Development and Transition of a Computational Materials Framework to Support Qualification of AM Components

Part 2 – NASA's Perspective

Presented at:

AA&S 2020 Conference

August 25-28, 2020

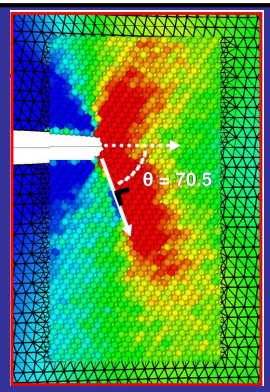
Presented by:

Dr. E.H. Glaessgen

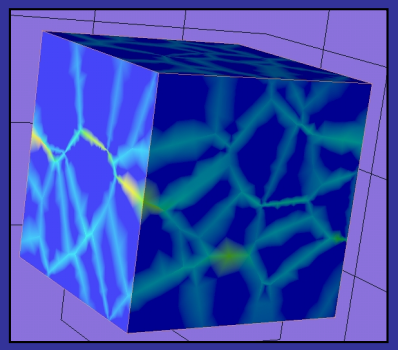
NASA Senior Technologist for Computational Materials
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Computational Materials for Material Performance



Modeling Plasticity at a Crack Tip



Simulation of Crack Growth in a Material Microstructure

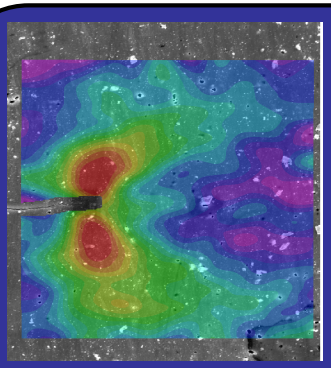
Simulate Operative Physical Processes at Relevant Length Scales

- Simulate critical damage processes
- Develop micro-/nano-structure-based simulations that interrogate damage processes at local length scales and local environments
- Propagate uncertainties across length scale to predict component reliability

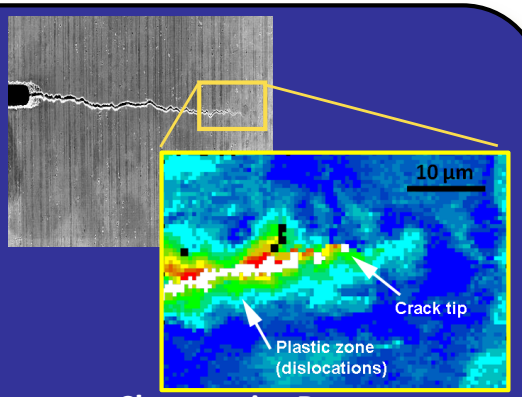
Physics-Based Material Design & Certification Requires Close Integration of Analysis and Experimentation

Characterize the Physics of Damage via Experimental Evaluation

- Develop micro-/nano-structure-based testing & characterization that interrogates damage processes at local length scales and local environments
- Validate damage models and understand operative processes
- Fabricate and evaluate model materials

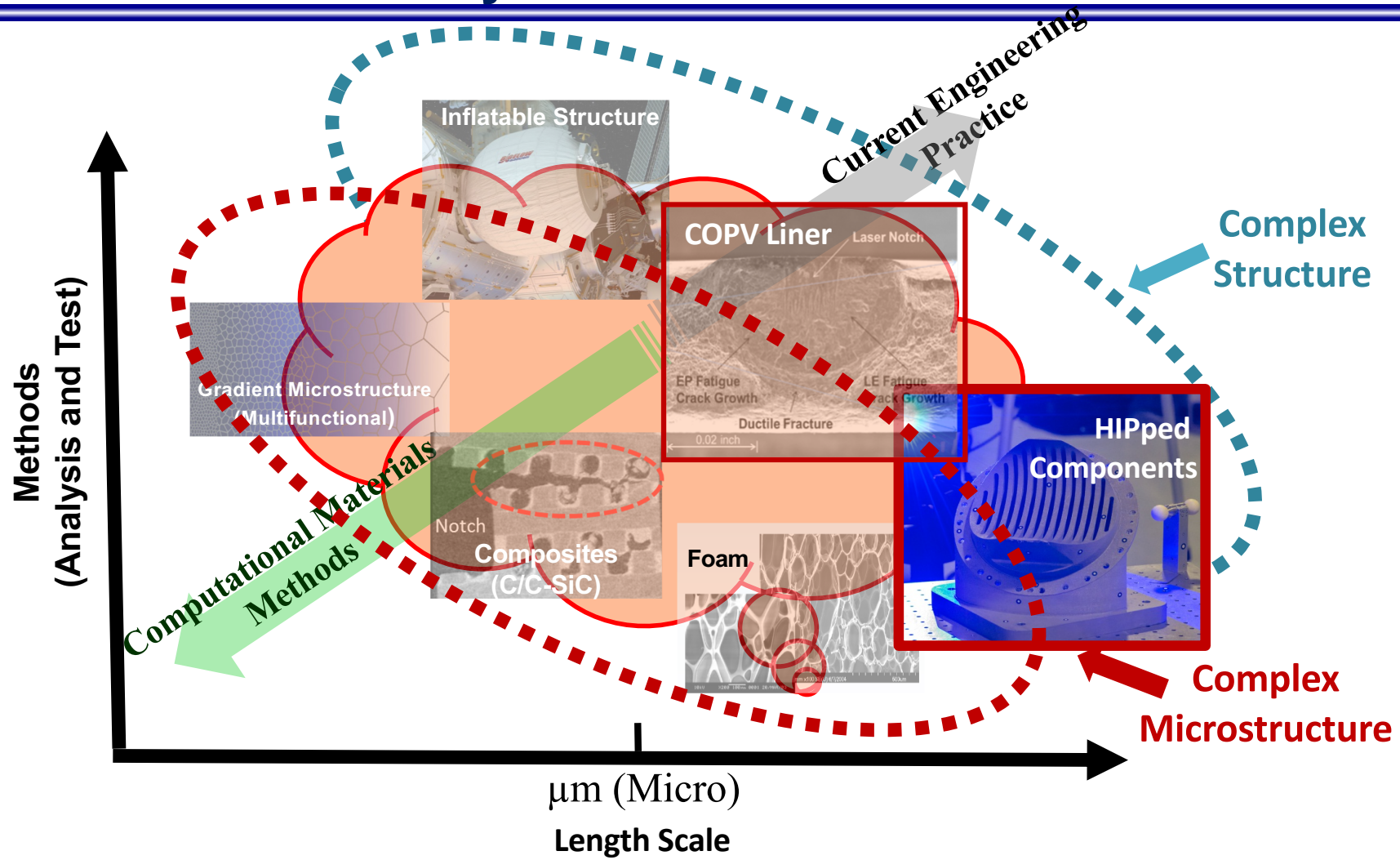


Measure Deformation at Crack Tip



Characterize Damage Evolution

Durability and Damage Tolerance Analysis and Test Shortfall*



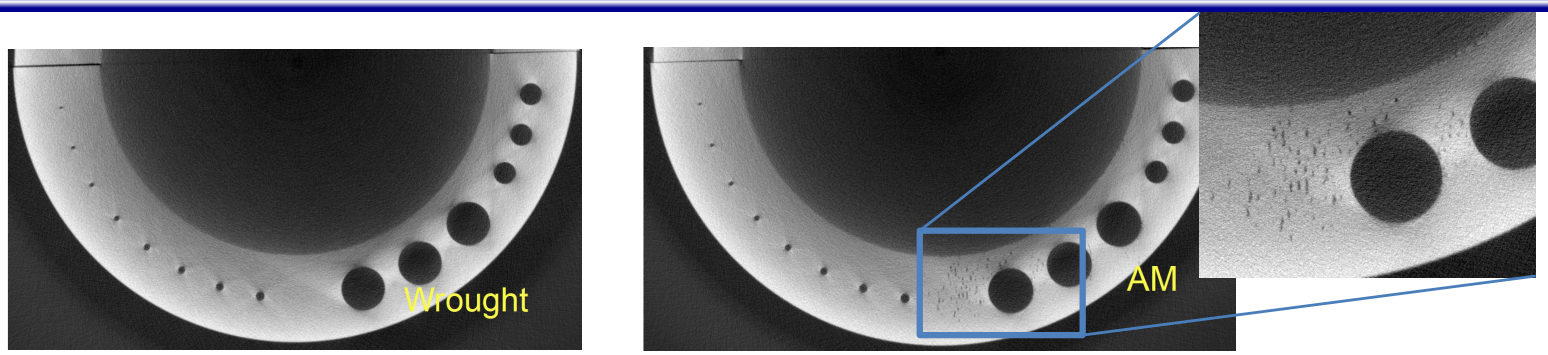
Future designs include microstructure-dependent D&DT influences:

- Very thin or functionally-graded structural components (where traditional methods are suspect)
- Advanced materials and manufacturing, which preclude brute-force testing programs

*NASA/TM-2017-2017-219621; NESC-NPP-17-01, R. Piascik & N. Knight, Re-Tooling the Agency's Engineering Predictive Practices for D&DT

Images: NASA

Issues Posed by Hot Isostatic Pressed (HIPped) AM Components*



Wrought **Additively Manufactured**

6061 Aluminum Non-Destructive Evaluation (NDE) Test Articles**

Increasing number of fracture critical components produced via SLM & HIP

- HIP is performed at high temperature and pressure to improve consolidation of material
  - High Pressure (10ksi-15ksi) → reduces defect state
  - High Temperature (typically > 80% melt point) → transforms microstructure

MSFC Standard engineering policy on HIP of AM components:

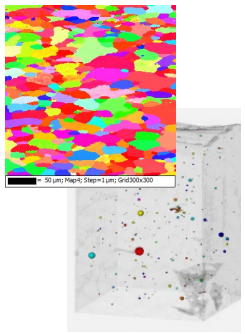
- MSFC-SPEC-3717 Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes requires HIP as a mandatory process for all Class A (Fracture Critical) AM hardware
- The HIP requirement is set based on perceived best practice with current knowledge
- Assumption is that voids produced during Selective Laser Melting are "healed"

→ Engineering policy is made in the absence of a full understanding of the benefits of HIP and the HIP requirement is often challenged

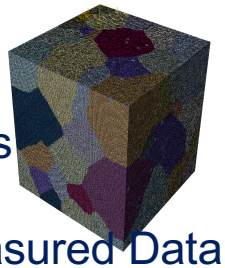
** Doug Wells, Brian West, MSFC*

*** Beshears, R., "Computed Tomography Inspection and Analysis for Additive Manufacturing Components," ASNT Annual Conference, November 2, 2017.*

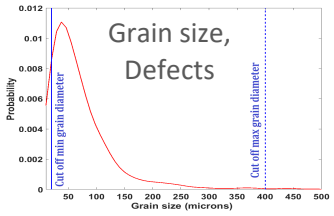
Microstructurally-Informed D&DT - Work Flow



Characterize Microstructure using Quantitative Measurements



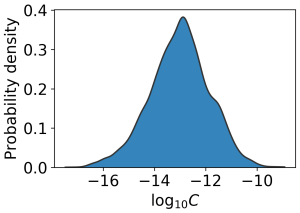
Localized Models and Analyses using Fitted Measured Data



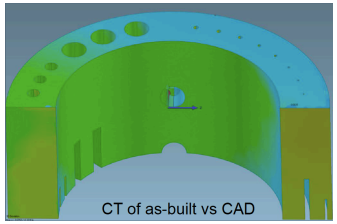
Microstructurally Small Crack Growth Model and Analysis to Understand Local Parameters

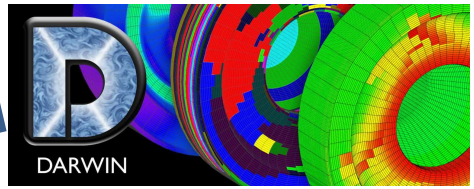


Fatigue Crack Growth Parameter Distributions



Global Models and Analyses Subject to Service Environments





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D&DT Analysis Tools

Today's D&DT Engineering Standard Practice

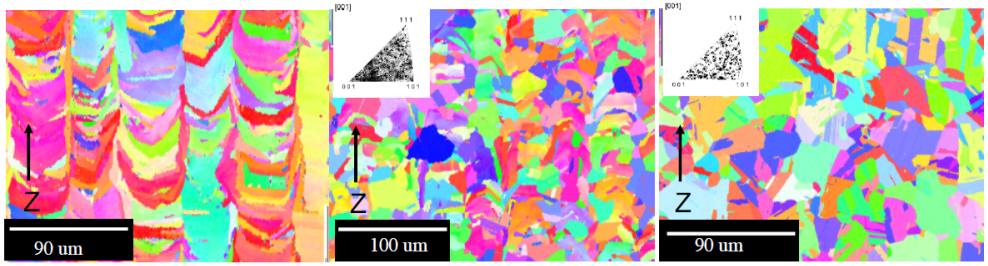
- Today's standard D&DT engineering practice relies on continuum assumptions
- Microstructurally-informed D&DT considers local length scales, environments and material properties
  - Expanded effort on small-scale testing and physics-based material model calibration
  - Produce distributions of behavior by relying more heavily on modeling and simulation

***Image: Southwest Research Institute**

Assessing Hot Isostatic Pressing (HIP) Treatment for Additively Manufactured Hardware (1/2)

*Determine Microstructure as a Function of HIP Temperature and Pressure**

• Standard thermal treatments may not work for AM hardware - can have dramatic effect on mechanical properties

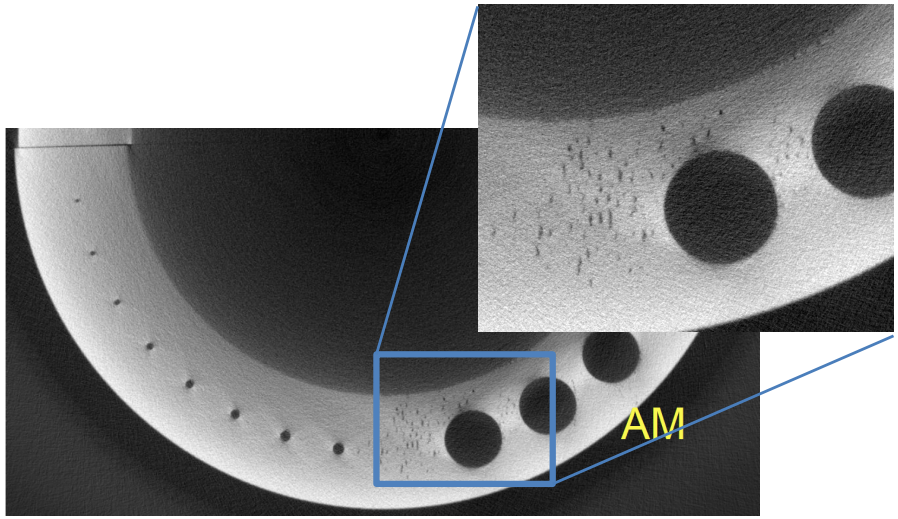


Three microstructures, in three different Inconel 718 builds, all subjected to the same thermal treatment.

*Bob Carter, NASA GRC

Assess Remnant Porosity as a Function of HIP in Complex Components

• AM processing parameters vary as a function of position on the build plate and local part geometry - can lead to local variation in pore content



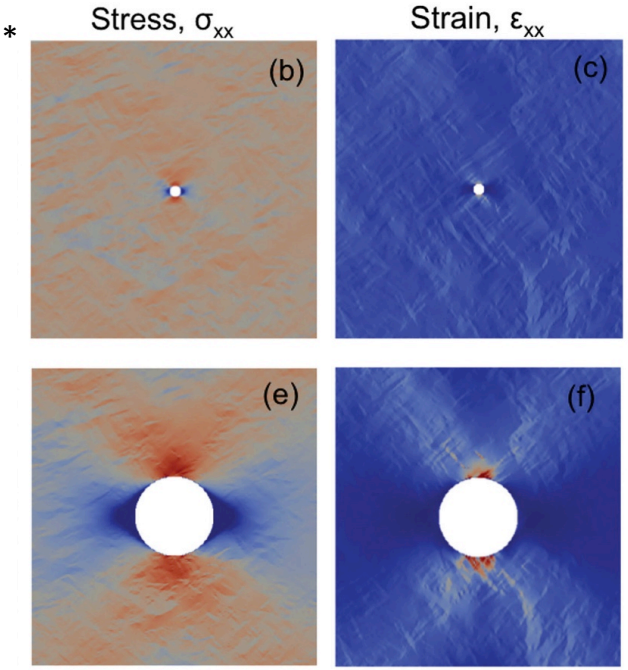
Porosity in 6061 Aluminum NDE Test Articles **

**Beshears, R., "Computed Tomography Inspection and Analysis for Additive Manufacturing Components," ASNT Annual Conference, November 2, 2017.

Assessing Hot Isostatic Pressing (HIP) Treatment for Additively Manufactured Hardware (2/2)

Determine Probability of Defect Closure from HIP

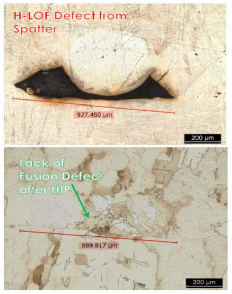
- Develop capability for predicting defect closure in response to HIP for AM materials
- Multiphysics simulation of heat & pressure to determine defect size as a function of HIP parameters



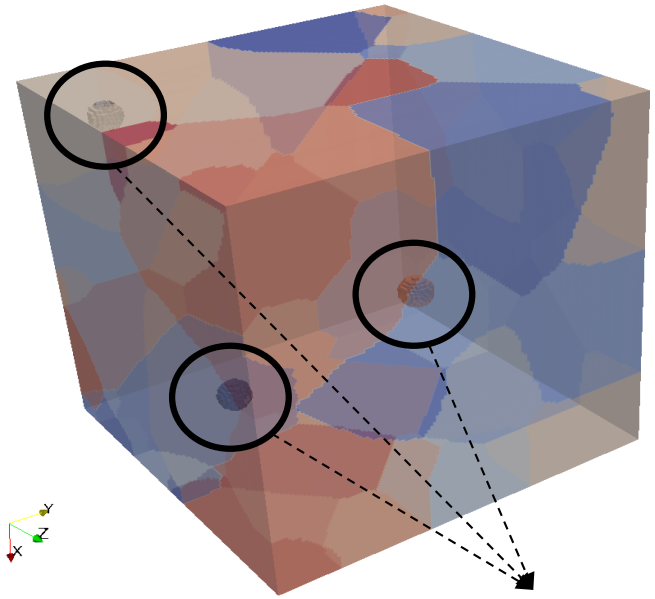
*Cunningham, Nicolas, Madsen, Fodran, Anagnostou, Sangid, Rollett, "Analyzing the effects of powder and post-processing on porosity and properties of electron beam melted Ti-6Al-4V", Materials Research Letters, Vol. 5, No. 7, 2017,pp.516-525.

Determine As-Built and Post-HIP Mechanical Properties, including Fatigue Life

- Inhomogeneity in microstructure, residual stress, and defect content in hardware can influence mechanical, fracture and fatigue properties



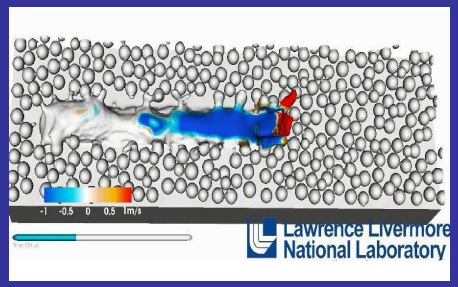
HIPped Defect



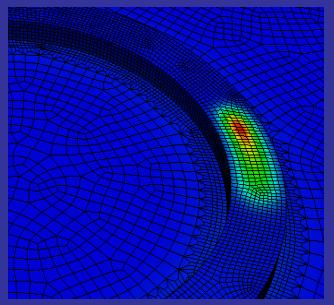
Porosity

Process-Specific Defects in 3D Simulations

Computational Materials for Material Processing



Simulation of Laser-Powder Bed Interactions



Prediction of Local Heat Distribution

Simulate Fundamental Physics Governing Processing

- Determine role of processing parameters and composition on microstructure
- Simulate physical processes including laser beam absorption in powder bed, heat transfer via conduction and radiation, and fluid flow at the melt pool, particle flow
- Simulate residual stress, distortion, microstructural evolution and precipitate growth

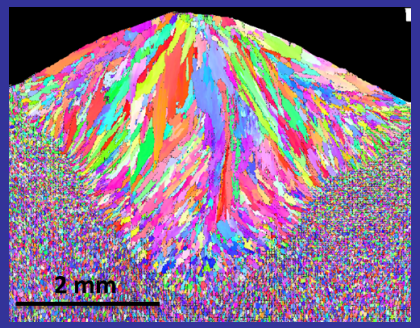
Develop Physically Correct Models Needed to Support Certification of AM Feed Stock and Manufacturing Process

Characterize Material Evolution using Experimental Methods

- Employ heavily-instrumented SLM machine and synchrotron beam lines
- Produce coupon-size specimens using well-controlled parameters
- Understand details of the relationship between processing parameters and resulting microstructure

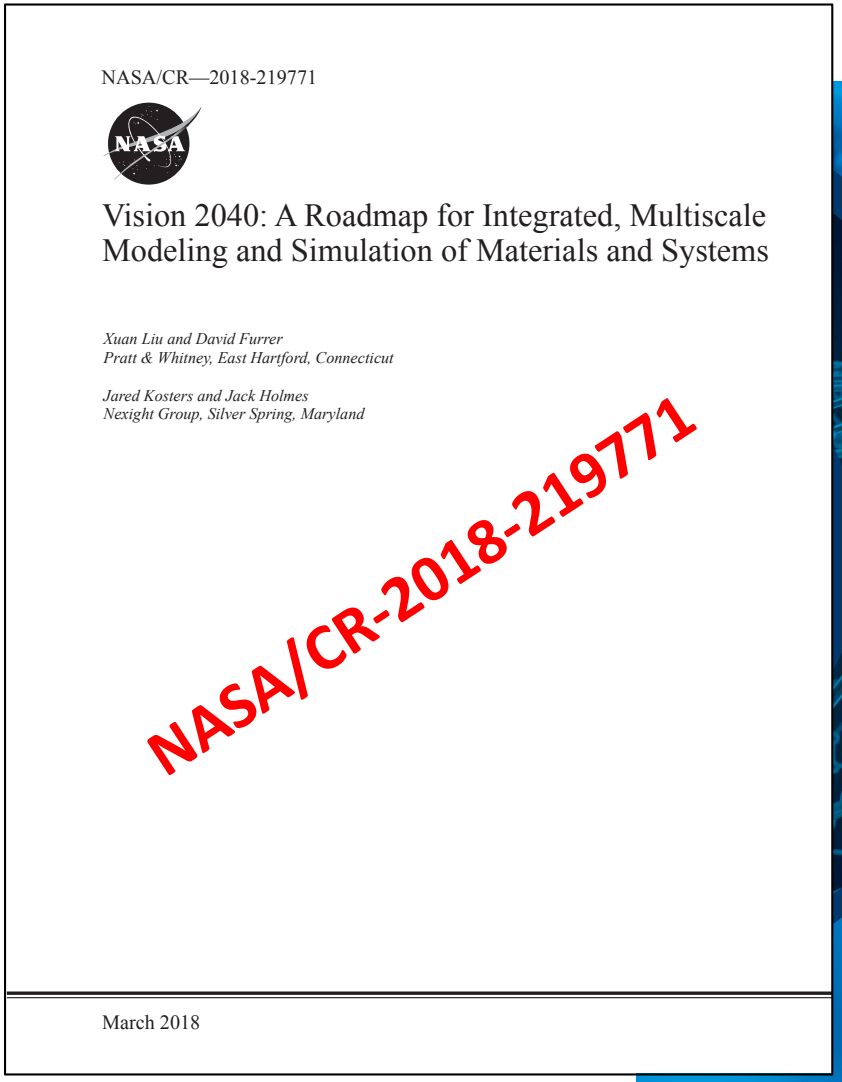


Selective Laser Melting



Grain Structure from Additive Process

Vision 2040 for Integrated, Multiscale Materials and Structures Modeling / Simulation


NASA/CR—2018-219771

Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems

Xuan Liu and David Furrer
Pratt & Whitney, East Hartford, Connecticut

Jared Kosters and Jack Holmes
Nexight Group, Silver Spring, Maryland

NASA/CR-2018-219771

March 2018


Vision 2040:
A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems

Prepared under Contract NNC15BA06B


Vision 2040 Overview

2040

5. Verification & Validation
6. Data, Informatics, & Visualization
7. Workflows & Collaboration Frameworks
8. Education & Training
9. Computational Infrastructure

between these prior efforts and this one is that Vision 2040 calls for the holistic integration of materials, structural, and systems design and simulation needs within individual companies and, eventually, throughout supply chains. Prior studies looked primarily at similar technical challenges from either a materials or structures/systems perspective.

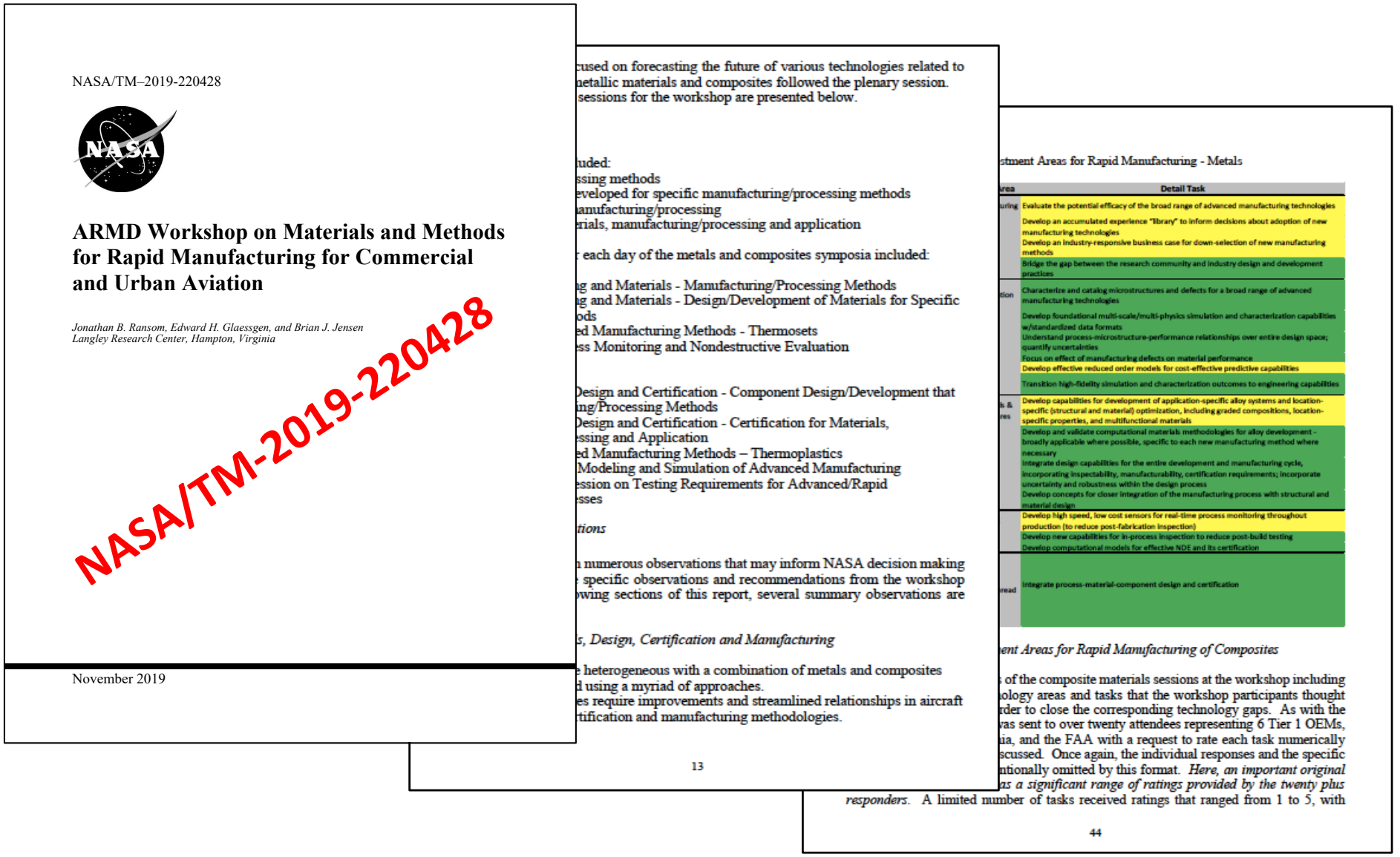
The Vision 2040 Roadmap is consistent with NASA's ARMD objectives, which recognizes six Strategic Thrusts that affect the aviation industry, the nation, and the world [8]:

1 **Safe, efficient growth in global operations**
Enable the continued development of a modernized air transportation system that will achieve greater capacity and operational efficiency while maintaining or improving current and future safety and other performance measures.

2 **Innovation in commercial supersonic aircraft**
Advance technologies to overcome the major environmental and efficiency barriers to market innovation in supersonic transport to both advance

NASA/CR—2018-219771 12

Materials and Methods for Rapid Manufacturing for Commercial and Urban Aviation Workshop



NASA/TM–2019-220428

ARMD Workshop on Materials and Methods for Rapid Manufacturing for Commercial and Urban Aviation

Jonathan B. Ransom, Edward H. Glaessgen, and Brian J. Jensen
Langley Research Center, Hampton, Virginia

NASA/TM-2019-220428

November 2019

cused on forecasting the future of various technologies related to
netallic materials and composites followed the plenary session.
sessions for the workshop are presented below.

luded:
ssing methods
eveloped for specific manufacturing/processing methods
anufacturing/processing
erials, manufacturing/processing and application

each day of the metals and composites symposia included:

g and Materials - Manufacturing/Processing Methods
g and Materials - Design/Development of Materials for Specific
ods
ed Manufacturing Methods - Thermosets
ss Monitoring and Nondestructive Evaluation

Design and Certification - Component Design/Development that
ng/Processing Methods
Design and Certification - Certification for Materials,
ssing and Application
ed Manufacturing Methods – Thermoplastics
Modeling and Simulation of Advanced Manufacturing
ession on Testing Requirements for Advanced/Rapid
sses

tions

numerous observations that may inform NASA decision making
specific observations and recommendations from the workshop
wing sections of this report, several summary observations are

s, Design, Certification and Manufacturing

heterogeneous with a combination of metals and composites
using a myriad of approaches.
es require improvements and streamlined relationships in aircraft
tification and manufacturing methodologies.

13

stment Areas for Rapid Manufacturing - Metals

rea	Detail Task
uring	Evaluate the potential efficacy of the broad range of advanced manufacturing technologies
	Develop an accumulated experience "library" to inform decisions about adoption of new manufacturing technologies
	Develop an industry-responsive business case for down-selection of new manufacturing methods
	Bridge the gap between the research community and industry design and development practices
tion	Characterize and catalog microstructures and defects for a broad range of advanced manufacturing technologies
	Develop foundational multi-scale/multi-physics simulation and characterization capabilities w/standardized data formats
	Understand process-microstructure-performance relationships over entire design space; quantify uncertainties
	Focus on effect of manufacturing defects on material performance
	Develop effective reduced order models for cost-effective predictive capabilities
	Transition high-fidelity simulation and characterization outcomes to engineering capabilities
s & res	Develop capabilities for development of application-specific alloy systems and location-specific (structural and material) optimization, including graded compositions, location-specific properties, and multifunctional materials
	Develop and validate computational materials methodologies for alloy development - broadly applicable where possible, specific to each new manufacturing method where necessary
	Integrate design capabilities for the entire development and manufacturing cycle, incorporating inspectability, manufacturability, certification requirements; incorporate uncertainty and robustness within the design process
	Develop concepts for closer integration of the manufacturing process with structural and material design
	Develop high speed, low cost sensors for real-time process monitoring throughout production (to reduce post-fabrication inspection)
	Develop new capabilities for in-process inspection to reduce post-build testing
	Develop computational models for effective NDE and its certification
read	Integrate process-material-component design and certification

ent Areas for Rapid Manufacturing of Composites

of the composite materials sessions at the workshop including
ology areas and tasks that the workshop participants thought
rder to close the corresponding technology gaps. As with the
as sent to over twenty attendees representing 6 Tier 1 OEMs,
ia, and the FAA with a request to rate each task numerically
scussed. Once again, the individual responses and the specific
ntionally omitted by this format. *Here, an important original*
as a significant range of ratings provided by the twenty plus responders. A limited number of tasks received ratings that ranged from 1 to 5, with

44

NASA / NIST / FAA Technical Interchange Meeting on Computational Materials Approaches for Qualification by Analysis

NASA/TM–2020-

NASA / NIST / FAA Technical Interchange Meeting on Computational Materials Approaches for Qualification by Analysis

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M. Gorelik
Federal Aviation Administration, Scottsdale, Arizona

N.A. Ashmore
Boeing Research and Technology, St. Louis, Missouri

R. Barto
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Air Force Research Laboratory, Dayton, Ohio

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Pratt and Whitney, East Hartford, Connecticut

NASA/TM-2020-

August 2020

Question 9: What capabilities should NASA & NIST champion to enable next-generation qualification of process intensive metallic materials (e.g., AM). What is the timeline and phased approach at 5, 10, 20 years?	
All years: • NIST, NASA, and AM-Bench can provide robust data for simulation V&V. • Think beyond direct physics-based approaches – i.e. data driven approaches. • Develop an understanding of the inherent sources of variability – not just with machines, but in the process and feed stock. • Work with partner organizations to develop improved mechanisms and guidance for acquiring and sharing data and metadata. *5 years:* • Provide prescription for measurements and calibrations to validate a basic set of process parameters. These should be used to qualify both process parameters and machines. Example parameters for laser powder bed fusion include laser power, scan velocity, laser power distribution function, and hatch spacing. • Make the connection between the set of process parameters and the local state of the material for a narrow set of materials and conditions. This goes beyond existing PV maps that only deal with two process parameters. • Develop a framework for defining and implementing model maturity levels, with specifications for V&V at each step. • Although a given feedstock chemistry typically falls within formal alloy specifications, these specs are often broad enough to introduce substantial variation in the part performance. Work with standards organizations such as ASTM to address this problem of material specifications for AM feedstocks. *10 years:* • Make the connection between the set of process parameters and the local state of the material for a wide range of materials and conditions. • Develop best practice guides for achieving a specific material state by adjusting the qualified build parameters. *20 years:* • Develop specifications that will lead to build characteristics that are consistent between multiple machines and multiple machine vendors. Provide statistically valid data to demonstrate this. This is a 20-year goal largely because rapid changes in the state-of-the-art makes this a moving target.	• Need for computational-based design for inspectability integrated into design process. • Need to focus on probabilistic methods. • Focus on UQ methods. • Focus on incremental progress and demonstrable deliverables. • Need to mentor industry in ICME best practices. • Non-standard characterization and testing methods. • Create an industry group to develop requirements for an ICME framework (V&V, etc.). • Develop a broader joint roadmap for technology developers (including educators), end users, and regulators. • Workforce training and development. • Champion standards development. • Quantitative in-situ micro-structure characterization and evolution. • NDE of thick additive parts (high-z, complex) • Micro-structure sensitive defect-mediated durability, damage tolerance, fatigue. • Accelerated high-cycle fatigue tests and models. • Micro-structurally small crack initiation and propagation.

Summary

- Gradual maturation of ICME is a good path forward
  - **Meaningful balance between experimental and modeling projects**
  - **Demonstrating early successes outside of regulatory domain (e.g. material & process optimization, preliminary design)**
- Key enablers for Qualification and Certification: UQ and V&V
- AM as a "use case" for Computational Materials
  - ***Special topic*: effect of defects in AM – experimental and analytical studies (including probabilistic modeling)**
- Importance of inter-agency and industry-government collaboration, and engagement with SDOs
  - **Focused R&D programs (reflecting interests of multiple stakeholder groups)**

National Aeronautics and Space Administration



A Storied Legacy, A Soaring Future

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