadings of 3, 5, and 7wt% of NGP were evaluated in filaments that were not annealed and annealed at 80ºC. Tensile, flexural, and electrical resistivity test coupons were prepared using FFF on a Lulzbot TAZ 6 3D printer and subsequently tested.

2:10 PM Manufacturing and Application of PA11-glass Fiber Composite Particles for Selective Laser Sintering: Maximilian Dechet1; Lydia Lanz2; Yannick Werner3; Dietmar Drummer4; Andreas Bück5; Wolfgang Peukert6; Jochen Schmidt7; 1Institute of Particle Technology (LFG) - FAU Erlangen-Nürnberg; 2Institute of Polymer Technology - FAU Erlangen-Nürnberg

In order to enhance the isotropic mechanical properties of parts manufactured via selective laser sintering, the manufacturing of glass fiber-filled PA11 particles is shown in this contribution. We present a single-pot approach to produce glass fiber-filled polyamide 11 (PA11) composite particles. The particles are manufactured via liquid-liquid phase separation and precipitation [1] (also known as solution-dissolution process) from ethanol glass fiber dispersions. Bulk polymer material of PA11 is directly converted to composite microparticles in a single process. The produced particles are characterized regarding their size and morphology. The amount of glass fibers in the bulk is assessed via thermogravimetric analysis and the effect of the fibers on the processing window is investigated via DSC. Subsequently, the powder is employed in the SLS process to produce glass fiber-enhanced test specimens for mechanical testing.[1] Dechet, Goblirsch, Romeis, Zhao, Lanyi, Kaschta, Schubert, Drummer, Peukert, Schmidt, Chem. Eng. Sci. 197 (2019) 11–25

2:30 PM Recent Advances in Direct-write Additive Manufacturing of Thermoset Composites: Brett Compton1; 1University of Tennessee

This talk will focus on recent developments in direct-write additive manufacturing (DIW) of thermoset-based composite materials. Special focus will be paid to the rheological requirements for successful printing and curing, as well as the relationship between fiber morphology, ink rheology, print parameters (i.e. nozzle size and print speed), and anisotropy in the printed part. Insights gained from recent studies on printed epoxy composites will be discussed, as will new opportunities for DIW of high temperature epoxy composite systems, foams, and polymer-derived ceramic composites.

2:50 PM Break

3:20 PM Manufacturing of Nanoparticle-filled PA11 Composite Particles for Selective Laser Sintering: Maximilian Dechet1; Lydia Lanz2; Alisa Wilden3; Maria-Melanie Sattes4; Dietmar Drummer5; Wolfgang Peukert5; Jochen Schmidt6; 1Institute of Particle Technology (LFG) - FAU Erlangen-Nürnberg; 2Institute of Polymer Technology - FAU Erlangen-Nürnberg

In this contribution, the manufacturing of nanoparticle/alumina-, titania- and silica-filled polyamide 11 (PA11) particles for selective laser sintering (SLS) is demonstrated. The particles are manufactured via liquid-liquid phase separation and precipitation [1] (also known as solution-dissolution process) from ethanol dispersions. Bulk polymer material of PA11 is directly converted to composite microparticles in a one-pot approach. The produced particles are characterized regarding their size and morphology. The amount of nanoparticles in the bulk is assessed via thermogravimetric analysis, whereas microscopy on cut thin-films shows the incorporation of the nanoparticles into the PA11 matrix. Furthermore, the effect of the nanoparticles as nucleating agents is investigated via DSC and correlated with surface energies as determined by inverse gas chromatography (IGC).[1] Dechet, Goblirsch, Romeis, Zhao, Lanyi, Kaschta, Schubert, Drummer, Peukert, Schmidt, Chem. Eng. Sci. 197 (2019) 11–25

3:40 PM Technique for Processing of Continuous Carbon Fibre Reinforced PEEK for Fused Filament Fabrication: Jing Pu1; Ehab Saleh2; Ian Ashcroft3; Arthur Jones4; 1University of Nottingham; 2University of Leeds

3D printing of light-weight and mechanically-strong structures facilitates several applications, such as aerospace components and medical implants. 3D printing of continuous carbon fibre-reinforced PEEK (CF/PEEK) presents exciting possibilities as the high stiffness and strength of the high-performance plastic PEEK reinforced with carbon fibre are paired with the agility of the 3D printing process. The Fused Filament Fabrication (FFF) 3D printing process is chosen as the process to develop here. Currently, the 3D printing of CF/PEEK is limited to relatively low CF volume fractions (<30%). No CF/PEEK filament with a high volume fraction of continuous carbon fibre is commercially available. Based on the material characterisation of the CF/PEEK composites, a pultrusion system to manufacture filament with a fibre volume fraction higher than 57% has been designed and built. A modified deposition strategy has been developed to print the filament. Finally, the printability of the filament produced is demonstrated.

4:00 PM Processing and Characterization of 3D-printed Polymer Matrix Composites Reinforced with Discontinuous Fibers: Ankit Gupta1; Semyur Hasanov2; Ismail Fidan3; 1University of Texas at Austin

Objective of this study is to fabricate the discontinuous fiber reinforced polymer matrix composites by AM technology using single extruder 3D printers. For this study, short carbon fibers reinforced filaments were extruded with fiber concentrations of 5-10% by volume. Input process parameters for 3D printer to obtain a good quality short fiber reinforced polymer specimen are closed chamber temperature and printing speed by fixing nozzle temperature, layer thickness, cooling fan speed, bed temperature and print orientation. It was analyzed that surface characteristics and mechanical performance of 3D printed samples were greatly influenced by varying input process parameters. Optical microscopy and scanning electron microscopy were performed to observe micro-structural behavior of 3D printed samples. Tensile strength was examined to validate the adhesiveness of the matrix and reinforcement. Results obtained in this study are quite useful in fabricating the PMC with improved overall characteristics for applications in automotive industry and medical field.
4:40 PM
Reactive Injet of Quantum Dot – Silicone Composites: Liesbeth Birchall; Ricky Wildman; Chris Tuck; Aleksandra Foerster; University of Nottingham

Quantum dots are fluorescent semiconductor nanocrystals with applications in lighting, solar cells, and sensors. Additive manufacture, particularly inkjet, is of great interest for such optoelectronic devices, due to its potential for geometric freedom, reduced material waste, and simplified design. However, development of printed devices has been slowed by stringent requirements for ink rheology and homogeneity between layers. While quantum dot-based devices have been produced via inkjet, the quantum dots are dispersed in volatile solvents which often leads to inconsistent jetting and coffee ring effects. This project uses reactive inkjet to synthesize quantum dot-silicone composites in situ to encapsulate quantum dots. Inks are formulated from a commercial addition-cure silicone to meet rheological requirements; printing parameters and nanoparticle loading are optimized towards stability and optical properties. It is expected that this approach will enable in-situ optical thermometry of inkjet-printed devices while potentially improving stability, design freedom, and reducing the amount of solvents.

Materials: Metals IX - Processing Effects

Wednesday PM
August 14, 2019
Location: Hilton Austin

Session Chair: Xiaojing Wang, Jacksonville State University

1:10 PM
Characterization of the Balling Defect in Stainless Steels during Laser Powder Bed Additive Manufacturing: Debomita Basu; Jack Beuth; Bryan Webler; Carnegie Mellon University

A major challenge in laser powder bed additive manufacturing is the navigation on processing regions of higher power and velocity. This region of processing space is desirable because it allows a reduction in the time necessary to build components without compromising part resolution; however, high power and high velocity induce melt pool instabilities, known as balling, along the length of the laser track. This creates uneven surfaces for subsequent layers, which can result in embedded pore-type flaws. In this work we investigate how balling develops with increasing laser power and velocity in 300-series stainless steels. This is studied with surface profilometry and as-built track width measurements. Melt pool and as-built part cross-sections are also characterized to examine the impact of balling on microstructure and porosity. Possible processing strategies to change melt pool shape at high powers and high velocities and mitigate balling are also discussed.

1:30 PM
Additive Manufacturing of Fatigue Resistant Materials: Avoiding the Early Life Crack Initiation Mechanisms during Fabrication: Jonathan Pegues; Michael Roach; Nima Shamsaei; Auburn University; University of Mississippi Medical School

The full potential of additive manufacturing (AM) has been limited by the process induced defects within the fabricated materials. Defects such as lack of fusions and gas entrapped pores act as stress concentrators and result in premature fatigue crack initiation, severely limiting the applicability of AM in fatigue-critical applications. However, by understanding the failure mechanisms associated with AM materials and leveraging the intimate localized thermal input (i.e. process conditions), the failure mechanisms for some materials may be avoided during the fabrication process. This study investigates the crack initiation behavior of two austenitic stainless steels subjected to fatigue testing. The microstructural features responsible for fatigue crack initiation are captured at the surface by ex-situ electron backscatter diffraction. Results show that the higher cooling rates during AM offer the opportunity to fabricate fatigue resistant austenitic stainless steel parts by avoiding the microstructural features that are most detrimental to fatigue performance.

1:50 PM
Graded Multimaterial Printing via L-PBF: Design, Development, and Characterization of AISI 316L and Fe35Mn Graded Specimens: Federico Lucchini; Riccardo Rossi; Ali Gokhan Demir; Fabio Caltanissetta; Barbara Previtali; A. John Hart; C. Cem Tasan; Bianca Maria Colosimo; Politecnico di Milano

The great potential of gradient multimaterial AM is still at its early stages, and can be further exploited by L-PBF techniques. This work demonstrates the feasibility of producing graded multi-material components using a novel L-PBF system, which achieves in-situ mixing of specific amounts of two feedstock powders. A graded increase of Mn content in AISI 316L was achieved by gradually adding Fe35Mn to the processed layers. Preliminary experiments were performed on AISI 316L and Fe35Mn as well as pre-mixed blends of the two materials, and fully-dense specimens were achieved. Finally, a complete gradient compositional transition was achieved, starting from AISI 316L and gradually changing the Fe35Mn percentage in four different steps along the building direction. Characterization of the printed specimens show a gradual variation of the Mn content and a related variation of the local hardness, along with columnar grains with a high aspect ratio oriented along the build direction.
Comparison of Rotating-Bending and Axial Fatigue Behaviors of LB-PBF 316L Stainless Steel: Rakish Shrestha1; Jutima Simsiriwong2; Nima Shamsaei1; 1Auburn University; 2University of North Florida

Results from the complex thermal histories resulted in the lack of fusion pores, which degrades the mechanical properties. In addition, the size of the EBM system without lack of fusion defects. In addition, the system is able to fabricate the components as large as the allowable envelope size of the EBM system without lack of fusion defects. In the current investigation of the microstructure and mechanical properties of in situ welded Ti-6Al-4V and IN718 round specimens with uniform gage section, while rotating bending fatigue tests are conducted on hourglass specimens (i.e. reduced gage section). Fractography analysis is conducted to determine the fatigue failure mechanisms as they are affected by the surface roughness and the type of testing performed. The experimental results are presented, highlighting the effect of stress gradient on the fatigue properties obtained.

Microstructure and Mechanical Properties of Nickel Superalloys and Ti6Al4V Fabricated Using a Renishaw’s Multi-laser Powder Bed Fusion System: Ravi Aswathanarayana1; Jenna Tong1; Marc Saunders1; Renishaw Plc

In this study, the density and mechanical properties of Nickel Superalloy 718 and Ti6Al4V parts fabricated using a quad-laser Renishaw machine were analysed. Tensile bars were built using 1) all four lasers to address the build platform with one laser assigned per part, and 2) using two lasers to address each part on the build platform. Irrespective of one laser per part or two lasers per part high part densities were observed. In both cases room temperature ductility of heat-treated samples was higher than reported literature data, which can be traced to improved gas flow.

Materials: Metals X - Stainless Steel

Effect of powder chemical composition on microstructures and mechanical properties of L-PBF processed 17-4 PH stainless steel in as-built and hardened-H900 conditions: Swathi Vunnam2; Sean Dabson1; Abhinav Saboo2; Dana Frankel1; Chantal Sudbrack2; Thomas Starr1; University of Louisville; QuesTek Innovations LLC

Post-build heat treatments such as solutionizing and precipitation hardening are recommended for selective laser melting (SLM) processed components to achieve a homogeneous microstructure. In this study, the effect of powder elemental composition on microstructures and mechanical properties of SLM processed 17-4 PH was studied in as-built and precipitation hardened (H900) condition without prior solutionizing. Microstructural characterization demonstrated that H900 increased martensite phase composition for samples from powder with low chromium to nickel equivalent (Creq/Nieq) value, whereas no significant difference was observed for the samples from high Creq/Nieq value powders from H900. None of the specimens exhibited austenite reversion and strain hardening behavior in as-built and H900 conditions. Low Creq/Nieq specimen exhibited higher yield and tensile strengths, and microhardness from H900, which are comparable to H900 wrought sample. However, no significant improvement in total elongation was observed other than enhanced uniform plastic elongation.
1:50 PM
Fatigue Life Prediction of Additive Manufactured Materials Using a Defect Sensitive Model: Muztahid Muhammad; Patricio Carrion; Nima Shamsaei; 1Auburn University

This study aims to utilize a defect sensitive fatigue model based on a fracture mechanics concept to predict fatigue life of 17-4 precipitation hardening (PH) stainless steel (SS) and Ti-6Al-4V fabricated using laser beam powder bed fusion (LB-PBF) process. Size of defects such as lack of fusions and gas entrapped pores are captured using fractography analysis and calculated employing a new method using Murakami approach. Considering the size of a /area determined from the Murakami approach as initial crack length, fatigue life is then calculated using NASGRO software and compared to the experimental data obtained from strain-controlled fatigue testing. A comparison between predicted fatigue lives using NASGRO software combined with the Murakami approach, and experimentally obtained ones will be presented to determine the applicability of the utilized model for predicting the fatigue performance of additive manufactured materials.

2:10 PM
Assessing the Corrosion Characteristics of Fe-based Alloys Prepared by Laser Powder Bed Fusion: Iwan Grech; Natalie Wint; Nicholas Lavery; James Sullivan; 1Swansea University

Whilst AM provides many opportunities, the corrosion susceptibility of as built components is relatively unknown. This lack of knowledge regarding the reliability and reproducibility of parts limits the integration of AM into several industries, particularly those in which safety critical components are used. During this work laser powder bed fusion (LPBF) is used to produce iron alloy (INVAR®, 17-4PH and H13) components. Build parameters are systematically changed and the corrosion performance of the samples produced is investigated using a combination of scanning vibrating electrode technique (SVET), in situ time lapse microscopy (TLM) and advanced conventional electrochemical techniques. SVET can resolve localised corrosion currents with respect to space and time and TLM is used to monitor localised corrosion behaviour on a microstructural length scale. The corrosion behaviour is explained in terms of the differences in microstructure observed in the case of AM samples compared to their wrought and cast counterparts.

2:30 PM
Comparison of Fatigue Performance Between Additively Manufactured and Wrought 304L Stainless Steel Using a Novel Fatigue Test Setup: Mohammad Masud Parvez; Yitao Chen; Frank Liu; Joseph Newkirk; 1Missouri University of Science & Technology

In this research, a novel adaptive controlled fatigue testing machine was designed for bending type high cycle fatigue test. A unique dual gauge section Krouse type mini specimen was designed for simply supported transverse bending. Displacement controlled fatigue tests were implemented using an electromechanical actuator. The variation in the control signal and load observed during the test provides unique insights into realizing the deterioration of the specimen due to fatigue. These analyses were utilized to compare the fatigue performance of wrought and additively manufactured 304L stainless steel. The influence of the build direction on fatigue performance was also investigated by testing specimens with 0, 45, and 90 degree build direction. These comparisons were carried out at different levels of displacement amplitude. This work was funded by the Department of Energy’s Kansas City National Security Campus which is operated and managed by Honeywell Federal Manufacturing Technologies, LLC under contract number DE-NA0002839.

2:50 PM Break

3:20 PM
The Impact of Porosity on the Mechanical Properties of 304L Stainless Steel Fabricated by Selective Laser Melting: Tan Pan; Sreekar Karnati; Austin Sutton; Matthew Bennish; Joseph Newkirk; Frank Liu; 1Missouri University of Science & Technology

Selective Laser Melting (SLM) is a layer-by-layer additive manufacturing process. Porosity is a paradigm that affects the mechanical properties of parts produced by SLM. This study investigated the impact of pore size in 304L stainless steel on mechanical properties. Among the PBF methods is the selective laser melting (SLM) process which utilizes a laser beam to melt particles to fabricate the creation of lightweight, small-sized parts with complicated geometries. However, SLM still suffers from the presence of porosity in built components causing uncertainties in the microstructure and mechanical properties. While it is known that porosity formation can be affected by altering the scan speed, and hatch spacing, the influence of the pore size on the mechanical properties is still not fully understood. In this work, the impact of pore size in 304L stainless steel on mechanical properties is investigated. This work was funded by the Department of Energy's Kansas City National Security Campus which is operated and managed by Honeywell Federal Manufacturing Technologies, LLC under contract number DE-NA0002839.

3:40 PM
Fatigue Behavior of Additive Manufactured 304L Stainless Steel Including Surface Roughness Effects: Seungjong Lee; Jonathan Pegues; Nima Shamsaei; 1Auburn University

The fatigue behavior of additive manufactured parts in the as-built surface condition is typically dominated by the surface roughness. However, the fatigue behavior of 304L stainless steel fabricated by laser beam powder bed fusion shows less sensitivity to surface roughness under strain-controlled loading conditions than other additive manufactured materials. Under force-controlled conditions, however, the high cycle fatigue resistance is much lower for the as-built surface condition than the machined one. This study investigates the underlying mechanisms responsible for fatigue failure for each condition (i.e. strain-controlled or force-controlled). The corresponding cyclic deformation behavior was characterized, and a thorough fractography analysis was performed to identify the features responsible for crack initiation. Results indicate that the crack initiation features in both loading conditions are similar, and that the reduced high cycle fatigue resistance for force-controlled fatigue loading compared to strain-controlled one is related to differences in the cyclic deformation behavior of the material.

4:00 PM
SS410 Process Development and Characterization: Derek Vaughan; Andrzej Nycz; Mark Noakes; Christopher Masuo; Abigail Barnes; 1Oak Ridge National Laboratory

Wire-fed stainless-steel additive manufacturing provides a potential alternative to the traditional stainless-steel tool making processes. SS410 stainless steel provides the necessary hardness for long term tool use and its corrosion resistance negates the need for post processing of non-critical faces. SS410 also has unique characteristics that require different design and welding parameters from other materials. This paper will look at the parameters and characteristics expected when using wire-arc deposition for 410 stainless steel. Individual weld beads and simple geometric features were printed using the MBAAM wire-arc system at ORNL to determine effective wire-arc parameters for SS410. Once parameters were chosen, additional features were printed to determine the geometric characteristics of printed SS410 as well as comparison of the differences between designed geometries and printed geometries. These results allowed for the formulation of smarter design rules when designing parts for SS410 additive manufacturing.
4:20 PM
Reconditioning 304L Stainless Steel Powder through Plasma Spheroidization for Use in the Selective Laser Melting Process: Austin Sutton1; M. Sehhat1; Ming Leu1; Joseph Newkirk1; 1Missouri University of Science & Technology
Selective laser melting (SLM) is an Additive Manufacturing (AM) process that utilizes a laser to consolidate particles in a powder-bed to form near fully dense three-dimensional components in a layer-by-layer fashion. While laser process parameters can be optimized to produce parts of acceptable quality, variations in the powder feedstock can exist causing uncertainty in the properties of components produced by SLM. In this study, plasma spheroidization using a TekSpherio-15 was employed as a method to recondition gas-atomized 304L stainless steel powder. Morphological characterization through measurements of particle size and shape distributions with a scanning electron microscope show very little change in the size distribution, but a drastic improvement in the powder asperity with spheroidization improving its suitability for the SLM process. This work was funded by the Department of Energy's Kansas City National Security Campus which is operated and managed by Honeywell Federal Manufacturing Technologies, LLC under contract number DE-NA0002839.

4:40 PM
Joining of Copper and Stainless Steel 304L Using Direct Metal Deposition: Xinchang Zhang1; Yitao Chen1; Tean Pan1; WenYuan Cui1; Lan Li1; Frank Liou1; 1Missouri University of Science & Technology
In the current study, the feasibility of joining copper (Cu) and stainless steel 304L (SS304L) through direct metal deposition was investigated by material characterization. Samples were analyzed in terms of microstructure, elemental distribution, phase identification, tensile and hardness properties. Direct depositing pure copper on SS304L shows copper was mechanically rather than metallurgical bonded with SS304L due to the poor dissolution of iron in copper. Iron was diffused into copper with a diluted distance of 1.5 mm and above that, pure copper deposits were obtained. Columnar structure was observed at copper region near the interface while the columnar grains became finer away from the interface and finally, equiaxed structure was observed. Tensile testing shows the yield strength of combined samples of copper and SS304L are 123 MPa and 250 MPa and samples fractured at copper section. Hardness measurement shows the hardness of copper is approximately 80 HV.

Materials: Metals XI - Titanium Alloys
Wednesday PM  Room: 417 AB  Location: Hilton Austin
Session Chair: Sneha Prabha Narra, Worcester Polytechnic Institute

1:30 PM
Selective Laser Melting (SLM) of Ti-6Al-2Sn-4Zr-2Mo (Ti6242) Alloy: Parameter Optimization: Haiyang Fan1; Yahui Liu2; Shoufeng Yang1; 1KU Leuven; 2Chongqing University
Ti-6Al-2Sn-4Zr-2Mo (Ti6242) is of interest to aerospace industry for providing superior high-temperature performance to Ti6Al4V. To the best authors’ knowledge, this is the first report on selective laser melting (SLM) of the Ti6242. The relative density of SLMed Ti6242 increased initially and then sharply decreased with increasing scan speeds, achieving a peak density of 99.5%. Meanwhile, the resulting voids gradually transitioned from spherical to irregular shapes, indicating that the pore-forming mechanism was converted from keyhole mode to insufficient fusion. The top-surface roughness showed an increase at both low and high scan speeds, while the minimum 9.4 ± 0.15 μm was obtained at an intermediate speed of 950 mm/s. Instead of a conventional duplex α/β microstructure, the as-built Ti6242 exhibited an acicular microstructure mainly consisted of martensitic a’ phase, regardless of scan speeds. These findings will provide basis for SLM and post processing of Ti6242 to achieve satisfactory performance.

1:50 PM
Investigating the Porosity Formation Mechanism in Electron Beam Melted Hydride-Dehydride (HDH) Ti-6Al-4V via Synchrotron X-ray Microtomography and Dynamic X-ray Radiography (DXR): Ziheng Wu1; Sneha Prabha Narra2; Jack Beuth1; Anthony Rollett1; 1Carnegie Mellon University; 2Worcester Polytechnic Institute
The application of HDH powder can reduce the feedstock cost since most of the commercially available powders for additive manufacturing are gas atomized which is more energy consuming. Prior work successfully uses HDH Ti-6Al-4V powder in powder bed fusion process to produce dense parts via process optimization. However, large cuboidal pores are observed in HDH part when fused with nominal parameters used for standard powders. This study uses synchrotron-based x-ray tomography to visualize the morphology and distribution of pores in 3D, and DXR to in-situ monitor the formation of porosity during fusion. Evidence shows the formation of certain pores links to low packing spots in HDH powder bed due to irregular powder morphology and large size distribution. An image-based Monte Carlo model is developed to investigate the formation of aforementioned porosity. Raw material defects and processing defects, e.g., lack-of-fusion and key-holing, in HDH part are also revealed in this study.

2:10 PM
Fatigue Behavior of LB-PBF Ti-6Al-4V Parts Under Mean Stress and Variable Amplitude Loading Conditions: Patricio Carrion1; Nima Shamsaei1; 1Auburn University
Additively manufactured components are intended for use in load bearing applications, which are often accompanied by fluctuating external loadings. Therefore, understanding the fatigue behavior of AM materials under variable amplitude loadings is necessary for ensuring reliable in-service component performance. This research focuses on the fatigue behavior of Ti-6Al-4V, fabricated via laser beam powder bed fusion process, under mean stress and variable amplitude loadings. Mean stress effects are investigated under strain-controlled constant amplitude loading under fully-reversed, R = -1, and tension-release, R = 0, strain ratios. The generated data is used to compare two mean stress models including Morrow and Smith-Watson-Topper. Variable amplitude loading conditions include fully reversed high-low and low-high loading to investigate load sequence and history effects. Finally, cumulative fatigue damage and life predictions are made using the linear damage accumulation model (i.e., Miner's rule).
Hot-wire laser metal deposition (HWLMD) has the potential of building large scale components with high deposition rates. In HWLMD, filler wire (Ti-6Al-4V wire) is pre-heated by electrical resistance before entering the molten pool. The HWLMD system at Oak Ridge National Laboratory (ORNL) consists of a 20kW fiber delivered diode laser as the primary heat source with secondary resistive heating of the wire using a Miller welding power source, a 6-axis KUKA robotic arm, a wire feeder, an enclosure chamber, and a profilometer. HWLMD offers several potential advantages such as higher deposition rates, improved process stability, lower dilution rates, reduced consumable costs, improved microstructure, and improved mechanical properties. Further, a control system is being developed in-house to increase the efficiency of the technology, and resulting quality of the components. In the present investigation, the effect of hot-wire on the deposition rate, micro-structure, and mechanical properties of Ti-6Al-4V components will be discussed.

The material properties of parts manufactured by the Selective Laser Melting Additive Manufacturing (SLM-AM) process are influenced by many factors, including the characteristics of the metal powders that are used as source material. We are investigating engineered metal platelets produced by a vacuum roll coating process for establishing next generation forms of AM source materials. Platelets are planar particles of uniform geometry and high aspect ratios. Some of potential advantages to vacuum roll coating engineered platelets include precisely controlled morphology (size and shape), increased packing density for the powder bed, ability to manufacture multilayer and/or coated particles, and tailorable material properties including surface textures and chemistries. In this development work, SLM-AM test parts were manufactured from Ti-6Al-4V platelets made via a vacuum roll coating process. The material properties of the finished parts were comprehensively characterized and compared against parts built with traditional Ti-6Al-4V powder.
1:30 PM
Investigation of Effect of Heat Treatment Process on PVDF Additively Manufactured Parts: Niknam Momenzadeh1; Thomas Berfield1; 1University of Louisville
Material extrusion additive manufacturing process utilizing thermoplastic polymers for fabricating 3D structures which are usable in variety of industrial applications. Polyvinylidene fluoride (PVDF) is an electroactive thermoplastic polymer, can be employed to build multi-functional components. The electro-mechanical coupling responses of PVDF can provide benefits in different sensing/actuation purposes. Although 3D-printing parts with this semi-crystalline polymer is challenging due to its inherent properties, filament-based deposition manufactured PVDF parts can be utilized in harsh environment. In this research, an attempt was made in order to find the changes in mechanical and electro-mechanical properties of fabricated samples with different heat treatment processing cycles in terms of time period and temperature. Mechanical behavior of heat treated and non-heat treated samples are evaluated by using the tensile testing machine and digital image correlation system. The crystalline phase and β-phase development of PVDF 3D parts were characterized by taking advantage of XRD and FTIR spectroscopy techniques.

1:50 PM
Investigation of the Processability of Different PEEK Materials in the FDM Process with Regard to Weld Seam Strength: Julian Wächter1; Elmar Moritzer2; 1Paderborn University / DMRC; 2Paderborn University / KTP
Due to the great popularity of the Fused Deposition Modeling (FDM) process, the material market is growing. In particular, processing of high-temperature materials such as PEEK is demanding. The aim of the investigations is to test different PEEK materials regarding their processability in the FDM process. An unreinforced PEEK, a thermally conductive PEEK and a carbon fibre reinforced PEEK are investigated. The processability is assessed with the help of the weld seam strength. The assessment of the weld seam strength is carried out by building tests. For this purpose, a method developed at the DMRC is used. In addition, a welding width factor between the strands deposited on each other is calculated and compared. Finally, a welding factor is determined to enable the comparison between the different materials. With this procedure, the influences of varying nozzle and build chamber temperatures on the achievable weld seam strengths is evaluated.

2:10 PM
Pre-treatment of Fused Deposition Modeling (FDM) Filament for Improved Interfacial Layer Adhesion Using an Atmospheric Pressure Plasma Discharge: Ellen Gupta1; Andres Bujanda1; Jian Yu1; 1Army Research Laboratory
Additive manufacturing (AM) layering methodologies allow full freedom to create any desired novel and complex structure. However, AM, particularly FDM parts, lack the consistency and strength needed for functionality due to poor fusion between interfacial layers. This research explores those connecting layers and how thermoplastic interlaminar strength can be maximized through atmospheric plasma exposure. These plasma treatments are capable of efficiently removing the filament’s surface of volatile organic materials and prepping the material for better adhesion to increase the energy and wettability of the surface layer. For analysis, acrylonitrile butadiene styrene filament was treated and then manufactured to create impact testing specimen to observe the absorbed impact energy of the interlaminar layer. Preliminary tests using derived plasma methodologies have shown promising results with an improvement of interfacial bonding. Thus, multiple materials can be treated to minimize delamination with hybrid AM and allow functionality during high impact operations.

2:30 PM
Exploring the Effects of Elevated Resin Temperatures on Vat Photopolymerization Process Parameters and Part Mechanical Properties: Viswanath Meenakshisundaram1; KTP; Timothy Long2; Christopher Williams3; 1DREAMS Lab, Virginia Tech; 2Macromolecules Innovation Institute, Virginia Tech
High-temperature vat photopolymerization expands the materials catalogue by enabling the processing of photopolymer resins that exhibit viscosities greater than 10 Pa.s or are solids at room temperature. However, operating at elevated temperatures alters the reaction kinetics and the optical properties of the photopolymer. In this work, the authors investigate the effect of temperature on the material’s photo-absorption parameters and the printed parts’ mechanical performance. First, the authors explored the variation in the minimum energy required for photocrosslinking (Ec) and the depth of UV penetration (Dp) with temperature using working curves generated at different resin temperatures. Calibration specimens were then fabricated using printing parameters generated with and without temperature compensated Ec and Dp and the relative change in cure-through between the specimens was evaluated. Test specimens were printed with the resin maintained at elevated and room temperatures and the relative change in hardness and tensile properties was evaluated.

2:50 PM
Break

3:20 PM
Reactive Powder Bed 3D Printing – A New Paradigm in Materials and Scalability?: Kaiyang Wang1; Yinfeng He1; Belen Begines Ruiz2; Ricky Wildman3; Richard Hague4; Christopher Tuck5; 1University of Nottingham; 2University of Seville
We present a new powder-bed based inkjet 3D print method that fuses polymeric particulate feedstock together through selectively triggered polymerization. Powder-bed based inkjet printing techniques have been recognized as a polymeric 3D printing method that can be used for large-scale production. Recent advances through systems such as High-Speed Sintering (HSS) (Xaar 3D and Voxeljet) and Multi Jet Fusion (MJF) from HP, have shown great balance between product quality and production speed compared to other techniques. However, sintering based processes in Powder-bed 3D printing need to overcome traditional issues of powder fusion within the part which occurs due to insufficient polymer chain entanglement formed between particles during the process. In addition, current powder-bed inkjet-based systems continue to require relatively high operating and sintering temperatures which can affect the lifetime of both the printheads and unused polymeric powder in the machine. Here, a polymeric powder fusion method based on reactive inks is described. Once deposited onto the powder bed, the ink(s) polymerize with the powder to form polymer chains that provide connection between particles. An advantage of this kind of in-line polymerization is that it is able to form strong covalent bonding and achieve polymer chain entanglement between particles, which improves the overall performance of the final structure. As a proof of concept, we show the production of polyurethane (PU) particles and components. The PU particles are synthesized locally with the molecular chain capped with -OH to trigger the reaction between the particle and ink. Simple cubic and more complex woodpile structures have been achieved.
3:40 PM
Vat Photopolymerization of Latex: Decoupling Viscosity and Molecular Weight to Enable Additive Manufacturing of Performance Elastomers: Viswanath Meenakshisundaram1; Philip Scott1; Maruti Hegde1; Christopher Kasprzak2; Keyton Feller2; Timothy Long2; Christopher Williams3; 1DREAMS Lab, Virginia Tech; 2Macromolecules Innovation Institute, Virginia Tech; 3Applied Physical Sciences, University of North Carolina at Chapel Hill

High-molecular weight polymer backbones impart exceptional mechanical properties, such as high strain and toughness, to performance elastomers. Vat-photopolymerization of these elastomers could enable manufacturing of complex geometries for application in customized damping, soft-molding and soft-robotics. However, increasing molecular weight increases photopolymer viscosity, making it difficult, if not impossible, for processing via vat-photopolymerization. In this work, the authors present a novel photocurable latex resin to decouple viscosity from molecular weight, therefore enabling the fabrication of previously inaccessible elastomers. First, the authors describe the general photopolymer design framework that allows photo-crosslinking and interpenetration. Then using styrene butadiene as a model system, the authors explore the effect of resin formulation on the process-structure-property relationships. Using irradiance modeling to compensate for scattering, the authors demonstrate fabrication of complex geometries. Fabricated parts exhibit tensile strengths of 9 MPa and elongations > 500% and low plastic deformation, thus exceeding the performance of commercial photocurable elastomers.

4:00 PM
Stereolithography of Highly Elastic Material Using Natural Rubber Latex: Sasitorn Srissawadi1; Panithi Wiroonpocht1; Sittikorn Lapapong1; Sopita Dokkhan1; 1National Metal and Materials Technology Center

Typically, natural rubber (NR) offers a wide range of application possibilities because of its exceptional mechanical properties, particularly elasticity. However, due to its unique mechanism of vulcanization, the illiteracy of 3D fabrication techniques for the NR is still present. The vulcanization of rubber is necessary to form crosslinks between the NR chains and greatly improve its elasticity and tensile strength. In this study, the pre-vulcanized NR latex was prepared for the stereolithography (SLA) process to additively manufacture highly elastic parts. Process parameters were studied to investigate the feasibility of the fabrication process. In particular, the parameters include the laser power, scan speed, and layer thickness. This work originally demonstrates a promising technique of 3D fabrication using the NR latex that yields the mechanical properties comparable to those from the conventional processes.

4:20 PM
Rheological and Cure Behavior of a Dual-cure Thermostat For DIW: Jessica Kopatz1; Leah Appelhans2; Derek Reinholdt2; Adam Cook2; Michael Lanagan3; 1Sandia National Laboratories & Pennsylvania State University; 2Sandia National Laboratories; 3Pennsylvania State University

Direct ink writing (DIW) of thermoset polymers requires the material to possess shear thinning behavior and controlled curing. To enable shear thinning, fillers such as clay or silica are added, where the clay is usually modified to enable better dispersion within the polymer matrix. Dual-cure systems enable the onset of rapid curing, via temperature, UV exposure, etc., to lock the structure in while printing. This research describes the impact of different filler materials and filler surface functionalization on the rheological and cure behavior of a UV/thermal epoxy-acrylate dual-cure system while also studying the effect on printability via DIW.

4:40 PM
Mylar Capacitor Edge Margin Reduction Using Robust Dielectric: Ste-ven Kayser1; Judith Lavin1; Alex Robinson1; 1Sandia National Laboratories

Mylar capacitors are inherently large due to the edge margin associated with ensuring electrodes are insulated. Typical methods use a winding system such as a reel winder to wind the Mylar and electrode material together on a core. By using a similar method but incorporating a Mirwec Reel-to-Reel Microgravure coater to coat the edge of the Mylar with a dielectric material prior to the winding of the capacitor, the size of the edge margin could be reduced. This presentation will explore the selection of dielectric materials, the coating process, issues associated with process, and experimental results. SNL is managed and operated by NTiESS under DOE NNSA contract DE-NA0003525

Modeling II - Structure-based Processing

Wednesday PM
August 14, 2019
Room: Salon A
Location: Hilton Austin

Session Chair: Olaf Diegel, University of Auckland

1:10 PM
A Standardized Framework for Communicating and Modelling Parametrically Defined Mesostructure Patterns: Glen Williams1; Adnen Mezghani2; Matthew Eachus1; John O’Brien1; Christopher McComb3; Nicholas Meisel4; 1Pennsylvania State University

Intricate mesostructures in additive manufacturing (AM) designs can offer enhanced strength-to-weight performance. Although complex mesostructure patterns can offer benefits, they can also hinder designers, often resulting in unpalatably large digital files that are difficult to modify. Similarly, existing methods for defining and communicating complex mesostructures are highly variable, which further increases the challenge in realizing such structures for AM. To address these gaps, we propose a standardized framework for designing and communicating mesostructured components tailored to AM. Our method uses a parametric language to describe complex patterns, defined by a combination of macrostructural, mesostructural, and vector field information. We show how various mesostructures, ranging from simple rectilinear patterns to complex, vector field-driven cellular cutouts can be represented using few parameters (unit cell dimensions, orientation, and spacing). Our proposed framework has the potential to significantly reduce file size, while its extensible nature enables it to be expanded in the future.

1:30 PM
A Universal Material Template for Multiscale Design and Modeling of Additive Manufacturing Processes: Yunlong Tang1; Yi Xiong2; David Rosen3; 1Singapore University of Technology and Design

In this paper, a universal material template is developed to digitally describe the materials with spatially distributed compositions and microstructures for multiscale design and modeling of additive manufacturing processes. The developed template is organized in the form of a multi-level hierarchical structure. On the first level, the root node is defined. It contains the material’s name and other related information. Under the root node, material constituents and their associated properties are defined on the second level of this template. To describe the shape and distribution of each constituent, parametrically driven geometric primitives are defined on the third level. These primitives can be further divided into the sub-primitives from the lower levels if necessary. To validate the effectiveness of the proposed template, the microstructures of several different types of commonly used materials in additive manufacturing processes are reconstructed from the pre-defined material templates.
Stress and Deformation Evaluation of Novel Toolpath in Powder Bed Fusion Process: Xinyi Xiao; Sanjay Joshi; Hanbin Xiao; Penn State; Wuhan University of Technology

In Powder bed fusion (PBF) processes, powder is melted by a laser beam to form a 2D geometry further print parts in a layer-by-layer mode to build up a 3D component for additive manufacturing (AM). The toolpath and build orientation significantly impact the porosity, dimensional accuracy, and mechanical properties of the parts. This process accompanies with non-uniform heating and cooling can lead to high residual stress zone which further creates distortion. The altering of the toolpath can influence on the centralized heating area that reduces the residual stress. In this study, a 3D finite element method (FEM) model is developed coupled with volumetric moving Gaussian heat source as well as the five traditional toolpath and a novel toolpath to study the thermomechanical process of PBF. The proposed toolpath generates less residual stress and distortion per layer than the traditional toolpath.

Simulation of Path Strategies and Analysis of Residual Stress and Deformation in Wire and Arc Additive Manufacturing: Runsheng Li; Haiou Zhang; Xushan Zhao; Guilan Wang; Huazhong University of Science and Technology

Wire and arc additive manufacturing (WAAM) is an additive manufacturing technology with high production efficiency and low cost, which has been widely applied to produce large scale metal parts. In this study, a simulation methodology of element birth and death between layers is developed to simulate the thermal and residual stress fields of part with cross features by arranging monitory points on such features. Residual stress and deformation of the monitory points and of the whole part are found to be different via different path patterns. The simulation results showed that symmetry strategy is adopted to minimize the residual stress of part and warping of substrate when the heat source path is dispersed.
Theory

they are good predictors for microstructural evolution within an additively and materials. We compare these results to experiments and show that and temperature gradients across an array of processing conditions predict temperature fields at any given point during the scanning process, loads. We have created a semi-analytical model that is able to rapidly predict temperature fields and solidification metrics such as cooling rate and temperature gradients across an array of processing conditions and materials. We compare these results to experiments and show that they are good predictors for microstructural evolution within an additively produced specimen.

2:30 PM

Prediction of Mechanical Properties of Fused Deposition Modeling Made Parts Using Multiscale Modeling and Classical Lamine Theory: Aslan Nasirov1; Seymur Hasanov1; Ismail Fidan1; 1Tennessee Technological University

Fused deposition modeling (FDM) is one of the most popular additive manufacturing (AM) processes that works based on the layer-by-layer buildup of a 3D modeled part from plastic or fiber-reinforced plastic materials. In recent years, extensive research has been done to characterize the mechanical properties of FDM produced parts using classical laminate theory (CLT). However, considering the limitation of micromechanics approach to simple unit cells, there is a need to explore different techniques to alleviate those limitations. Taking into account the periodicity and multiscale nature of FDM infill patterns, one such technique is the asymptotic homogenization method used in this study to find mechanical properties. In order to check the validity of this technique, mechanical properties are found experimentally, then CLT is applied to characterize mechanical behavior and compared with theoretical results.

2:50 PM Break

2:30 PM

Numerical Modeling and Evaluation of Material Jetting-based Additive Manufacturing: Chad Hume1; David Rosen1; 1Georgia Institute of Technology

Material jetting-based additive manufacturing is a promising manufacturing approach with increasing interest in mesoscale applications such as microfluidics, membranes, and microelectronics. At these size scales, droplet size, deposition pattern, and flow induced edge deformation are critical factors governing minimum resolvable feature size. Previously, a quasi-static boundary-based method was demonstrated as a low cost and accurate means of predicting the line-by-line, layer-by-layer feature development enabling simulation of feature fabrication in minutes as opposed to hours or days when using traditional high fidelity approaches. The present work leverages this approach to understand the effects of varying printing parameters on predicted feature resolution. Simulation results are benchmarked with physical test specimens. An improved understanding will enable future process development as well as control schemes.

3:40 PM

Study on the Numerical Simulation of Laying Powder for Selective Laser Melting Process: Liu Cao1; 1Guangzhou University

Based on the discrete element method theoretical model and SLM laying powder process, the numerical simulation of SLM laying powder process was carried out. For the performance measurement experiment of TC4 titanium alloy powder, the powder bulk density, tap density and angle of repose were calculated and analyzed. It was found that the tap density increased by 7.5% compared to the bulk density, and the calculated average angle of repose (32.6°) was in good agreement with the experimental data (33.2°), thus verifying the accuracy of the calculation model used for SLM laying powder. The influences of different scraping methods and scraping speeds on the quality of laying powder were calculated and analyzed. It was found that the scraping method using the roller (not rotating) obtained the highest thickness and uniform powder distribution, and as the scraping speed increased, the laying tightness tended to decrease linearly.

4:00 PM

Simulating Powder Spreadability in the Selective Laser Melting Process Using the Discrete Element Method: Austin Sutton1; Ming Leu2; Joseph Newkirk3; 1Missouri University of Science & Technology

Selective laser melting (SLM) belongs to a subset of Additive Manufacturing (AM) processes commonly referred to as powder-bed fusion where three-dimensional components are created by successive melting of powder particles in a layer-by-layer fashion. In addition to optimizing laser parameters for production of high-density parts, a critical component of SLM is the recoating process where achieving dense layers of powder is a necessity for good part quality. While the recoating process can be studied through experimentation, the dynamics of particle movement can be difficult to analyze experimentally. Therefore, in this study, powder spreading in the SLM process was simulated through the Discrete Element Method (DEM) with emphasis on the effects of particle size distribution and interparticle friction on powder spreadability. This work was funded by the Department of Energy’s Kansas City National Security Campus which is operated and managed by Honeywell Federal Manufacturing Technologies, LLC under contract number DE-NA0002839.

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Phase-field Simulation of Solidification Morphology in Laser Powder Deposition of Ni-based Binary Alloys: Xueqin Huang1; 1Texas A&M University

The understanding of Ni-based binary alloys is essential for studying Additive Manufacturing in materials design. Considering the alloys Ni-Cu, Ni-Nb and, Ni-Al, the simulation shows that the micro segregation rises as the freezing zone range increases, indicating that the solute is trapped in the solid phase. Furthermore, the cellular structure is more apparent in the materials with a larger freezing zone. The microstructure is finer due to higher cooling rates and solidification speeds. The simulations use COMSOL, a thermal model numerical solver platform, to calculate two thermal parameters, temperature gradient and solidification speed, that are used as inputs in the finite interface dissipation Phase-field model. The simulation is implemented with GPU hardware for rapid computation, and in three-dimensions to observe the cellular and columnar structures from multiple angles.
112 2019 Annual International Solid Freeform Fabrication Symposium

TECHNICAL PROGRAM

Process Development IX - Innovative Methods and Processes
Wednesday PM  Room: 408  August 14, 2019  Location: Hilton Austin
Session Chair: Phill Dickens, University of Nottingham

1:10 PM  Additive and Subtractive Electrohydrodynamic Jet Printing Behavior of Polymers for Patterning Area-selective ALD: Nazanin Farjam1; Christopher Pannier1; Tae Cho1; Neil Dasgupta1; Kira Barton1, 1The University of Michigan
Electrohydrodynamic jet printing(e-jet) is a novel micro/nano additive-manufacturing technology that has received attention due to its wide range of applications. Combining e-jet with atomic layer deposition(ALD) [Dasgupta et al. Chem. Mater. 28, 1943 (2016)] could enable customizable nanomanufacturing of integrated systems, due to their unparalleled spatial resolution and their ability to deposit a variety of functional materials. E-jet printed layers can act as functional or structural components of an integrated system. Importantly, these layers can also be used to pattern surface chemistry to activate or passivate local regions for nucleation of inorganic layers by ALD. This capability enables the patterning of ALD growth without the need for lithography. We investigate the behavior of different polymers by positive and negative e-jet printing at different resolutions for the first time, through atomic force microscopy measurements. Auger electron spectroscopy is performed to demonstrate the growth or inhibition of area-selective ALD on the e-jet printed patterns.

1:30 PM  3D Printing of Metals with Xenon Flash Lamp: Krzysztof Nauka1; Lihua Zhao1; 1HP Inc
High power Xenon flash can produce intense irradiation of the metal powders causing their rapid heating, sintering, and even melting. Present experiments employed commercial Xenon lamp capable of producing irradiation pulses with energy up to 60 – 80 J/cm2 per pulse with pulses lasting up to few tens of milliseconds. Custom mirror surrounding the lamp provided uniform irradiation over powder’s area of about 140 cm2. Powder sintering and melting under a single pulse irradiation was demonstrated for a variety of commercial metal powders, including Al, Cu, Ni, Hastelloy, stainless steel, Ti, and Cr. Tuning of the pulse shape and energy, and application of multiple pulses allowed to overcome difficulties related to a very high surface energy of molten metal particles and provided layers with density exceeding 98% of the solid metal. Advantages and challenges of this 3D printing process will be discussed.

1:50 PM  Laser Cooking: A Novel Processing Technique for Food Layered Manufacture: Jonathan Blutinger1; Yoran Meijers1; Gabriel Seymour1; Alissa Tsai1; Erika Storvick1; Hod Lipson1; 1Columbia University
Additive manufacturing of food has great potential but in its current state, it lacks the ability to create fully cooked printed food products. While food printers have the ability to create tailored nutritious meals, precision cooking appliances to selectively cook printed food layers do not yet exist. This has driven our exploration of laser cooking, a novel software-controlled heating technology that targets heat from lasers—via mirror galvanometers—to cook thin-layered foods. By varying laser parameters such as power, speed, cooking pattern, and utilizing feedback from an infrared camera, we aim to characterize proper laser cooking conditions for various types of meat and dough products. We investigate the use of a blue laser (445 nm) and a CO2 infrared laser (10.6 μm) to cook food products. Laser cooking is poised to augment conventional cooking methods and food printing technology and transform the way we cook and think about food production.

2:10 PM  Parallelizing Energy Deposition for Powder Bed Additive Manufacturing via a 2D-Laser Array: Athanasios Illiopoulou1; John Michopoulos1; John Steuben2; Benjamint Graber3; Andrew Birnbaum1; 1US. Naval Research Laboratory
Some of the main factors limiting the widespread adoption of powder bed additive manufacturing (AM) include non-linear size scalability, low throughput and high costs. To address all of these issues simultaneously, a low-cost laser array powder bed AM system was prototyped and provisionally tested. The combined parallel-serial nature of heat deposition in this system required a new build planning paradigm to calculate the proper scheduling of laser elements activation. A description of the hardware system design and its main operational characteristics will be presented followed by an overview of the slicing/laser sequencing system based on space-tiling subdomains. Initial tests using polymer powders will be presented to demonstrate the functionality of the prototype system. The conclusion will discuss the future work required to generalize the laser array system, and enable its use with broader classes of materials such as metals and ceramics.

2:30 PM  Electroforming Process to Additively Manufactured Microscale Structures: Bishal Silwal1; Amelia McNamee1; Krish Patel1; 1Georgia Southern University
Electroforming is a metal forming process that forms parts through electrodeposition. The overall study and production of the copper mandrel was conducted by examining the growth and depth of the depositions at microscopic levels. The study of the plating constant for copper plate in Copper Sulfate was performed via production of copper mandrels. Each mandrel was produced by performing multiple experiments and qualitatively and quantitatively examining the resultant depositions and the initial and final states of the experiment. The results were measured based off variations of current, voltage, and velocity distribution in the bath cycle, time duration, solution concentration, and change in mass of both the anode and cathode. The variables such as plating constant and direct current distribution are determined. It seems the rate at which the structure can be fabricated depends on the type of electrolytes used and the parts that are deposited can be scalable.

2:50 PM  Break

3:20 PM  Design Paradigms for Vibration-enabled Support Structure Removal: Joni Mici1; Jonathan Harris1; Duann Scott1; Ryan O’Hara3; Bradley Rothenberg1; 1Columbia University; 3nTopology Inc
Support structure removal introduces post processing labor and considerable design limitations on the geometry of additively-manufactured parts. In the present work, we optimize the dynamic properties and print orientation of support structures to break off when forced at natural frequencies that are sufficiently different from those of the model. The designs presented in this work are applicable to a wide variety of geometries, and additive manufacturing processes. Sample parts with support structures were designed and analyzed using lattice generation design tools, and manufactured on Powder Bed Fusion printers. Samples were tested on an electrodynamic shaker capable of a high range of forcing frequencies. The resulting design paradigms and limitations of this work are discussed based on the as-tested parts.
Selective Laser Flash Sintering of Aluminum Nitride

SLFS to demonstrate the ability to sinter only specified regions at a time, while simultaneously applying a DC electric field. We have already demonstrated SLFS on 8% yttria-stabilized zirconia. Here we utilize SLFS to demonstrate the ability to sinter aluminum nitride. We show that at moderate to high combinations of laser flux and field strengths, current flows through the sample. The presence of current is indicative of neck formation. We will present the effects of electric field strength, laser repetitions, laser power, and laser scan speed, and the varying effects on current measured.

In-Process UV-Curing of Pasty Ceramic Composite: Stefan Mischlowski; Matthias Weigold

Within the recent years a wide range of additive manufacturing processes have been developed. While powder bed based fusion processes like selective laser melting and melting processes like fused layer modeling are increasingly used in industrial applications and prototyping other processes are in an initial stage. In this paper a new method for an extrusion-based process of pasty uv-curing ceramic composite material is developed. The method proposes an approach to continuously cure the material while it is deposited to reduce process time and to generate complete cured parts. A milling machine has been modified with a syringe and a uv-light source to accommodate the process. Experimental studies have been carried out to examine the influence of the process parameters on melt-pool size variation. Experiments are then performed on a custom-controlled LPBF testbed to verify the optimal control parameters determined from the FE simulations, and comparing melt pool size through in-situ melt-pool monitoring, in combination with post-process part quality measurements.

Effect of Sensitization and Etching Parameters to Selectively Dissolve Support Structures from PBF-processed Metal Components: Penglei Yang; Avinash Maridanna; Subbarao Raikar; Owen Hildreth

For metal additive manufacturing (AM), supports are an inconvenient necessity. This presentation details a simple and novel technique to selectively dissolve supports in metal components fabricated using Powder Bed Fusion technologies. This technology requires no changes to build settings or component design and integrates seamlessly into existing build processes. Additionally, it enables facile removal of internal and external supports; reduces surface roughness for both internal and external surfaces (= 4 μm); reduces post-processing time and costs; can process entire build platforms at once; and expands design freedoms. This presentation will detail the process itself and provide demonstrations of its ability to remove supports from complex geometry. Characterization tools such as contact profilometer, optical microscope, and SEM will be used to understand how sensitization and etching parameters impact surface roughness and mechanical performance of processed components.
Powder Bed Fusion (PBF) is a type of Additive Manufacturing (AM) technology that builds parts in a layer-by-layer fashion out of a metal powder bed via the selective melting action of a laser or electron beam heat source. Despite its rapid adoption, part temperature regulation in PBF is largely open loop, designed primary by heuristic methods. This paper uses linear systems theory to investigate two fundamental control properties of PBF: controllability and observability, which are metrics that determine if all the target dynamics (temperatures in PBF) can be controlled in a process. The main result is that PBF is stabilizable, detectable, and structurally controllable (observable) provided that any portion of the build is exposed to the heat source and thermal camera measurement. These properties are shown to hold in both time-invariant and time-varying models. The guarantee of controllability and observability provides a path for multivariable process temperature estimation and control.

Evaluation of a Feed-forward Laser Control Approach for Improving Consistency in Selective Laser Sintering: Timothy Phillips; Scott Fish; Joseph Beaman; University of Texas Austin

Selective Laser Sintering (SLS) is a popular industrial additive manufacturing technique for creating functional polymer components. One of the biggest limitations today with SLS is its poor mechanical consistency when compared with traditional manufacturing techniques, inhibiting the use of SLS among structurally critical components. Evaluation of the SLS process has revealed that the quality of components is strongly affected by the thermal history during the build process and poor control over this can lead to premature part failure. This paper will discuss a novel technique of improving in-situ thermal control by implementing a feed-forward laser controller that uses dynamic surrogate modeling to predict optimal laser power to achieve desired thermal characteristics. Thermal and destructive testing results will be presented showing that the described laser power controller is capable of decreasing the standard deviations of post sintering temperature by up to 57% and ultimate flexural strength by up to 45%.

Theory on the Continuation of Melting Processes as Basic Requirement for Robust Processing Conditions in Laser Sintering of Polymers: Andreas Wegner; University of Duisburg

Additive manufacturing techniques and especially the laser sintering of plastics win more and more importance as a series production technique. However, several unsolved problems still exist. One is the insufficient understanding of the decisive process step: the melting of the powder caused by the laser energy input. The article picks up this central problem and generates a profound understanding of the process. The laser-powder interaction is characterised by using high-speed thermal imaging. Therefore, the decisive temperature-time profiles during the melting of the powder are initially measured depending on the energy input. Fundamental correlations between process parameters and measured melt temperatures were established based on these measurements. In addition to that, a significant correlation between the measured temperature profile and the part quality was confirmed in this context. This ascertained fundamental knowledge is summarized to a new process theory named “Theory on the Continuation of Melting Processes in Laser Sintering”.

Towards the Real-time Control - A Meltpool Prediction Based Scan Strategy: Ho Yeung; Zhuo Yang; Lu Yan; National Institute of Standards and Technology

In this study a feedforward control method for laser powder bed fusion (LPBF) AM process is demonstrated, it minimizes the meltpool variation based on a predictive model developed. The model utilizes a deep-learning based melt pool classification method to generate fast and accurate melt pool size prediction from the scan path. A small rectangular part are built twice on a customized LPBF testbed. The meltpool is in-situ monitored by a high-speed camera optically aligned with the heating laser. A typical ‘hatch’ pattern constant laser power and speed scan strategy is applied for the first built, its meltpool images are used to train the model and process the scan strategy for the second build. The meltpool images from both builds are compared, significant reduction in meltpool variation is found. The classifier, based on convolutional neural network, once trained can process layer-wise scan commands within seconds. This makes the real-time implementation possible.

A Machine-agnostic Feedforward Controller for Commercial Powder Bed Fusion Systems: Christopher Stutzman; Abdalla Nassar; Jeffrey Irwin; Qian Wang; Panagiotis Michaleris; David Corbin; The Pennsylvania State Department of Engineering Science and Mechanics; The Pennsylvania State University Applied Research Laboratory; The Pennsylvania State University Department of Mechanical Engineering; Autodesk

Powder bed fusion additive manufacturing (PBFAM) is a rapidly evolving field in which complex components can be constructed directly from digital models. However, complex component geometries coupled with complex laser-material interactions may result in significant deviations in mechanical properties and dimensional accuracy of the component. Numerical and analytical models of the process are thus invaluable predictive tools that may be leveraged for feedforward control. While feedforward control has been demonstrated on small, lab-built machines, there have been few proposed and demonstrated frameworks for feedforward control on commercial PBFAM systems. In this presentation we demonstrate a feedforward controller that is not limited to lab-built systems, and is capable of interfacing with commercial machines. This controller is demonstrated on an EOS M280 machine where single-track deposits were controlled by both numerical and reduced-order analytic models.

Spatially Resolved Particle Size Distribution and Morphological Characterization of Powder Ejecta Created by the Laser Powder Bed Fusion Process: Thien Phan; Justin Whiting; Vinip Tondare; Alkan Donmez; National Institute of Standards and Technology

For laser powder bed fusion (LPBF), powder feedstock characteristics such as particle size distribution (PSD), morphology, porosity, and chemistry can influence powder thermal properties, spreadability, and ultimately the mechanical properties of the final parts. After the build process, it is common that non-solidified powder is sieved and mixed with virgin powder for further reuse/recycle. This can result in re-used/recycled powder with characteristics different from virgin powder. Here, a custom enclosure with removable walls and floor was used to collect the spatially-resolved powder ejecta generated during the laser melting process. SEM imaging is then used to characterize the location, size, and morphology of the captured powder ejecta. The result of the ejecta PSD, morphology, and location distribution will be presented and compared with the starting feedstock.
A new prototype for in-situ monitoring of defects and in-situ and in-line flaw removal has been developed and patented. This prototype allows one to identify a defective layer thanks to an innovative in-situ monitoring approach that combines image and video-image data in the visible and infrared ranges. When the alarm is issued, the layer containing the defect is removed in-situ and in-line, thanks to a novel self-repairing system acting as a grinder on the powder bed. After this removal step, the following layers are additively produced starting from the healed height. By comparing specimens obtained with and without the intermediate layer removal, we will show that no change in porosity and in mechanical performances is introduced by this intermediate removal step. This solution paves the way to zero-defect additive manufacturing.

Process Development XI - Deposition B

Wednesday PM
Room: 616 AB
August 14, 2019
Location: Hilton Austin

Session Chair: Luis Folgar, AMT Inc.

1:10 PM
Electrophotographic Multi-layer Powder Pattern Deposition for Additive Manufacturing: Thomas Stichel; Bayerisches Laserzentrum GmbH

In this paper, the use of electrophotographic polymer powder transfer for the preparation of multi-material layers is discussed with respect to the application in powder bed-based additive manufacturing technologies as selective laser sintering (SLS). Therefore, an experimental setup with a two-chamber design was realized which enables the investigation of the electrophotographic powder transfer at typical process conditions of SLS. Using this setup, the electrophotographic powder transfer of typical SLS powders was demonstrated. The quality of the powder transfer was valued by optical analysis and it could be shown how the system parameters influence the transfer results. Moreover, a new strategy was invented which allows the residual electrophotographic powder deposition in general, which is independent from the already produced part height. This is known to be a huge challenge but is mandatory for the buildup of three-dimensional multi-material components.

1:30 PM
Using Non-gravity Aligned Welding in Large Scale Additive Metals Manufacturing for Building Complex Parts: Joshua Penney; William Hamel; University of Tennessee

One of the most difficult aspects of printing large, complex metal parts is building large overhangs without the use of support structures. When using typical gas metal arc welding techniques, the torch is kept aligned to build in progress. After this removal step, the following layers are additively produced starting from the healed height. By comparing specimens obtained with and without the intermediate layer removal, we will show that no change in porosity and in mechanical performances is introduced by this intermediate removal step. This solution paves the way to zero-defect additive manufacturing.

1:50 PM
Industrializing the Robotized Laser Wire-feed Metal Additive Manufacturing (LWMAM) From 3-D Model to NNS Component: Yaoyu Ding; Scott Woida; Timothy Haag; Midwest Engineered System

Laser Wire-Feed Metal Additive Manufacturing (LWMAM) is a promising additive technology that is well suited for building large sized near-net-shape components. This technology lends itself to any metal commercially available in welding wire and provides extremely high deposition rates and efficient material usage. LWMAM is finding applications in diverse industrial sectors such as aerospace, automotive, and rapid prototype tooling. Several challenges have been identified that have inhibited this technology from being transformed into a commercially available industrialized process. These challenges include lack of robust real-time process sensing and control, effective management of heat induced geometric distortion, and off-the-shelf slicing and process control software. ADDere, a division of Midwest Engineered Systems has developed an 8-axis robotized LWMAM system that addresses these challenges resulting in a commercially available industrialized system. This paper details the system hardware and software. Several parts have been built to demonstrate the capabilities of the ADDere system.

2:10 PM
Active Cooling of Direct Energy Deposition: Jennifer Bennett; Kornel Ehmann; Jian Cao; Northwestern University

The thermal history generated by the additive manufacturing process determines the resulting part microstructure and material properties. Thermal control of the process is necessary to achieve constant microstructure and material properties in the final part. State of the art solutions prescribe a methodology for changing one or more of the processing parameters to account for changing melt pool temperature or size. However, even with a system that effectively maintains melt pool temperature and/or size, part quality is not ensured. This solution does not compensate for changing thermal gradients or cooling rates within the rest of the build. As a result, although melt cool control can improve build quality, it is only a partial solution toward achieving uniform microstructure and optimizing mechanical properties. This work establishes a mechanism and methodology for active cooling to bound the thermal gradient and cooling rate within the additively manufactured build in progress.

2:30 PM
Thermal Process Monitoring for Wire-arc Additive Manufacturing using IR Cameras: William Carter; Christopher Masuo; Andrzej Nycz; Mark Noakes; Derek Vaughan; Abigail Barnes; Oak Ridge National Laboratory

Wire-arc additive manufacturing systems use robotic MIG welders to build parts using welding wire. As more layers are added to a part, heat is stored and the temperature rises as energy is input and thermal mass increases. While some pre-heat is ideal for welding, improper thermal management can lead to defects and negatively affect material properties. Thermal imaging allows for non-contact thermal monitoring and can be used to track thermal gradients as well as layer temperatures before and after deposition providing a method to ensure proper thermal management. A typical IR camera setup on an mBAAM system will be presented along with methods to use thermal monitoring to improve material properties and reduce defects in the final part.
2:50 PM  Break

3:20 PM
The Effects of Gravity on Laser Wire Out of Position Deposition for Additive Manufacturing: Shariq Akhtar; "Cranfield University
To study the effects of gravity using Laser Wire Deposition, it is necessary to understand the process parameters, which influence the quality and shape of deposition in out of position welding. In this research, the titanium alloy Ti6Al4V substrate and 0.9 microns wire is used. The disposition will be carried out in two positions (horizontal and over the head) with different deposition rate and heat source. The shape of the melt pool, the appearance of the layer, the strength will be evaluated. The experiments will be conducted using high power (2500W) and low power (500W) laser heat source. The results will help us create effective process parameters for microgravity 3D printing and development of sophisticated numerical models for further testing and enchantments.

3:40 PM
Multi-material Direct Energy Deposition for Custom Alloy Compositions: Shaun Whetten; Raymond Puckett; Dylan Casey; Andrew Kustas; "Sandia National Laboratories
Laser Engineered Net Shaping (LENS) is a 3D printing platform that enables controlled placement of multiple materials during the printing processes. The LENS 3D printer at Sandia National Laboratories has recently been upgraded to a 5-powder feeder system expanding the number of options the user has available in creating a multi material AM part. Experimentalists can also use this system to control the flow of multiple powder feeders simultaneously which enables the in-situ mixing of custom alloy compositions during the deposition. This talk will go over work that characterizes the powder feed system and show how this system can be used to control the alloy composition of 3D printed parts. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

4:00 PM
Melt Pool Measures and Effective Sensor Bandwidth for Direct Energy Deposition: Douglas Bristow; "Missouri University of Science and Technology
Direct energy deposition processes are increasingly using thermal camera measurements of the melt pool in feedback control. Often these control schemes adjust laser power in order to maintain better consistency of the melt pool size. The first step in such a scheme is to process the thermal image to reduce the 2D thermal profile into a scalar measurement of melt pool size. Many measures for melt pool size have been proposed in the literature including width, length, area, as well as fitted geometries. An unexplored aspect of these measures is their effect on measurement time constant, determining how quickly the transition of the 2D melt pool from one state to another can be detected. This paper will use the Rosenthal solution as a baseline for determining analytical relationships between various measures and their dynamic bandwidth. Experiments on a laser wire direct energy deposition system will be presented for validation.

4:20 PM
Industrialization of Laser Wire Directed Energy Deposition for Large Ti 6-4 Aerospace Components: Chad Henry; "GKN Aerospace
Hardware, monitoring, and controls are being researched and developed at GKN Aerospace to mature the laser wire DED process for certification and qualification for flight worthy components. The maturation plan (past, present, and future) will be discussed, including details on the process control algorithms and the corresponding monitoring required to do so. Component thermal history will be discussed as: - 1) a method to control and target resulting material properties, and - 2) a key requirement for certification and qualification.
3D Printed Production Fixtures for the Automotive Electronic Manufacturing Industry: Quinatzin Hidalgo1; Amit Lopes3; 1The University of Texas at El Paso

Current innovations in the automotive industry are driving the market to launch projects in compressed time and to adopt new manufacturing techniques such as additive manufacturing. The purpose of this work is to evaluate an additive manufacturing method to manufacture production fixtures to aid the assembly of electronic boards into plastic or metallic cases, a typical process utilized in the automotive manufacturing industry. The main focus is to minimize the time required to implement a fixture and assess the differences in cost, fabrication time, recommended materials and expected durability of production intent fixtures built with additive manufacturing vs traditional subtractive methods. This study shows that by using additive manufacturing the overall implementation time is dramatically reduced, though additional effort is required for the fixture design phase and tools such as finite element analysis shall be used in order to maximize expected fixture durability for the industrial manufacturing environment.

A Novel Method of 3D Reconstruction for Additive Manufacturing: Shangyong Tang1; Guilan Wang3; Cheng Huang1; Haiou Zhang2; 1Huazhong University of Science and Technology

The 3D modeling data of the formed parts in metal additive manufacturing is of great significance to better understand the part size, deformation, morphology features and subsequent strategy. Meanwhile, the accuracy and efficiency of 3D modeling should be concerned to satisfy the stability, efficiency and continuity in additive manufacturing. This paper presents a method of efficient 3D reconstruction method based on six-axis robot and laser-based 3D measurement sensor. The measuring theory, reconstruction process, and demarcation method about parameters of the system were introduced. With the combination of data pre-splicing based on robot coordinates and high-precision splicing based on iterative closest points method, the kinematic error of robot and efficiency problem of iterative closest points method were restrained. Experiments were designed to verified the feasibility and stability of the system and the results indicate that an efficient 3D modeling process with an accuracy of 0.1mm was realized without auxiliary identification point.

A Passive On-line Defect Detection Method for Wire and Arc Additive Manufacturing Based on Infrared Thermal Imager: Haiou Zhang1; Xi Chen1; Jiannan Hu1; Yu Xiao1; Guilan Wang3; 1Huazhong University of Science and Technology

According to the additive manufacturing process, this paper proposes a passive infrared thermography non-destructive testing method. The temperature field of the arc-melting layer is collected in real time, and the multi-frame temperature data stream is stacked for maximum value, and the region where the maximum value is greater than 800 °C is intercepted to obtain the current molten layer profile. The neural network is used to classify and identify the contour images of the molten layers, such as normal, offset, flowing and hump, determine the current forming quality of the molten layer, and the processing such as milling and repair welding will be taken in time. This method avoids detection of waste products after processing which will cause irreversible losses, and the current layer detection information is also used as the basis for adjusting the processing parameters of the next layer and realizes the closed-loop feedback of the additive manufacturing process.

An Experimental Study on Selective Laser Melting of Tungsten: Effects of Substrate Material and Process Parameters: Jianchi Huang1; 1Texas A&M University

Experiments were conducted to investigate the effects of substrate material and process parameters on the print quality of pure tungsten using selective laser melting process. Tungsten and stainless steel substrates were evaluated to achieve good adhesion between the printed layers and the substrate. The stainless steel substrate was recommended. In a full-factorial design of experiment, the effects of hatch distance and point distance on the bulk density, open porosity, closed porosity, and melt pool size of the printed specimens were studied. A hatch distance of 75 μm and a point distance of 100 μm were recommended to achieve a relatively high bulk density with a small number of pores. The results led to the selection of an optimized process condition to obtain good print quality. The research also led to the development of more comprehensive print quality assessment criteria, including not only the relative bulk density but also pores.

Applications of Supervised Machine Learning Algorithms in Additive Manufacturing: A Review: Mugdha Joshi1; Aaron Flood1; Todd Sparks2; FueWen Liu2; 1Missouri University of Science and Technology; 2Product Innovation and Engineering LLC

Additive Manufacturing (AM) simplifies the fabrication of complex geometries. Its scope has rapidly expanded from fabrication of pre-production visualization models to the manufacturing of end use parts driving the need for better part quality assurance in the additively manufactured parts. Machine learning (ML) can be used to achieve this goal. Current research in this field includes the use of supervised and unsupervised ML algorithms for quality control and prediction of mechanical properties of AM parts. This paper explores the applications of supervised learning algorithms - Support Vector Machines and Random Forests. Support vector machines provides high accuracy in classifying the data and is used to decide whether the final parts have the desired properties. Random Forests consist of an ensemble of decision trees capable of both classification and regression. This paper reviews the implementation of both algorithms and analyzes the research carried out on their applications in AM.

Atom Probe Tomography Study of Second-phase Precipitates in Wire-arc Additive Manufactured Nickel Aluminum Bronze: Dharmendra Chalasani1; K Gururaj2; K.G. Pradeep3; Mohsen Mohammadi2; 1Marine Additive Manufacturing Centre of Excellence; 2Indian Institute of Technology Madras

In this work, wire-arc additive manufacturing (WAAM) was used to deposit NAB wire in the form of square bars (160 mm height, 25 mm side) on austenitic stainless steel plate of 10 mm thick. The microstructural evolution and phase transformation along the building direction was characterized with X-ray diffraction (XRD), electron backscatter diffraction (EBSD), transmission electron microscopy (TEM), and atom probe tomography (APT). The formation of κ was suppressed in WAAM-NAB. κ', (Fe3Al) and κ' (NiAl) phases were formed in the interdendritic regions whereas fine Fe-rich κ' particles were distributed uniformly within the Cu-matrix. APT studies provided significant insights into the microstructure at near-atomic scale enabling in the understanding of variations in phase formation, precipitate evolution at the bottom, middle, and top segments of the bar, specifically in terms of precipitate size, morphology, and their volume fraction.
Binder Jetting 3D Printer: Wenchao Du1; Guanxiong Miao; Texas A&M University
A modular ceramic binder jetting 3D printer was created from scratch for advanced biomedical and aerospace applications. The primary objective is to increase the mechanical properties of a final part by maximizing powder bed packing density. To accomplish this, we set primary criteria as effective powder spreading, powder bed temperature control, and isolation of the printing environment from outside. Our secondary objectives consist of increasing printing resolution, improving both software and firmware, and obtaining a scalable print volume while keeping the printer open-source, affordable, and user-friendly. Some updates regarding the original design were made to solve the issues during assembling. Belt tensioners were re-designed for a robust connection. A full enclosure was created for a closed printing environment. Future modifications and improvements include re-coding the slicing software and Marlin firmware, adding bed heating resistors, and creating a replacement boost-demultiplexing circuit board for an ungraded jetting cartridge. Moreover, the scalable print volume will simultaneously allow large part dimensions and minimal consumption of expensive materials. By tailoring our printer under different application scenarios, it will ultimately save material, lower printing time, and increase dimensional accuracy.

Binder Jetting Additive Manufacturing of Ceramics: Effects of Particle Size on Powder Flowability and Resultant Mechanical Properties: Mohammadadamin Moghadasi1; Wenchao Du1; Ming Li1; Zhijian Pe1; Chao Ma1; Texas A&M University
Binder jetting additive manufacturing is a promising method to produce ceramic parts. The properties of the raw powder could affect on the printing process, and as a result, the quality of the final part after printing and sintering. The objective of this research is to investigate effects of particle size on the powder flowability and resultant mechanical properties. A commercial ceramic composite, with the composition of 50 wt% silica, 25 wt% kaolinite, and 25 wt% potassium feldspar, was sieved into different particle size ranges. The Hausner Ratio and Repose Angle tests were conducted on the sieved powders of different sizes to study the effects of the particle size on the flowability of the sieved powder. Then, after printing and sintering, to investigate the quality of the parts, compression test was performed. Lastly, the thermal gravity analysis (TGA) and differential scanning calorimetry (DSC) tests were done on the raw powder and also the printed samples to study their sintering behavior.

Binder Jetting Additive Manufacturing of Ceramics: Simulation of Powder Spreading Process: Guanxiong Miao1; Wenchao Du1; Zhijian Pe1; Chao Ma1; Texas A&M University
Binder jetting additive manufacturing is a promising way to process ceramic materials which are hard to be manufactured into complex shapes using conventional methods. However, the application of binder jetting is limited by the relatively low density of manufactured parts. Investigating and understanding the powder spreading process is necessary to improve the part density since the powder bed forming process is a critical step that determines the powder bed density and consequently the part density. A numerical model is developed to study the powder bed forming process at the particle scale and predict the powder bed density under different spreading conditions using the discrete element method (DEM). A modular ceramic binder jetting printer is built to experimentally measure the powder bed density. Through comparing the experimental results with the simulation, the prediction accuracy will be further improved.

Binder Jetting Additive Manufacturing of Metals: Ming Li1; Wenchao Du1; Alaa Elwany1; Zhijian Pei1; Chao Ma1; Texas A&M University
Binder jetting, a powder-bed-based additive manufacturing method, has attracted increasing attention due to its separated shape formation and sintering process. In the recent decades, many studies have been carried out on the resultant properties of the metal parts manufactured by binder jetting. This poster presents an overview on the current development and potential research opportunities of metal binder jetting.

Effect of Different Hot Isostatic Pressing Treatments on the Mechanical Performance of EBM Ti-6Al-2Sn-4Zr-2Mo: Ahmad Abu-Issa1; Christina Pickett1; Donald Godfrey2; Ryan Wicker1; Francisco Medina1; Magnus Ahlors1; Edel Arrieta1; Andres Escarcega1; University of Texas at El Paso; Honeywell Aerospace; Quintus Technologies
Hot Isostatic Pressing (HIP) is used to improve the mechanical properties of metal specimens by increasing pressure and temperature inside a vessel. In this environment of high pressure and heat, plastic deformation and diffusion bonding are induced, internal pores within the solid body of specimens collapse, density increases, micro defects heal, and the mechanical properties are improved. The application of titanium alloys will grow in various industries particularly aerospace and biomedical due to their exceptional strength-to-weight ratio, corrosion resistance, and operating temperatures. The Ti-6Al-2Sn-4Zr-2Mo (Ti 6242) pieces were made from Arcam's Q20 and A2X systems; both samples of HIPed and as-built EBM Ti6242 were cut into cross sections to check porosity, cracking, analyze density, as well as look at the microstructure, Hardness measuring, chemical analysis, tensile testing, and failure analysis will be done to compare HIPed and as-built pieces.
Effects of Layer Orientation on Mechanical Properties in Large Area Projection Sintering (LAPS): Derek Black; Clinton Abbott; Dunstan Chi; Joseph Andrew; Nathan Crane; Brigham Young University Large area projection sintering (LAPS) is a powder bed fusion (PBF) process that is currently being developed. LAPS fuses layers of polymer similar to laser sintering (LS), but utilizes a projected grayscale image from a modified projector to fuse the layers. Initial research has shown that mechanical properties from samples oriented in the build plane are superior to LS samples produced from the same material. However, it is necessary to examine the properties produced orthogonal to the build plane as well. This study compares the properties (strength, elongation at break, and density) of samples oriented in the build plane and orthogonal to the build plane. Printing orthogonal tensile bars requires a smaller sintering area and more layers—increasing sensitivity to edge effects. The potential effects of these requirements are discussed. To better understand the sources of disparity between samples, the temperature history was recorded and analyzed as well.

Elevated Temperature Mechanical and Microstructural Characterization of SLM SS304L: Grant Hecht; Sriram Isanaka; Joseph Newkirk; Missouri University of Science and Technology Residual stresses are inherent in SLM made parts due to the complex stress-strain relationship that results from the directional build process and rapid cooling rates. Annealing SLM built NS 304L using both air and water was employed to minimize residual stress and avoid carbide precipitation. The effects of the different cooling rates achieved through air and water annealing and the corresponding changes in the material behavior between the as-built and annealed cases was investigated in detail. Mini-tensile characterization of strength and elongation and their associated microstructural transformations at temperature conditions up to 800°C are utilized to understand the changes produced in SS 304L due to the presence of these residual stresses. This work was funded by the Department of Energy's Kansas City National Security Campus which is operated and managed by Honeywell Federal Manufacturing Technologies, LLC under contract number DE-NA0002839.

Emittance and True Temperature Measurement at the NIST Additive Manufacturing Metrology Testbed: Ivan Zhirnov; Brandon Lane; Steven Grantham; Vladimir Khromchenko; Sergey Mekhontsev; National Institute of Standards and Technology This paper summarizes recent results of measuring the spatially-resolved emittance and true temperature in the heat affected zone during selective laser melting of a metal substrate. Currently realized temperature range 1100 °C to 1850 °C allows measurements of the melt pool geometry and temperature distribution for common steel, nickel, or titanium alloys. The measurement method was validated using high purity Fe, Ni, and Ti, with precisely known melting temperatures. Radiance temperature calibration of the high speed imager is carried out using a custom-designed LED-driven source, and emittance determination performed using a hemispherical reflectometer. Longier term objectives of this research at NIST are to create a database of apparent and true temperature distributions across the process area for common materials and process parameters, as well as optical and physical properties of materials under the influence of laser radiation, with potential use in design of multiphysics simulations or process monitoring systems.

Exploring Additive Manufacturing Techniques in Creating a Model Aircraft: Richard Woods; Farzaneh Sameni; Alex Gullane; University of Liverpool; University of Loughborough; University of Nottingham This project explores the capabilities of Additive Manufacturing (AM) when designing, and fabricating a model aircraft. Different AM techniques were explored including, Powder Bed Fusion, VAT Photopolymerization, Material Extrusion, and Material Jetting. Identifying which AM technique to use for each part of the model was completed through comparing the techniques attributes. The wings required a lattice structure, therefore Powder Bed Fusion was used. The DC motors used Material Extrusion, VAT Photopolymerization, Material Jetting, and Powder Bed Fusion. The Supercapacitor used Material Extrusion. Carbon-fibre filaments for use with Material Extrusion were extruded. Ultimately the model encountered issues, the Supercapacitors failed when drying, the DC motors failed to spin and the carbon fibre filaments produced low-quality parts. The lattice structures printed successfully reducing the weight of the plane by 80% compared to solid structures, there is room for future work in incorporating AM to design a model aircraft.

Fatigue Behavior of Post-build Surface Processing on Electron Beam Melted Ti-6Al-4V: Carter Keough; Harvey West; Richard Wysk; Ola Harrysson; North Carolina State University Translation of metal additive manufacturing (AM) into industry is limited by the inability to directly produce components that achieve desired geometric and dimensional tolerances with desired mechanical performance. The unique rough surfaces of AM affects the fatigue behavior of functional parts and additional surface processing is often required to enhance this mechanical performance. For successful product design and realization, a comprehensive understanding is still needed to predict the effects of surface modification on the fatigue response of AM parts. The current study investigates the effects and surface characteristics of mechanical and chemical surface conditioning methods on the fatigue life of Ti-6Al-4V test parts made via electron beam melting (EBM). The ultimate objective of this work is to relate the measured fatigue performance to the surface condition in order to develop a series of guidelines for finishing AM components. Examination and implications of the treatment conditions and results are described.

Feasibility of On-line Defect Detection with Current Thermal Tomography Techniques: Nicholas Wallace; Matthew Jones; Nathan Crane; Brigham Young University Defects smaller than 100 microns are common in many 3D printed parts, due to the dynamic layer by layer process which they undergo. Even small defects of this magnitude can cause inconsistencies in the mechanical properties of the final part. There is therefore a need to improve technologies that can identify and monitor such defects. Our research explores the conditions necessary to detect small defects within 3D printed parts using thermal tomography techniques. The heat transfer is modeled in COMSOL to estimate the temperature profile over time for different combinations of pulse profiles. Simulated noise is added to the simulation results and existing thermography correlations are applied. These results provide a minimum defect size that existing thermal tomography techniques can identify for a range of thermal inputs. These results are compared to common 3D printing defects.

Green Bio-printing: An Investigation of Suitable Bio-inks to Support Plant Tissue Growth: Livia Kalossaka; Imperial College London Bio-printing has so far been applied to the field in the medical field of tissue engineering. However, research into the application of bio-printing with photosynthetic organisms such as algae is still in its infancy. In this research, a range of suitable bio-inks that allow for the development of a scaffold that enables the growth of plant tissue is going to be investigated. The use of 3D printing, is vital in this aspect as complex geometries with designed patterns, pore sizes and stiffness can be created. At this stage, the formulation of a bio-ink which is widely available, biocompatible and suited for an extrusion based 3D printing has been identified and its characteristics will be presented.
Laser Additive Manufacturing of Dissimilar Metals for Nuclear Reactor Applications: Xuan Zhang; Wei-Ying Chen; Meimei Li; Andrew Chihpin Chuang; Tao Sun; 1Argonne National Laboratory

This work explores the joining process of two dissimilar metals by laser additive manufacturing, taking advantage of the ultrasonic imaging and high-speed diffraction capabilities at the beamlines 32-ID-B and 1-ID-E, respectively, of the Advanced Photon Source (APS). The materials system that we focuses on is stainless steel (ss) (base) + Ni-based superalloy (cladding) for their proposed applications in the molten salt reactor concepts due to the good liquid salt corrosion resistance of Ni superalloy. The goal is to identify the optimum manufacturing conditions to achieve satisfying interface properties. Following the APS work on studying the process parameters, the manufactured samples will be studied by electron microscopy for microstructural characterization and mechanical testing for property screening.

Learning Design for Additive Manufacture through Competition: The 3rd Annual 3D Printed Aircraft Competition: Robert Taylor; 1University of Texas at Arlington

The University of Texas at Arlington (UTA) hosts the 3rd Annual 3D Printed Aircraft Competition on July 13, 2019. This competition provides an opportunity for undergraduate and graduate students to apply design and process knowledge to innovatively design an aircraft with a 3D printed airframe. Designs submitted to either fixed wing or rotary wing categories compete for the longest flight duration and most innovative design awards. A rule limiting powered flight to no more than 5 seconds challenges designs to emphasize lightweight airframe design within the constraints of 3D printing process capability and material constraints. Students engage in team-based design and gain hands-on experience in the full design cycle along with fabrication and testing.

Machine Learning Assisted Control of Melt Pool Geometry in Nickel-based Superalloys under Constrained Computational Resources: Sudeepa Mondal; Asok Ray; 1Pennsylvania State University

Additive manufacturing (AM) processes such as directed energy deposition (DED) require control of the pertinent process parameters for maintaining the melt pool geometry throughout the build process. Model-based optimization of such process parameters may often result in intractable computational costs in exploration of the search space of optimization, since the underlying models for predicting melt pool geometries can be inherently complex and computationally expensive. This poster presents a machine-learning-assisted statistical modeling framework that is built upon the concepts of Gaussian processes and Bayesian Optimization for controlling the pertinent process parameters efficiently during material deposition in a resource-limited model-based optimization setting. The results are potentially useful for obtaining model-based estimates of the optimal process parameter evolution in a DED process for a range of popular hot-section nickel-base superalloys belonging to the class of CMSX, René 142 and PWA series that are conventionally cast with directionally solidified and single-crystal microstructures.

Metal Casting Applications Using Zirconia Molds Produced by NanoParticle JettingTM: John Martin; 1Bharagi Mummareddy; Matthew Heffinger; Jason Walker; 1Youngstown State University

NanoParticle jetting is a new form of material jetting involving the dispersion of nanoparticles, of either metal or ceramic, which are suspended in a liquid solution. Highly detailed parts can be created as the layer thickness is 10 microns and the jetting resolution is 1200 DPI (20 microns). The development of creating finely detailed 3D printed zirconia objects has opened many doors into new applications regarding high performance ceramics. This study focuses on exploring utilizing this technology for use in metal casting applications. 3D printed zirconia parts possessing superior geometrical accuracy and surface smoothness are to be tested for use in both mold inserts for sand casting as well as for molds for microcasting applications. Areas of focus are interactions of the metal with the zirconia material and improvements in accuracy of geometrically complex cast part features.

Method for Determining Light Intensity in Large Area Projection Sintering (LAPS): Dunstahn Chai; Joseph Andrew; Clinton Abbott; Nathan Crane; 1Brigham Young University - Provo

Large Area Projection Sintering (LAPS) is a developing powder bed fusion (PBF) process that is similar to laser sintering (LS). LAPS uses a projected image from a modified high intensity projector to fuse powder particles on a selected area across the powder bed. Knowing the distribution of light intensity across the projected image is important for predicting how the powder will sinter. Additionally, tracking degradation of the light intensity from the projector over time will determine lifespan of LAPS systems and assist in understanding the process performance. This paper focuses on finding a cost effective and time efficient way to collect light intensity data across the projected area. An optical power meter was used in conjunction with photodiodes to gather data, from which a light intensity map was generated. The light intensity data of a projector in a prototype LAPS system were collected over time and evaluated for degradation.

Nozzle-integrated Pre-deposition and Post-deposition Heating of the Platform Bed in Polymer Based Additive Manufacturing: Darshan Ravoo; Hardikdram Pratapati; Ankur Jain; 1University of Texas Arlington

Additive manufacturing (AM) offers advantages of tailored physical properties of built parts. Heat transfer plays a key role in polymer extrusion based additive manufacturing processes. In an effort to understand the heat transfer role in the merging of filaments with time, results from a moving heat source model is compared against the infrared based-temperature field measurement in a variety of process conditions. Results indicate that temperature distribution on bed is combination of thermal energy deposited through filament and heat transfer from the hot, moving nozzle tip. Based on this, a pre-deposition and post-deposition heater is designed and integrated with the moving nozzle in order to provide significant, in situ heating and maintain filaments above glass transmission temperature for longer time. Experimental data show significant additional temperature rise due to the pre/post-heater. Cross-sectioning of printed parts also shows improved filament-to-filament bonding compared to the baseline case. In contrast with other past efforts for heating of deposited filaments, this approach offers significant thermal localization and operational simplicity.

On the Physical Characteristics of 3D Printed Sand for Metal Casting Tooling: Nathaniel Bryant; Jerry Thiel; Travis Frush; Jason Walker; 1Imerys S&T; 2University of Northern Iowa; 3Youngstown State University

During the last decade there have been significant advancements made in additive manufacturing technology that caused widespread change in the metal casting industry. Although the equipment and materials used are rapidly advancing, there is limited information regarding the process changes that influence the product created by this technology. Here, an investigation was conducted to realize the influence of machine settings on the physical characteristics of 3D printed sand. Two factorial matrices were constructed to directly measure the significance of six settings that change the resin content and compaction characteristics of the bonded sand. Factors include: X-resolution, printhead voltage, layer thickness, and the frequency, speed, and angle of the recoater blade. Responses include: density, permeability, strength, scratch hardness, loss-on-ignition, and print resolution. Several relationships are reported between machine settings and physical properties of the product. These results will help inform mold manufacturing as the foundry industry continues to adopt additive technologies.
Parameter Optimization of AISI10Mg Alloy System in 200W Direct Metal Laser Sintering Process: Matthew White; Harvey West; Ola Harrysson; North Carolina State University-CAMAL

Due to its high strength-to-weight ratio and high thermal and electrical conductivity, AISI10Mg is a desirable alloy in many functional applications. These properties, coupled with the complex geometric capabilities of additive manufacturing (AM) make it a useful alloy for structural components and heatsinks among other applications. Parameters for the AM fabrication of AISI10Mg using laser powder bed fusion processes are currently only commercially available for 400 watt laser based systems. Many AM users already have 200 watt based systems and therefore would not be able to fabricate parts with this alloy without costly machine upgrades to a 400 watt laser. This study aims to investigate if minor machine adaptations could render a 200 watt laser system capable of manufacturing components out of AISI10Mg. Development of process parameters and analysis of produced part density and other metallurgical properties are conducted to determine its success.

Application of Schlieren Technique in Additive Manufacturing: A Review: Bharadwaja Ragampeta; Aravind Murugan; Yitao Chen; Frank Liu; Missouri University of Science and Technology

Additive manufacturing (AM) has gained a lot of attention in the past few decades for its substantial advantages in terms of design freedom, lower lead time, and ability to produce complex shapes. One of the key factors affecting the part quality in additive manufacturing is shielding gas flow. However, a large portion of shielding gas is unutilized as it is often set at maximum supply to achieve enough gas cover over the substrate. Recognizing the need to optimize the shielding gas, various studies have been carried out to visualize and monitor the shielding gas. Schlieren visualization is one such major technique that has been used as a powerful tool to visualize fluctuations in optical density. This paper aims to provide a review of the impact of shielding gas on part quality in Additive Manufacturing, and an overview of the Schlieren imaging used for visualization of shielding gas.

Simulation of Hybrid WAAM and Rotation Compression Forming Process: Xushan Zhao; Haiou Zhang; Yuanxun Wang; Guilian Wang; Huazhong University of Science and Technology

Wire arc additive manufacturing (WAAM) has been studied and widely applied due to its high forming efficiency and low production cost. In the process of WAAM, there are problems of cracking, deformation, large residual stress, insufficient properties and instability caused by repeated rapid heating and chilling. Welding with rotation compression can control the performance and shape synchronously in the semi-solidified state of the weld pool. In this study, a new solution of hybrid WAAM and rotation forming metal flows is obtained by arranging history monitory points on bead, hybrid process, the force energy curve of the rotation forming metal flowing process is obtained by arranging history monitory points on bead, and the relationship between the shape and forming load is revealed. The simulation results were verified by forming tests and metallographic observations on low carbon steel.

Multiple Scanning to Reduce Spatter of Nickel-based Superalloy in Electron Beam Selective Melting: Yang Li; Saleh; Yefeng Yu; Jun Zhou; Feng Lin; Tsinghua University

It has many advantages to produce nickel-based superalloy by electron beam selective melting (EBSM). Nonetheless, spatter in the process could lead to unexpected defects. The influence of spatter on EBSM parts of variant nickel-based superalloy, such as Inconel 718 and K4002 and its mechanism will be presented. It was found that the spatter was more significant for Inconel 718 than K4002, and could be weakened by slowing down electron beam scan speeds, but the surface became rougher. In the presentation, a dual scanning strategy will be proposed to get a better deposited surface and was applied to make the high quality samples, of which the density, hardness, surface morphology will be presented as well.

Process-concurrent Visual Inspection of Glass Laser Additive Manufacturing Deposition Products: Aidan Brooks; Emilio Perez; Joseph Fischer; Robert Landers; Douglas Bristow; Missouri University of Science and Technology

Glass additive manufacturing has shown great promise for many fields, but traditional methods of 3D fabrication, such as selective laser sintering (SLS), create too much porosity for printed glass to be optically transparent. Direct energy deposition (DED) methods, which utilize a glass filament feedstock, can create optically transparent parts, but the process contains more variability than SLS due to different material fusion mechanisms and the nature of printing without inherent support material. Here, we report the utilization of a visual-spectrum camera to monitor and provide instantaneous feedback on the deposition products of glass DED manufacturing by live inspection of the material melt pool. By providing the means to continuously monitor the melt pool geometric dimensions with a visual-spectrum camera, we create the opportunity for feedback control to reduce DED manufacturing variability. Our research is ongoing, but early tests demonstrate great potential for the use of visual-spectrum cameras as simple and effective in-process inspection sensors.

Self-powered Hydrophone with Broadband Frequency and Rationally Designed Directivity Pattern via 3D Printing Using Piezoelectric Metamaterials: Huachen Cui; Ryan Hensleigh; Desheng Yao; Xiaoyu Zheng; Virginia Tech

Recently, there has been considerable interests of hydrophones for the purpose of underwater signal detection. However, conventional hydrophones suffer from the narrow working frequency and limited directivity patterns. Herein, we designed and fabricated novel hydrophones consisting of micro-architected metamaterials to accommodate diverse situations, in which the piezoelectric composites convert mechanical vibrations into electrical voltages. 3D printable piezoelectric composites were used to fabricate these architected hydrophones that have high sensitivity. Through tuning geometry of the micro-architectures, resonance frequencies of these hydrophones can vary from 100Hz to 10MHz, which is across 5 orders of magnitude. With this broad frequency range, we combined multiple architecture designs and fabricated hydrophones with arbitrary directivity patterns. Compared to conventional hydrophone arrays, the metamaterial hydrophones have no limitation on the shape of the directivity patterns. In addition, we showed the applicability of these hydrophones for the purpose of source detection, liquid quality monitoring, and directional sensing.

In-Situ Ultrasonic Quality Inspection for Metallic Additive Manufacturing: Peter Fickenwirth; Gregory Mellos; Colt Montgomery; Eric Flynn; Adam Wachtler; Los Alamos National Laboratory

The recent growth in the metal additive manufacturing (AM) industry and transition of AM parts from prototypes to deployment of service environments has increased the necessity for quality inspection methods of AM parts. This study investigates the use of acoustic wavenumber spectroscopy (AWS) as a non-destructive evaluation (NDE) method for in-situ inspection of AM processes. AWS is a scanning laser-ultrasound measurement system that performs structural health evaluation; it has previously been used for structural health monitoring (SHM) of plate-like structures. AWS is significantly faster than current industry standards for ultrasonic based structural health monitoring making it an ideal candidate for in-situ AM quality inspection. 2D scans made of each build layer are used to create a 3D NDE inspection volume made during the build process. A prototype implementation of the AWS system was used on an EOS M290 powder bed fusion AM machine. Initial data analysis has successfully identified delaminations and geometrical defects.
In-situ monitoring of additively manufactured (AM) parts has become a topic of increasing interest to the manufacturing community, because defects in AM parts are generated as the part is built. In this work, the use of acoustic measurements of metal powder-bed laser sintering processes were investigated as a detection tool for pore formation made during the sintering process. Post-build radiography images were used to locate pores, which are correlated with localized acoustic time series partitions. Ensemble empirical mode decomposition (EEMD), singular spectrum analysis (SSA), and statistical measures of the time series partitions. Ensemble empirical mode decomposition (EEMD), sequential feature selection revealed that measures associated with EEMD are most useful in classifying acoustic monitoring data accordingly. The reduced feature vectors were then used to train a support vector machine model to predict pore formation with up to 95% accuracy.

Use of 3D Printed Molds for Foam in Place Prototyping Cost and Time Reduction for Optimization in DFM/A: Edgar Villa; Javed Firozeh; 1University of Texas at El Paso

The Additive Manufacturing is used in most of the stages in the automotive industry such as design communication, prototype validation, pre-production, production and customization. A study of additive manufacturing benefits in the automotive industry foam in place processes was conducted comparing an aluminum mold versus a 3D printed mold during prototype phases. The aspects evaluated were cost and time of mold fabrication and quality grade regarding design for manufacturing optimization. Material selection criteria for the 3D printed mold was done based on average pressure, average temperature, chemicals and most common problems involved in the current process referenced in mold design guidelines. By using 3D printed molds, the expectation is to reduce the prototyping cost in about 60% and the lead time by 40% or more. Capabilities and constraints of the proposed additive manufacturing method are given as a result of the study.

The Five-axis 3D-printing of Carbon Fiber Reinforced Composites: Pedro Miralles; Emilio Perez; Robert Landers; Douglas Bristow; Edward Kinzel; 1Missouri University of Science and Technology; 2University of Notre Dame

Glass Laser Additive Manufacturing (GLAM) is an additive manufacturing technique where glass fibers or filaments are deposited on a substrate material using laser melting. Deposition of glass using a fiber fed technique provides important improvements to the filament feed process. For example, fiber deposition provides the possibility to continuously deposit material with interruptions. Another benefit to the use of fiber is that it can be deposited without the formation of air bubbles because of its small diameter. On the other hand, fiber deposition presents challenges because of its small diameter. It is very difficult to set the correct parameters for adequate and reliable printing. In this report, ideal print parameters were explored by conducting print experiments with different power and scan speed settings. Quartz fiber was used as feedstock material. Single track lines of 18 millimeters were printed to determine the best scan speed and laser power ranges.

Validating Thermographic Testing in Fused Deposition Modeling: Alberto Castro; Soderia Kakoulakis; Amit Lopes; 1UTEP IMSE

Additive Manufacturing (AM) is continually utilized in various industries. One of the biggest concerns with AM is testing the strength and durability. This paper will examine the profiles of certain printing techniques combined with Acrylonitrile Butadiene Styrene (ABS). The fan speeds on Fused Deposition Modeling (FDM) printers will be adjusted to affect the temperature of the ABS as it is extruded from the nozzle and the effects this will have on the final product will be evaluated using a radiometric IR camera. The intent of this research is to create a profile on the printer and the material based on the filament temperature.

Lab-designed Laser-based 3D Printer: Chao Ma; Zhijian Pei; Ming Li; Jianchi Huang; Michael Hurst; Tanner Ramirez; Adam Pipe; Mohit Padhye; Jonatan Espinoza; Conner Murphy; Charles Splevak; Duo Wang; 1Texas A&M University

Additive manufacturing (AM) is one of the most exciting technologies in the engineering field today. This method of making three-dimensional parts in a layer-wise manner enables the manufacturing of “impossible” parts. Selective laser melting (SLM) is a type of AM method that applies a high-power laser to powdered materials to fabricate objects. SLM is capable of processing a variety of materials with superior properties. A project that aims to build a lab-designed SLM 3D printer is reported. The SLM 3D printer, named the Laser Station, allows for the high versatility in materials and flexibility in processing conditions. The laser station consists of a laser generator, a scanhead, an inert chamber, and a control system. The project provides a group of undergraduate students an active, hands-on, and collaborative learning opportunity. The students went through a procedure from design to fabrication and assembly. This project helps promote the AM education and move the AM industry forward.
Defect Identification in Additively Manufactured Parts Using the Modal Assurance Criterion: Nicholas Altese; Tristan Cullom; Robert Landers; Douglas Bristow; Edward Kinzel; 1Missouri University of Science and Technology; 2University of Notre Dame

Validating Additively Manufactured (AM) parts adds significant cost to production. This poster investigates the effectiveness of modal analysis as a means of identifying defects. Specifically, the Modal Assurance Criterion (MAC) is accessed as a processing tool to distinguish the mode shapes (eigenvectors) of parts with localized defects from nominal parts. To explore the technique, a roving hammer impact test is applied to a simple part produced with Selective Laser Melting, before and after damage is introduced. The findings suggest that the MAC is not as sensitive as the resonant frequencies (eigenvalues) to the presence of defects, however, the MAC and related techniques may be useful for identifying the location and classification of defects. It also provides a further validation of the frequency response testing methods.

The Study of Conductivity of Silver Lines Over a Large Surface Area with Aerosol Jet Printing: Leticia Mercado; Xiaowei Yu; Heng Pan; 1University of New Mexico; 2Missouri University of Science and Technology

Aerosol Jet Printing (AJP) advances the fabrication of complex 3D circuitry over other additive manufacturing processes because it offers direct-writing and eliminates a wasteful subtractive process. Studies over the past few years have successfully shown the precision AJP permits, but only on a small scale. This research will explore the printing parameters to print conductive silver lines over a large surface area while maintaining constant conductivity. Using aerosol jet printing technology alongside an ultrasonic atomizer, silver ink is deposited on polyimide (PI) substrates. Several parameter tests were conducted to ensure the repeatable fabrication of uniform conductive silver lines for a large surface area. The success of this experiment will further research in microelectronics as it offers large-area, high-speed and low-cost manufacturing approach.

Local Microstructure and Mechanical Properties Analysis of SLM 304L Stainless Steel: Ezekiel Buck; James Vranas; Cody Lough; Xin Wang; James Drellmeier; Robert Landers; Edward Kinzel; Douglas Bristow; 1Missouri University of Science and Technology; 2University of Notre Dame

Selective Laser Melting (SLM) is an Additive Manufacturing (AM) process in which a laser scans and fuses areas of a powder bed corresponding to part cross-sections layer-by-layer. The use of different laser parameters, complex scan pathing, and differences in geometry lead to inhomogeneity in the local thermal history experienced by parts during manufacturing. These parameters affect the resulting microstructure and mechanical properties of the parts and introduce the potential for variations and local defects. This poster reports the results of local microstructure (light-to-dark feature ratio, porosity) and mechanical properties (microhardness) characterization of SLM 304L stainless steel to quantify the effects of the machine parameters. A Renishaw AM250 was used to manufacture simple geometries with various laser processing parameters (power, exposure time), and intricate geometries with constant parameters. Maps of the properties were generated to show the microstructure and microhardness of the parts as a whole, and small variations in the cross-section. The results show the ability to correlate varying machine parameters and part geometries with microstructural and mechanical properties of the SLM 304L stainless steel parts on a local basis.

Embedding Distributed Fiber Optic Sensors in Components Manufactured via Laser Metal Deposition: Clara Scotte; Michelle Gegel; Douglas Bristow; Robert Landers; 1Missouri University of Science and Technology

Embedding fiber optic sensors in metal structures is of great interest in the evolution of smart materials. The ability to embed fibers will allow for sensing the internal conditions of the structure, such as temperature and induced stress and strain. If successful, this could lead to lifelong health monitoring of the material. Here methods and processes are developed for embedding fiber optics into stainless steel parts using the laser engineered net shaping process (LENS), also known as laser metal deposition (LMD). This research also studies the feasibility of embedding a bare fiber, without a metal coating, such that the inclusion of the fiber does not compromise part quality or behavior.

Glass to Metal Seals by Additive Manufacturing: Catalina Young; Jincheng Bai; Cody Lough; Richard Brow; 1Florida International University; 2Missouri University of Science and Technology

Glass to metal seals are a technology that has been around in the aerospace and defense industries for decades. This technology is used specifically for electrical components of aircrafts and vehicles that can be exposed to harsh chemical environments or high temperature environments. With the traditional methods of creating glass to metal seals, there are limitations to what can and cannot be done based on fixturing and materials. Venturing into the realm of additive manufacturing to create such seals can aid in cutting costs of creating these seals. Additive manufacturing can eliminate the limitations and need for expensive fixturing when using atmosphere-controlled furnaces of theses traditional methods by allowing for the creating free standing, complex designs better suited for application needs. Our research provides a promising approach to manufacturing these glass to metal seals via additive manufacturing processes.

The Effect of Laser Welding Modes on Mechanical Properties and Microstructure of 304L Stainless Steel Parts Fabricated by Laser-foilprinting Process: Allen Bradley; Chia-Hung Hung; Ming Leu; 1Missouri University of Science and Technology

In this study, we demonstrate the comparison of 304L stainless steel parts fabricated by the laser-foilprinting (LFP) additive manufacturing process with two different laser welding modes (conduction-mode and keyhole-mode). The porosity, microstructure, and tensile properties of both parts are measured and compared in the laser scanning direction and building directions. The parts made by conduction-mode have slightly higher density than those made by keyhole mode (>99.91% vs. >99.41%), but both are near fully dense. On the tensile properties both of their yield strengths and ultimate tensile strengths are similar, without significant difference between them based on ANOVA analysis. However, the conduction-mode part has higher elongation at the break point than the keyhole mode part.

Glass laser additive manufacturing (GLAM) is a process that uses glass filament or fiber and disperses it onto a substrate material through laser melting. GLAM can print complex geometries, but due to multiple factors, the start and stop of each print may vary widely when compared to the rest of a print. This variance can mainly be seen in buildup, or “globing,” where the start and stop of each print experience a larger volume of glass than in the confined regions. Although globing does eventually withdraw throughout the print, it can cause the printed geometry to be skewed from the intended design. This research looks at two major topics surrounding the start and stop of each print: the initial end state of the filament and the printing parameters that affect globing. To control the initial condition of the filament, a filament cutter was developed to cut the print-end of the filament in a clean and consistent manner. To come up with a reliable method of reducing globing at the beginning and end of each print, printing techniques and parameters were tuned by printing two linear tracks, 20 mm long.
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