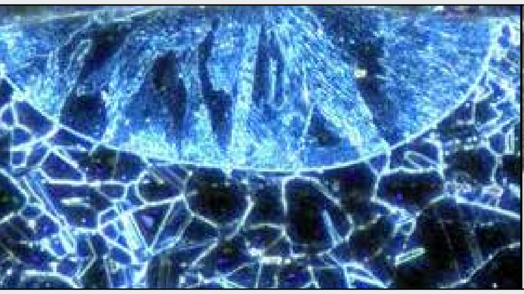
AM BENCH 2018

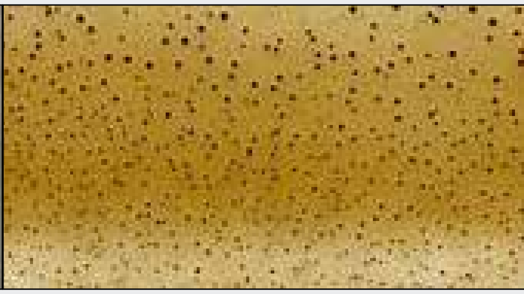
ADDITIVE MANUFACTURING BENCHMARKS

June 18–21, 2018 | National Institute of Standards and Technology (NIST) Headquarters
Gaithersburg, Maryland, USA

FINAL PROGRAM

www.tms.org/AMBench2018





TMS

Sponsored by the TMS Additive Manufacturing Committee, Process Technology and Modeling Committee, and Integrated Computational Materials Engineering Committee, in collaboration with National Institute of Standards and Technology (NIST), the Naval Research Laboratory (NRL), and the Army Research Laboratory (ARL)

ABOUT THE CONFERENCE

Monday, June 18	Time	Location
Bus Transportation from Hilton to NIST	7:15 a.m. to 8:45 a.m.	Hilton Washington DC North/Gaithersburg
Registration	7:30 a.m. to 5:00 p.m.	Green Auditorium Foyer
Exhibit Set-Up	8:00 a.m. to 10:00 a.m.	Poster Hallway
Welcome and Introduction	9:00 a.m. to 9:30 a.m.	Green Auditorium
Plenary	9:30 a.m. to 10:30 a.m.	Green Auditorium
Break and Exhibit Viewing	10:30 a.m. to 10:50 a.m.	Poster Hallway
Benchmark Presentations	10:50 a.m. to 12:20 p.m.	Green Auditorium
Lunch	12:20 p.m. to 1:30 p.m.	Cafeteria
Poster Set-Up	12:20 p.m. to 1:30 p.m.	Poster Hallway
Technical Sessions	1:30 p.m. to 3:00 p.m.	See Technical Program
Break and Exhibit Viewing	3:00 p.m. to 3:20 p.m.	Poster Hallway
Technical Sessions	3:20 p.m. to 4:50 p.m.	See Technical Program
Bus Transportation from NIST to Hilton	4:30 p.m. to 5:15 p.m	NIST Adminstration 101 Building Main Entrance
Tuesday, June 19		
Bus Transportation from Hilton to NIST	7:15 a.m. to 8:45 a.m.	Hilton Washington DC North/Gaithersburg
Registration	7:30 a.m. to 5:00 p.m.	Green Auditorium Foyer
Plenary	8:30 a.m. to 10:00 a.m.	Green Auditorium
Break and Exhibit Viewing	10:00 a.m. to 10:20 a.m.	Poster Hallway
Benchmark Presentations	10:20 a.m. to 12:20 p.m.	Green Auditorium
Lunch	12:20 p.m. to 1:30 p.m.	Cafeteria
Technical Sessions	1:30 p.m. to 3:00 p.m.	See Technical Program
Break and Exhibit Viewing	3:00 p.m. to 3:20 p.m.	Poster Hallway
Technical Sessions	3:20 p.m. to 4:50 p.m.	See Technical Program
Bus Transportation from NIST to Hilton	4:30 p.m. to 5:15 p.m.	NIST Adminstration 101 Building Main Entrance
Wednesday, June 20		
Bus Transportation from Hilton to NIST	7:15 a.m. to 8:45 a.m.	Hilton Washington DC North/Gaithersburg
Registration	7:30 a.m. to 5:00 p.m.	Green Auditorium Foyer
Plenary	8:30 a.m. to 10:00 a.m.	Green Auditorium
Break and Exhibit Viewing	10:00 a.m. to 10:20 a.m.	Poster Hallway
Benchmark Presentations	10:20 a.m. to 12:20 p.m.	Green Auditorium
Lunch	12:20 p.m. to 1:30 p.m.	Cafeteria
Technical Sessions	1:30 p.m. to 3:30 p.m.	See Technical Program
Poster and Exhibit Viewing	3:30 p.m. to 5:00 p.m.	Poster Hallway
Exhibit Tear-Down	5:00 p.m. to 6:00 p.m.	Poster Hallway
Bus Transportation from NIST to Smokey Glen Farm	5:00 p.m. to 5:15 p.m.	NIST Adminstration 101 Building Main Entrance
Conference Dinner and Awards	5:30 p.m. to 7:30 p.m.	Smokey Glen Farm
Bus Transportation from Smokey Glen Farm to Hilton	7:15 p.m. to 8:00 p.m.	Smokey Glen Farm
Thursday, June 21		
Bus Transportation from Hilton to NIST	7:15 a.m. to 8:45 a.m.	Hilton Washington DC North/Gaithersburg
Registration	7:30 a.m. to 5:00 p.m.	Green Auditorium Foyer
Plenary	8:30 a.m. to 9:30 a.m.	Green Auditorium
Benchmark Presentations	9:30 a.m. to 10:30 a.m.	Green Auditorium
Break	10:30 a.m. to 10:45 a.m.	Poster Hallway
Tours	10:45 a.m. to 12:30 p.m.	Various NIST locations
Lunch	12:30 p.m. to 1:30 p.m.	Cafeteria
Technical Sessions	1:30 p.m. to 3:00 p.m.	See Technical Program
Break	3:00 p.m. to 3:20 p.m.	Poster Hallway
Poster Tear-Down	3:00 p.m. to 3:20 p.m.	Poster Hallway
Discussion and Closing	3:20 p.m. to 5:00 p.m.	Green Auditorium
Bus Transportation from NIST to Hilton	4:30 p.m. to 5:15 p.m.	NIST Adminstration 101 Building Main Entrance

TABLE OF CONTENTS

CONFERENCE ORGANIZING COMMITTEE

AM-Bench 2018 is sponsored by the TMS Additive Manufacturing Committee, Process Technology and Modeling Committee, and Integrated Computational Materials Engineering Committee, in collaboration with the National Institute of Standards and Technology (NIST), the Naval Research Laboratory (NRL), and the Army Research Laboratory (ARL).

COMMITTEE CO-CHAIRS:
Brandon Lane, NIST
Lyle Levine, NIST

ORGANIZING COMMITTEE:
Richard Fonda, NRL
Jarred Heigel, NIST
Brandon McWilliams, ARL
Kalman Migler, NIST
Shawn Moylan, NIST
Mark Stoudt, NIST

REGISTRATION

Your registration badge ensures admission to each of these events:

- Technical and poster sessions
- Daily lunch
- Wednesday dinner event*
- Refreshment breaks during session intermissions

**Please note that while one ticket for the conference dinner is included, registration was required for this event through the conference registration form. Check at the registration desk for more information.*

REGISTRATION HOURS

The registration desk will be located in the Green Auditorium Foyer at NIST Administration 101 Building at the following times:

Monday, June 18:	7:30 a.m. to 5:00 p.m.
Tuesday, June 19:	7:30 a.m. to 5:00 p.m.
Wednesday, June 20:	7:30 a.m. to 5:00 p.m.
Thursday, June 21:	7:30 a.m. to 5:00 p.m.

CONFERENCE DETAILS

TECHNICAL SESSIONS

All oral presentations will be held in NIST Administration 101 Building. All poster presentations will be held in the Poster Hallway at NIST Administration 101 Building. See the Technical Program on pages 12–31 for room locations.

INTERNET ACCESS

Complimentary wireless internet access is available for attendees at NIST facilities. For access, select the **NIST-Guest** network on your device and open a web browser. Review and complete the Access and Use Policy by scrolling to the bottom of the window. Acknowledge that you agree to the terms identified by selecting ACCEPT.

EXHIBITION HOURS

The exhibition will be located in the Poster Hallway at the NIST Administration 101 Building at the following times:

Monday, June 18:	10:30 a.m. to 10:50 a.m. and 3:00 p.m. to 3:20 p.m.
Tuesday, June 19:	10:00 a.m. to 10:20 a.m. and 3:00 p.m. to 3:20 p.m.
Wednesday, June 20:	10:00 a.m. to 10:20 a.m. and 3:30 p.m. to 5:00 p.m.

PUBLISHING OPTIONS

Selected authors will be invited to submit a paper to the *Integrating Materials and Manufacturing Innovations* (*IMMI*) journal. Further instructions will be provided with the invitation. All papers are subject to a peer review process.

NETWORKING & SOCIAL EVENTS

CONFERENCE DINNER*

The AM-Bench 2018 conference dinner and awards will be held on Wednesday, June 20, from 5:30 p.m. to 7:30 p.m. at the Smokey Glen Farm. Please note that anyone driving to the conference daily will also have to drive to dinner, as vehicles are not permitted to be left on the NIST campus.

For those driving, please use the following address:
Smokey Glen Farm
16407 Riffle Ford Rd
Gaithersburg, MD 20878

For those staying at the Hilton Washington DC North/Gaithersburg hotel, shuttle transportation will be available. Buses will depart NIST at the Administration 101 Building Main Entrance at 5:00 p.m. and 5:15 p.m. and go directly to the dinner location at Smokey Glen Farm. The buses will cycle from Smokey Glen Farm to the Hilton Washington DC North/Gaithersburg from 7:15 p.m. to 8:00 p.m., with 8:00 p.m. being the last departure time from the Smokey Glen Farm.

Please note that while one ticket for the dinner is included, registration was required for this event through the conference registration form. Onsite ticket sales are based on availability. Check with TMS staff at the registration desk, located at the Green Auditorium Foyer, for more information.

CONFERENCE LUNCHEONS

Your conference registration includes daily luncheons held in the Cafeteria at the NIST Administration 101 Building. Lunch will be available from 12:20 p.m. to 1:30 p.m. on Monday, June 18, through Wednesday, June 20. On Thursday, June 21, lunch will be available from 12:30 p.m. to 1:30 p.m.

HILTON WASHINGTON DC NORTH/ GAITHERSBURG CONFERENCE HOTEL

The Hilton Washington DC North/Gaithersburg is located a short distance from the AM-Bench 2018 technical sessions and other events being held at NIST headquarters. It is also within walking distance of Gaithersburg Square and Lakeforest Mall, offering a variety of restaurants and food options, as well as convenience stores and other shopping. The hotel itself has a pool, a fitness room, room service, a bar area, an onsite restaurant, and a Starbucks café.

NIST HEADQUARTERS CONFERENCE LOCATION

Founded in 1901, the National Institute of Standards and Technology (NIST) is a non-regulatory federal agency within the U.S. Department of Commerce. NIST's mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life. The NIST cafeteria is open daily from 7:30 a.m. to 3:00 p.m. and sells a variety of food and beverages.

ROOM FOR NURSING MOTHERS

A private room is located in the NIST Administration 101 Building for nursing mothers. To access the room, please see TMS staff at the registration desk, located at the Green Auditorium Foyer.

TRANSPORTATION

Complimentary shuttle transportation will be provided between the Hilton Washington DC North/ Gaithersburg hotel and NIST Headquarters. Each morning (Monday through Thursday), shuttle buses will cycle between the Hilton hotel and NIST. On Monday, Tuesday, and Thursday evenings, the shuttle buses will cycle between NIST and the Hilton hotel. On Wednesday evening, the buses will shuttle to the conference dinner location, Smokey Glen Farm, and will cycle back to the Hilton hotel at the conclusion of dinner and awards.

	Morning Shuttle Cycle	Evening Shuttle Cycle
MONDAY, JUNE 18	Hilton to NIST 7:15 a.m. to 8:45 a.m. *Last departure from Hilton at 8:45 a.m.*	NIST to Hilton 4:30 p.m. to 5:15 p.m. *Last departure from NIST at 5:15 p.m.*
TUESDAY, JUNE 19	Hilton to NIST 7:15 a.m. to 8:45 a.m. *Last departure from Hilton at 8:45 a.m.*	NIST to Hilton 4:30 p.m. to 5:15 p.m. *Last departure from NIST at 5:15 p.m.*
WEDNESDAY, JUNE 20	Hilton to NIST 7:15 a.m. to 8:45 a.m. *Last departure from Hilton at 8:45 a.m.*	NIST to Smokey Glen Farm 5:00 p.m. and 5:15 p.m. Smokey Glen Farm to Hilton 7:15 p.m. to 8:00 p.m. *Last departure from Smokey Glen Farm at 8:00 p.m.*
THURSDAY, JUNE 21	Hilton to NIST 7:15 a.m. to 8:45 a.m. *Last departure from Hilton at 8:45 a.m.*	NIST to Hilton 4:30 p.m. to 5:15 p.m. *Last departure from NIST at 5:15 p.m.*

SPONSORS AND EXHIBITORS

TMS would like to thank the following Corporate Sponsors and Exhibitors for their gracious support of the event:

SILVER LEVEL

Granta Design
To achieve the full potential of additive manufacturing (AM), it's essential you know how to better manage your AM project data. Using the GRANTA MI: Additive Manufacturing software from Granta Design, find out how to capture accurate information, analyze it for insight, ensure traceability, and future-proof your AM research. Discover how you can consolidate, control and share AM data, including managing AM workflows for the lab and the enterprise. Improve your understanding of critical process/property relationships, get AM solutions to market faster, and ensure you are capturing the full testing and analysis picture—for powders, materials, and parts. Granta also provides access to the Senvol Database™, enabling you to search and compare materials for AM applications, identify and compare machines, and focus on the most likely routes to achieve project goals.

BRONZE LEVEL

ASTM International
Committed to serving global societal needs, ASTM International positively impacts public health and safety, consumer confidence, and overall quality of life. We integrate consensus standards—developed with our international membership of volunteer technical experts—and innovative services to improve lives…Helping our world work better.

VEXTEC Corporation
Founded in 2000, VEXTEC Corporation is the home of VPS-MICRO®: the only probabilistic microstructure durability simulation software for metals. Based in ICME (integrated computational materials engineering), this software and technology fills a gap in the landscape of existing PLM capabilities. VPS-MICRO effectively integrates FEA, statistical modeling, and physical material and component testing, into a single computational processing framework. With industries rapidly embracing and turning toward 3-D printed parts, VPS-MICRO's algorithms have been correspondingly optimized to accommodate the unique and critical challenges posed by additive manufacturing. Our clients include leading multinationals in the aerospace, automotive, electronics, energy, heavy industry and medical device manufacturing sectors, as well as many federal government agencies. VEXTEC has received over $25 million in development funding from the United States Department of Defense and has been granted seven US patents for its technology. For more information, please visit: www.vextec.com

Xact Metal
At Xact Metal, we're taking the essential specs for metal powder-bed fusion and combining them with breakthrough technology to establish a new level of price and performance for additive manufacturing. We're dedicated to supporting the next generation of innovative manufacturing solutions powered by metal 3D printing. Our products include the XM200C which makes quality metal powder-bed fusion available for universities, labs and small-to-medium businesses who need prototyping, tooling capabilities, or low volume casting alternatives; and the XM200S which is ideal for printing of small parts where high-performance metal powder-bed fusion applications and print speed are critical.

TABLETOP EXHIBITORS

Thermo-Calc Software
Thermo-Calc Software is a leading developer of software and databases for calculations involving computational thermodynamics and diffusion-controlled simulations. Calculations are based on thermodynamic databases produced by the CALPHAD method and databases are available for steels, Ti-, Al-, Mg-, Cu-, Ni-superalloys, HEAs, refractory oxides, slags and other materials. Thermo-Calc: for performing thermodynamic calculations for multicomponent systems. DICTRA: for accurate simulations of diffusion in multicomponent alloys. TC-PRISMA: for predictions of concurrent nucleation, growth, dissolution and coarsening of precipitate phases. Software Development Kits are available which enable Thermo-Calc to be called directly from in-house developed software or MATLAB™. Applications for additive manufacturing include generating chemistry and temperature dependent properties for FEM codes where handbook data may be insufficient, predicting compositional segregation and phase formation during solidification, simulating the growth and dissolution of precipitate phases during thermal cycling and thermal post-processing and designing new alloys specifically tuned for AM processes.

CONFERENCE SUPPORT PROVIDED BY:

The National Institute of Standards and Technology (NIST)
The National Institute of Standards and Technology (NIST) was founded in 1901 and is now part of the U.S. Department of Commerce. NIST is one of the nation's oldest physical science laboratories. Congress established the agency to remove a major challenge to U.S. industrial competitiveness at the time—a second-rate measurement infrastructure that lagged behind the capabilities of the United Kingdom, Germany, and other economic rivals. From the smart electric power grid and electronic health records to atomic clocks, advanced nanomaterials, and computer chips, innumerable products and services rely in some way on technology, measurement, and standards provided by the National Institute of Standards and Technology. Today, NIST measurements support the smallest of technologies to the largest and most complex of human-made creations—from nanoscale devices so tiny that tens of thousands can fit on the end of a single human hair up to earthquake-resistant skyscrapers and global communication networks.

MEETING POLICIES

BADGES

All attendees must wear registration badges at all times during the congress to ensure admission to events included in the paid fee, such as technical sessions, exhibition, and receptions.

REFUNDS

The deadline for all refunds was May 25, 2018. No refunds will be issued at the congress. Fees and tickets are nonrefundable.

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.

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 or by visiting the registration desk onsite.

ANTI-HARASSMENT

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

TMS 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 TMS Board of Directors, 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 TMS 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.

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

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TMS 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.

TMS DIVERSITY AND INCLUSION STATEMENT

The Minerals, Metals & Materials Society (TMS) is committed to advancing diversity in the minerals, metals, and materials professions, and to promoting an inclusive professional culture that welcomes and engages all who seek to contribute to the field. TMS recognizes that a diverse minerals, metals, and materials workforce is critical to ensuring that all viewpoints, perspectives, and talents are brought to bear in addressing complex science and engineering challenges. To build and nurture this diverse professional community, TMS welcomes and actively engages the participation of underrepresented groups in all of its initiatives and endeavors.

The chances of an emergency situation occurring at AM-Bench 2018 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 maps of the NIST Headquarters printed in this program (on page 39 and the 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. All AM-Bench 2018 attendees will also receive a NIST Visitor Safety and Security Information brochure where you can find more information on procedures for fire, severe weather, medical emergencies, and security emergencies.

In case of a fire at NIST Headquarters, an alarm will sound and all attendees should leave the building using the nearest safe exit. Do not use elevators. Once outside, head directly to the closest assembly point marked with a yellow "Evacuation Meeting Area" sign in the building parking lot. Await further instructions from there.

Please use the following local safety and security contact information if you or someone near you is experiencing an emergency.

EMERGENCY RESPONSE

(Fire, Medical, and Other Emergencies)

Internal NIST Phone: 2222
Local Direct Dial: 1–301–975–2222

WELCOME TO TMS

The Minerals, Metals & Materials Society

DID YOU KNOW?

If you registered for the Additive Manufacturing Benchmarks (AM-Bench 2018) conference at the nonmember rate, your registration includes a TMS electronic membership through December 31, 2019.

WHAT CAN YOU DO WITH YOUR NEW MEMBERSHIP?

- **Read:** Access more than 20 journals published by TMS and Springer for free and explore online publication libraries available only to members
- **Network:** Join a TMS technical committee or connect with colleagues through the TMS Membership Directory
- **Advance Your Career:** Post your resume on the TMS Career Center or download the PE Exam Study Guide for Metallurgical and Materials Engineering
- **And Much More!**

Visit **members.tms.org** to view a complete listing of benefits available to you as a TMS member.

HOW CAN YOU ACCESS YOUR BENEFITS?

Following the meeting, you'll receive an e-mail from TMS with your member user-name and password. Once you receive this, you can log in to the "Access Member Benefits" section of the TMS website at members.tms.org.

QUESTIONS?

Contact our customer service representatives at any time at members@tms.org or by phone at 1-724-776-9000 and press "1" for assistance.

We're glad to have you as a member—welcome to TMS!

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Gaithersburg, Maryland, USA

TECHNICAL PROGRAM

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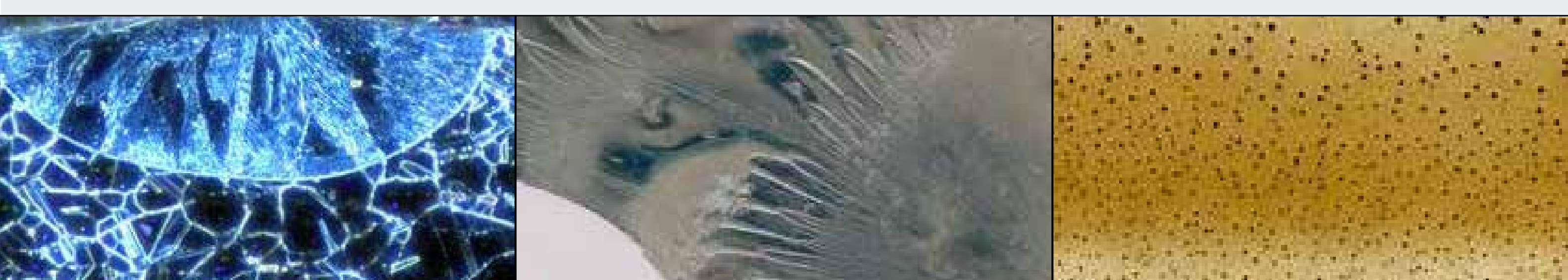

Monday Plenary Session

Monday AM | Room: Green Auditorium
June 18, 2018 | Location: NIST Headquarters

Session Chair: Brandon Lane, National Institute of Standards and Technology

9:00 AM Introductory Comments

9:30 AM Plenary
Modeling Challenges and Opportunities in Powder-bed Fusion Additive Manufacturing (PBFAM) Process: *Ade Makinde*[1]; [1]GE Global Research Center
Qualification of additively manufactured parts is a challenge today due to a lack of understanding of the interactions between the physics involved in the process. Our talk will examine the various models that are in use, ranging from laser-particle interaction, through distortion/residual stress and performance property prediction. We shall examine the various models and how they are validated. The need for a reliable and consistent data set for the community to use in validating the various thermal and mechanical models will be discussed. The AM-Bench and other similar ones planned will help. Our talk will focus more on distortion and residual stress modeling. The various approaches in use will be compared and discussed using simple examples to outline the differences in the simplification approaches using two commercial codes. Results of the predictions of the AM-Bench 2018 geometry will also be provided and submitted separately to the modeling challenge.

10:00 AM Plenary
Challenges and Opportunities for Metal Additive Manufacturing to be an Automotive Game Changer: *Anil Sachdev*[1]; Susan Smyth[1]; [1]General Motors Global Research & Development
Additive manufacturing (AM) is promising to disrupt the well-established manufacturing framework for many business sectors, including impacting the high volume, high tonnage automotive industry. The transition from metal prototyping, available currently, to full scale production, is projected as seemingly in the horizon. Several challenges remain however, to make metal additive manufacturing viable for automotive production. These "showstoppers" are addressed in this talk with a simple evaluation-driven framework called SAM-CT (Size, Accuracy, and Materials that represent technology challenges, and Cost and Throughput that represent the economic barriers). The elements of this framework will be described with reference to the automotive enterprise, and the need for the various breakthroughs and standards in each of the elements will be elucidated.

10:30 AM Break

Monday Benchmarks

Monday AM | Room: Green Auditorium
June 18, 2018 | Location: NIST Headquarters

Session Chair: Brandon Lane, National Institute of Standards and Technology

10:50 AM Introductory Comments

11:20 AM
Design and Fabrication of the AM Bench Bridge Structures and the Thermographic Measurements Performed on the Commercial Powder Bed Fusion Machine: *Jarred Heigel*[1]; Brandon Lane[1]; Lyle Levine[1]; [1]National Institute of Standards and Technology
This talk discusses the design and execution of the 3D metal bridge structure experiments (AMB2018-01) and presents in situ thermographic measurements from the experiments performed on the commercial build machine. While the AM-Bench tests are one of the most comprehensive publicly available studies into parts manufactured using metal powder bed fusion, the requirements of multiple metrology techniques and capabilities of the two different systems (commercial build machine and the Additive Manufacturing Metrology Testbed) created unique constraints on the experiment design that are first discussed. Next, the preliminary builds and in situ measurements that guided the selection of the final process parameters and build strategy are presented. Finally, in situ thermographic measurement obtained from the single track and 3D builds are presented and discussed.

11:50 AM
Processing and Characterization of PA12 Benchmark Test Specimens by Polymer Powder Bed Fusion: *Erich Bain*[1]; [1]US Army Research Laboratory
Polymer powder bed fusion (PPBF), often referred to as selective laser sintering (SLS), is an additive manufacturing (AM) technique in which powdered polymeric material is fused into parts by thermally melting with a laser rastered over a heated powder bed in a layer by layer fashion. It is a production technique known for producing highly complex parts with good dimensional accuracy and mechanical strength. This talk will discuss production and characterization of benchmark specimens from polyamide 12 (PA12), currently the most widely used PPBF feedstock. An array of tensile dogbone and cubic specimens was produced covering a range of orientations including vertical (z-orientation), flat (x-y plane), side (x-z plane), and 45 degrees to z-normal. The specimens vary in their proximity to other specimens, resulting in thermal variations that may affect resulting microstructural and mechanical properties. Parts were characterized for dimensional accuracy according to ASTM D3171, density by pycnometry, tensile properties according to ASTM D638, failure mode and localization by optical and scanning electron microscopy, void distribution by X-ray micro computed tomography (ì-CT), melting and crystallization temperatures and heats of transition by differential scanning calorimetry (DSC), crystallinity by DSC and X-ray diffraction (XRD), and degradation by thermogravimetric analysis (TGA).

Materials Performance and Residual Stress I: Residual Stress and Mechanical Response

Monday PM | Room: Lecture Room B
June 18, 2018 | Location: NIST Headquarters

Session Chair: Thien Phan, National Institute of Standards and Technology

1:30 PM Invited
Diffraction Measurement of Residual Stresses on Components of Varying Complexity: *Donald Brown*[1]; John Carpenter[1]; Bjorn Clausen[1]; Maria Strantza[1]; Lyle Levine[2]; Thien Phan[2]; Wayne King[3]; Rishi Ganeriwala[3]; Joseph Bishop[4]; Jarad Bradley[4]; Kyle Johnson[4]; [1]Los Alamos National Laboratory; [2]National Institute of Standards and Technology; [3]Lawrence Livermore National Laboratory; [4]Sandia National Laboratory
Common to the myriad metals additive manufacture (AM) techniques that are currently used are rapid quenching of and strong thermal gradients in the deposited material. These necessarily result in large, often yield-level, residual stresses in the as-built component. Diffraction measurements of residual stress have been completed in test objects of varying levels of complexity, from simple line depositions to complex net-shape components for purposes of model development and validation. For instance, simple single line depositions were studied to see if models could predict the difference between the start and stop end. On the other end of the complexity spectrum, a component with complex geometry including multiple bore holes in different orientations was measured for validation of a process model. The technique of diffraction measurement of stress will be presented as well as results from the various test objects including comparison to model results.

2:00 PM

Modeling of Residual Stresses and Distortions in a 17-4 PH Stainless Steel Part Produced by Laser Powder Bed Fusion: *Daniel Galles*[1]; Christopher Kube[2]; [1]Oak Ridge Institute for Science and Education; [2]Bennett Aerospace Inc.

Metal parts produced by laser-based additive manufacturing (AM) processes are susceptible to residual stresses and distortions, both of which diminish part quality. The prediction and subsequent mitigation of these unwanted defects is of great interest to industry. In this study, a 17-4 PH stainless steel arch-shaped geometry is produced by laser powder bed fusion and then simulated to study residual stresses and distortions that arise during laser-based AM. For the experiments, two opposing scan strategies are utilized to induce different levels of residual stress. Upon removal of the arches from the build plate, the resulting vertical deflections differ by a factor of 2. In addition, microstructure-sensitive ultrasonic measurements are conducted before and after build plate removal in order to establish their sensitivity to residual stress. For the simulations, a sequentially coupled heat transfer-stress analysis is performed using a commercial finite element code and reveals good agreement between simulations and measurements.

2:20 PM

An Efficient Numerical Simulation of the Laser-powder Bed Fusion of Full-size Ti-6Al-4V Parts: *Mohammad Masoomi*[1]; Nicole Apetre[2]; Nagaraja Iyyer[2]; Scott Thompson[1]; Nima Shamsaei[1]; [1]Auburn University; [2]Technical Data Analysis, Inc. (TDA)

The mechanical response and fatigue life of additive manufactured parts are directly affected by the thermal history experienced during fabrication. In this study, a numerical model is employed for predicting the temperature distribution, local temperature gradients and cooling rates in Ti-6Al-4V parts fabricated using laser-powder bed fusion (L-PBF). To be useful, the simulation was designed as to take a reasonable amount of time to perform while retaining sufficient physical fidelity so as to yield trustworthy results. This was addressed through adaptive mesh refinement, which localizes more resolution in the vicinity of the active material transformation. To overcome the computational challenges when simulating the fabrication of a part with dimensions of cubic centimeters, individual powder layers and laser scan lines are no longer resolved. Multiple layers are lumped together and a larger “effective” laser beam is employed. The model has been validated using thermocouple measurements of the L-PBF process.

2:40 PM Break

Melt Pool I: Fluid Dynamics and Phenomena

Monday PM — Room: Heritage Room
June 18, 2018 — Location: NIST Headquarters

Session Chair: Manyalibo Matthews, Lawrence Livermore National Laboratory

1:30 PM Invited

In Situ Characterization of Laser Metal Additive Manufacturing Using High-speed X-ray Techniques: *Tao Sun*[1]; Lianyi Chen[2]; Anthony Rollett[3]; [1]Argonne National Laboratory; [2]Missouri University of Science and Technology; [3]Carnegie Mellon University

At the Advanced Photon Source (APS), we recently applied high-speed x-ray imaging and diffraction techniques for in situ studying laser metal additive manufacturing (AM) processes. The high-penetration power of high-energy x-rays make it possible to look through dense metallic materials and watch the dynamic structural evolution during the laser-metal interaction. Many significant phenomena, including vapor depression, melt pool dynamics, powder-spatter ejection, and phase transformation, were quantitatively measured with extremely high spatial (i.e. micrometer) and temporal resolutions (i.e. nanosecond). These experimental results can not only help understand the physics underpinning the formation of various defects in AM parts, but also validate the multi-physics models developed for simulating the laser AM processes. We believe the high-speed hard x-ray techniques will contribute largely to the advance of AM technologies by facilitating the determination of optimal processing conditions, design of new alloys, and development of innovative techniques for manufacturing functionally graded and multi-materials products.

2:00 PM

Transient Dynamics of Powder Spattering in Laser Powder Bed Fusion Additive Manufacturing Process Revealed by In-situ High-speed High-energy X-ray Imaging: Qilin Guo[1]; Cang Zhao[2]; Luis I. Escano[1]; Lianghua Xiong[1]; Wes Everhart[3]; Tao Sun[2]; *Lianyi Chen*[1]; [1]Missouri University of Science and Technology; [2]Argonne National Laboratory; [3]Department of Energy’s Kansas City National Security Campus Managed by Honeywell FM&T

Powder spattering is a major cause of defect formation and quality uncertainty in the laser powder bed fusion (LPBF) additive manufacturing (AM) process. The detailed dynamics of powder spattering in the LPBF are still not fully understood. Here, we report insights into the transient dynamics of powder spattering in the LPBF process that were observed with in-situ high-speed high-energy x-ray imaging. Powder motion dynamics, as functions of time, environment pressure, and location, are presented. The moving speed, acceleration, and driving force of powder motion that are induced by metal vapor jet/plume and argon gas flow are quantified. A schematic map showing the dynamics and mechanisms of powder motion during the LPBF process as functions of time and pressure is constructed. Potential ways to mitigate powder spattering during the LPBF process are discussed and proposed, based on the revealed powder motion dynamics and mechanisms.

2:20 PM

A Novel Method for the Surface Tension Modeling in Laser Powder-bed Fusion Additive Manufacturing: *Min Zheng*[1]; Lei Wei[1]; Xin Lin[1]; Wei dong Huang[1]; [1]Northwestern Polytechnical University

The three dimentional height functions(HF)-lattice Boltzmann method(LBM) coupled model is developed to study the melt flow in selective laser melting process.Since the shape of melt track will effect the performance of final parts,there is a need to capture the free surface of the melt accurately.In view of the high performance of HF in calculating the curvature and the high computational efficiency of LBM,we establish an approach coupling these two method together to account for the surface tension of the melt flow.Results suggest that the HF-LBM model can be a new alternative to incorporate surface tension and surface tension rather than gravity drives the melton powder particles together in selective laser melting process.We also study the influences of marangoni and recoil force on the shape evolution of the flow.

2:40 PM Break

Microstructure I: Alloy Design and Differentiation

Monday PM June 18, 2018

Room: West Square
Location: NIST Headquarters

Session Chair: Carelyn Campbell, National Institute of Standards and Technology

1:30 PM Invited
New High Performance Fe, Al and Ti-based Alloys Designed Specifically for Additive Manufacturing Processes: *Ricardo Komai*[1]; Thomas Kozmel[1]; Chantal Sudbrack[1]; Abhinav Saboo[1]; Chris Kantner[1]; Dana Frankel[1]; Greg Olson[1]; [1]QuesTek Innovations LLC
Current alloys used in Additive Manufacturing were originally designed to be processed via traditional metallurgy paths such as forging and have different microstructures and properties when put through AM processes. Additionally, heat treating AM-built alloys according to standard industry practice causes material performance issues. New material chemistries designed specifically for AM processing and the subsequent thermal processing steps tailored for the unique microstructures must be developed to enable AM components to reach enhanced performance. QuesTek has been using Integrated Computational Materials Engineering technologies to optimize legacy alloys and design entirely new alloys tailored specifically for AM, and also to optimize post-build heat treatments across a variety of alloy systems including Al, Ti, Ni, Cu, W, Fe and stainless steel. This talk will provide insights into QuesTek's ICME modeling approach for AM and component design opportunities based on several ongoing projects where properties are being demonstrated in powder and wire AM.

2:00 PM
Use of PFIB-SEM and TEM in Materials Characterization and Engineering for Metallic Additive Manufacturing: *Brandon Van Leer*[1]; Kristin Mulherin[1]; [1]Thermo Fisher Scientific
DualBeam FIB-SEM instrumentation has offered new insights to micro- and nano-scale characterization of materials and enabled researchers to better understand a variety of complex materials and engineering questions including atomic structure of materials, interfacial stress or morphological and phase characterization. Much consideration has been given to the number of times metal feedstock can be reused for additive manufacturing without degrading the performance factors of the material. DualBeams offer a way to characterize the microstructure of the powders via conventional electron imaging, analytical techniques like EDS or EBSD or prepare S/TEM samples for high resolution techniques in a TEM. This talk will compare and contrast the microstructural differences between raw and recycled feedstock and describe a Xe+ Plasma Focused Ion Beam-Scanning Electron Microscope (PFIB-SEM), which extends a conventional DualBeam's ability to characterize features in the mesoscale as compared with the micron-scale.

2:20 PM
Martensitic Transformations in Ti-6Al-4V (ELI) Alloy Manufactured 3D Printing: *Nataliya Kazantseva*[1]; P. Krakhmalev[2]; I. Yadroitsev[3]; M. Thuvander[4]; A. Fefelov[5]; N. Vinogradova[1]; I. Ezhov[1]; [1]Institute Of Metal Physics; [2]Karlstad University; [3]Central University of Technology, Free State, Department of Mechanical and Mechatronic Engineering; [4]Department of Physics, Chalmers University of Technology; [5]Regional Engineering Center of Laser and Additive Technology, Ekaterinburg
Comparative study of the structure and phase transformation in Ti6Al4V samples is presented. We used two EOSINT M280 machines (EOS GmbH) from two scientific centers (Russia and South Africa) for the manufacturing of the alloys by the direct metal laser sintering. The chemical composition of used powders complies with the ASTM F-136 (grade 5), ASTM B348 (grade 23) standard for medical applications. It is found that the structure of 3D printed samples show two different variants of metastable martensitic phases, namely HCP alpha prime martensitic phase and small amounts of the orthorhombic alpha double prime martensitic phase. Atom probe tomography (APT) confirmed localization of ß-stabilizing elements at interfaces. The structure and origin of martensitic phases in 3D printed titanium alloys are discussed. This work is supported by Russian Fund of Basic Research N 17-03-00084, South African Research Chairs Initiative of the Department of Science andTechnology and National Research Foundation of South Africa (Grant No97994), the Collaborative Program in Additive Manufacturing (Contract NoCSIR-NLC-CPAM-15-MOA-CUT-01) and, the Swedish Agency for Economic and Regional Growth, (Grant No20201144).

2:40 PM
Quantitative Prediction for Static Recrystallization Nucleation during Heat Treatment at the Overlap Zone of AMed Inconel 718 Superalloy: *Xinbo Qi*[1]; Yong Li[1]; Zhongjiao Zhou[2]; Changpeng Li[2]; Guofeng Chen[2]; [1]Tsinghua University; [2]Siemens Ltd, China
Residual stress usually distributes in Additive Manufactured (AMed) part, especially at the overlap zone. It is evidenced that heat treatment is a valid way to release residual stress. Furthermore, if static recrystallization occurs during heat treatment, it provides an extra freedom to manipulate grain texture. Hence, it is essential to quantitatively predict whether recrystallization nucleates or not in order to find an optimal heat treatment configuration for AMed parts. Here, we utilize the criteria proposed by Zurob et.al. to predict the critical incubation time and critical stress for static recrystallization at the overlap zone of AMed Inconel 718 superalloy. The calculated results indicate that the incubation time increases with the decreasing Maximum Residual Stress at the overlap zone. The criteria is then compared to heat treatment experiments for Selective Laser Melted and Electron Beam Melted In718 alloy, and good agreements between calculations and experiments are achieved.

3:00 PM Break

Multi-Scale Simulations I

Monday PM June 18, 2018

Room: Lecture Room D
Location: NIST Headquarters

Session Chair: Gretar Tryggvason, Johns Hopkins University

1:30 PM Invited
Leveraging Exascale Computational Resources for Simulation of Additively Manufacturing Processes: *John Turner*[1]; James Belak[2]; Curt Bronkhorst[3]; Lyle Levine[4]; [1]UT-Battelle / Oak Ridge National Laboratory; [2]Lawrence Livermore National Laboratory; [3]Los Alamos National Laboratory; [4]National Institute of Standards and Technology
The Exascale Additive Manufacturing Project (ExaAM) is a collaboration between U.S. Dept. of Energy laboratories as part of the Exascale Computing Project (ECP, https://exascaleproject.org/). ECP is a broad program including research efforts in hardware component and system design, system software, and science application development to deploy a computational ecosystem capable of delivering at least fifty times the performance of today's largest systems. ExaAM is one of the applications selected for the development and implementation of models that would not be possible on even the largest of today's computational systems. With the prospect of Exascale computing resources in mind, ExaAM is coupling high-fidelity sub-grid simulations within continuum process simulations to determine microstructure, properties, and hence performance using local conditions. We briefly describe the approach being taken in ExaAM, which involves integrating and extending existing physics components for microstructure evolution, melt pool dynamics, polycrystalline properties, and part scale performance.

2:00 PM Invited
Effect of Chain Alignment on Thermal Welding in Fused Filament Fabrication: Marco Galvani[1]; Thomas O'Connor[1]; *Mark Robbins*[1]; [1]Johns Hopkins University
Extrusion in fused filament fabrication is typically fast enough to produce significant chain alignment that may change welding in several ways. Some studies suggest that alignment may enhance interdiffusion because of the entropic force driving chains towards unaligned conformations or by reducing entanglement density. Alignment of strong backbone bonds along the interface may also change the mechanical properties of material near the joint. We have used molecular dynamics simulations of a generic polymer model to examine the effect of alignment on the dynamics of welding and evolution of weld strength. Entropy drives chain retraction in the tube, but this does not speed interdiffusion since the tubes are aligned along the interface. There is also no indication of accelerated interdiffusion due to entanglement loss. Alignment does reduce the strength of bulk material. At intermediate times this greatly enhances weld strength by moving failure away from the interface.

2:30 PM
Predicting Deformation and Cracking as a Function of Additive Manufacturing Process Parameters: Cornelia Altenbuchner[1]; Kevin Wheeler[1]; *Richard Otis*[1]; Andrew Shapiro[1]; [1]Jet Propulsion Laboratory
A key challenge in maturing metal additive manufacturing (AM) technology is contending with heterogeneity of the thermal profile due to differences in part geometry and build orientation. Even if the process metallurgy of a given alloy is well-understood, these part-level differences lead to empirical process optimization work being required for every new part, or even between revisions of the same design. In this work, a part-level FEM model of residual stresses is combined with a CALPHAD-based phase transformation model to predict part deformation due to thermal stresses, as well as cracking due to precipitation of brittle intermetallic compounds, during the AM building process. In addition to enabling faster optimization of process parameters, this work is a step toward fully-coupled, part-level thermomechanical simulation of the additive manufacturing process, including secondary phase precipitation.

2:50 PM Break

Materials Performance and Residual Stress II: Mitigating Residual Stress Effects

Monday PM	Room: Lecture Room B
June 18, 2018	Location: NIST Headquarters

Session Chair: Maria Strantza, Los Alamos National Laboratory

3:20 PM Invited
Stress, Distortion, and Temperature Prediction of AM Processes Using Multi-scale FEA: *Pan Michaleris*[1]; Erik Denlinger[1]; Michael Gouge[1]; Chao Li[1]; [1]Autodesk
A primary challenge for Laser Powder Bed Fusion (LPBF) to become a reliable and economically feasible method of component production is the buildup of stress and warping of parts during production. This study shows through simulation-experimental comparisons that this software can be used to make timely and useful predictions of distortion for common AM metals. It will also document the successful modeling of the secondary failure mechanisms of support structure delamination and recoater blade interference. Simulation based distortion mitigation will be demonstrated by simulating a part and compensating the build geometry to reduce deformation. Finally, the concept of multi-scale modeling will be extended to the prediction of hot-spots and lack of fusion related defects on Part-Level AM builds. Simulations of large models (10M+ equations) are used to demonstrate the scalability of the concepts.

3:50 PM
Prediction of Powder Bed Fusion Part Manufacturability and CAD Conformity: Pierre-Adrien Pires[1]; Olivier Desmaison[1]; Joerg Willems[1]; *Mustafa Megahed*[1]; [1]Esi Group
Powder Bed AM is reshaping industries by offering design freedom, reducing material waste and post-processing steps. The energy used during the process leads to distortions that may interrupt the process, distort the final component significantly and residual stresses may lead to cracking. In order to prevent process failures, quick redictive tools are used to assess distortions from the first layer to the removal of the piece from the baseplate. As-built residual stresses are accurately predicted enabling planning of post processing steps.The modelling approach is summarized before presenting several validation cases addressing challenges like thin gaps and walls. Application of the tools to an industrial part will then be presented; specifically focusing on support structure relocation and optimized orientation. Comparing numerical recommendations with manufacturing experience verifies the tool relevance for industrial activities.

4:10 PM
Design against Distortion for Additive Manufacturing: *Anas Yaghi*[1]; Sabino Ayvar-Soberanis[2]; Shanmukha Moturu[3]; Ravi Bilkhu[2]; Shukri Afazov[1]; [1]Manufacturing Technology Centre; [2]Advanced Manufacturing Research Centre; [3]Advanced Forming Research Centre
This paper presents the methodology and findings of a novel piece of research with the purpose of understanding and mitigating distortion caused by the combined processes of additive manufacturing (AM) and post machining to final specifications. The research work started with the AM building of a stainless steel 316L industrial impeller that was then machined by removing around 0.5mm from certain surfaces of the impeller's blades and hub. Distortion and residual stresses were experimentally measured.The manufacture of the impeller by AM and then machining was numerically simulated by applying the finite element (FE) method. Distortion and residual stresses were simulated and validated. The FE distortion was then used in a numerical procedure to reverse distortion directions in order to compensate for them and produce a new impeller with mitigated distortion. The results have shown that distortions in the new impeller, on average, have reduced to less than 50% of the original non-compensated values.

4:30 PM
Mechanical and Metallurgical Characterization of Topology Optimized SS-316-L Parts Fabricated by Additive Methods: *Behzad Rankouhi*[1]; Kaila Bertsch[1]; Mythili Thevamaran[1]; Dan Thoma[1]; Krishnan Suresh[1]; [1]University of Wisconsin-Madison
In this work, we aim to rationalize the performance of topology optimized components made by additive manufacturing (AM), through mechanical and metallurgical tests. A benchmark component was topologically optimized and fabricated using laser engineering net shaping (LENS®) and selective laser melting (SLM). Mechanical and metallurgical properties of these components were investigated and compared against computer models under uniaxial displacement-controlled tensile loading. The microstructures of AM components were compared before and after deformation using scanning electron microscopy, electron backscattered diffraction, and transmission electron microscopy to determine the origin of the differences in mechanical response. Microstructural characteristics such as porosity, grain morphology, and crystallographic texture were evaluated in an attempt to relate the mechanical performance, microstructural characteristics, and processing parameters. These findings are helpful in better understanding of the correlation between design, microstructure and mechanical performance of load bearing components.

Melt Pool II: Obtaining and Using Melt Pool Information

Monday PM
June 18, 2018

Room: Heritage Room
Location: NIST Headquarters

Session Chair: Jarred Heigel, National Institute of Standards and Technology

3:20 PM Invited
Towards and Integrated Process Control Software Toolbox for Metal Additive Manufacturing: *Mark Cola*[1]; Darren Beckett[1]; Michael Brennen[1]; Alberto Castro[1]; Alonso Peralta[1]; [1]Sigma Labs, Inc
This presentation reports on spatial (3D) and temporal (time-based) quantitative, in-process quality metric™ (IPQM®) data based on interrogation of "attributes of the process" not "attributes of the part". These IPQM®s were inferred from and reported on using the in-process dynamical behaviors of the melt pool at a scan, layer and part level. Effects on the melt pool energy balance were first considered and understood before mining the melt pool for representative in-process thermal-history feature data. This feature data was then used to generate 3D point clouds and 2D trend plots of melt pool behavior as a function of process input variables (laser power and laser scan speed). An alloy-specific process map was generated for Alloy 718Plus using variations in laser power, laser scan speed, quantitative density data, and the associated, independently measured in-process quality metric™ data from the melt pool.

3:50 PM
Evaluation of Spectral and Thermal Imaging Sensors for Measurement of Melt Pool Temperature and Dimension with Comparisons to Modeling Results: *James Craig*[1]; Alan Abul-Haj[2]; Tom Wakeman[1]; Alonso Peralta[3]; Edwin Martinez[3]; Mustafa Megahed[4]; Pierre-Adrien Pires[4]; [1]Stratonics Inc; [2]ARA Engineering; [3]Honeywell Aerospace; [4]ESI-Group
Spectral and thermal imaging sensors are evaluated for measurement of melt pool temperature and dimension with comparison to modeling results. Processing parameters play a significant role in the physical conditions of the melt pool produced in laser power bed fusion, LPBF. Melt pool temperature and dimensions are key components of the melting and deposit formation process in LPBF. Under the DARPA Open Manufacturing Program, a measurements effort has been undertaken to develop a data base of the physical characteristics of melt pools in LPBF. Both spectral and thermal imaging sensors have been integrated into a commercial LPBF machine to facilitate experimental measurements. Measurements were obtained for a Design of Experiments, using two processing parameters, laser power and scan speed. Hundreds to thousands of measurements are recorded during the formation process. The measurement statistics are compared with results from models of the melt pool formation process.

4:10 PM
In-situ Process Monitoring of Melt pool, Plume and Spatter Features in Powder Bed Fusion AM Process: *Yingjie Zhang*[1]; Geok Soon Hong[1]; Dongsen Ye[2]; Jerry Y H Fuh[1]; [1]National University of Singapore; [2]University of Science and Technology of China
Powder-bed fusion (PBF) is a promising AM process for end-use part fabrication, however the quality repeatability and reliability is crucial for its wider acceptance in industry. The information of melt pool, plume and spatter are related to the built-part quality. However, their signals are convoluted as an effect caused by the combination of heat, mass and momentum transfer. To further investigate their capability on process anomalies detection, a machine vision system with a novel image processing technique is proposed for in-situ side-viewing process monitoring. It allows to extract respective features of melt pool, plume and spatters. The capability of quality level identification by using the extracted features was studied via the support vector machine (SVM) classification algorithm. The results demonstrate that features of plume and spatter are potential quality indicators, and the feature fusion of melt pool, plume and spatter can significantly improve the accuracy of quality level identification.

4:30 PM
Effect of Laser Power and Scanning Velocity on Selective Laser Melting (SLM) Part Using 3-Dimensional Finite Element Method: *Abattouy Mohammed*[1]; [1]FSTT
Additive manufacturing (AM) or known as 3D printing is a direct digital manufacturing process where a 3D part can be produced, layer by layer from 3D digital data with no use of conventional machining Modeling the AM process provides an important insight into physical phenomena that lead to improve final material properties and product quality and predict the final workpiece characteristics. It's very challenging to measure the temperature gradient due to the transient nature and small size of molten pool on SLM. A 3-dimensional finite element model has been developed to simulate multilayer deposition to predict temperature gradient on melting pool and study the effect of laser power and scanning velocity on SLM part, as well as a review of different models used to simulate the selective laser melting is given

Microstructure II: Characterization and Behavior I

Monday PM
June 18, 2018

Room: West Square
Location: NIST Headquarters

Session Chair: Andrew Allen, National Institute of Standards and Technology

3:20 PM Invited
Three Dimensional Characterization of AM 316L Stainless Steel: *David Rowenhorst*[1]; Lily Nguyen; Richard Fonda; [1]Naval Research Laboratory
Predicting and validating the behavior of Additively Manufactured (AM) materials requires a proper understanding of the underlying microstructure. The AM process tends to produce much more complicated microstructures than what is typically observed in traditional processing. In the case of as-built AM 316L, the AM microstructure features complex columnar growth that is not easily derived from simple 2D analysis. We will show how EBSD serial sectioning can be used to characterize this complex structure by collection thousands of grains in an as-build AM 316L material, revealing true grain shapes, morphological and crystallographic neighbor correlations. These features will be related to the non-equilibrium solidification and rapid quenching process present during the AM process.

3:50 PM Invited
Microstructural Evolution during Post-build Thermal Processing of Additively Manufactured Inconel 625: *Eric Lass*[1]; Mark Stoudt[1]; Michael Katz[1]; Maureen Williams[1]; [1]National Institute of Standards and Technology
The microstructure and properties of laser powder-bed fusion produced Inconel 625 (IN625) are quite different than those of the conventional cast/wrought alloy. The as-built material exhibits a highly microsegregated solidification microstructure, where interdendritic regions are enriched in solute elements Mo and Nb. These local compositional heterogeneities give rise to enhanced precipitation behavior of secondary phases during post-build stress-relief annealing, such as the orthorhombic Ni_3Nb δphase and the tetragonal Ni_3Nb δ-phase. Precipitation in AM IN625 occurs one hundred times faster than in wrought IN625 and ten times fast than in IN625 welds. Dissolution of the precipitates, or avoiding their formation, requires annealing well above their equilibrium solvus temperature. Homogenization eliminates the solidification microstructure, mitigating the enhanced precipitation kinetics and any potential degradation of properties while in service. The microstructure and properties of homogenized AM IN625 are more reproducible than as-built or stress-relieved material, and approach those of conventional wrought material.

4:20 PM Invited
The Relationship Between Post-build Microstructure and the Corrosion Resistance of Additively-manufactured Alloys: *Mark Stoudt*[1]; Eric Lass[1]; Maureen Williams[1]; Richard Ricker[1]; [1]National Institute of Standards and Technology
The AM build process creates segregated microstructures with significant variations in local composition and phases that are uncommon in traditional wrought alloys. These microstructural heterogeneities promote variability in mechanical performance, but the influence on corrosion resistance is not well understood. Consequently, examinations of the relationships between post-build heat treatment, microstructure and corrosion resistance are being performed in representative environments for two industrially-relevant alloys, Inconel 625 and SS17-4. Wrought IN625 is a solid-solution strengthened, nickel-based super alloy, but the as-built material exhibits a highly microsegregated solidification microstructure, where the interdendritic regions are enriched in Mo and Nb. Wrought SS17-4 steel is primarily a martensite matrix with delta-ferrite stringers, whereas the as-built microstructure of nitrogen-atomized SS17-4 is a mixture of alpha-ferrite and austenite that does not easily transform to martensite. However, it has shown enhanced pitting resistance. The results will be presented and compared to the wrought conditions of both alloys.

Multi-Scale Simulations II

Monday PM
June 18, 2018

Room: Lecture Room D
Location: NIST Headquarters

Session Chair: John Turner, UT-Battelle / Oak Ridge National Laboratory

3:20 PM Invited
Multiresolution Process-structure-property Prediction for Metal-based Additive Manufacturing: *Wing Liu*[1]; Zhengtao Gan[1]; Yanping Lian[1]; Gregory Wagner[1]; Orion Kafka[1]; Cheng Yu[1]; Stephen Lin[1]; [1]Northwestern University
This presentation introduces a multiresolution approach, where various multiscale multiphysics simplifications of process-structure-property relationships are used. The multiresolution approach includes three levels: (1) part-scale model which only considers heat transfer; (2) thermal-fluid model which in addition couples thermal-fluid flow; (3) powder-scale model which further accounts for detailed melting and solidification of individual powders. To obtain microstructure and properties at multiple resolutions, the combination of the three process models with a cellular automaton (CA) model has been developed, as well as crystal plasticity self-consistent clustering analysis (CPSCA). We will present five technologies: the MPI-based parallel thermodynamics code GAMMA, the coupled multiphase thermo-fluid flow code AM-CFD, the powder-scale code interfaced with Flow3D, the grain growth code CAFE and the mechanical properties prediction code CPSCA. The predicted process-structure-property information as well as possible validation methods is summarized, which rationalizes the design of the next AM-Bench.

3:50 PM
Data-driven Machine Learning Approach to Analyze the Relationships between Additive Manufacturing Process Parameters and Material Performance: *Annie Wang*[1]; Zach Simkin[1]; [1]Senvol
This presentation showcases an ongoing STTR project funded by the Navy. The technology being developed is a data-driven machine learning algorithm for additive manufacturing (AM). A modularized ICME probabilistic framework for AM data serves as the foundation for Senvol's technical approach. In this framework, AM data is categorized into four modules: Process parameters, process signatures, material properties, and mechanical performance. The algorithm being developed quantifies relationships between the four modules. The algorithm is also material, machine and process agnostic. The Navy intends to use this algorithm to assist in developing statistically substantiated material properties in hopes of reducing conventional material characterization and testing that is needed to develop design allowables. We will discuss why a data-driven machine learning algorithm was employed over other modeling approaches, along with its advantages and disadvantages. We will also discuss some of the data that we have collected and demonstrate some of the algorithm's capabilities.

4:10 PM
Towards Large-scale Modeling of Powder Bed Additive Manufacturing: *Pramod Zagade*[1]; BP Gautham[1]; Amitava De[2]; [1]TCS Research, TRDDC, Tata Consultancy Services; [2]Indian Institute of Technology, Bombay
Modelling of large scale structures produced through powder bed AM remains challenging due to diversity in length scales at which process events occur. Detailed models of melting, solidification and subsequent evolution of thermo-mechanical distortion and stresses from a localized small-scale to a relatively larger dimension are yet unavailable. The purpose of present work is to investigate the feasibility of creating computationally efficient models based on detailed simulations at small scale that can be augmented for predictions of process features in larger dimensions. Local region made of few layers, hatches is considered for detailed study. Transient thermal model is implemented in FE software and validated with results from literature. The effects of laser power, scanning speed and direction on thermal behavior and evolution of microstructural features are studied for Ti6Al4V alloy. An attempt is made to develop process-structure-property relations in the form of easy to use maps based on computed results.

4:30 PM
FEMPAR-AM: A Parallel Finite-element Framework for the Simulation of Metal Additive Manufacturing: *Eric Neiva*[1]; Santiago Badia[1]; Michele Chiumenti[1]; Alberto F. Martín[1]; Francesc Verdugo[1]; [1]Centre Internacional de Mètodes Numèrics en Enginyeria
The numerical simulation of metal Additive Manufacturing (AM) processes involves dealing with multiple scales in space and time, coupled multiphysics, and complex and growing-in-time geometries. This leads to extremely expensive high-fidelity analyses, where body-fitted meshes are not suitable. To overcome this challenge, a highly-scalable parallel FE framework for the thermal analysis in metal AM at the component scale has been recently developed by the authors. The main features are: (1) the modelling of the deposition process with a parallel search, (2) octree meshes that are refined and coarsened following the laser movement, and (3) implicit representations of the geometry with unfitted FE methods.Numerical experiments will be presented to assess the framework's ability to deal with large size problems and complex geometries. Finally, iterative mathematical tools will be used to calibrate and validate the model against physical experiments executed at the Monash Centre for Additive Manufacturing (Melbourne, Australia).

Tuesday Plenary Session

Tuesday AM
June 19, 2018

Room: Green Auditorium
Location: NIST Headquarters

Session Chair: Richard Fonda, Naval Research Laboratory

8:30 AM Plenary

Absorptivity Measurements in Laser Powder-bed Fusion Additive Manufacturing: Laser Parameters, Materials Dependence and Model Validation: *Manyalibo Matthews*[1]; Jianchao Ye[1]; Gabe Guss[1]; M. Crumb[1]; Saad Khairallah[1]; John Roehling[1]; A. Rubenchik[1]; [1]Lawrence Livermore National Laboratory

Absorption of laser radiation in Laser Powder Bed Fusion (LPBF) is a complex process involving multiple reflections along an irregulate surface, light interaction with metal vapor and material phase transitions. Experimental measurements are needed to clarify the physics of the process and to validate modeling. We present direct measurements of the absorptivity for different materials (SS316, In625, Ti64) as a function of laser power, scan velocity and beam diameter. We demonstrate that absorptivity, with reasonable accuracy, can be approximated by a universal function of normalized enthalpy which is given by the ratio of the deposited laser energy density to the material melting enthalpy. Model predictions are shown to agree well with the experimental data. The results enable methods to rescale the optimal processing parameters between different materials and machines. Prepared by LLNL under Contract DE-AC52-07NA27344.

9:00 AM Plenary

The Exascale Additive Manufacturing Project (ExaAM): Coupling Microstructure Development with Continuum Thermomechanics*: *James Belak*[1]; John Turner[2]; Curt Bronkhorst[3]; [1]Lawrence Livermore National Laboratory; [2]Oak Ridge National Laboratory; [3]Los Alamos National Laboratory

The Exascale Additive Manufacturing (ExaAM) application development project is a partnership between ORNL, LANL, and LLNL whose goal is a modeling and simulation environment to compliment experiment and to qualify and realize the potential of AM parts. Here, we present our coupled exascale simulation environment for AM focusing on microstructure development during the melt-resolidification process and mechanical properties of AM microstructures. Macroscopic continuum codes (Truchas and ALE3D) are used to simulation the metal melt-refreeze, within which mesoscopic codes (Phase-field and Cellular Automata) are used to simulate the development of microstructure. These AM microstructures are then use in crystal plasticity codes (ExaConstit) to calculate local material properties.* Work performed under the auspices of the U.S. DOE by LLNL, LANL and ORNL under contracts DE-AC52-07NA27344, DE-AC52-06NA25396, DE-AC05-00OR22725, and supported by the Exascale Computing Project (17-SC-20-SC), a collaborative effort of the U.S. DOE Office of Science and the NNSA.

9:30 AM Plenary

Improved Process Control for SLS Processing: Adam Lewis; Timothy Phillips; Samantha Taylor; Scott Fish[1]; *Joseph Beaman*[2]; [1]University of Texas at Austin; [2]University of Texas

Recent work in our group includes discovery of statistically significant correlations between part properties and thermal camera data, improved post-sinter temperature uniformity through laser control, and the development and application of OCT as a new process sensor in the Selective Layer Sintering (SLS) process. This talk will discuss the results from this work and how this can lead to Additive Manufactured parts with more consistent properties. The correlation project focused on finding correlations between tensile strength, elongation to break, and fracture location and the observed thermal history of manufactured parts. The improved post-sinter temperature uniformity work was motivated by the fact that the quality of selectively laser sintered parts relies heavily on the temperatures at which the polymer was processed. The OCT sensor has enabled depth resolved spatial measurements (such as scan line depth on overhang portions of layers) in SLS.

10:00 AM Break

Tuesday Benchmarks

Tuesday AM
June 19, 2018

Room: Green Auditorium
Location: NIST Headquarters

Session Chair: Kalman Migler, National Institute of Standards and Technology

10:20 AM Invited

Establishing Benchmark In-situ Melt Pool Measurements on the NIST Additive Manufacturing Metrology Testbed: *Brandon Lane*[1]; Ivan Zhirnov[1]; Vladimir Khromschenko[1]; Steven Grantham[1]; Sergey Mekhontsev[1]; [1]National Institute of Standards and Technology

The NIST Additive Manufacturing Metrology Testbed (AMMT) is a unique facility that enables broad and flexible research into the additive manufacturing process. Foremost, the AMMT instrumentation enables in-situ melt pool temperature measurements, as well as surface reflectance/emittance, and in-situ calibration sources with traceability to the NIST primary standards. This talk briefly introduces the overall system and highlights several unique design features. The experiment setup for the AMB2018-02 single-track benchmark test is presented, including description of the temperature calibration, melt pool image analysis, and melt pool geometry and cooling rate results. Finally, some of the most recent advancements are presented, including plans for improving and standardizing procedures and measurements for additive manufacturing benchmark tests.

10:50 AM

Topographic Analysis of AM-bench Laser Tracks: *Richard Ricker*[1]; Brandon Lane[1]; Jason Fox[1]; Jarred Heigel[1]; [1]National Institute of Standards and Technology

Additive manufacturing is a complex process that incorporates all the complexities of materials processing with constraints imposed by product shape and physics. For laser powder bed fusion (L-PBF), single autogenous laser tracks on bare metal plates promise to provide data free of variability due to the stochastics of the powder layer and consolidated substrate. The AM Bench challenge (CHAL-AMB2018-02-TP) was selected for this purpose. This paper presents the results of topographic analysis of this artifact using scanning laser microscopy. This data will be compared to in-situ measurements made on this artifact as it was being built in the NIST Additive Manufacturing Metrology Testbed. Methods for presenting and archiving this data will be discussed.

11:20 AM

Characterizing the Post-Build Microstructures of the AM Benchmark Artifacts: *Mark Stoudt*[1]; Maureen Williams[1]; Sandra Claggett[1]; Lyle Levine[1]; [1]National Institute of Standards and Technology

The AM build process creates segregated microstructures with significant differences from those of traditional wrought alloys. Understanding how the local build conditions generate specific microstructures is key to developing post-build heat treatments with the goal of producing parts with reliable and predictable properties. This presentation examines the local microstructures from thoroughly characterized locations within the 3D builds and individual laser traces. Detailed characterizations of these as-built microstructures are discussed for both the IN625 and 15-5 AM-Bench artifacts, including the solidification microstructures, compositional heterogeneities, grain structures and orientations, and melt pool geometries. Submitted simulation results for the microstructure challenges will be compared to these benchmark measurement results.

11:50 AM
Benchmark Structure and Microstructure Tests of Inconel 625 and 15-5 Stainless Steel using Synchrotron X-ray Techniques [AMB2017-01]: *Fan Zhang*[1]; Lyle Levine[1]; Andrew Allen[1]; [1]National Institute of Standards and Technology
Additive manufacturing (AM) of metals, due to its complex thermal cycle, often leads to microstructures different from those of conventionally manufactured alloys. As a key element of the structure-process-property relationship, the statistically meaningful atomic structures and microstructures of AM alloys must be understood. We made use of synchrotron-based high-resolution powder X-ray diffraction (XRD) to probe the phases and phase fractions in the as-built Inconel 625 and 15-5 SS specimens prepared from different-sized legs of the benchmark bridge structure. We also performed combined ultra-small-angle X-ray scattering (USAXS), small-angle X-ray scattering (SAXS), and XRD experiments on the same set of samples at post-build heat treatment conditions. The in situ USAXS/SAXS/XRD experiments, which encompass a length scale from sub-angstrom to micrometers, provide insights into the phase-evolution landscape and its related kinetics, information important in predicting the mechanical properties of the alloys.These measurements correspond to AM-Bench modeling challenges CHAL-AMB2018-01-PF and CHAL-AMB2018-01-PFRS.

Materials Performance and Residual Stress III: Optimizing Mechanical Behavior

Tuesday PM
June 19, 2018

Room: Lecture Room B
Location: NIST Headquarters

Session Chair: Eric Lass, National Institute of Standards and Technology

1:30 PM Invited
Multiscale and Micromechanics Based Design of Fatigue Resistant Metal AM Solutions: *Anssi Laukkanen*[1]; Tom Andersson[1]; Tatu Pinomaa[1]; Matti Lindroos[1]; [1]VTT Technical Research Center of Finland
Part performance against fatigue is critical to metal AM solutions. Overall two options are available for improving fatigue design of AM components: product manufacturing optimization to minimize defects responsible for fatigue and increasing accuracy of analysis to better capture material features critical for fatigue life. We present a multiscale approach capturing features at part to microstructural scales in order to link part manufacturing to micromechanical analysis of fatigue. The resulting simulation workflow can be utilized to both evaluate defect generation mechanisms and their criticality when the part is subjected to operational cyclic loading. The presented micromechanical modeling founded on crystal plasticity can capture material features critical to fatigue, particularly surface roughness, internal defects such as porosity and on the other hand inclusions in material microstructure. Use cases for metallic materials such as maraging and stainless steel are presented, different defect types evaluated with respect to their impact to product lifetime.

2:00 PM
Effects of Internal Porosity and Anisotropic Microstructure on Instrumented Charpy Impact Energy for EBM Ti-6Al-4V: *Nik Hrabe*[1]; Enrico Lucon[1]; Ryan White[1]; [1]National Institute of Standards and Technology
EBM Ti-6Al-4V material was characterized in four conditions to ascertain the effect of internal porosity and anisotropic microstructure on instrumented Charpy impact energy. Testing material before and after hot isostatic pressing (HIPing) enabled investigation of the effect of internal porosity. Testing both horizontal (crack propagates parallel to build direction) and vertical (crack propagates perpendicular to build direction) orientations of mini-Charpy specimens enabled investigation of the effect of anisotropic microstructure (elongated prior-ß grains and associated texture). An increase in Charpy impact energy was observed through a decrease in internal porosity during HIPing (verified by x-ray computed tomography). Negligible differences in Charpy impact energy were observed for horizontal and vertical specimens, despite observed differences in fracture surface features and differences in crack propagation direction with respect to the observed anisotropic microstructure (elongated prior-ß grains and associated texture characterized using electron backscatter diffraction (EBSD)).

2:20 PM
Impact of Powder Supply Variation on Mechanical Properties for Additive Manufacture of Alloy 718: *Cheryl Bowman*[1]; Chantal Sudbrack[2]; Bradley Lerch[1]; Robert Carter[1]; Timothy Smith[1]; David Ellis[1]; [1]NASA Glenn Research Center; [2]Ques Tek Innovations
NASA is pursuing additive manufacturing for unique aerospace component requirements. The selective laser sintering process is being vetted to replace complex, expensive, and long-lead time components for the RS-25 Engine on the Space Launch System. NASA has performed a broad survey of commercially available Alloy 718 powder in order to understand the roll of powder variability on the quality of additively manufactured components. This paper will overview powder variability results and go into greater detail on mechanical characterization of the samples built from these powders. Virgin powder from eight suppliers and sixteen powder lots and three once-recycled powder lots were used to build coupons for room temperature tensile and fatigue testing. After characterizing powders, build microstructures, and mechanical properties from this broader powder supply survey, five lots from four vendors were selected for elevated temperature tensile, fatigue, and creep testing. Preliminary results of the elevated characterization will be presented.

2:40 PM
Micro-tensile Characterization of Additive Manufactured Materials: *Marc Zupan*[1]; Michael Duffy[1]; Joao Santos[1]; Steve Storck[2]; Richard Everett[1]; [1]University of Maryland, Baltimore County; [2]Johns Hopkins University Applied Physics Laboratory
Additive Manufacturing (AM) introduces new factors such as material-, geometry-, position-, and machine-dependent microstructures due to complex thermal profiles associated with consolidation of material on small length scales. This work presents experimentally-determined mechanical properties, using a novel micro-tensile testing technique, that allows for location- and orientation-specific characterization of AM materials that standard tensile testing techniques cannot achieve. In this presentation, we discuss micro-tensile and fatigue testing, with specimens having a footprint of 1 x 3 mm and a gage section of 250 x 250 µm, of non-ferrous AM microstructures derived from unique part geometries. Materials were produced on a laser powder bed fusion (L-PBF) AM system and were consolidated via selective laser melting (SLM). Examples include the effects of build direction, laser power density, and skin vs. core preset sintering parameters. Accurate mechanical properties are vital to validate modeling and predict the performance of AM parts and components.

3:00 PM Break

Microstructure III: CALPHAD Approach

Tuesday PM Room: West Square
June 19, 2018 Location: NIST Headquarters

Session Chair: Ricardo Komai, QuesTek Innovations LLC

1:30 PM Invited
Insights to AM Microstructure Evolution using CALPHAD-based Approaches: *Carelyn Campbell*[1]; [1]National Institute of Standards and Technology
The initial rapid solidification followed by multiple heating and cooling cycles that occur during additive manufacturing (AM) produce unexpected microstructures. The unexpected microstructures provide opportunities and challenges to using AM parts. A variety CALPHAD-based tools can be used to better understand how to control the evolving microstructures during the AM build process and how to process the as-built structures for optimal properties. Several examples of CALPHAD-based tools applied to AM microstructure and property control will be presented, including predicting microsegregation during the build process, optimization of post-build heat treatments, and predicting properties of as-built and post-process AM structures. These examples will also illustrate some of the benefits and limitations of using CALPHAD approaches in evaluating AM microstructure evolutions.

2:00 PM
Simulation of TTT Curves for Additively Manufactured Inconel 625: *Greta Lindwall*[1]; Carelyn Campbell[2]; Eric Lass[2]; Fan Zhang[2]; Mark Stoudt[2]; Andrew Allen[2]; Lyle Levine[2]; [1]KTH Royal Institute of Technology; [2]National Institute of Standards and Technology
The ability to use common computational thermodynamic and kinetic tools to study the microstructure evolution in Inconel 625 (IN625) manufactured using the additive manufacturing (AM) technique laser powder-bed fusion is evaluated. Solidification simulations indicate that laser melting and re-melting during printing produce highly segregated inter-dendrite regions. Precipitation simulations for different degrees of segregation show that the larger the segregation; i.e. the richer the inter-dendritic regions are in Nb and Mo, the faster d precipitation. This is in accordance with the accelerated d precipitation observed experimentally during post-print heat treatments of AM IN625 compared to wrought IN625. The results are presented in the form of a TTT diagram and agreement between the simulated diagram and experimental TTT diagram is obtained and show how these computational tools can be used to guide when optimizing post-print treatments of AM materials.

2:20 PM
Applications of CALPHAD Based Tools to Additive Manufacturing Models: *Adam Hope*[1]; Kaisheng Wu[1]; Paul Mason[1]; [1]Thermo-Calc Software Inc
Finite element modelling of additive processes requires material property data which are not always readily available, especially when using non-standard alloys. CALPHAD tools can calculate properties such as specific heat, density, enthalpy, and mobilities, which can be used as inputs to other codes. These properties are expressed as functions of composition and temperature, which is useful since the additive process can impart large thermal and compositional gradients during a build. More advanced CALPHAD simulations that predict diffusional phase transformation and precipitation behavior can also be used to determine the effect of not only solidification, but also repeated thermal cycling on the final microstructure. As thermal histories will be location specific in a build, these types of simulations can give insight into the local mechanical behavior, when coupled with more advanced structure/property relationships. A few case studies have been highlighted to demonstrate the importance of CALPHAD tools in additive modeling.

2:40 PM
A Fast-acting Microstructural Model for Additive Manufacturing Materials: *Guilherme Faria*[1]; Kamal Kadirvel[1]; Wei Zhang[1]; Yunzhi Wang[1]; Antonio Ramirez[1]; [1]Department of Materials Science and Engineering - The Ohio State University
Taking advantage of fast-acting heat conduction models available for modelling the additive manufacturing process, we present a fast-acting microstructural model (FAMM) that can be directly coupled with thermal models. This coupling allows modelling microsegregation, local variation of precipitates, liquation during reheating, and texture formation, which are all crucial factors determining the performance of as-build part and for designing post-build heat-treatment processes. Comprised of a modified-Scheil model for solidification and Kurtz-Fisher model of dendrite arm-spacing, FAMM takes as input the thermal cycles computed from the thermal models and CalPhaD derived data, and predicts solute segregation and then use such profile to compute spatially resolved Transformation-Temperature-Time curves from which localized precipitation and second phase formation are predicted. The computed segregation profile is also utilized to analyze the effect of thermal cycles from subsequent build layers on homogenization. The model was implemented for L-PBF (Laser- Powder Bed Fusion) process on IN718 as-built parts.

3:00 PM Break

Multi-Scale Simulations III

Tuesday PM Room: Lecture Room D
June 19, 2018 Location: NIST Headquarters

Session Chair: Mark Robbins, Johns Hopkins University

1:30 PM Invited
Linking Additive Manufacturing Process with Part Performance via a Multiscale and Multiphysics Integrated Computational Materials Engineering Framework: *John Michopoulos*[1]; Athanasios Iliopoulos[1]; John Steuben[1]; Andrew Birnbaum[1]; [1]U.S. Naval Research Laboratory
Contemporary AM processes continue to be exhibit process-induced features both from material and geometry perspectives across multiple length scales. AM products suffer from performance issues such as residual stresses and strains, layer delamination, porosity and poor or indeterminate material properties. These issues lead to further uncertainty in functional performance that may preclude usage of AM technology in performance-critical applications.To address these issues our team has embarked on the development of a Multiscale and Multiphysics Integrated Computational Materials Engineering (MMICME) framework for AM. Our description will be the topic of this talk. This framework incorporates multiscale multiphysics modeling and experimentation in order to fully encapsulate the important roles that micro- and meso-structures play in tailoring material properties and responses in engineering applications. The immediate goals of this effort is to enable on-demand control of AM processes for tailoring meso- and micro-structures to endow desirable properties and eliminate undesirable ones.

2:00 PM
Fully Resolved Simulations of Additive Manufacturing Processes: *Gretar Tryggvason*[1]; Huanxiong Xia[1]; Jiacai Lu[1]; [1]Johns Hopkins University
Additive manufacturing processes include complex multiphysics/multiscale processes, and an evaluation of material/process models require accurate solutions of the governing equations to determine how well the predictions of the model agree with experimental results. Here, a numerical method for fully resolved simulations of Fused Deposition Modeling is described. The method is based on a finite volume/front tracking method used earlier for a large number of multiphase systems, extended in several ways. The polymer is modeled as an elasto-plastic

material whose properties depend on the temperature. The residual stresses due to the cooling and shrinking of the polymer as it cools down, the solidification and the deformation due to residual stresses are, in particular, captured. The method is tested using a simple geometry consisting of two short filaments and a more complex geometry, consisting of a two layer infilled rectangle is also simulated to show the capability of the method.

2:20 PM
Methods to Reduce the Computational Time when Simulating Additive Manufacturing: *Andreas Lundback*[1]; Lars-Erik Lindgren[1]; [1]Luleå University of Technology
Modelling of additive manufacturing poses a number of challenges. The differences in length scales is one. The size of the component is typically three orders of magnitude larger than the layer thickness in the powder bed fusion (PBF) process. This makes it challenging to model the full-sized component while resolving the local phenomena that occurs near the heat source. A few approaches using temporal and spatial reduction to reduce the computational time will be presented. One of the methods are lumping layers. In the current example, blown powder and a laser heat source, the computational time was reduced to 5% compared to a fully detailed analysis with maintained accuracy of the resulting deformations. Another method is dynamic local mesh adaptivity. The methods described above introduces simplifications that may or may not be acceptable. It depends on the scope of the simulation and what result that is sought for.

2:40 PM
Modeling Additive Manufacturing Processes using DEFORM: Jaebong Yang[1]; Harigopal Polisetty[1]; Weiqi Luo[1]; Jin Yong Oh[1]; *Shankar Ravi*[1]; Wei Tsu Wu[1]; [1]Scientific Forming Tec Co
We will present AM models demonstrating the capability to slice part geometry into multiple layers and generate compatible layered tetrahedral mesh for each layers. Additionally, voxel mesh with hundreds of layers is generated internally during simulation. By using layered tetrahedral mesh and voxel mesh, AM process can be modeled more efficiently. Few case studies that demonstrates AM modeling capabilities will be presented along with future targeted AM modeling enhancements. These AM models can use laser path and laser energy characteristics along with other relevant processing conditions to predict the temperature distribution, residual stresses and part distortion while considering the support fixtures. AM process models provide insight in to build parameters and its impact on part distortion and helps to effectively design support fixtures for AM processes.

3:00 PM Break

Validation and Verification I: Qualification Metrics and Requirements

Tuesday PM — Room: Heritage Room
June 19, 2018 — Location: NIST Headquarters

Session Chair: Mustafa Megahed, Esi Group

1:30 PM Invited
Towards Simulation Enabled Qualification Metrics in Additive Manufacturing: *Deepankar Pal*[1]; Pradeep Chalavadi[1]; Javed Akram[1]; Abdul Khan[1]; Dave Conover[1]; [1]ANSYS
Qualification enables a manufacturing technique to become reliable and repeatable such that the quality of goods produced could be ascertained. Traditionally manufactured parts are generally qualified using extensive experimentation. This further results in A or B basis design allowables such that 99 or 90 percent of the fabricated parts are above a certain mechanical property threshold. Additive Manufacturing (AM) presents a very complex interaction of materials, process parameters, geometry, scan pattern and the energy source. It is difficult to control these aspects since AM produces grain sizes at the same length scales of the energy source resulting in a coupled design space.In this talk, experimentally validated simulation-based benchmark metrics for as-built thermal signature, distortion and microstructure will be discussed followed by deviations which could be measured using available sensors and could be tolerated for successful and quality manufacture of the parts produced via AM.

2:00 PM
3D Printing Process Controls: *Ryan Siskey*[1]; [1]Exponent
As 3D printing is adopted by regulated industries, the need to perform initial and routine printer qualification is more necessary. Quality systems encourage users to implement process control to understand the range of performance that can be expected from a 3D printer. Tools like the NIST Test Artifact can be used to establish process control and confirm printer precision. The objective of this paper will be to describe the use of the NIST Test Artifact to assessing three commercially available printers used to support a biomedical laboratory. Measuring the printed artifact can be accomplished through a variety of methods. This paper will present the use of a computed tomography method, which enables 3D visualization of geometrical variation and efficient measurement of geometrical features to establish process control limits. Overall, the method has been successfully used to qualify printers from multiple manufacturers and provide data to support statistical process control.

2:20 PM Invited
Supporting Analysis and Traceability for Additive Manufacturing Measurements: Najib Baig[1]; *Debbie Mies*[1]; [1]Granta Design
Qualification and certification (QC) of Additive Manufacturing (AM) require extensive measurements and characterization to understand the material and part properties. However, there are some significant data management and analysis challenges that need to be addressed first. The amount of data generated can reach frightening amounts which makes data access, data analysis and process traceability difficult. Different expensive test types (e.g. tensile, fatigue, creep) are needed from different machines, plus people and departments to characterize a part. Furthermore, simulations can generate gigabytes of data that need to be calibrated with empirical tests. In addition, data from machines, powders and builds needs to be captured and linked to test data to enable process-property relationship analysis.This presentation will discuss a methodology and process to efficiently capture measured and simulated data, enabling instant data access, data analysis and process traceability.

2:50 PM Break

Microstructure IV: Characterization and Behavior II

Tuesday PM
June 19, 2018

Room: West Square
Location: NIST Headquarters

Session Chair: Donald Brown, Los Alamos National Laboratory

3:20 PM Invited
In Situ Operando Measurements of Microstructure & Precipitate Phase Evolution in Additive Manufactured Alloys: *Andrew Allen*[1]; Fan Zhang[1]; Lyle Levine[1]; Jan Ilavsky[2]; [1]National Institute of Standards and Technology; [2]Argonne National Laboratory
Elemental segregation presents problems for additive manufactured (AM) alloys due to solute rejection/redistribution during solidification. During post-build heat treatments designed to remove residual stresses within as-built AM parts, deleterious precipitate phases emerge. We need to measure alloy microstructure and precipitate phase evolution during such anneals under *in situ operando* conditions. This is possible by combining ultra-small-, small-, & wide-angle X-ray scattering & diffraction, USAXS/SAXS/WAXS (XRD), at a high-brilliance X-ray synchrotron source such as the Advanced Photon Source (APS), Argonne National Laboratory. NIST has worked with APS to deliver USAXS/SAXS/WAXS measurements within a few minutes. Microstructure is characterized from several micrometers down to sub-nanometers, together with XRD determination of phase composition. We illustrate *in situ operando* USAXS/SAXS/WAXS studies, used together with other methods, to show that in AM Ni-based superalloy, *Inconel 625*, deleterious δphase precipitates grow during post-build stress reliefs on time scales short compared to wrought alloys (minutes *versus* hours).

3:50 PM
Microstructural Characterization of the Influence of SLM Scan Parameters by Means of X Ray and Neutrons Sources: *Itziar Serrano-Munoz*[1]; René Laquai[1]; Bernd R. Müller[1]; Tatiana Mishurova[1]; Tobias Thiede[1]; Giovanni Bruno[1]; [1]BAM (Bundesanstalt für Materialforschung und -prüfung)
An overview of the main Non-Destructive activities conducted at BAM for the microstructural characterization of Additive Manufacturing (AM) materials will be presented. Focus is made on the study of the influence of Selective Laser Melted (SLM) scan strategies on the defect population of a Ti-6Al-4V alloy using the Analyzer Based Imaging (ABI) technique available at the BAMline (BESSY II synchrotron facility). ABI technique takes advantage of X Ray refraction at interfaces to enable the determination of porosity features (orientation, homogeneity, etc.) within large volumes, otherwise not possible to image by means X ray micro Computed Tomography. Additionally, for a SLM IN718 material, Energy Dispersive X Ray Diffraction (subsurface measurements at 100 µm depth) and neutrons diffraction (internal measurements at 3 mm depth) are combined with distortion measurements to produce a 3D description of the Residual Stress distribution throughout the entire sample.

4:10 PM
In-Situ Deformation Characterization of 3D Printed Stainless Steel: *Soo Yeol Lee*[1]; Hobyung Chae[1]; E-Wen Huang[2]; Stefanus Harjo[3]; Ke An[4]; [1]Chungnam National University; [2]National Chiao Tung University; [3]Japan Atomic Energy Agency; [4]Oak Ridge National Laboratory
In this study, deformation behavior of 3D printed stainless steel was characterized using electron backscatter diffraction (EBSD) and in-situ neutron diffraction. Two types of specimens are prepared: 1) a flat type dog-bone specimen, in which the direction of powder building is perpendicular to the axial loading direction; 2) a cylindrical dog-bone specimen, in which the direction of powder building is parallel to the axial loading direction. The microstructure and phase evolution were examined before and after deformation using EBSD. In-situ neutron diffraction experiment was performed to investigate the influence of manufacturing direction on the deformation behavior of 3D printed stainless steel. Strain partitioning and phase evolution between body-centered cubic and face-centered cubic were quantitatively investigated as a function of applied stress. The variations of lattice parameter, phase fraction changes, and strain hardening mechanisms are demonstrated.

Polymers and Gels I

Tuesday PM
June 19, 2018

Room: Lecture Room D
Location: NIST Headquarters

Session Chair: Gerrit Peters, Eindhoven University of Technology

3:20 PM Invited
Computational and Experimental Analysis of Particle Sintering for SLS: *Patrick Anderson*[1]; [1]Eindhoven University
Selective laser sintering (SLS) is a promising additive manufacturing technique, where products ranging from gadgets to functional industrial parts are made out of locally heated layers of polymer powder. We developed a setup to study the sintering of two powder particles in a controlled environment and in-situ visualization of the sintering dynamics using optical microscopy and X-ray. Furthermore, we developed a computational model using an in-house code based on the finite element method to assess the mechanisms of viscoelastic flow and temperature dependency of two powder particles. Moreover, we investigated the isothermal crystallization of polyamide 12 (PA12) using in-situ synchrotron Wide Angle X-ray Diffraction (WAXD) during Flash-DSC measurements. With these results, we parameterized and validated a new numerical model to quantify the quiescent crystallization kinetics of the three important crystal structures of PA12.

3:50 PM Invited
Selective Laser Sintering of PA-11 Powders Containing Silica Nanoparticles: *Raymond Pearson*[1]; Gabrielle Esposito[1]; Phacharapol Tanasarnsopaporn[1]; [1]Lehigh University
In Selective Laser Sintering (SLS), the Andrew Number is often used to relate the effect of various of laser parameters on print quality. In this work, the addition of various amounts of silica nanoparticles to polymamide-11 SLS powder on the critical Andrew Number for processing will be discussed. A low power, blue diode laser sintering printer is used and the mechanical strength of the processed parts are characterized using both a strength of materials approach and a fracture mechanics approach.

4:20 PM Invited
Weld Formation during Material Extrusion Additive Manufacturing: *Jonathan Seppala*[1]; Seung Hoon Han[2]; Kaitlyn Hillgartner[3]; Chelsea Davis[1]; Kalman Migler[1]; [1]National Institute of Standards and Technology; [2]Montgomery College; [3]Colorado School of Mines
In material extrusion additive manufacturing a thermoplastic filament is extruded though a rastering nozzle on the previous layer. The resulting strength of the 3D produced part is limited by the strength of the weld between each layer. While numerous factors can affect the weld strength, the temperature of the extrudate and the previous layer dictate the amount of interdiffusion and thus the weld strength. Temperature measurements were performed using forward looking infrared imaging. Interdiffusion estimates were calculated from temperature profiles, normalized using horizontal shift factors from offline rheological measurements of the neat polymer. Weld strength was measured directly by mode III fracture using a simplified geometry limiting the measurement to a single weld. Since the processing conditions are known aprioi this approach provides the data needed to estimate the final build strength at time of design. The resulting agreement between interdiffusion estimates and weld strength for a range of printing conditions and thermoplastics are discussed.

Validation and Verification II: Qualification Frameworks

Tuesday PM June 19, 2018 | Room: Heritage Room | Location: NIST Headquarters

Session Chair: Deborah Mies, Granta Design

3:20 PM Invited

Obtaining Accurate Data for Validation of Additive Manufacturing Models: Richard Martukanitz[1]; Frederick Lia[2]; [1]CIMP-3D at Penn State; [2]Applied Research Laboratory, Pennsylvania State University

The presentation will discuss various practices and techniques for capturing various data necessary for validation of additive manufacturing models. Several important methods will be briefly introduced, which includes: process calorimetry for measuring energy transfer coefficients, attenuation measurements of laser energy absorption within a powder layer, measuring thermal response using high temperature embedded thermocouples, and determining thermally induced distortion after processing. The detailed measurement of thermal data during various additive manufacturing processes will be discussed in terms of accuracy of the data and its validity for model comparisons. The recent completed Modeling Challenge for Additive Manufacturing will be used as an example for discussing the applicability of several techniques in validating models capable of simulating the process, microstructural evolution, and resultant static mechanical properties.

3:50 PM

Application of Uncertainty Quantification Techniques in the Sandia Fracture Challenge: John McFarland[1]; James Sobotka[1]; *Barron Bichon*[1]; [1]Southwest Research Institute

Southwest Research Institute (SwRI) recently participated in the 3rd Sandia Fracture Challenge, which was framed around a unique geometry with voids, holes, and intersections that demonstrates the capabilities of additive manufacturing and that introduces potential issues in existing modeling and simulation approaches. This presentation will describe the analysis framework SwRI constructed to address this challenge with a particular focus on the rigorous uncertainty quantification techniques required throughout. Topics include: accounting for uncertainty in model calibration, dimensionality reduction via principal components analysis, creation and verification of surrogate models, consideration of uncertainty types, global sensitivity analysis via variance decomposition, accommodating ensemble vs. point data, propagation of uncertainties through computational models, and establishing prediction intervals on quantities of interest. This study provides a detailed demonstration on the importance, role, and application of uncertainty quantification in establishing model validity, which will be critical to the success of the AM-Bench initiative.

4:10 PM

Integrated Computational Materials Engineering to Quantify the Effect of Uncertainty in Microstructure on the Fatigue Performance of Additively Manufactured Parts: *Robert Tryon*[1]; Chad Duty[2]; Robert McDaniels[1]; Andrew Chern[2]; [1]VEXTEC Corp; [2]University of Tennessee

The presentation discusses a NAVAIR funded program to develop an integrated computational materials engineering (ICME) software to decrease the time and resources needed to certify metal additive manufactured (AM) structural components exposed to fatigue. The software incorporates relevant information from multiple sources, including data from the open literature and from prior material certification programs, to build material models that explicitly characterize the material microstructure. The models are physics-based and can predict other materials and microstructures, to extrapolate outside of the test database. The probabilistic nature of the models allows for the quantification of the tails of distributions that govern minimum properties. The models are updated as more data and knowledge become available. During the program, two overarching tasks were worked simultaneously: building the models, and laboratory testing to gather data for calibration and validation of the models. Electron beam melting (EBM) processed Ti-6Al-4V components were selected for modelling and testing.

4:30 PM

LPBF Right the First Time – The Right Mix Between Modelling & Experiments: *Mustafa Megahed*[1]; Pierre-Adrien Pires[1]; Mark Cola[2]; James Craig[3]; Alonso Peralta[4]; James Neumann[4]; [1]Esi Group; [2]Sigma Labs, Inc.; [3]Stratonics Inc; [4]Honeywell Aerospace

Within the scope of the DARPA Open Manufacturing program, a rapid qualification framework is developed that relies on parallel modelling and experimental efforts for verification and validation of the process. Product manufacturability is tested a priori via modelling. In-process monitoring is deployed to ensure input parameters are rapidly screened. Process consistency and repeatability is further ensured through process characterization, process qualification and via quantitative analysis of digital In-Process Quality Metrics™ (IPQM®s).This paper discusses the rapid qualification methodology and its application towards manufacturing of a challenging part. The combination of numerical predictions, experimental refinement and in-process monitoring delivered the first print right at first trial. Distortions are within predictions and metallurgical analysis shows dense as-built material with properties expected to fulfill performance requirements. In-process monitoring results provide a quantitative, digital Quality Signature™ or Digital Quality Record™ of process consistency and product quality.

Wednesday Plenary Session

Wednesday AM June 20, 2018 | Room: Green Auditorium | Location: NIST Headquarters

Session Chair: Miriam Rafailovich, Stony Brook University

8:30 AM Plenary

Microstructure Predictions for Additively Manufactured Metals using a Cellular Automaton/Finite Element Model: *Gregory Wagner*[1]; Yan Ping Lian[1]; Zhengtao Gan[1]; Wing Kam Liu[1]; [1]Northwestern University

The complex temperature variations to which metals are subjected during additive processes have a large and often unpredictable effect on grain structures in the resulting material. To predict the detailed microstructure in additively manufactured parts, a 3D, parallelized Cellular Automaton/Finite Element (CAFE) model has been developed linking the thermal field with the formation of grain structure. Influences of melt pool flow, partial remelting of layers, material-specific grain growth physics, and grain nucleation statistics are included in the model. This capability is used to compute grain structures both for individual laser tracks and for multiple layer material addition in an additive process. Simulations exploring the effects of process parameters are compared with experimental measurements, showing very good agreement. Grain structures predicted by the CAFE simulations, including crystal orientations, can be post-processed to yield statistical descriptors of the microstructure, allowing quantitative comparison with experiments and suggesting directions for future benchmark measurements.

9:00 AM Plenary
Modelling Amorphous and Semi-crystalline Polymer Melts during Fused Filament Fabrication: *Claire McIlroy*[1]; Richard Graham[1]; Peter Olmsted[2]; [1]University of Nottingham; [2]Georgetown University
The most common method for printing polymer melts is known as fused filament fabrication (FFF), which involves melting a thermoplastic, followed by layer-by-layer extrusion, cooling and re-solidification. The main concern with FFF is strength at the welds between printed layers; bulk strength is rarely achieved. We use a molecularly-aware, non-isothermal polymer model (Rolie-Poly) to predict how high-shear rates during the deposition process, which involves a 90° turn, can stretch and align the polymers with the flow direction [1]. For amorphous melts, we attribute reduced weld strength to a partially disentangled structure at the onset of the glass transition [2]. For semi-crystalline melts, we explore how the stretch induced by the printing flow can enhance nucleation and lead to a gradient in the number of nuclei across a printed layer. [1] McIlroy & Olmsted J. Rheology 61 (2017) 379-397 [2] McIlroy & Olmsted Polymer 123 (2017) 376-391

Wednesday Benchmarks

Wednesday AM
June 20, 2018

Room: Green Auditorium
Location: NIST Headquarters

Session Chair: Lyle Levine, National Institute of Standards and Technology

9:30 AM
Multiscale Mechanical Characterization of Polycarbonate Test Specimens Processed through Fused Deposition Modeling: *Dan Cole*[1]; Frank Gardea[1]; [1]US Army Research Laboratory
Fused deposition modeling (FDM), also known as fused filament fabrication (FFF), is an extrusion-based additive manufacturing technique for thermoplastic materials. A typical FDM process consists of a feedstock polymer heated into the melt state and forced through a print nozzle onto a substrate. The material is deposited layer-by-layer according to a computer-aided design, which allows for the rapid fabrication of complex objects. However, the processing-structure-property relationships of materials fabricated through FDM are not well understood. Variations in melt temperature, nozzle speed, co-mingling time of adjacent layers, among other process parameters, can all have significant effect on the resulting material properties. In this work, FDM was used to additively manufacture polycarbonate mechanical test specimens in 0, 45, and 90 degree raster orientations with respect to the tensile loading direction. Global mechanical properties were determined through ASTM D3039. Digital image correlation was used to characterize the full-field strain behavior during mechanical loading. The local mechanical behavior of the printed specimens was characterized through nanoindentation and atomic force microscopy. The local material behavior across build-build interfaces was examined in attempt to discern structure-property relationships of the FDM process.

10:00 AM Break

10:20 AM
X-ray Microcomputed Tomography of SLS and FDM Polymer Additive Manufactured Samples: *Edward Garboczi*[1]; Erich Bain[2]; Daniel Cole[2]; Kalman Migler[1]; Jonathan Seppala[1]; [1]National Institute of Standards and Technology ; [2]US Army Research Laboratory
Tensile dogbone specimens were made using two kinds of additive manufacturing: selective laser sintering (SLS) with nylon, and fused deposition modeling (FDM) with polycarbonate. Two FDM specimens were examined, with four scans each in the gauge sections, and four SLS specimens were examined, with two scans each in the gauge sections. Each specimen was made in a different orientation with respect to the build plate. The whole specimen was imaged in each instance, using a voxel size of about 12 micrometers for the FDM specimens and about 7.5 micrometers for the SLS samples. The pore defects in the two kinds of samples were clearly seen and were very different from each other. The pore defects in the FDM specimens were long and connected, tending to lie between successive ribbons of material. The pore defects in the SLS specimens were isolated and fairly rounded and equiaxed, with a rough surface. This image data can serve as a basis for finite element modeling and/or process modeling.

10:50 AM
Neutron Diffraction Residual Strain Measurement of Additively Manufactured Inconel 625 and 15-5 Stainless Steel: *Thien Phan*[1]; Thomas Gnaupel-Herold[1]; Lyle Levine[1]; [1]National Institute of Standards and Technology
Additive manufacturing (AM) is a promising technique due to its ability to readily produce components with complex geometries near to their final shape. However, the high heating and cooling rates, along with the directionality of the build/solidification process, result in numerous issues in the as-built parts. One of the main issues is the substantial residual stress within the part. Here, neutron diffraction measurements were conducted at the NIST Center for Neutron Research for Inconel 625 and 15-5 stainless steel AM benchmark samples. Residual strain results along the transversal, longitudinal, and vertical directions, along with measurement limitations and issues will be discussed. Submitted simulation results for the residual stress challenge will be compared to these benchmark measurement results.

11:20 AM
Residual Strain Characterization of Additively Manufactured Inconel 625 Using Energy Dispersive X-ray Diffraction: *Maria Strantza*[1]; Bjørn Clausen[1]; Thien Phan[2]; J. Y. P. Ko[3]; Darren Pagan[3]; Lyle Levine[2]; Donald Brown[1]; [1]Los Alamos National Laboratory; [2]National Institute of Standards and Technology; [3]Cornell High Energy Synchrotron Source
The additive manufacturing processes belong to a novel and innovative production technology. However, the additively manufactured (AM) components are not yet ready to be used as critical engineering components. Currently, there is a limited understanding of the process/structure/property/performance relationship, which limits confidence in the ability of process models to predict final behavior. The aim of AM-Bench program is to help close this gap. The main objective of this investigation is to produce high quality residual strain measurements in order to provide input on the controlled benchmark tests for AM nickel based superalloy. In support of this effort, we performed energy dispersive X-ray diffraction measurements on F2 beamline at Cornell High Energy Synchrotron Source (CHESS). Our aim was to use the measured lattice parameter in order calculate and profile the residual strains on the AM Inconel 625 component to be used as a strong validation challenge to the modeling agencies. During this presentation, the results on the residual strain along the build and the longitudinal direction will be discussed, as well as the shear residual strain component.

11:50 AM
Mechanical Relaxation Measurement Techniques and Application to Build for AMB2018-01: *Michael Hill*[1]; [1]University of California Davis
Residual stress fields in metallic components have a role in their performance. Residual stresses in metals are commonly measured using techniques based in diffraction or mechanical relaxation. State of the art engineering practice includes the comparison of data from both diffraction and mechanical measurements, and a subsequent accounting of the impacts of similarities and differences in resulting data from the perspective of on component operability. The present effort focuses on mechanical residual stress measurements relevant to metal additive manufacture (AM). The presentation will review the physical principles behind common mechanical relaxation techniques and describe their application within AM-Bench benchmark AMB2018-01.

Metrology and Uncertainty

Wednesday PM Room: West Square
June 20, 2018 Location: NIST Headquarters

Session Chair: Richard Ricker, National Institute of Standards and Technology

1:30 PM
Uncertainties in Validation Metrics: *Ben Thacker*[1]; [1]Southwest Research Institute
Comparison of simulation and experimental outcomes requires some type of quantitative validation metric, which will usually take the form of a difference measure. Example metrics might include the difference between the average values of predicted and measured outcomes, difference between statistics of outcomes, or even the difference between the probability distribution of outcomes. A validation metric should fully incorporate simulation and experimental uncertainties, quantify the difference between the model prediction and experimental measurement, and reflect the level of uncertainty in the comparison. Because uncertain quantities are involved, care must be taken to choose the validation metric such that the model is appropriately and sufficiently challenged. For example, if we are interested in how well the model predicts the measured uncertainty, a metric that quantifies the difference between the predicted cumulative distribution function (CDF) and experimentally measured CDF would be appropriate. Other uncertain validation metrics are possible and will be illustrated.

1:50 PM
3D Powder Shape Characterization via X-ray CT: *Edward Garboczi*[1]; [1]National Institute of Standards and Technology
At a very basic level, the size and shape of powder particles are not independent quantities. Most particle size measurements assume spherical shape, while some do measure both size and shape but only on 2D projections. X-ray computed microtomography, coupled with spherical harmonic analysis, measures 3D size and shape and is thus 3D ground truth that can be used to evaluate all other particle size/shape measurement methods. In addition, knowing the 3D shape of individual particles can be used as input into powder mechanical models such as the discrete element method to determine the effect of particle shape on powder flow and packing properties.

2:10 PM
Surface Metrology of Additive Manufacturing Components: Understanding the Complex Texture of Powder Bed-based Surfaces: *Agustin Diaz*[1]; [1]REM Surface Engineering
AM-produced components present extremely rough textures, and are packed with significant defects that bias the surface texture profiles obtained with classical profiling techniques. The aerospace and biomedical industries, as well as several universities and governmental entities (such as NIST) are working together to define and develop proper methods of surface texture characterization for AM-produced components which correlate to the actual conditions of the AM-produced surfaces. In this paper we will discuss the surface anatomy of AM-components produced by the powder bed techniques. We will dissect the different types of textures that characterize AM-built components. We will discuss different profilometry techniques that can be employed to interrogate these surfaces. Based on these techniques, surface texture characterization parameters can be defined using the proper filters, thus generating realistic values. In addition, surface texture components such as form, waviness and roughness will be defined correctly in a case by case scenario for AM-components.

2:30 PM
Determination of the Pores' Volume within Micro-scale Metallic Powder Particles Using X-ray Computed Tomography: *Shihua Wang*[1]; Baoxi Xu[1]; [1]National Metrology Centre/A*STAR
A high resolution X-ray computed tomography (XCT) is applied to determine the porosities in four (4) types of metallic powders. Related sample preparation, measurement set-up and post-data process are described. The XCT images demonstrate that the pores' sizes could be from 10 µm to 30 µm in those powders with their size up to 100 µm. The porosities as calculated in volume are found to be 0.02% for Inconel (718), 0.11% for Virgin Inconel (625), 0.31% for Recycled Inconel (625), and 0.03% for Stainless steel (316), respectively. To validate the method reliability, the volume of a hemisphere (Nominal diameter: 0.381 mm) is measured by the proposed XCT method and a high precision coordinate measuring machine (CMM). The measured volume difference between XCT and CMM is less than 5%. This indicates that application of this methodology on the powders' pore volume and porosity measurement has yielded reasonable results.

2:50 PM
Design, Development and Analysis of Cellular Lattice Support Structures for Selective Laser Melting: *Behzad Rankouhi*[1]; Kaila Bertsch[1]; Mythili Thevamaran[1]; Dan Thoma[1]; Krishnan Suresh[1]; [1]University of Wisconsin-Madison
Cellular lattice structures offer unique thermo-mechanical properties that make them a prime candidate for use as support structures. In this work, we investigate the use of cellular lattice structures as a potential remedy to the above-mentioned problems. Specimens with diverse unit cell structures were designed and manufactured to serve as support structures for a benchmark component. Cells were design and later fabricated from SS316L powder using SLM process. Manufacturability, build time, density and effectiveness of each cell structure, as well as microstructural development of the part at the support structure interface were analyzed. Furthermore, compression test was performed to determine the mechanical properties of each design. Experimental results revealed that the type, density and size of each cell structure are the contributing factors that influence the effectiveness and manufacturability of these designs as support structures.

3:10 PM
Advances in Multiscale 3D Metrology for Additive Manufacturing: *Bartlomiej Winiarski*[1]; Grzegorz Pyka[1]; Ben Young[1]; Austin Wade[2]; [1]Thermo Fisher Scientific, Czech Republic; [2]Thermo Fisher Scientific, Netherlands
Metrology research for industrial Additive Manufacturing is focusing mainly on the dimensional metrology and the porosity measurements of AM components. Herein practical lengths scales are above several dozens of microns and more. Few studies measures the surface characteristics of AM components or precursor powder composition. Circular Scanning micro X-Ray Computed Tomography (CS-XCT) becoming a primary tool in the repertoire of many metrologists. Nevertheless CS-XCT needs calibration prior scanning and reconstructed volumes are prone to dimensional distortions and noisy data. These factors together with insufficient voxel information in the sub-micron range, lack of 3D microstructural and compositional quantifications at various length scales fall short in the current demand for advanced industrial additive manufacturing. This contribution shows methods and directions to overcome these shortcomings. The multiscale 3D metrology strategy is supported with Explorer4™ Additive, HeliScan™ Helical-XCT, Plasma_FIB/SEM and Talos™_STEM microscopes and unique, software integrated instrumental environment using inter-linked software: ASV4™ and Avizo™.

Polymers and Gels II

Wednesday PM Room: Lecture Room D
June 20, 2018 Location: NIST Headquarters

Session Chair: Patrick Anderson, Eindhoven University

1:30 PM Invited
From Processing to Properties: Understanding the Key Steps for Selective Laser Sintering: *Gerrit Peters*[1]; [1]Eindhoven University of Technology
Polymer product properties are determined by intrinsic molecular features and, to a great extent, the thermo-mechanical conditions during product shaping. Much work on this topic has been dedicated to classical processes (extrusion, injection molding etc.) but similar effort is required for additive manufacturing processes as the same issues apply. The goal of this work is to develop the required models and experimental methods and procedures to bridge the gap between processing conditions and the final mechanical properties for Selective Laser Sintering. This includes full characterization and modelling of the multi-phase crystallization of PA 12, including the effect of post-condensation, comparison between intrinsic mechanical properties and those obtained for specific SLS conditions The mechanical part focusses on yield stress and life time predictions. These tools should help to understand and improve the performance of SLS products in relation with polymer features and processing conditions and make experimental results comparable

2:00 PM Invited
The Fracture Behavior of Welds Formed by the Fused Filament Fabrication Additive Manufacturing Process: *Thao Nguyen*[1]; [1]Johns Hopkins University
Fused Filament Fabrication (FFF) is one of the most cost-effective and widely used polymer additive manufacturing method. However, applications of FFF are limited by the lower strength and toughness properties of the printed parts. Our long-term goal is to develop a multiscale-modeling framework to predict the mechanical properties of FFF printed parts based on the processing parameters and print path. As a first step, we developed finite element models to investigate the fracture properties of the weld between adjacent printed filaments. Cohesive zone elements and a viscoplastic traction-separation law were used to represent the weld and a viscoplastic model was used to describe the polycarbonate filaments. The parameters of the cohesive zone were fit to the peel force and displacement field of the peel arm. The results were analyzed to determine how the fracture strength, fracture energy, and plastic work varied with filament geometry, material properties, and temperature history.

2:30 PM
Correlation between Bioink Printability and Rheological Parameters: Teng Gao[1]; Gregory Gillispie[1]; Joshua Copus[1]; Young-Joon Seol[1]; Anthony Atala[1]; James Yoo[1]; Sang Jin Lee[1]; Anil Kumar Pallickaveedu Rajan Asari[1]; *Bhushan Mahadik*[2]; [1]Wake Forest Institute for Regenerative Medicine; [2]University of Maryland
"Printability" has been poorly defined in literature, mostly consisting of gross qualitative measures that impair direct comparison of bioinks. Little is known about the effects of dynamic modulus of viscoelastic materials, storage modulus (G') and loss modulus (G"), on the printability of hydrogel-based bioinks. This study developed a framework for evaluating printability and investigated moduli-based effects on the printing outcome. Gelatin and alginate hydrogels were mixed at various concentrations and the resulting bioink was evaluated for quantitatively defined values of extrudability, extrusion uniformity, and structural integrity. For extrudability, increasing loss or storage modulus increased the extrusion pressure. A mathematical model relating the G' and G" to the required extrusion pressure was derived based on data. A lower loss tangent (G"/G') was correlated with increased structural integrity while a higher loss tangent correlated with increased extrusion uniformity. Using this approach, various bioink formulations can be quickly and accurately evaluated for printability.

2:50 PM
In-Situ Simultaneous Infra-red and X-ray Imaging of FDM Printing with Polymer Nanocomposites: Yuval Shmueli[1]; Jiaolong Jiang[1]; Dilip Gersappe[1]; Rafael Delgado-Ruiz[1]; Gad Marom[2]; Ellen Wachtel[3]; Sungsik Lee[4]; *Miriam Rafailovich*[1]; [1]Stony Brook University; [2]Hebrew University of Jerusalem; [3]Weizmann Institute of Science; [4]The Advanced Photon Source at Argonne National Laboratory
FDM printing is a rapidly developing new area where new methodology is required to explore phenomena far from equilibrium. In this study, we use in-situ synchrotron X-ray scattering and high resolution infra-red imaging to study in-situ the relationship between the extrusion parameters and the internal structure of the nanocomposite. The results are then compared with Lattice Boltzmann Modeling which simulates the welding between filaments as a function of nozzle parameters, printing protocols, and the system thermodynamical response function. In filled systems, using in-situ SAXS and WAXS, we observed the effect of extrusion shear forces on the orientation of the nanoparticles and the influence of the particle/polymer interactions on the polymer crystallization. This phenomenon ("Transcrystallization") leads to templating of the polymer crystalline structures by the fillers which, we show, can enhance the thermal, mechanical and electrical properties of the printed nanocomposite structures, under directional control by the printing algorithm. Acknowledgement: NSF-Inspire.

3:10 PM
Flow-induced Crystallization during Materials Extrusion Additive Manufacturing: Lily Northcutt[1]; Sara Orski[1]; *Kalman Migler*[1]; Anthony Kotula[1]; [1]National Institute of Standards and Technology
Material extrusion additive manufacturing processes often force molten polymer through a printer nozzle at high (> 100 s-1) wall shear rates prior to cooling and crystallization. These high shear rates can lead to flow-induced crystallization in common polymer processing techniques, but the magnitude and importance of this effect is unknown for additive manufacturing. A significant barrier to understanding this process is the lack of in situ measurement techniques to quantify crystallinity after polymer filament extrusion. To address this issue, we use a combination of infrared thermography and Raman spectroscopy to measure the temperature and crystallinity of extruded polycaprolactone during additive manufacturing. We quantify crystallinity as a function of time for the nozzle temperatures and filament feed rates accessible to the apparatus. Crystallization is shown to occur faster at higher shear rates and lower nozzle temperatures. Our measurements provide experimental evidence of the effect of shear flow on polymer crystallization in additive manufacturing.

Thermal Simulations

Wednesday PM
June 20, 2018

Room: Heritage Room
Location: NIST Headquarters

Session Chair: Li Ma, National Institute of Standards and Technology

1:30 PM Invited
A Scaleable Framework for Additive Manufacturing Process Simulation: *Victor Oancea*[1]; [1]Dassault Systemes Simulia Corp

A highly customizable general simulation framework for a wide spectrum of additive manufacturing processes based on a thermal-stress or eigenstrain approaches in a general purpose finite element code (Dassault Systemes 3DX Platform - Abaqus) is discussed. The framework allows for: 1) arbitrary meshes of CAD representations; 2) exact or homogenized specification in time and space of machine tooling (laser trajectories, etc.); 3) precise tracking of the progressive raw material addition via geometric computations; 4) precise integration of the moving energy sources (e.g., laser, electron beams, arc welds, etc.); 5) automatic computation of the continuously evolving convection and radiation surfaces, and 6) simulation of a wide spectrum of AM processes such as laser and electron beam powder bed fabrication, direct energy deposition, arc welding, polymer extrusion, ink jetting, etc. Is simulation predictive? Successes and challenges for computed temperatures, distortions, stresses, defects, metallurgical phase transformations and mechanical properties prediction are discussed.

2:00 PM
Thermal Models of Additive Manufacturing at Part Scale: Impact of Rastering on Thermal History: *Angel Yanguas-Gil*[1]; Samantha Webster[2]; Alvaro Rodriguez-Prieto[3]; Jian Cao[2]; Shashikant Aithal[1]; [1]Argonne National Laboratory; [2]Northwestern University; [3]UNED

Thermal models able to provide the thermal history of every point of a part can become a useful tool both to enhance our ability to predict the outcome of the fabrication process, and to optimize rastering sequences for complex shapes. These models also provide a link between experimental conditions and other observables such as composition, phase, and microstructure. Here we introduce and compare two models that provide the thermal history of 3D printed parts: adad is an additive model of additive manufacturing that carries out drastic linearization and discretization approximations that result on an analytic solution. In contrast, sadman treats phase change and transport in a self-consistent way, yet simplifies the process by ignoring length scales smaller than the scan width or hatch spacing. Both models provide a simple yet powerful way of identifying areas within a part with significantly different thermal histories.

2:20 PM Invited
An Adaptable, 3D Finite Element Model of Material Extrusion Additive Manufacturing Heat Transfer: *Amy Peterson*[1]; [1]Worcester Polytechnic Institute

Bonding in additive manufacturing (AM) remains a key challenge in improving part properties. For thermally driven AM methods, such as material extrusion (MatEx), temperature governs bonding. Experimental temperature measurements are limited in their ability to probe many points in space and time. These limitations may be overcome with computational methods; however, computing power confined simulations to one or two dimensions until recently. In this work, an adaptable FEA model capable of simulating heat transfer in 3D and at sufficiently small time scales to capture the rapid cooling in AM is presented. Cooling trends from simulation are shown to be in agreement with experimental data. Uniformity in equivalent time at Tg suggests weld strength will not vary with print speed; however, high cooling rates for common print speeds may lead to greater residual stresses. The model has also been expanded to larger (BAAM) scales and new materials/material properties.

2:50 PM
Meshfree Modeling of Powder Bed Fusion (PBF) Based Additive Manufacturing of Metals: *Bo Li*[1]; Zongyue Fan[1]; [1]Case Western Reserve University

We present a powder-scale direct numerical simulation (DNS) capability for the PBF-based additive manufacturing of metals based on the Hot Optimal Transportation Meshfree (HOTM) method. The HOTM method is a monolithic Lagrangian meshfree computational framework for dynamic materials response under extreme thermomechanical loading conditions, possibly involving phase transition and multiphase mixing, history-dependent material models, dynamic contact, and fracture. A powder bed by considering particles size and shape distribution, material properties and packing density is modeled using material points and nodes. The fully-discretized momentum and energy equations are solved semi-implicitly to calculate the deformation and temperature of the domain at each iteration. A full-field constitutive model is developed to automatically simulate the materials phase change (e.g., melting, vaporization and solidification). The influence of various processing parameters on the deformation and motion of the melt pool is studied by the DNS of PBF processes for a single layer powder bed.

3:10 PM
Empirically Driven Physics Based Model Development for Fused Filament Fabrication: Part Quality and Residual Stresses: *Michael Bortner*[1]; David Dillard[1]; Jonathan Seppala[2]; [1]Virginia Tech; [2]National Institute of Standards and Technology

Process design and control for predictive analysis in fused filament fabrication is critical for consistency and quality control in AM produced parts. Reduced integrity results from several factors including incomplete diffusion and insufficient wetting, resulting in flaw-like interstitial voids that can act as stress risers or even precracks, and insufficient molecular interdiffusion across interfaces, even when intimate contact is achieved. The rapid transient variability of the 3-D thermal profile and geometry during deposition prevents prediction of final part properties. To address this issue, we have begun developing a three-dimensional thermal model driven by a combined empirical and theoretical analysis, and that follows the process from nozzle extrusion to road lay down and part cooling. With knowledge of the thermal profiles and road deposition geometry, coupled with history from the model predictions, we can begin to understand the stress state throughout the layer by layer fabricated part.

Thursday Plenary Session

Thursday AM Room: Green Auditorium
June 21, 2018 Location: NIST Headquarters

Session Chair: Wing Kam Liu, Northwestern University

8:30 AM Plenary
Numerical Modeling and Experimental Validation of AM Processes by Metal Deposition: *Michele Chiumenti*[1]; [1]Universitat Politècnica de Catalunya
In this work the current developments on the numerical simulation of different AM processes by Metal Deposition are presented. A fully coupled thermo-mechanical framework has been tailored to the analysis of both wire-feeding and powder-based technologies. The accurate definition of the power input is addresses taking into account its actual movement along the scanning path as defined for the machine. The result is a high-fidelity simulation of the metal deposition process leading to an accurate layer-by-layer building sequence. An advanced high-performance and object-oriented software platform has been enhanced to include the parallel FE activation technique used to follow the growth of the geometry according to the metal deposition process. The thermo-viscoelastic-viscoplastic constitutive model introduced is calibrated and the numerical results are validated through the experimental campaign carried out at the Northwestern Polytechnical University (Xi'an, China) as well as at the Monash University (Melbourne, Australia).

9:00 AM Plenary
Polymer-based Additive Manufacturing Characterization and Qualification Guidelines for Aircraft Design and Certification: *Rachael Andrulonis*[1]; [1]Wichita State University - NIAR
A standardized qualification framework and database for advanced materials, such as additively manufactured materials, is critical to the design and insertion of these materials in aerospace or other applications. Leveraging the experience and lessons learned from the National Center for Advanced Material Performance (NCAMP) and the Composite Materials Handbook – 17 (CMH-17) qualification databases, a new qualification program for polymer additive materials has been developed utilizing several currently available standards and test methods. As part of this collaborative research effort, new material and process specifications and modifications to existing standards have been developed to fit the unique needs of AM materials. An overview of the qualification results, along with a review of the framework documents, specifications and recommended test plan for polymer additive materials, will be presented.

Thursday Benchmarks

Thursday AM Room: Green Auditorium
June 21, 2018 Location: NIST Headquarters

Session Chair: Mark Stoudt, National Institute of Standards and Technology

9:30 AM
Multi-level High-order Finite Elements for the Simulation of Melt Pool Sizes and Cooling Rates in Metal Additive Manufacturing: *Stefan Kollmannsberger*[1]; Massimo Carraturo[2]; Davide D'Angella[1]; Ferdinando Auricchio[2]; Ali Özcan[2]; Alessandro Reali[2]; Ernst Rank[1]; [1]Technische Universität München; [2]University of Pavia
The presentation addresses numerical modelling of the benchmark AMB2018-02 where we take upon the challenge of verifying the melt pool geometry (CHAL-AMB2018-02-MP) and the cooling rate (CHAL-AMB2018-02-CR). We employ a variant of the numerical model presented in [1] and extend it to hierarchical B-Splines [2]. The principal idea is to use high-order refinements to resolve the region around the boundary of the weld pool with high accuracy. The numerical model is properly coarsened in parts of the domain remote from the laser impact to preserve computational efficiency. [1] Kollmannsberger; Özcan; Carraturo; Zander; Rank. A hierarchical computational model for moving thermal loads and phase changes with applications to Selective Laser Melting Computers & Mathematics with Applications, DOI: 10.1016/j.camwa.2017.11.014 [2] D'Angella, D.; Kollmannsberger, S.; Rank, E.; Reali, A. Multi-level Bézier extraction for hierarchical local refinement of Isogeometric Analysis, Computer Methods in Applied Mechanics and Engineering, DOI: /10.1016/j.cma.2017.08.017

10:00 AM
Solution to the AM Benchmark 2018 Challenge Problem AMB2018-02 using AMP2 (Additive Manufacturing Parameter Predictor) Software: Anil Chaudhary[1]; Tim Vincent[1]; Ben Schlutheis[1]; Jessica Marquis[1]; *Jonathan Robichaud*[1]; [1]Applied Optimization, Inc.
This work presents solutions to the AM benchmark challenges CHAL-AMB2018-02-MP (melt pool geometry), CHAL-AMB2018-02-GS (Grain Shapes), CHAL-AMB2018-02-DM (Dendrite Microstructure) and CHAL-AMB2018-02-3D (3D structure). These solutions were obtained using the ICME (Integrated Computational Materials Engineering) suite of software, AMP2, developed by Applied Optimization, Inc. The melt pool geometry is obtained using a thermal-CFD solution of melt pool physics. The melt pool geometry, mean track cross-section, 3D distribution of thermal gradient (G), and the liquid-to-solid interface velocity are predicted by this solution, which in turn are utilized as input for the solidification microstructure computations. The grain shapes and 3D structure are modeled using cellular automata (CA). The dendrite microstructure is obtained using thermodynamic and kinetic modeling and an interface response function procedure.

Microstructure V: Solidification Structures

Thursday PM Room: West Square
June 21, 2018 Location: NIST Headquarters

Session Chair: James Belak, Lawrence Livermore National Laboratory

1:30 PM Invited
Application of Phase Field Methods to Additive Microstructures in Metals: *Jon Guyer*[1]; Supriyo Ghosh; Trevor Keller; Kevin McReynolds; [1]National Institute of Standards and Technology
As part of the broader NIST effort in the materials science of additively manufactured metals, we are employing phase field techniques to better understand the unique microstructural aspects of additive manufacturing. Phase field methods are widely applied because of their ability to capture complex morphogical and topological change in evolving microstructures, but the method is computationally demanding. A number of different formulations are possible, with different sets of advantages and challenges. I will discuss our experience applying three types of phase field models to different aspects of additive manufacturing: a dilute, binary anti-trapping model in the rapid solidification regime; a multi-component, multi-phase solid-state model coupled with CALPHAD-based thermodynamics; and an amplitude expansion structural phase field crystal model. I will also describe ongoing efforts to develop benchmarking problems for phase field methods and codes as a point of comparison for the AM-Bench activities.

2:00 PM
Modeling the Solidification of a Stainless Steel 316 with Phase-field Method as a Part of a Process-structure-properties-performance Chain: *Tatu Pinomaa*[1]; Tom Andersson[1]; Matti Lindroos[1]; Anssi Laukkanen[1]; Nikolas Provatas[2]; [1]VTT Technical Research Centre of Finland; [2]McGill University
A major challenge in additive manufacturing is relating process parameters and microstructure. This relation can be explored with a phase-field model coupled to a larger scale heat transfer model. Here we investigate the selective laser melting of a type 316 stainless steel. Based on the process parameters, the large scale heat transfer model predicts the overall temperature distribution, which in turn provides temperature data for phase-field modeling, specifically thermal gradients and cooling rates. Major segregating elements are identified, and the solidification patterns are modeled using the phase-field method in a dilute alloy limit. We demonstrate the usage of a model to obtain controlled levels of solute trapping. Predicted phase fractions and segregation profiles are compared to CALPHAD-based Scheil-Gulliver solidification model, and also to a one-dimensional diffusion model with a full mobility database. Finally the mechanical responses of various solidification microstructures are compared, using a micromechanical finite element model.

2:20 PM
Modeling Grain Microstructure in Laser Powder Bed Fusion Additive Manufactured Metals Using Combined Computational Fluid Dynamics and Cellular Automata: Yi Zhang[1]; *Jing Zhang*[1]; [1]Indiana University-Purdue University Indianapolis
Microstructure has profound effects on the properties of laser powder bed fusion (PBF) additively manufactured metals. This work presents a novel modeling approach to predict the grain microstructures in powder bed fused metals, using combined computational fluid dynamics (CFD) and cellular automata (CA). Laser heated powder bed melting and solidification are first simulated by a coupled fluid-thermal CFD model. Then the temperature profile and powder bed morphology are passed to an efficient CA algorithm to predict the evolution of grain microstructure. Preliminary results show that at a lower laser scan speed, the predicted grains are mostly columnar. However, when the scan speed is higher, equiaxed grains appear around the melting centerline. The microstructure characteristics, including grain size and orientation are predicted with varying processing parameters, and compared against experimental observations.

2:40 PM
Subgroup Nucleation In Cellular Automata For Additive Manufacturing: *Joel Tan*[1]; Wai Yee Yeong[1]; [1]Nanyang Technological University
Additive manufactured (AM) metals have unique grain structure. The grain structure tends to be primarily columnar with mixed equiaxed grains. Varying process parameters has shown to influence the size and aspect ratio of grain structure. Cellular automata (CA) can be used to numerically model the grain structure. However, current CA models inadequately represent the nucleation process in grain structure formation of AM metals. In this paper, a new nucleation model is introduced specific to AM. Average bulk liquid temperature is calculated for small groups of cells called subgroups. As the average temperature of each subgroup drop below the liquidus temperature, nucleation chances increases. If nucleation occurs, a random cell in the subgroup changes from liquid to solid and starts to grow. With this nucleation model, grain structure modeled by CA is more accurate with closer resemblance to experimental data.

3:00 PM Break

Parts and Part Design

Thursday PM June 21, 2018
Room: Heritage Room
Location: NIST Headquarters

Session Chair: Richard Otis, Jet Propulsion Laboratory

1:30 PM Invited
Design and Testing of Thin-walled Elements of Additively Manufactured Ni-base Superalloys: *Kevin Hemker*[1]; Arunima Banerjee[1]; Matthew Vaughn[1]; James Guest[1]; Connie Dong[2]; Sara Messina[2]; Jeff Rosin[2]; Matthew Begley[2]; Tresa Pollock[2]; Michael Groeber[3]; Jonathan Miller[3]; William Musinski[3]; Edwin Schwalbach[3]; Paul Shade[3]; [1]Johns Hopkins University; [2]Univeristy of California, Santa Barbara; [3]Air Force Research Laboratory
Powder bed printing of metal alloys allows for builds of various shapes and complexities far beyond what is possible with traditional manufacturing processes. Most finite element and topology optimization design methodologies assume homogenous and isotropic material properties, which is not representative of additive builds. Accounting for heterogeneity requires the ability to link local processing state to the performance of local material. The interplay of processing parameters, component geometry and local properties is especially important at the junctions of thin-walled structures. Superalloy specimens of "T" and "Y" elements containing thin-walled ligaments and junctions have been printed and tested to elucidate the effects of geometry, processing and location-specific properties on their mechanical response. Load-displacement curves and DIC plasticity maps inform analytical descriptions of junction response functions. Long-term goals include incorporation of these response functions into topology optimization codes that will not only account for, but exploit, the heterogeneity provided by additive manufacturing.

2:00 PM
Additive Manufacturing of Compact Manifold-microchannel Heat Exchangers Utilizing Direct Metal Laser Sintering: home Keramati[1]; *Martinus Arie*[1]; Farah Singer[1]; Michael Ohadi[1]; [1]University of Maryland
Direct Metal Laser Sintering (DMLS) is a metal additive manufacturing technique which uses a laser to fuse metal powders. In this study, DMLS was used to fabricate compact manifold-microchannel heat exchangers (M2HXs). Compared to the state of the art heat exchangers, M2HXs have been proven to yield superior performances. However, fabrication of M2HXs is a challenge using conventional fabrication methods because of its complex geometry. In order to fully utilize the potential of M2HXs, small fins (0.1-0.2mm) and channels (0.2-0.3mm) are required. Four different machines were used to study the effect of geometries and printing parameters on feature size. A comprehensive study has been performed to achieve fin thickness as small as 0.1mm. Based on the studies, a 3”×3” ×3” and a 3”×3” ×1.5” size M2HXs were fabricated with straight fins of 0.133mm out of maraging steel and incline fins of 0.165mm out of stainless steel 316 respectively.

2:20 PM Break

Thursday Closing Session

Thursday PM
June 21, 2018

Room: Green Auditorium
Location: NIST Headquarters

3:20 PM Discussion

4:50 PM Concluding Comments

Wednesday PM - Poster Session

Wednesday PM
June 20, 2018

Room: Poster Area
Location: NIST Headquarters

Effects of Different Orientations on Creep Damage of 316L Austenitic Stainless Steel Produced by Selective Laser Melting: *Van Hung Dao*[1]; Jong Min Yu[1]; Kee Bong Yoon[1]; [1]Chung-Ang University

Additive manufacturing is revolutionizing production method and application of materials. The clear tendency of varying from mass production to individual production of net-shape components has motivated using selective laser melting (SLM). In this study, austenitic 316L steel cubic sample was fabricated by selective laser melting technique with using optimization parameters. Partially molten powder particles and microstructures defects were revealed to be responsible for contributing premature failure and showing the heterogeneous characteristic structure. The difference of microstructure between each direction was also compared. Small punch creep test (SPC) were conducted at temperature of 650oC under various applied loadings along two different orientations of vertical and horizontal. The presented result indicates that a correlation of resulting microstructure and hardening curve of SPC testing. It also creates the premise for an optimal direction to resolve creep damage according to the process parameters used for their fabrication.

Effects of Processing Parameter on Creep Behavior of 316L Stainless Steel Produced by Selective Laser Melting: *Jong Min Yu*[1]; Van Hung Dao[1]; Kee Bong Yoon[1]; [1]Chung-Ang University

Additively manufactured parts using metal material are mainly used for special components such in aerospace field. The parts are likely to be used in high temperature and pressure conditions. In this study, small punch creep(SPC) testing were conducted with 316L stainless steel samples prepared by various processing parameters using selective laser melting(SLM) method to evaluate the influence of processing parameter on creep behavior. The 5 sample blocks were fabricated with fixed power of 275 W, layer thickness of 0.05 mm, and hatch spacing of 0.12 mm under different scan speed conditions from 420 to 980 mm/s. The SP specimens were machined which for punching direction is perpendicular to the build direction. SPC testing were conducted at 650°C according to various punch. From the results, the correlation between minimum punch displacement rate and punch load for each block was evaluated by power law equation.

Laser Power Prediction Using Deep Learning of Melt Pool Images for Selective Laser Melting: *Ohyung Kwon*[1]; Hyung Giun Kim[1]; Min Ji Ham[1]; Wonrae Kim[1]; Gun-Hee Kim[1]; Jae Hung Cho[2]; Nam Il Kim[2]; Kangil Kim[3]; Chang-Woo Lee[1]; [1]Korea Institute of Industrial Technology; [2]Winforsys; [3]Konkuk University

By applying deep learning methods to melt pool images, we develop a model to predict laser power for selective laser melting of CoCr/Inconel718/SUS316L. Multi-layer perceptron algorithms are applied to create the prediction model that can be used to analyze melt pool images. Melt pool images are obtained by an on-axis high speed camera system of maximum 3000 frames per second. Total 138,000 images for six laser powers from 100 watt to 350 watt are used to training, validating, and testing the model. The trained model predicts melt pool images into the correct laser power with greater than 99% accuracy. The model also identifies abnormal images through comparing the predicted laser power with the correct laser power. These results indicate the possibility of monitoring variations in melt pools and diagnosing the product quality non-destructively.

Probabilistic Modelling and Simulation of Microstructural Evolution in Zr Based Bulk Metallic Glass Matrix Composites during Solidification: *Muhammad Rafique*[1]; [1]RMIT University

Bulk metallic glass and their composites are unique new materials which have superior mechanical and structural properties as compared to existing conventional materials. However, their mechanical behavior is dubious, unpredictable and requires extensive experimentation to draw conclusive results. In present study, which is continuation of previous work of author, a linear iterative model is combined with probabilistic cellular automaton method to describe nucleation and growth of second phase dendrites from melt in glassy matrix during solidification. Model is programmed and coded in MATLAB®. Its validation is done by optical microscopic studies performed on actual samples. Results indicate that the effect of incorporating all heat transfer and diffusion coefficients play a vital role in refining the model and bringing it closer to actual experimental observations. Two types of hypo and hyper eutectic systems were studied with two different inoculants. Simulation results were found to be in good agreement with experimental observations.

Thermography in Metal AM: Comparison of High-speed NIR Thermography and MWIR Thermography: *Simon Altenburg*[1]; Christiane Maierhofer[1]; Andrey Gumenyuk[1]; Gunther Mohr[1]; [1]Bundesanstalt für Materialforschung und -prüfung

Additive manufacturing (AM) opens the route to a range of novel applications. However, the complexity of the manufacturing process poses a challenge for the production of defect-free parts with a high reliability. Since process dynamics and resulting microstructures of AM parts are strongly influenced by the involved temperature fields, thermography is a valuable tool for process surveillance. The high process temperatures in metal AM processes allow one to use cameras usually operating in the visible spectral range to detect the thermally emitted radiation from the process. In our work, we compare the results of first measurements during the manufacturing processes of a commercial laser metal deposition (LMD) setup and a laser beam melting (LBM) setup using a MWIR camera with those from a VIS high-speed camera with band pass filter in the NIR range.

Validation of Methods for Mechanical And Microstructural Property Measurement of Sub-standard Sized SLM Test Specimens: *Tanni Alam*[1]; Jonathan Raush[1]; Shengmin Guo[1]; [1]University of Louisiana at Lafayette

An efficient SLM product characterization method is developed and validated which involves optical strain measurement of sub-standard sized test specimens. The advantage of this method over conventional testing methods is the efficient testing, producing accurate results, with less raw material. The study focuses on the mechanical and microstructural properties of Ti-6Al-4V and stainless steel 316L components. Two series of samples; 40 mm and 20 mm long flat dog bones of both metals have been produced. Tensile and low cycle fatigue tests were carried out to establish localized mechanical behavior. Tensile properties were analyzed using DIC. Mechanical properties are compared with standard sized specimens, built via SLM as well as wrought, for quantitative comparison of the test method. The fracture surfaces from both tensile and fatigue tests were analyzed using SEM. The observed microstructural details of the as-built components and fractured components under tensile and cyclic loads will be discussed.

Effect of Porosity on the Mechanical Properties of Additive Manufactured Ti6Al4V: *Jun Wang*[1]; [1]Shanghai Jiaotong University

AM with Electron beam melting (EBM), has increasingly shown great expanding the application of Ti6Al4V orthopedic implants in recent years for it can fabricate the parts individually, fast and costly.However, the anisotropy of microstructure characterization and mechanical properties of Ti6Al4V manufactured by EBM has not been studied in detail. The microstructure was characterized as well as pores in EBM-build parts were analyzed. It was explored that the vaporization of Al contributed to the generating voids which were observed in both orientations and found it had a great effect on the tensile property as crack origin and junctions. What's more, the strain hardening of EBM-build parts during the tensile tests were very uniform.

Effects of Environmental Conditions on Printing Quality in the Fused Filament Fabrication Process: *Lichen Fang*[1]; Yishu Yan[1]; Ojaswi Agarwal[1]; Kevin Hemker[1]; Sung Hoon Kang[1]; [1]Johns Hopkins university

Fused filament fabrication (FFF) is one of the most popular additive manufacturing processes. FFF can print various high-performance thermoplastics and a FFF printer is lower in cost to build and operate. However, advanced applications of FFF are still held back by the large variability in property, and lower strength and toughness of the printed material compared to traditional polymer processing methods. To address these issues, we studied the effects of environmental conditions on printing quality of polycarbonates. Our infrared thermography showed that heating bed will still leave over 3 °C/mm temperature gradient within samples, and micro-CT data showed up to 5% porosity defects generated by absorbed moisture. To quantify the effects, we have fabricated polycarbonate samples under controlled environmental conditions and characterized them by conducting multi-fiber wall tests, tensile tests of printed dogbone samples, peel tests and geometrical accuracy measurements. Our in-depth study will provide guidelines for future FFF applications.

INDEX

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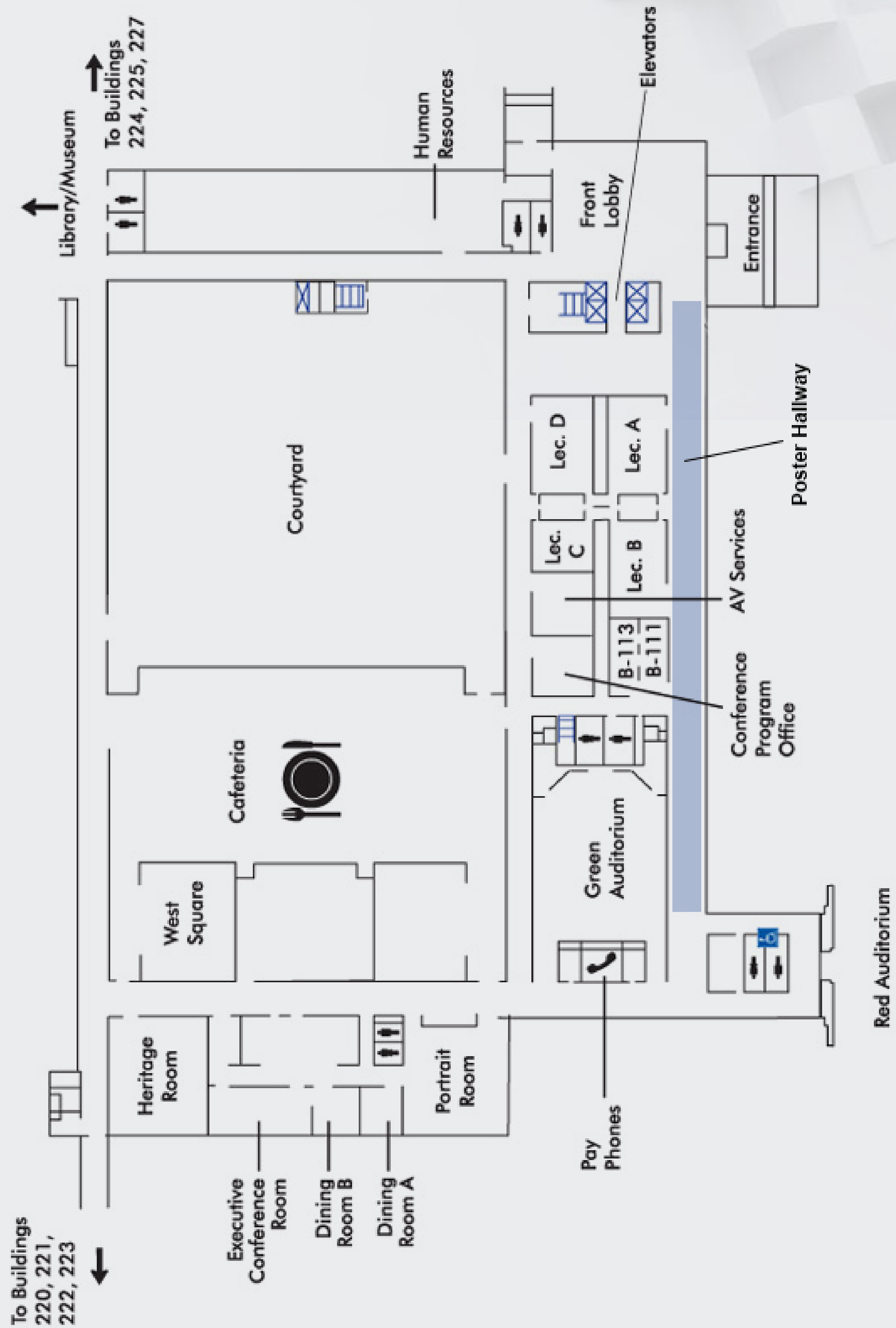
NIST ADMINISTRATION 101 BUILDING
MAIN FLOOR



VENUE CAMPUS MAP

NIST GAITHERSBURG CAMPUS