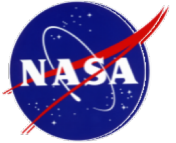


Development and Transition of a Computational Materials Framework to Support Qualification of Additively Manufactured Components



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NASA Langley Research Center**

Michael Gorelik

**Chief Scientist for Fatigue and Damage Tolerance
Federal Aviation Administration**

**Approved for Public Release on xx/xx/19
Tracking Number: xxxx**



FAA Perspectives

Computational Materials

- **Material Performance**
 - **Next Gen Durability & Damage Tolerance (D&DT)**
- **Material Processing**

Future Directions

- **ARMD Vision 2040 Roadmap**
- **ARMD Rapid Manufacturing Workshop**

ICME Application Benefits

Commonly identified as:

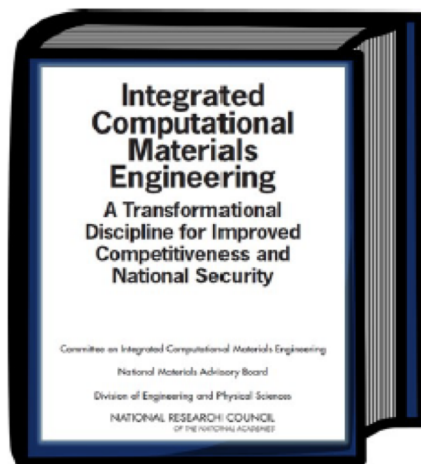
- Cost savings
- Novel fit-for-purposes materials
- Integrated design, certification, and flexible manufacturing
- Risk reduction (*program risk* vs. product safety risk)

Accelerated Insertion of Materials (AIM) Program Overview



The AIM program initiative created a new materials development methodology that accelerates the insertion of new materials in order to achieve parity with the engine/platform development/design cycles. Accomplishments of the AIM program include:

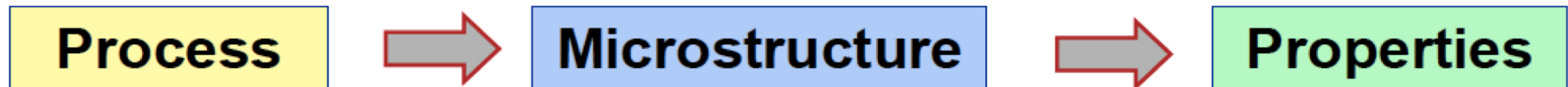
- Establish design-driven material requirements by tightly coupling design and materials activities and tools.
- Providing earlier information (with confidence bounds) to designers throughout the development cycle.
- Controlling the performance, producibility, and cost of materials.
- Reducing risks of new material insertion risk while also decreasing costly, time-consuming data generation.
- Creating a knowledge base and tool kit for designers that links with computational design tools.



*Keeping pace with
industry needs*

*Requires significant
maturation to
realize this benefit*

Multi-Scale Framework Considerations



- Not everything has to be (*or can be...*) derived from the first principles
 - A meaningful combination of physics-based and *empirical* models can be used as a maturation path
 - Machine Learning may provide a complementary approach
- Models validation is key
 - But the level of effort can sometimes overshadow the conventional characterization approach...
- “Meso” attributes can be used to streamline process control. *Examples:*
 - Use of microstructure attributes to control part’s properties
 - Controlling melt pool in Additive Manufacturing process



14 CFR Part 25 Regulations - Materials

(Transport Category Aircraft)

§ 25.603 Materials

- The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must —
 - a) Be established on the basis of experience or tests;***
 - b) Conform to approved specifications (such as industry or military specifications, or Technical Standard Orders) that ensure their having the strength and other properties assumed in the design data; and
 - c) Take into account the effects of environmental conditions, such as temperature and humidity, expected in service.

§ 25.605 Fabrication Methods

- a) The methods of fabrication used must produce a consistently sound structure. If a fabrication process (such as gluing, spot welding, or heat treating) requires close control to reach this objective, the process must be performed under an approved process specification.
- b) Each new aircraft fabrication method ***must be substantiated by a test program.***



14 CFR Part 25 Regulations - Materials

(Transport Category Aircraft)

§ 25.613 Material Strength Properties and Design Values

- a) Material strength properties must be **based on enough tests** of material meeting approved specifications **to establish design values on a statistical basis**.
- b) Design values must be chosen to minimize the probability of structural failures **due to material variability**.
- d) The **strength, detail design, and fabrication** of the structure must minimize the probability of disastrous fatigue failure, particularly at points of stress concentration.
- e) Greater design values may be used if a “premium selection” of the material is made in which a **specimen of each individual item** is **tested before use**.

No Allowance for Modeling or Analysis



Examples of “Model-Friendly” Domains

- Damage Tolerance → Part 25 (AC 25.571-1D)
 - In general, “analysis supported by test evidence” is accepted
- Damage Tolerance → Part 33 (AC 33.70-1)
 - Analysis is accepted (e.g. stress, heat transfer, crack growth, ...)
 - However, “...*the analysis approach should be validated against relevant test data*”
 - “The *probabilistic approach* to damage tolerance assessment is one of two elements *necessary to appropriately assess damage tolerance...*”
- AC 20-146 “*Methodology for Dynamic Seat Certification by Analysis*”
 - Needs to be validated by test
 - One of the few examples of “certification by analysis”
 - *Rational Analysis* - an analysis based on good engineering principles, judgment, and/or *accepted methodology* (AC 25.562-1b)

ICME Enablers for Qualification...

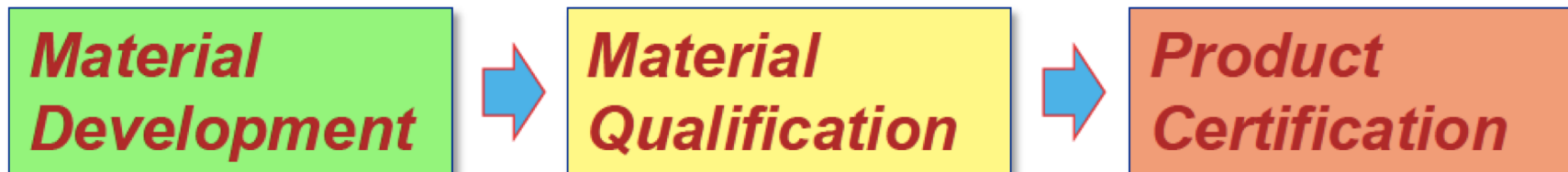
(... and Certification longer-term?)

- Multi-scale modeling
- Uncertainty Quantification (UQ)
- Models Verification and Validation (V&V) *See next slide*



ICME Maturation (*Crawl* → *Walk* → *Run*)

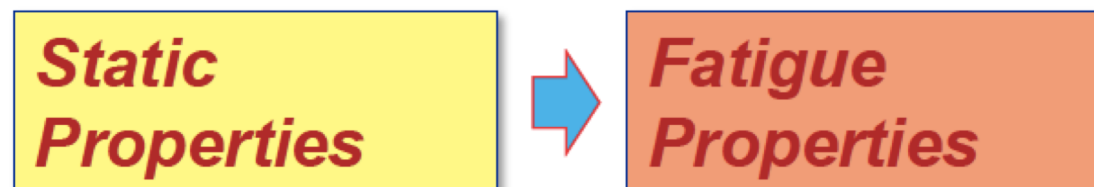
Process Level



System Level



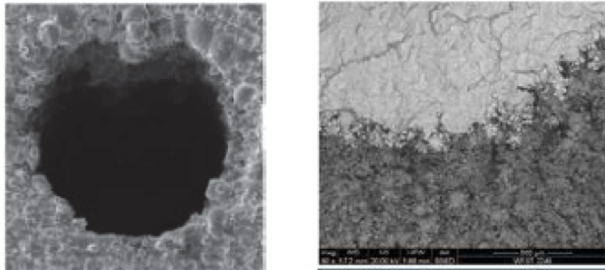
Component Level



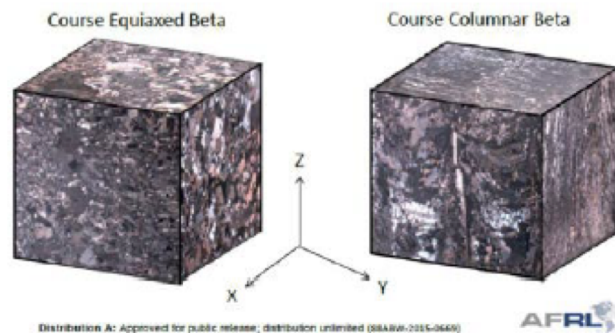
***AM as a Use Case* for Developing Model-based Qualification Framework**

- **Relevance to other material systems' attributes**
(*casting, welding, powder metallurgy, ...*)
- **Highly complex “ecosystem” (process → microstructure → properties)**
- **Pathway to future technologies (e.g. UAS) and applications:**
 - Topologically optimized structures
 - Location specific / gradient microstructures
 - Multi-material systems
 - Multi-functional systems (e.g. embedded electronics)

Examples of Risk Factors for AM



Surface Quality



Microstructure Variability



Powder Control

Powder feed rate (g/min)

Laser Power (W)

Scan speed (in/min)

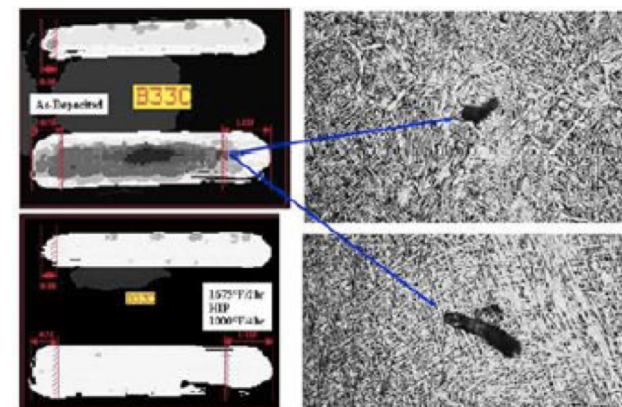
Laser spot size (in)

Substrate temp (°F)

Hatch spacing (% of calculated)

*Up to 150 (!)
process
parameters
identified*

Process Controls



HIP Effectiveness

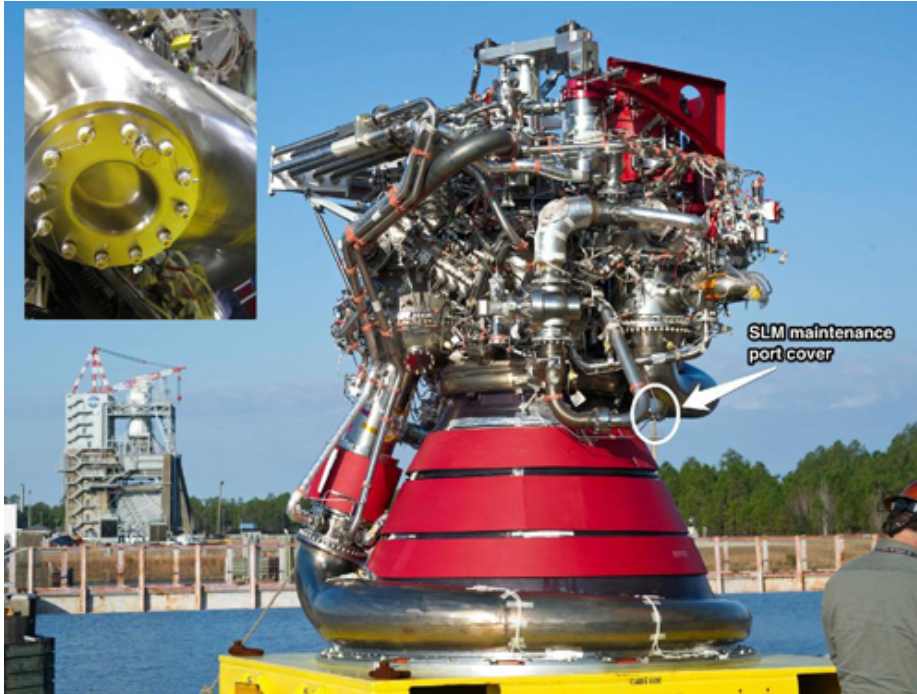
Images: AFRL

“Smarter Testing”

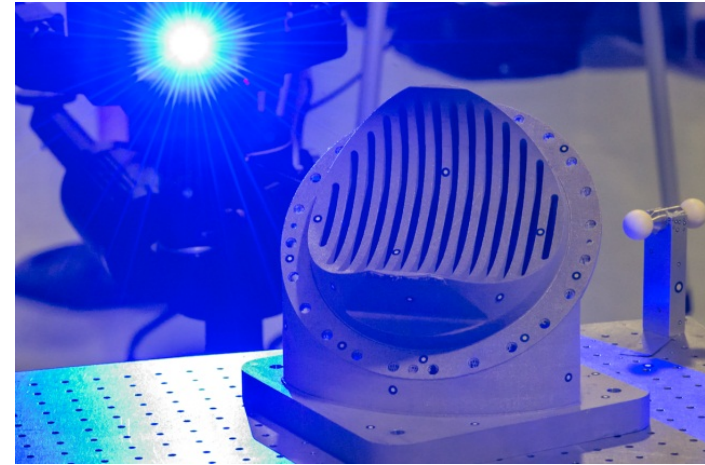
- “...Fatigue and damage tolerance considerations currently pose significant challenges to the use of AM parts on airplane structures”.
- “The presence of *inherent material defects* randomly distributed throughout the volume, which may be *below the threshold of detectability*, means that due consideration has to be given to size effects and the *possibility of cracks not always nucleating where they would ordinarily be expected...*”
- “The solution to these challenges for AM structural applications may lie in the *application of probabilistic fatigue analysis methods...*”

Credits: S. Chisholm et al, “Smarter Testing Through Simulation for Efficient Design and Attainment of Regulatory Compliance”, Boeing, Presented at 30th ICAF Symposium – Kraków, 5 – 7 June 2019.

Additive Manufacturing for Space Launch System (SLS)



RS-25 Engine prior to testing
at Stennis Space Center



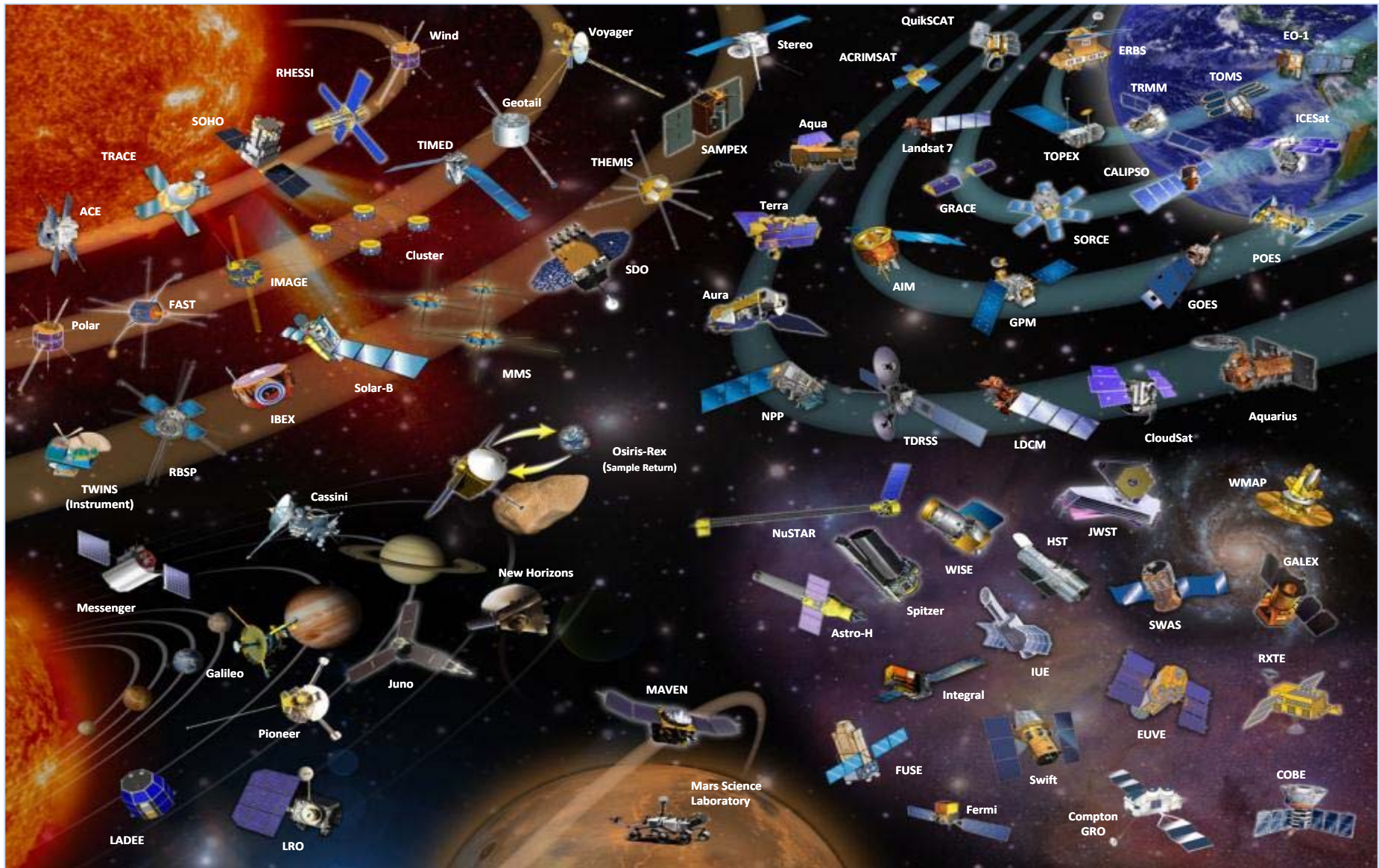
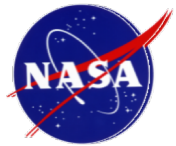
Pogo Z-Baffle made from
Selective Laser Melting (SLM)

Computational Materials for SLS

- **Improve Process Certainty**
 - **Design / Tailor Process**
- **Improve Part Certainty**
 - **Meet material specifications**
 - **Certify components**

Images: NASA

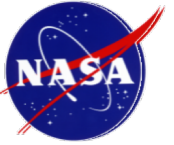
The Diverse Mission Portfolio at GSFC*



Images: NASA/Goddard Spaceflight Center

* Mike Viens, GSFC

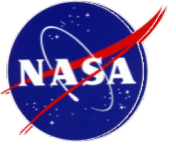
...and at JPL*



Images: NASA/Jet Propulsion Laboratory

* Bryan McEnerney, JPL

Outline



FAA Perspectives

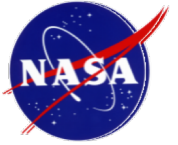
Computational Materials

- **Material Performance**
 - **Next Gen Durability & Damage Tolerance (D&DT)**
- **Material Processing**

Future Directions

- ARMD Vision 2040 Roadmap
- ARMD Rapid Manufacturing Workshop

NASA Low-TRL Portfolio



NASA Internal

Aeronautics

Transformative Tools and Technologies

- Next-generation Qualification of AM
- Collaborative with Airframe/Engine Manufacturers
- Process-Structure-Performance in Un-HIPped Ti-6-4

Office of Chief Engineer

Engineering Research & Analysis

- Next-generation D&DT
- Collaborative with Flight Centers
- Veracity of HIPping on In 718

NASA External

Space Technology

Early Stage Innovation

- Simulation of Powderbed AM Processing
- In 718

Aeronautics

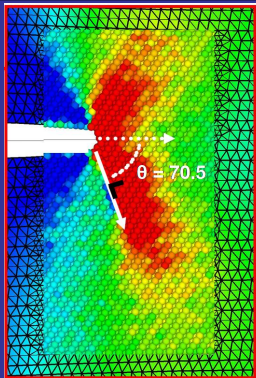
University Leadership Initiative

- Next-generation Qualification of AM
- Collaborative with OEMs
- Ti-6-4

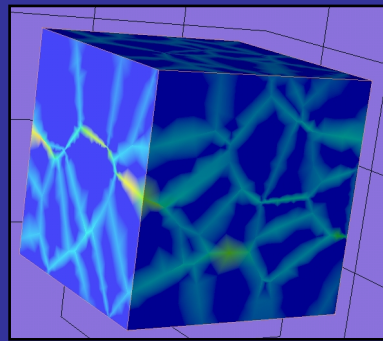
Space Technology

Early Stage Innovation

- Next-generation D&DT
- Inconel, Titanium or Aluminum



Modeling Plasticity
at a Crack Tip



Simulation of Crack Growth
in a Material Microstructure

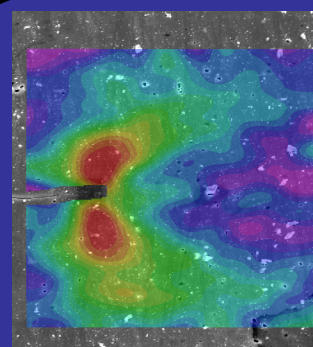
Simulate Operative Physical Processes at Relevant Length Scales

- 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
- Design materials to extend structural life

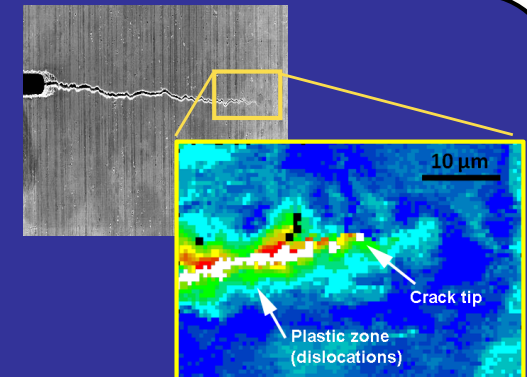
Physics-Based Material Design & Certification Requires
Close Integration of Analysis and Experimentation

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



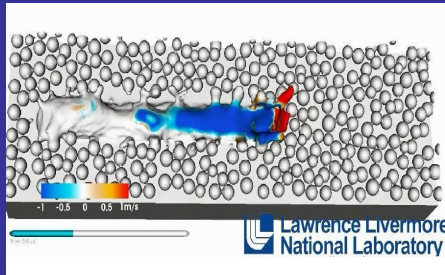
Measure Deformation
at Crack Tip



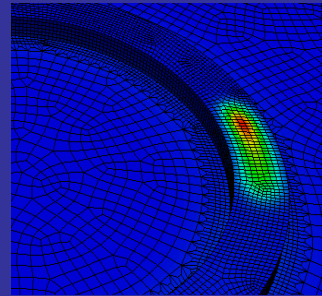
Characterize Damage
Evolution

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



Simulation of Laser-Powder Bed Interactions



Prediction of Local Heat Distribution

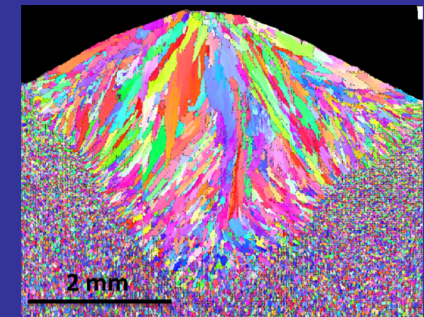
Develop Physically Correct Models Needed to Support Certification of AM Feed Stock and Manufacturing Process

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

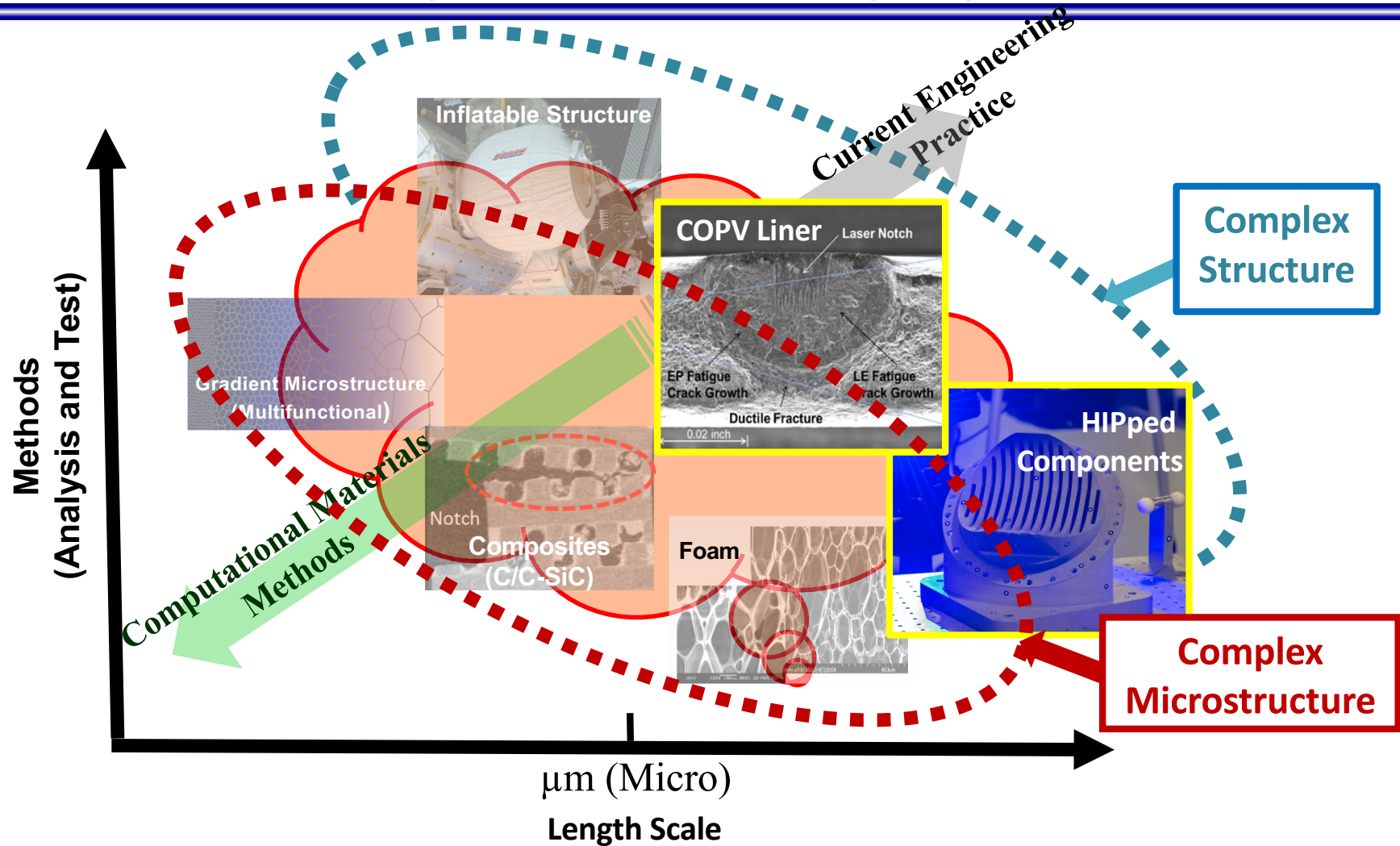
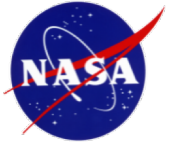


Selective Laser Melting



Grain Structure from Additive Process

D&DT Analysis and Test Shortfall (Micromechanics Regime)*

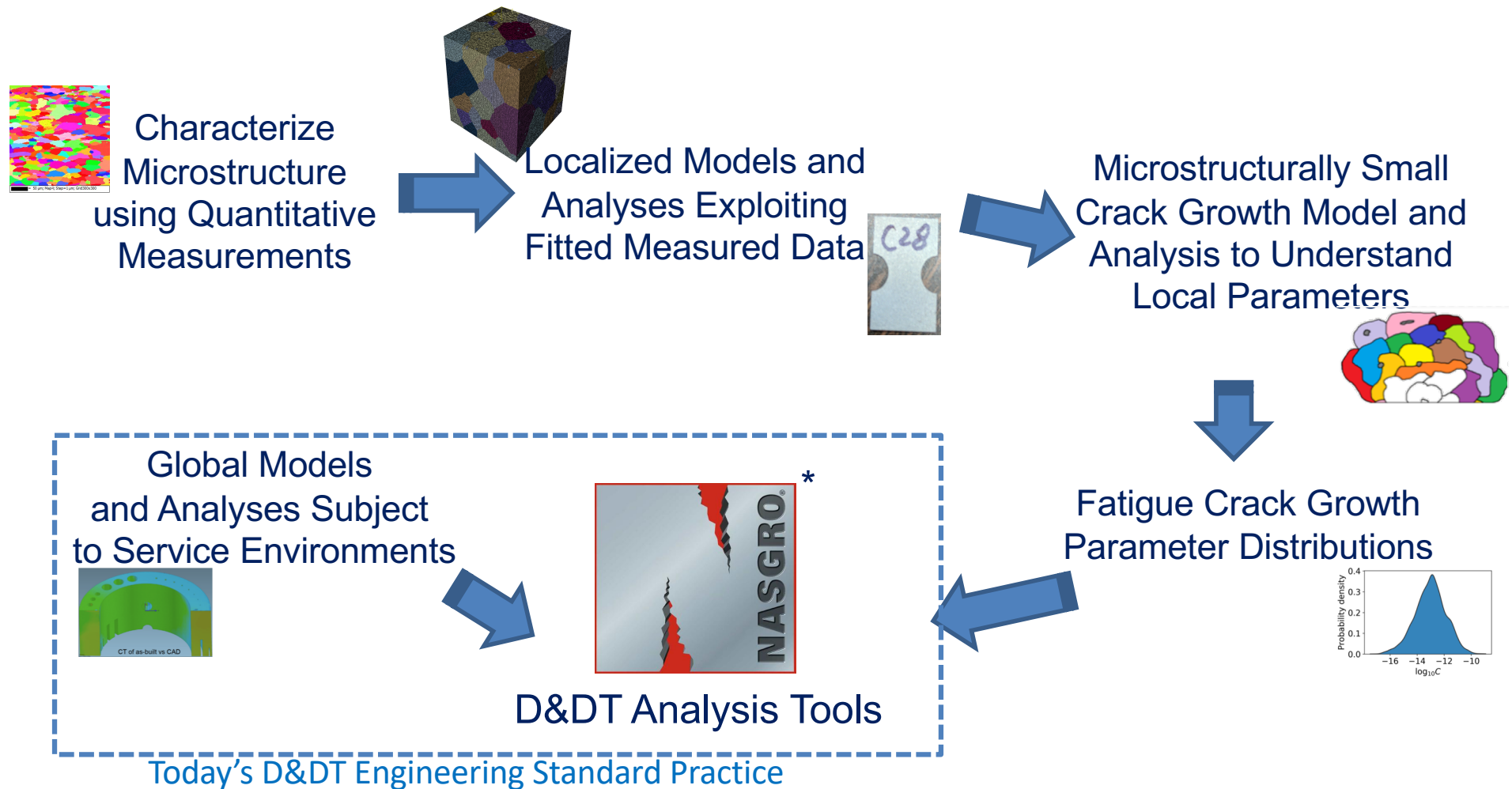
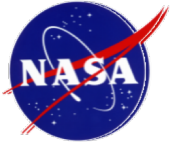


Future designs include microstructure-dependent D&DT influences:

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

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

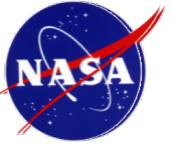
Development of Microstructurally-Informed D&DT -Work Flow



- Today's standard D&DT engineering practice relies on continuum assumptions
- Microstructurally-informed D&DT will consider 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

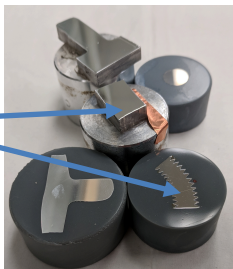
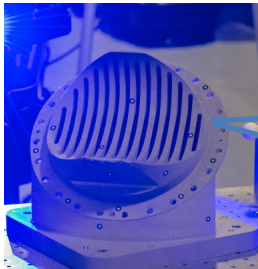
*Image: Southwest Research Institute

Development of Microstructurally-Informed D&DT (1/4)

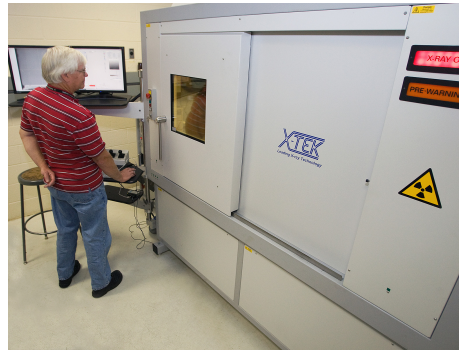


Characterize Microstructure using Quantitative Measurements*

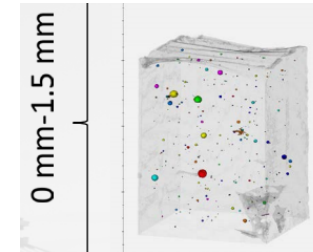
Sample Extraction
1-10 mm³



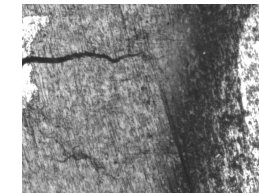
X-ray Computed Tomography



Characterize inherent voids

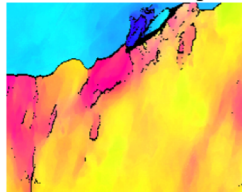


Characterize inherent cracks

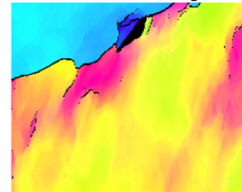


Serial Sectioning and EBSD†

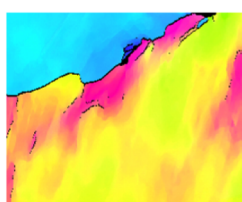
Slice 1: 0-50 nm depth



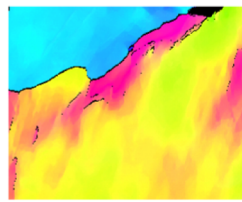
Slice 2: 200 nm depth



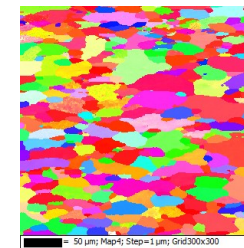
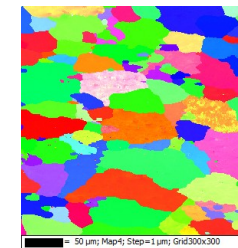
Slice 3: 400 nm depth



Slice 4: 600 nm depth



Characterize morphology



Microscopy methods are used to characterize distributions of key microstructural features, such as grain size and orientation, voids and second phase particle sizes and densities

Images: NASA

† EBSD – Electron Backscatter Diffraction

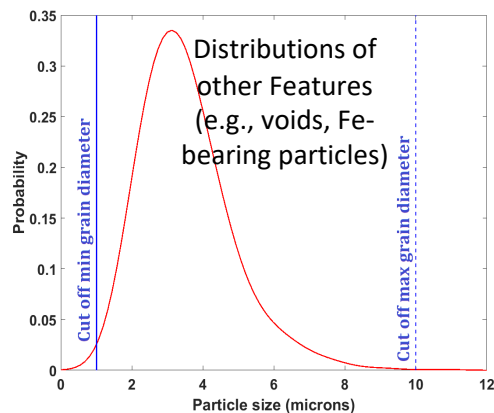
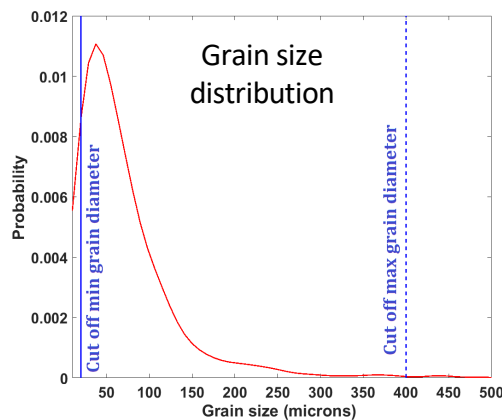
*Ruggles, Hochhalter, Dawicke, et al, LaRC

Development of Microstructurally-Informed D&DT (2/4)

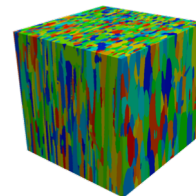
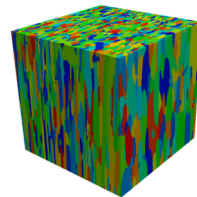
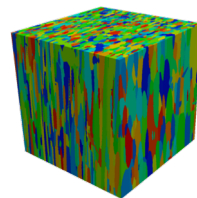


FEA¹ Simulations Consider Representative Microstructures that are Developed from the Fitted Distributions – Capture Microstructural Details and Responses*

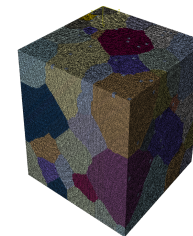
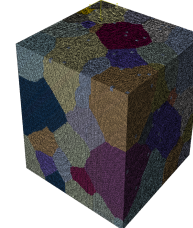
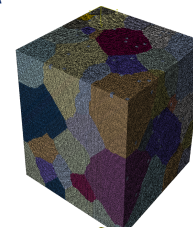
Fitted distributions to measured microstructure data



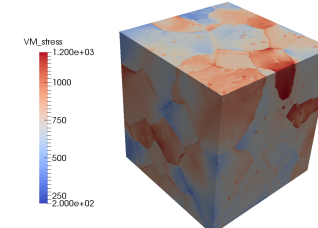
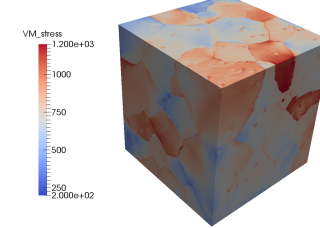
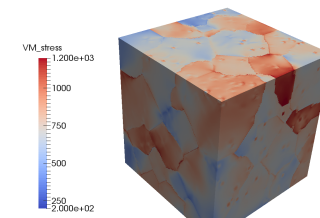
*Microstructure Realizations***



FEA Model (10-100M dof³)



*FEA Simulations****



- 100-1000 independent simulations

Statistically-equivalent representative volume element (SERVE) finite element models

are generated from input distributions and solved using NASA's HPC² FEA code

¹FEA – Finite Element Analysis

²HPC – High Performance Computing

³dof – Degrees of Freedom

*Yeratapally, Warner, Leser, Bomarito, Hochhalter, LaRC

DREAM.3D (<http://dream3d.bluequartz.net/>) * NASA SciFEN

Development of Microstructurally-Informed D&DT (3/4)

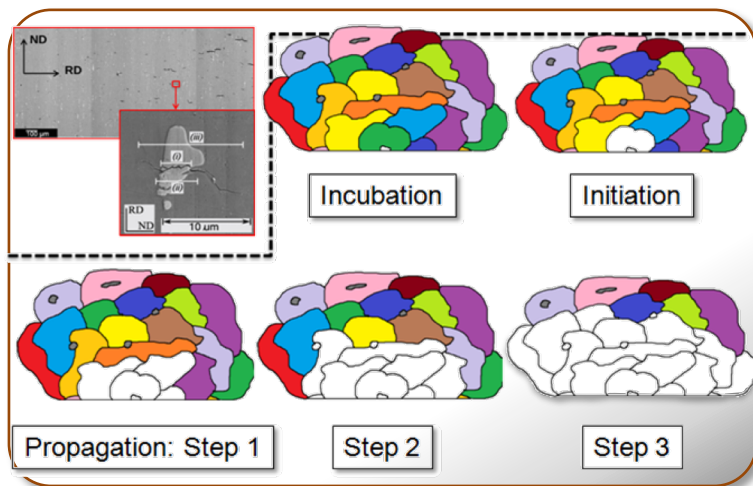
Transition from Microstructurally Small Crack Growth Estimates to Engineering Codes*

Fatigue Crack Growth (FCG) Estimates**

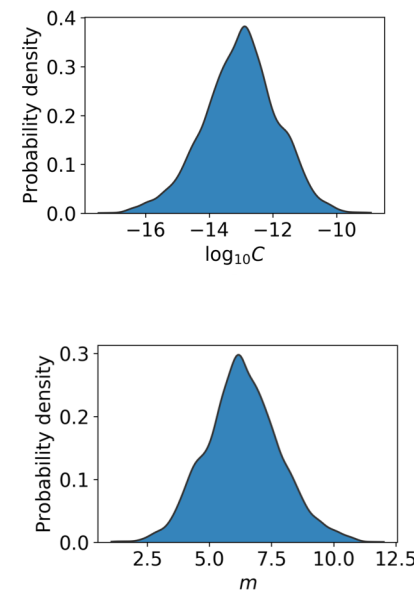
$$\left. \frac{da}{dN} \right|_{\text{MSC/PSC}} = \phi(\Delta CTD - \Delta CTD_{th})$$

$$N_{\text{MSC}} = \int_0^1 \frac{da_i}{dN} = \left[\frac{1}{\sqrt{c_1 c_2}} \tanh^{-1} \left(D_{st} \sqrt{\frac{c_1}{c_2}} \right) \right]$$

Microstructurally Small Crack (MSC) Growth Model**



Fatigue Crack Growth Material Parameter Distributions**



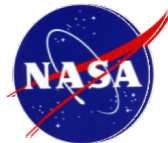
$$\frac{da}{dN} = C(\Delta K)^m$$

- Simulate fatigue cracking in hundreds of microstructure-sensitive models
- Produce input distributions of aggregated FCG parameters as input to D&DT engineering codes
- Sequential Monte Carlo methods needed to compute distributions are enabled by HPC

*Yeratapally, Warner, Leser, Bomarito, Hochhalter, LaRC

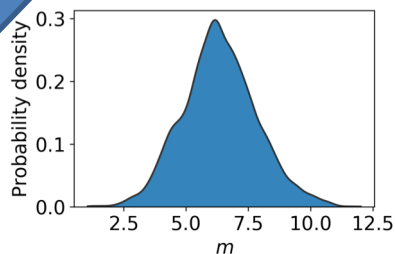
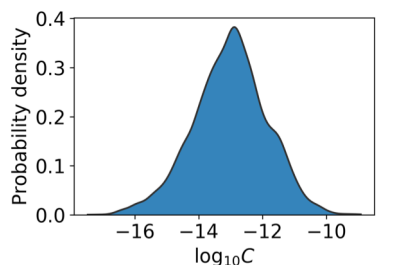
** McDowell, et al, GaTech

Development of Microstructurally-Informed D&DT (4/4)



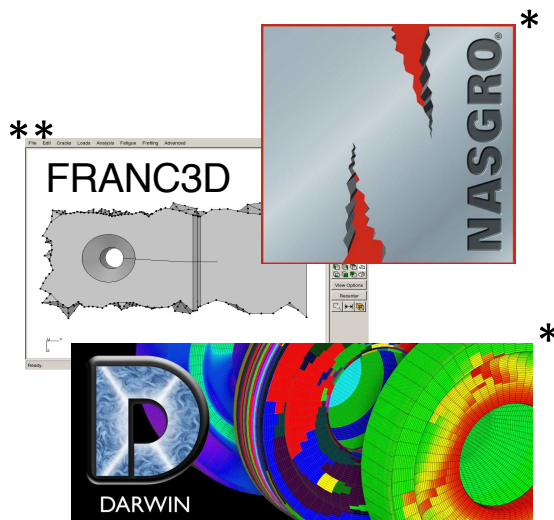
Microstructurally-Informed D&DT of Fracture-Critical Components

Fatigue Crack Growth
Material Parameter
Distributions

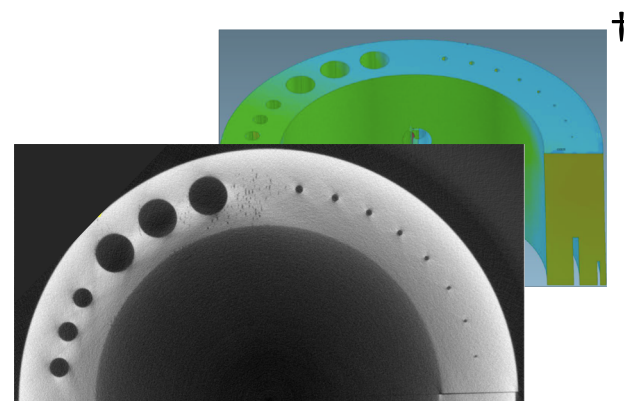


$$\frac{da}{dN} = C(\Delta K)^m$$

Embed these
Relationships within
Engineering Codes



Component Level Inputs



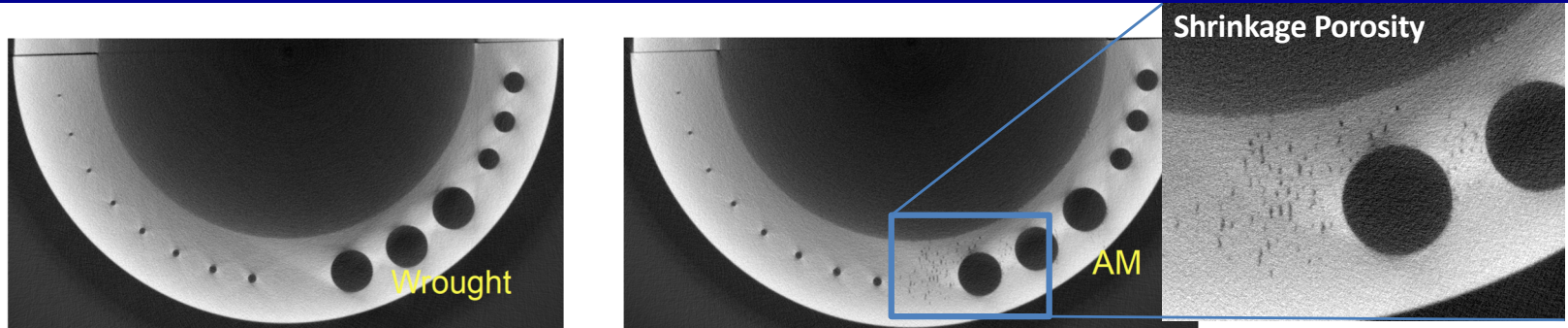
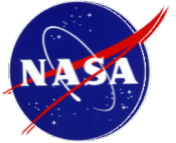
Apply microstructurally-informed D&DT simulation to determine fatigue life of fracture-critical components having small length scale features

- Important because of new processing methodologies, desire to save weight leading to thin structures, etc
 - Produce materials whereby small length scale features will increasingly become root cause for failure
- New approaches are required to understand and work at these length scales

Image: *Southwest Research Institute, **Cornell University

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

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

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

*Wells, West, MSFC

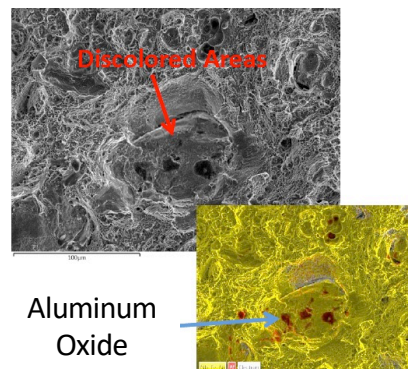
Questions Remain Unanswered Regarding HIP in AM*



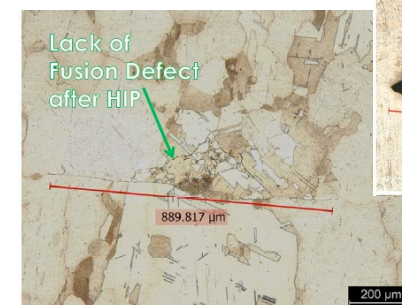
- Does the HIP process actually improve reliability? Under what service conditions?
- What types and sizes of AM induced defects cannot be removed through HIP?
- How does the mechanism of defect creation affect the ability of HIP to remove defects? (e.g., can defects associated with oxidation be healed?)
- How does the atmosphere during AM play a role? Vacuum versus Argon?
- Are the defects that HIP can remove already below a size that is of consequence?
- Does HIP reduce volume of defects but not eliminate them? Does this make them harder to detect in NDE? Are all “healable” defects below NDE detection limits?
- Do unhealed defects of reduced volume actually create a more damaging flaw with higher stress concentration or crack-like tendencies?
- Does pressure (in addition to temperature) influence microstructural evolution?



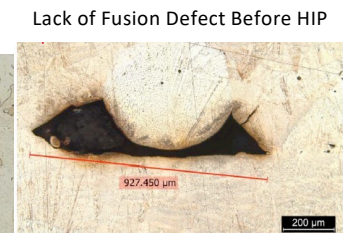
Defects due to inadequate ventilation on the powder bed.



Defects unhealed in HIP with apparent oxidation related cause.



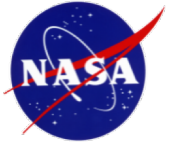
Large lack-of-fusion defect **post-HIP** with near zero volume. Do not know strength (if any) of the interface.



Lack of Fusion Defect Before HIP

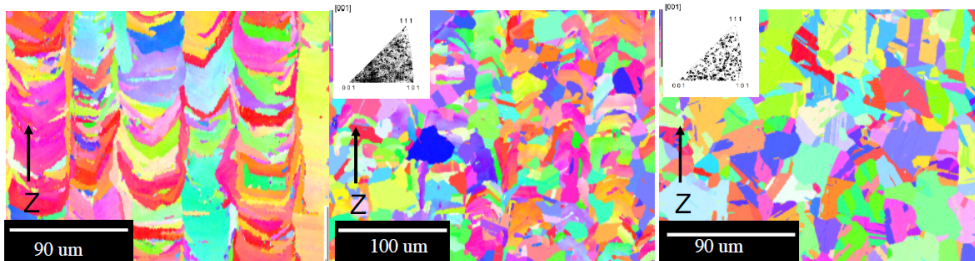
**Wells, West, MSFC*

Assessing Hot Isostatic Pressing (HIP) Treatment for Additively Manufactured Hardware (1/4)*



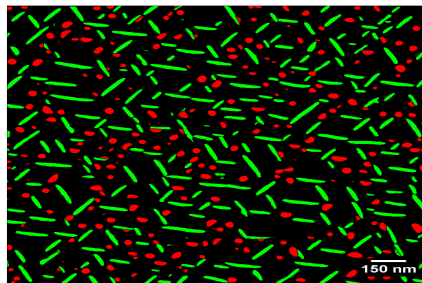
Determine Microstructure as a Function of HIP Temperature and Pressure

- Standard thermal treatments do not always 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.

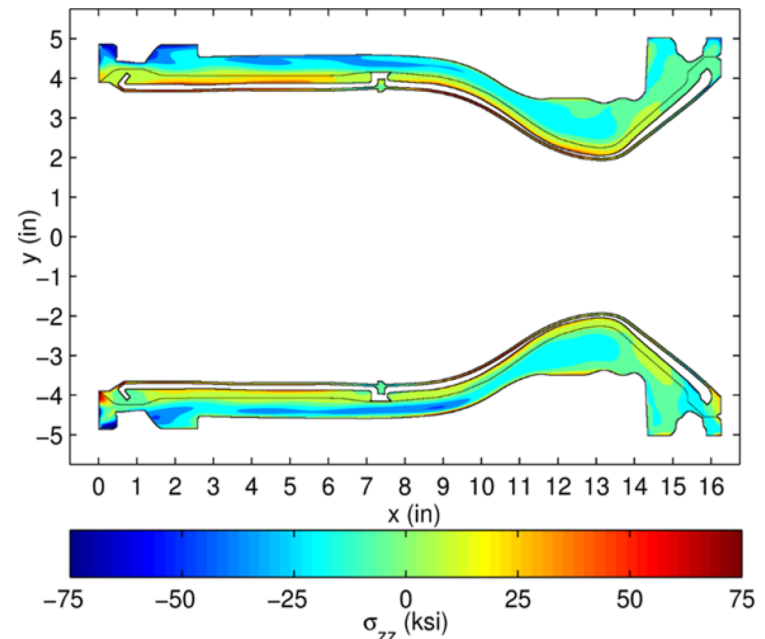
- Calculation of Phase Diagram (CALPHAD) models for precipitate volume fraction in AM 718 differ from experiment by as much as 15% - need to be updated



Quantification of strengthening precipitates in Inconel 718 through electron microscopy

Assess Residual Stress in Representative Hardware Geometries as a Function of HIP

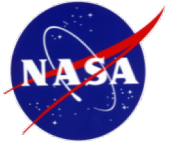
- HIP treatments may not fully relieve residual stress in AM hardware



Post HIP residual stress (hoop) in Low Cost Upper Stage Propulsion (LCUSP) combustion chamber. Compressive axial and radial stresses exceed 100 MPa (15 ksi) in the GRCop-84, tensile axial stresses were as high as 300 MPa (43 ksi) and radial stresses exceeded 600 MPa (87 ksi) in the IN-625 jacket.

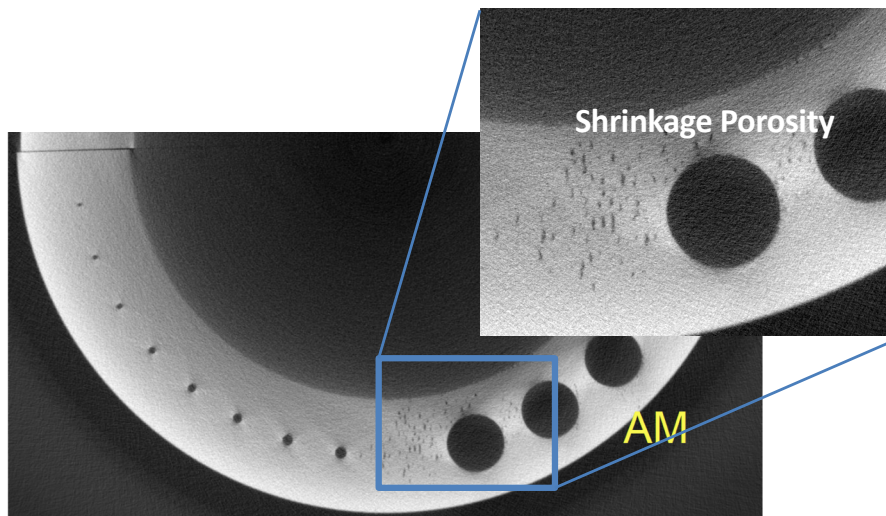
*Carter, et al, GRC

Assessing Hot Isostatic Pressing (HIP) Treatment for Additively Manufactured Hardware (2/4)



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 *

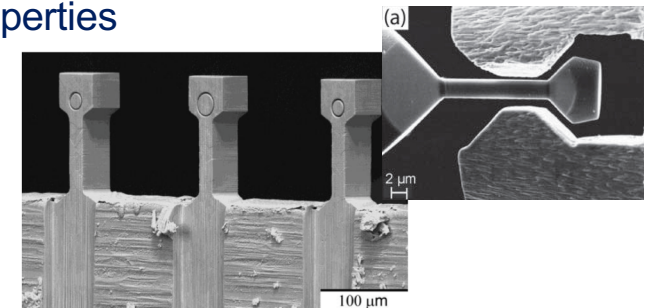
*Beshears, R., "Computed Tomography Inspection and Analysis for Additive Manufacturing Components," ASNT Annual Conference, November 2, 2017.

Determine Post-HIP Mechanical Properties in Representative Hardware Configurations

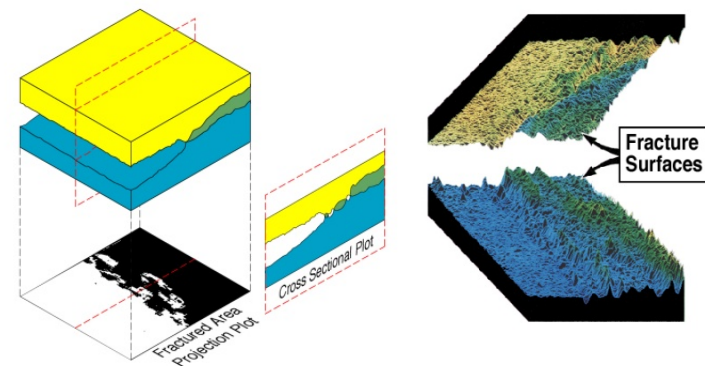
- Inhomogeneity in microstructure, residual stress, and defect content in hardware can influence mechanical and fracture properties



HIPped defect



Microtensile specimens extracted to assess location and orientation specific properties**

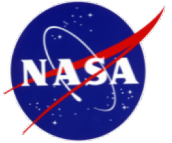


Examination of conjugate fracture surfaces will increase understanding of how voids affect fracture***

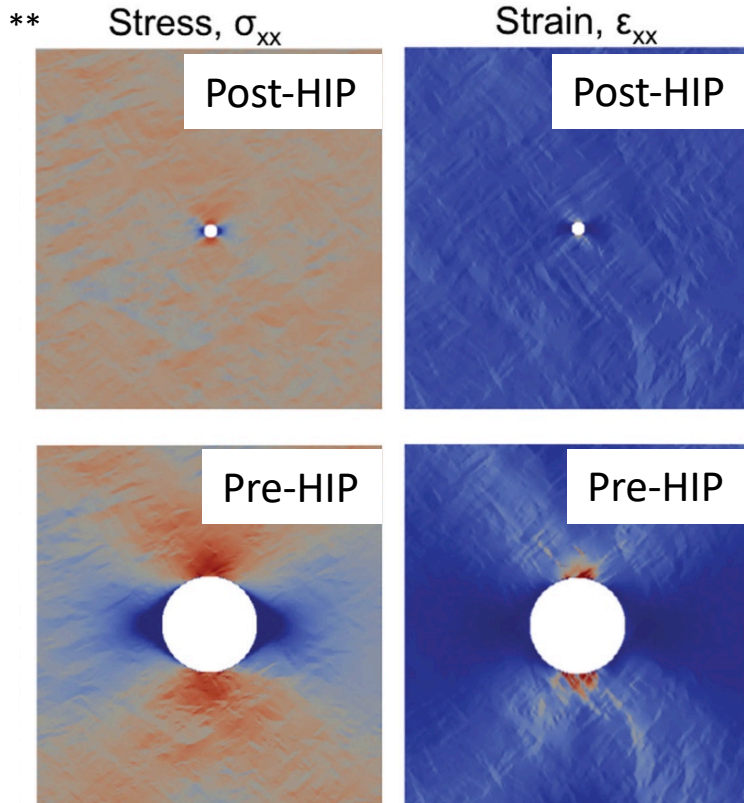
**Uchic, et al, AFRL

***Shockey, et al, SRI International

Assessing Hot Isostatic Pressing (HIP) Treatment for Additively Manufactured Hardware (3/4)*



Determine Probability of Void Closure from HIP



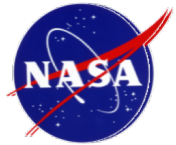
- Multiphysics simulation of heat & pressure, computes
 - Non-linear plasticity
 - Gas diffusion
- Non-linear functions of material parameters derived from MSFC and literature
- Prior probability of pore/void sizes derived from experimental data at MSFC
- Simulation executed for a range of HIP parameters - outcome is the resultant amount of void closures.
- Probability of closure from product of priors and simulation results
- Validation with experimental post-HIP pore data will guide refinement of simulation

- Develop a tool for predicting pore/void closure in response to heat treatment of AM materials
- Report on process requirements to minimize probability of pores/voids contributing to failure as they relate to certification requirements.

* Wheeler and Timucin, ARC

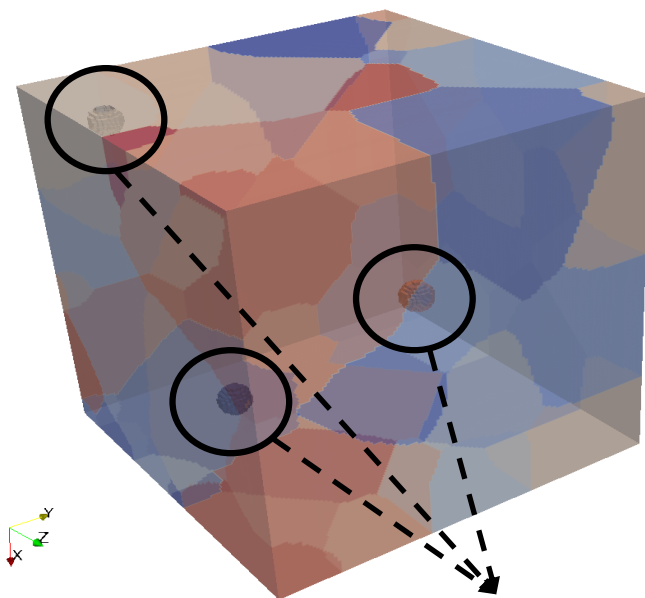
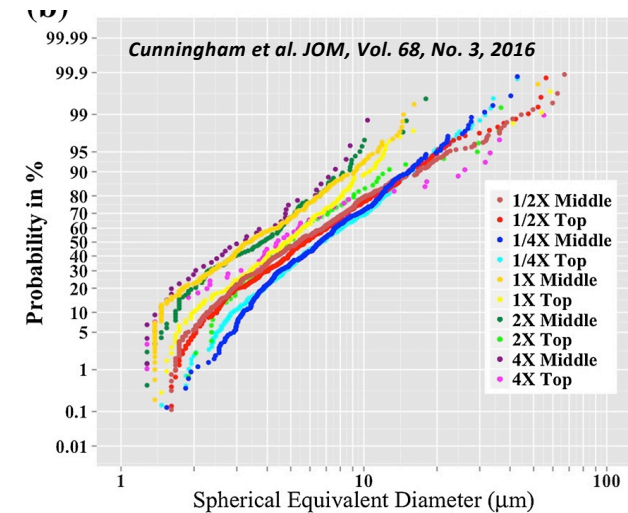
**Cunningham, Nicolas, Madsen, Fodran, Anagnostou, Sangid, Rollett, "Analyzing the effects of powder and post-processing on porosity and properties of electron beam melted Ti-6Al-4V", Materials Research Letters, Vol. 5, No. 7, 2017, pp.516-525.

Assessing Hot Isostatic Pressing (HIP) Treatment for Additively Manufactured Hardware (4/4)

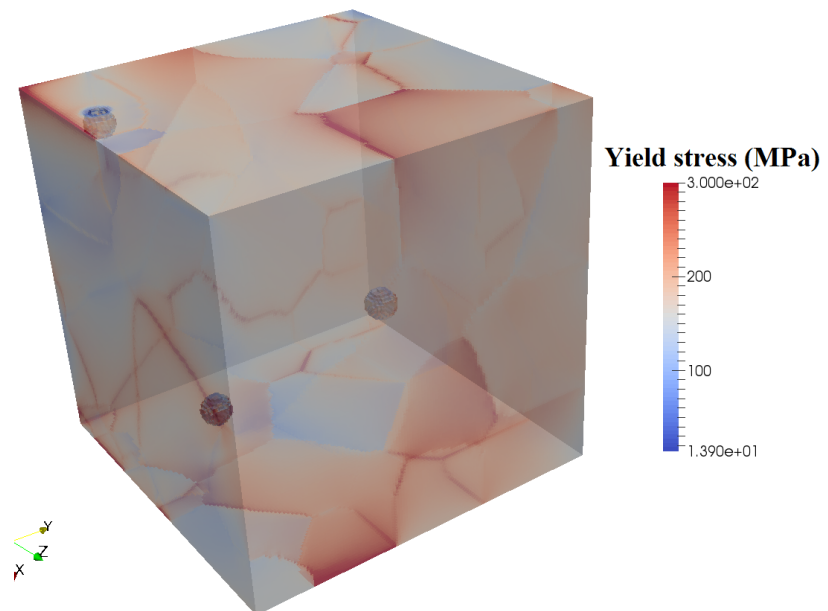


Incorporation of Process-Specific Defects in 3D Simulations

Example case: Entrapped gas porosity / Key-Hole porosity (SPHERICAL IN NATURE)



Pores

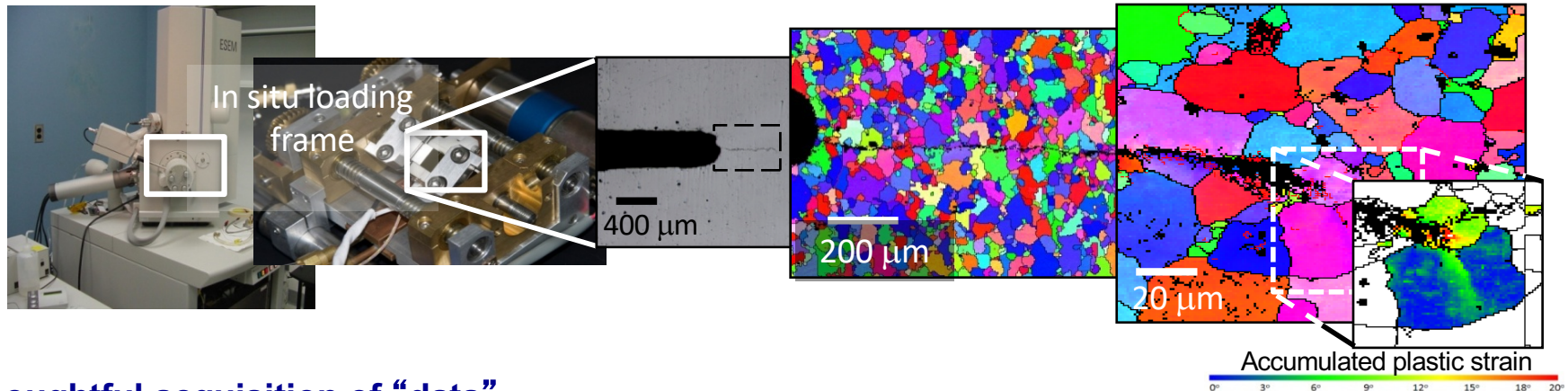




The Lab of the 20th Century

- Lots of “data”
- Little understanding
- Supported engineering by heuristics
- Primarily aluminum alloys and polymeric composites

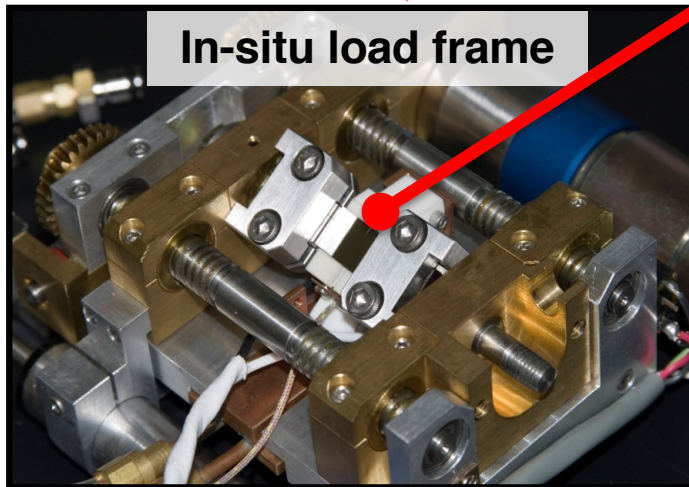
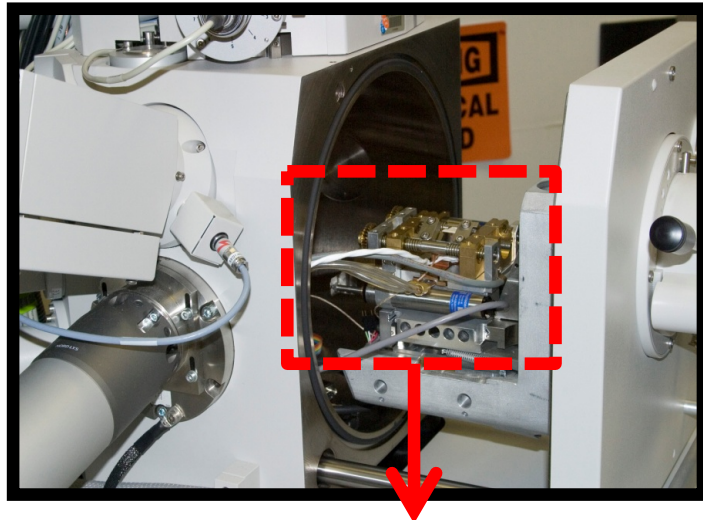
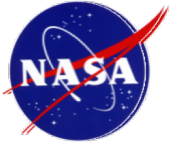
The Lab of the 21st Century



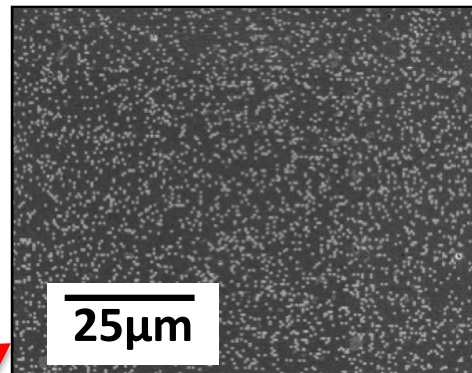
- More thoughtful acquisition of “data”
- More understanding of what the “data” means
- More collaboration with NDE and material developers
- Support “physics-based” computational methods

- Continue studying airframe materials
- Also, spacecraft materials, nano/micro-devices, ...

Micro-scale In-Situ Image Correlation*

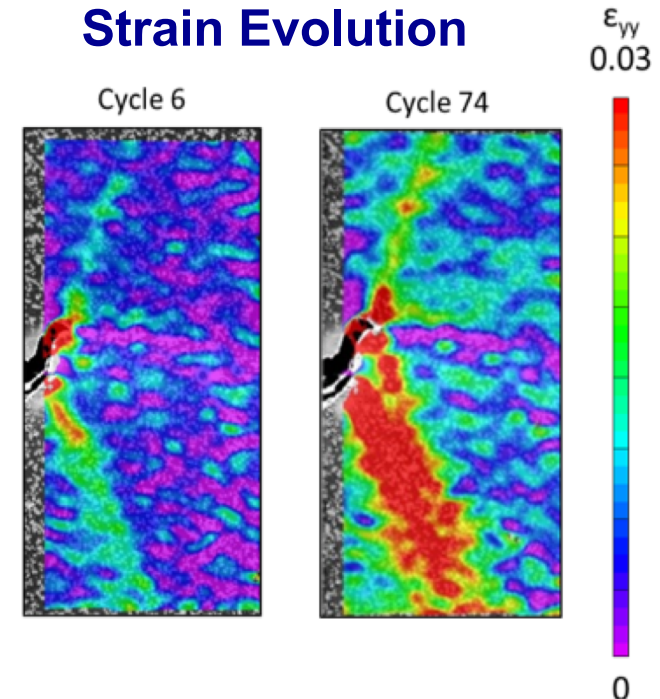


In-situ load frame



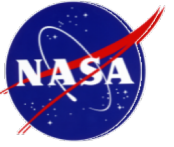
- E-beam lithography
- Base element ~150-5000 nm
- Resolution to ~50 nm
- Microstructural (grain boundaries, intermetallic particles, *etc.*) effects on strain fields
- Microstructurally sensitive cracking and deformation studies

Strain Evolution

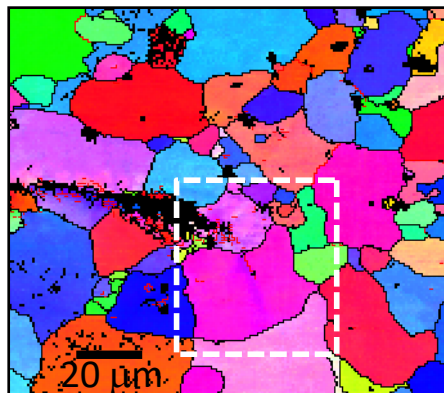
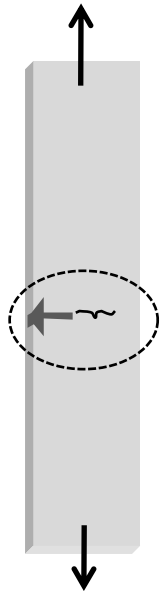
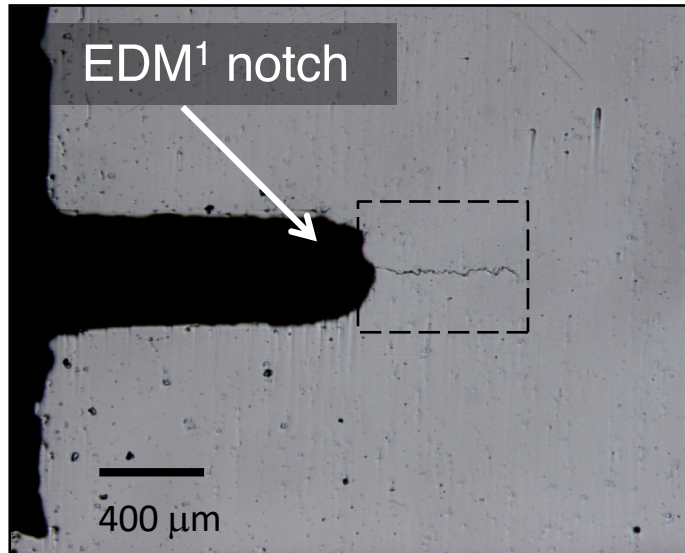
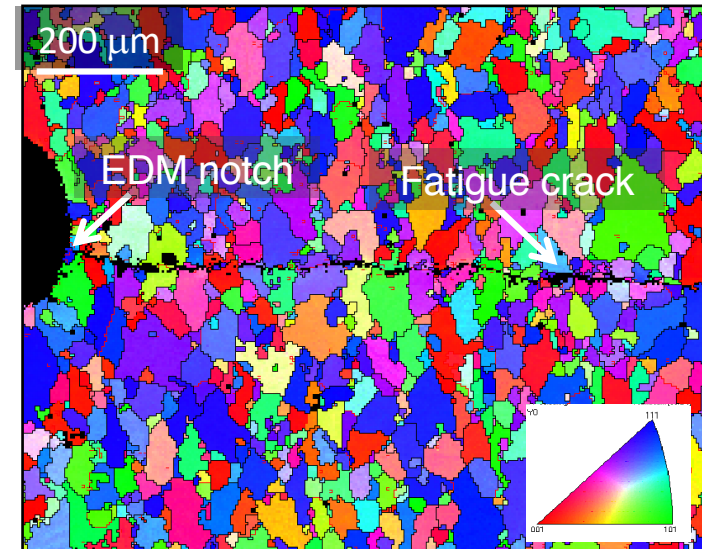


*with Correlated Solutions

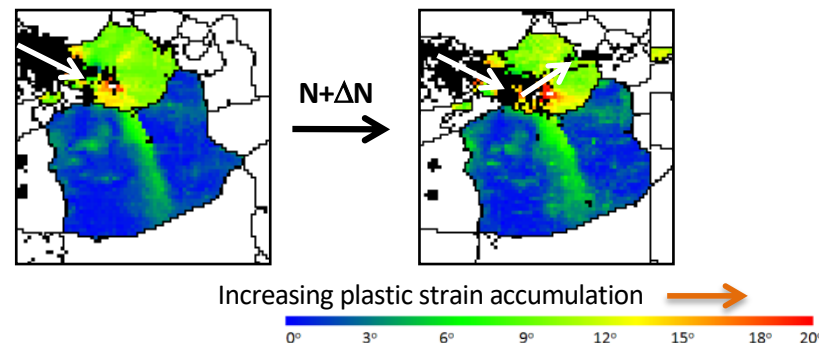
Cracking Path, Grain Structure, Local Plastic Damage Distribution



EBSD² Inverse pole-figure (IPF) map



- Damage progression ahead of fatigue crack-tip
- High Resolution-EBSD
 - Local misorientation map
 - Related to GND³ (Nye dislocation density tensor)

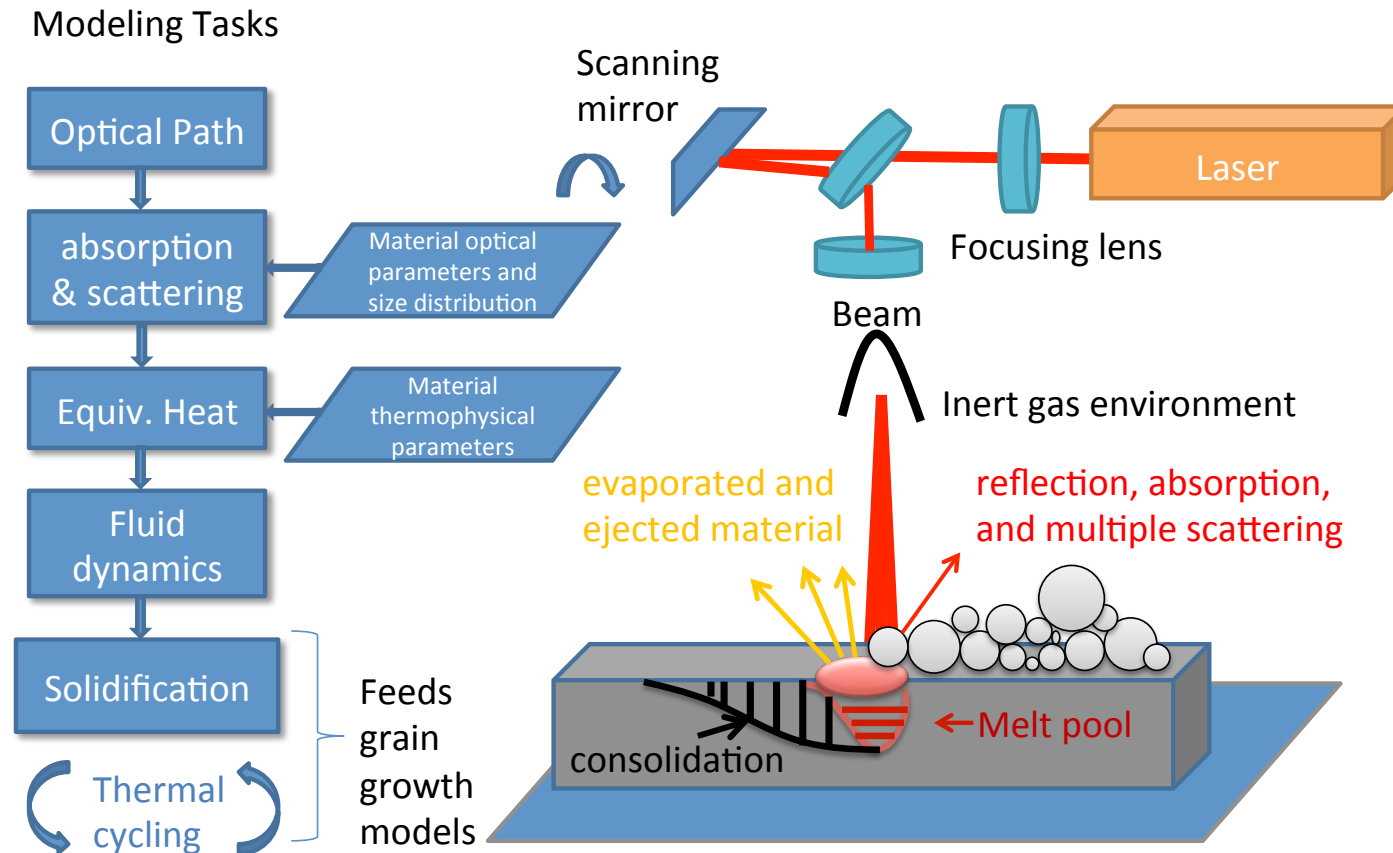


¹EDM – Electrical Discharge Machining

²EBSD – Electron Backscatter Diffraction

³GND – Geometrically Necessary Dislocations

Powder Scale to Solidification*



Laser – **Laser** electromagnetic scattering on spheres is translated into **equivalent computationally efficient heat source**

Heating – **Laser energy** is translated into **heat on spheres and subsequent conduction**

Melt pool

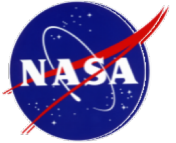
Fluid flow – Metal changes phase from **solid to liquid and subsequently flows**

Evaporation/Recoil pressure – Significant **sparking and metal evaporation** occurs which impacts depth of weld penetration and subsequent grain growth structure

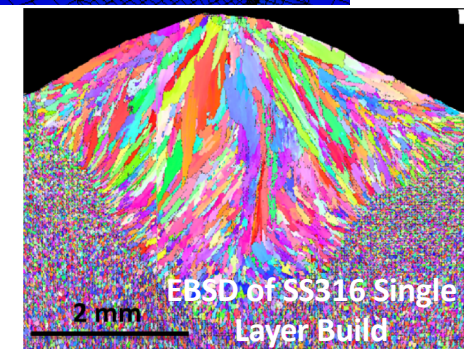
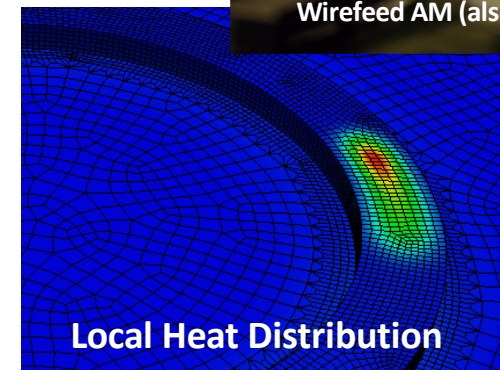
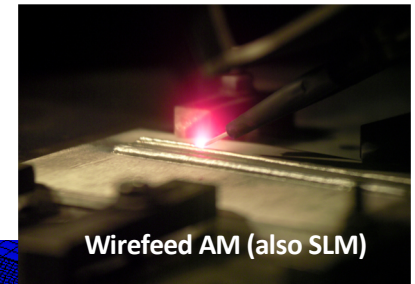
Grain growth – Models such as **CALPHAD** can be coupled with **thermal cycling history** simulated here

* K. Wheeler, D. Timucin, ARC

Thermal Modeling*

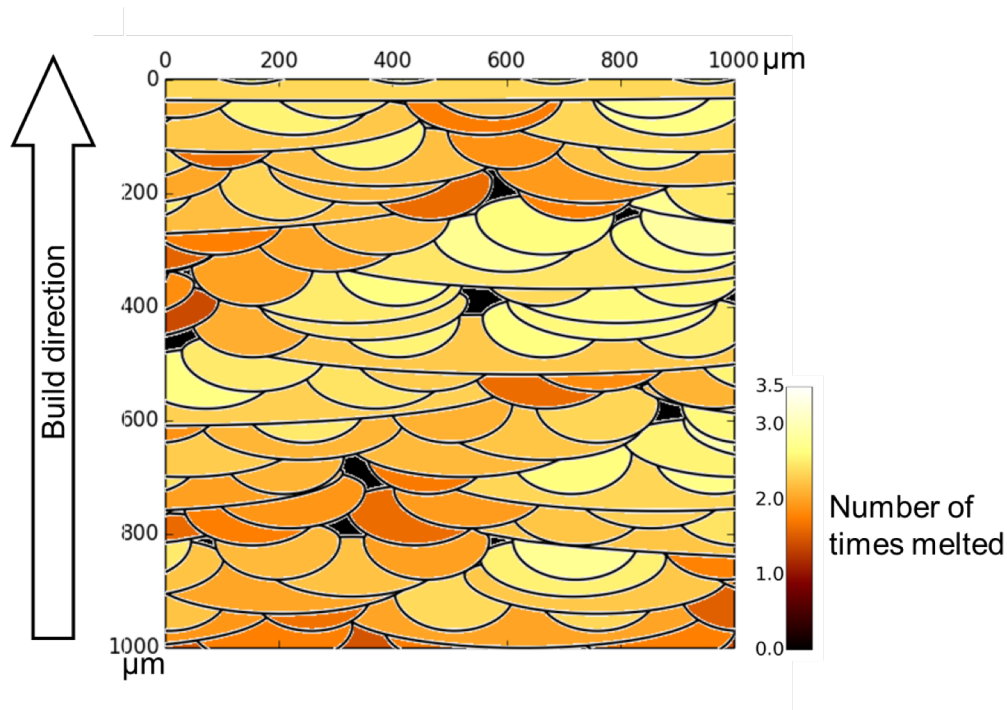
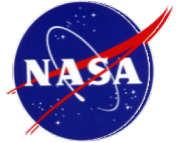


- Description of the FE Model
 - Transient heat diffusion with phase change
 - Set up model using final part geometry
 - Activate elements for the added powder per layer
 - Heat input model defines the distribution of volumetric heat source (units are $\text{J/m}^3\text{-sec}$)
- Details
 - Currently only heat diffusion is modeled in order to predict the thermal history for the entire part (thermal cycling will occur in the layers)
 - Convection and radiation boundary conditions included
 - All of the “action” takes place in the melt pool, requiring a very fine mesh to capture the steep gradients. This leads to high computational costs when modeling numerous layers.
 - Convection within the melt pool is captured by artificially increasing the conductivity of the melted material (factor of 2 [Yaghi 2012])
 - The effect of different heat input models is insignificant away from the melt pool zone



* Chris Lang, LaRC

Modeling of Microstructure Formation in AM IN718 with Emphasis on Porosity Prediction*



Research Objectives and Impact

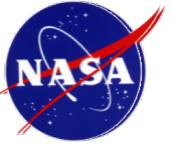
- Development of a validated model for 3D printing of In 718 parts
 - Incomplete melting
 - Porosity
 - Microstructure
- Increase confidence in manufacturability via powder bed AM
- Enabling for production of specialized, low production volume parts

Three major components to the approach

- An **incomplete melting model** based on scan geometry, deposited layer thickness and melt pool dimensions
- A **gas bubble in melts model** that is based on a hybrid of the Potts model with the cellular automaton method
- A **model for hardness** that is based on combining a computational thermodynamics package, such as Thermo-Calc, with kinetics, e.g., from available TTT, with thermal histories, measured or computed

*with A. Rollett and C. Pistorius, CMU (1 of 6 ESI on simulation of AM processing)

Configurable Architecture Additive Testbed*

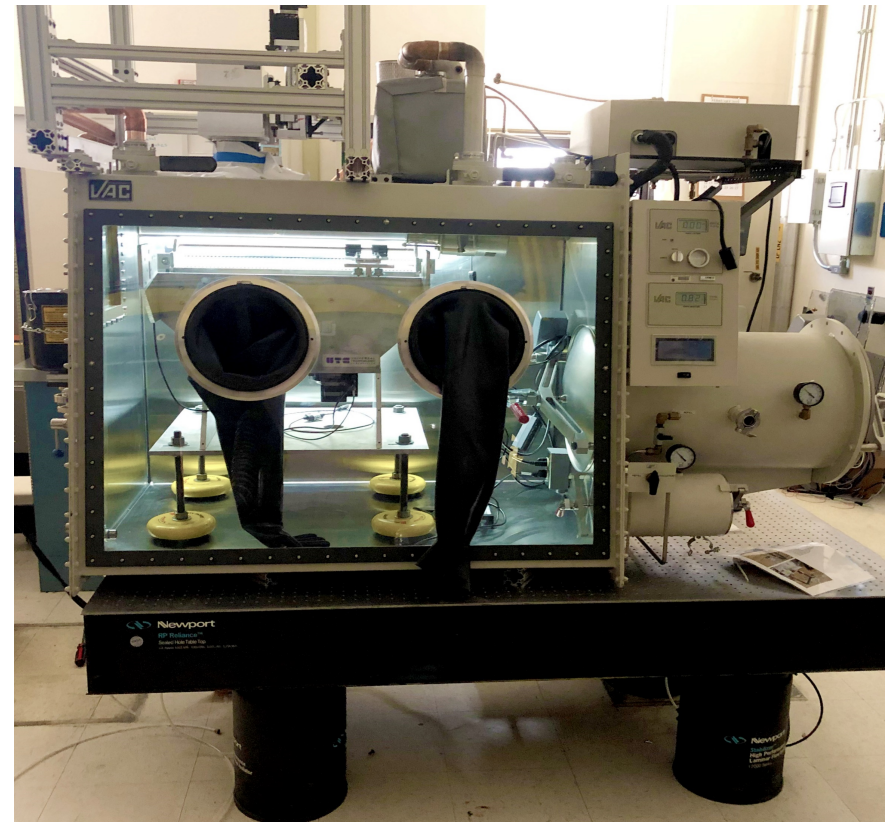


Description

Support development of *validated* capabilities for optimization, certification and sustainment of new designs that are enabled by laser-powderbed AM.

Approach

- Use Configurable Architecture Additive Testbed as a development platform:
 - Experiments to calibrate, validate and increase confidence in models
 - In-situ data: Video and Thermal cameras (include laser inline), plume emissivity, in-situ accelerometers, in-situ thermocouples, ppm humidity, ppm O₂ monitoring
 - Post-build: material & defect characterization
 - Pursue statistically significant relationships between in-situ monitoring and defects
 - “Tune / Calibrate” the instrument hardware for precise experimentation



*Samuel Hocker, LaRC

In-Situ Monitoring of Additive Manufacturing*



Approach

- Employ heavily-instrumented AM machine
- Spatial and radiometric calibrated infrared thermography
- Remotely acquire temperature images and apply advanced image processing techniques to determine deposition parameters such as molten pool size and semi-solid area in real time using tracking algorithm.

Results

- Imaged and measured deposition parameters such as melt pool area and semi-solid regions.
- Tracked melt pool and semi-solid area independent of orientation.
- Provided much greater resolution than previous measurements of melt pool system (1,000's pixels vs. 9 pixels).

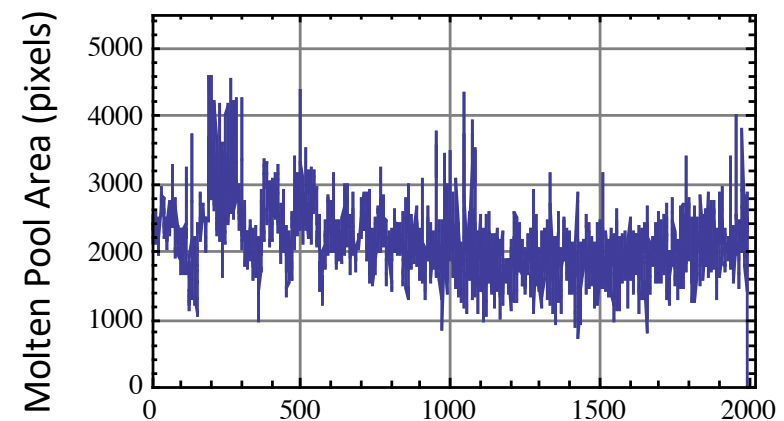
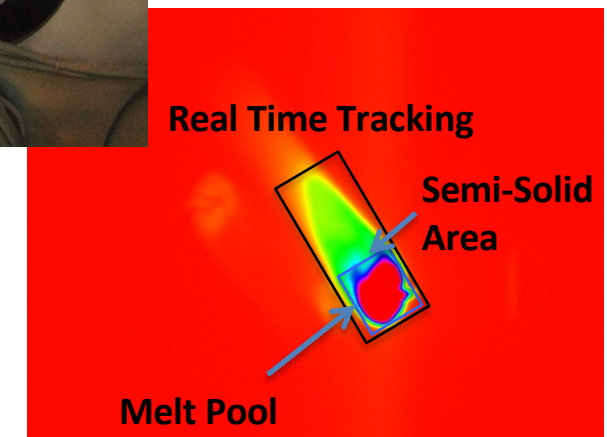
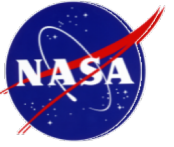


Image Number (N)

* Joe Zalameda, LaRC

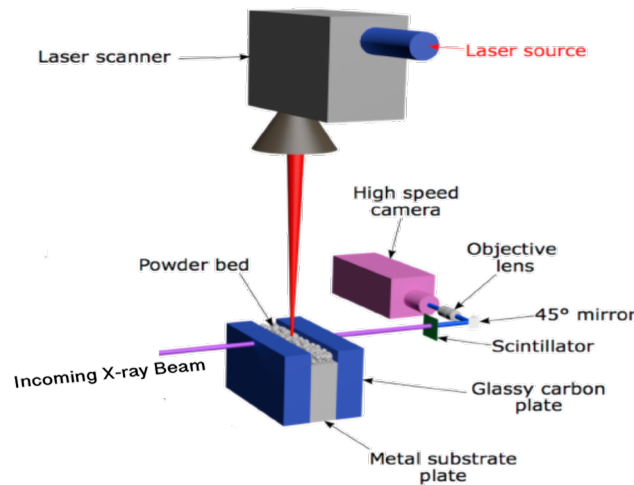
In-Situ SLM Process Characterization



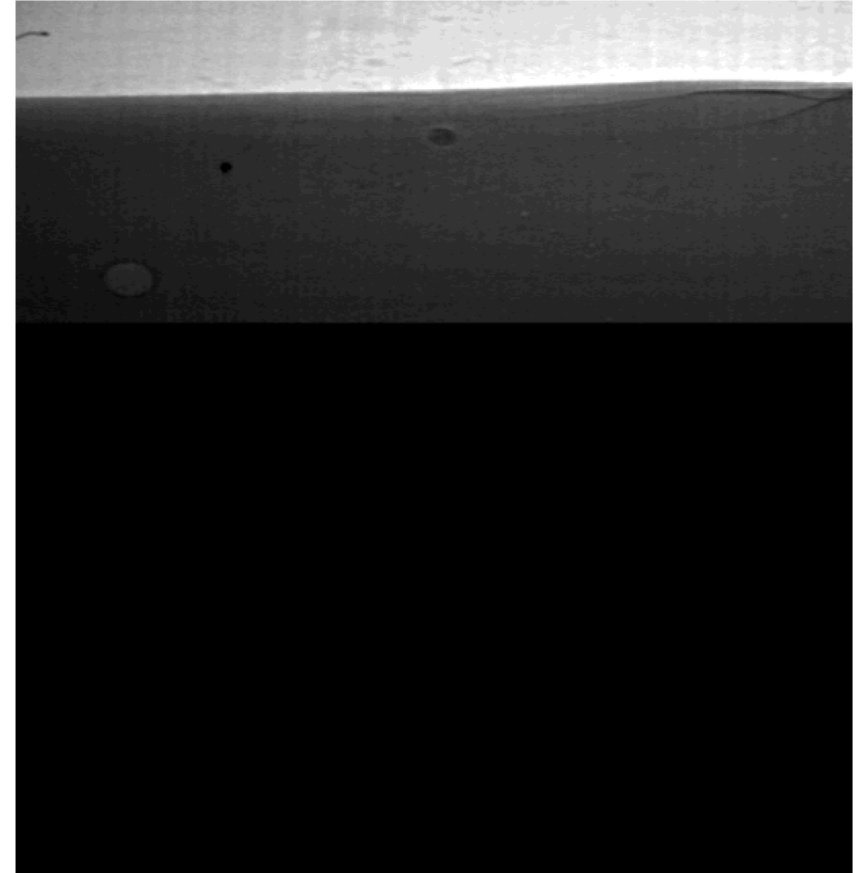
Advanced Photon Source (APS) at
Argonne National Laboratory

*

Collaboration with
APS and Carnegie
Mellon University



Parab, et al. J Synchrotron Radiation, 2018.

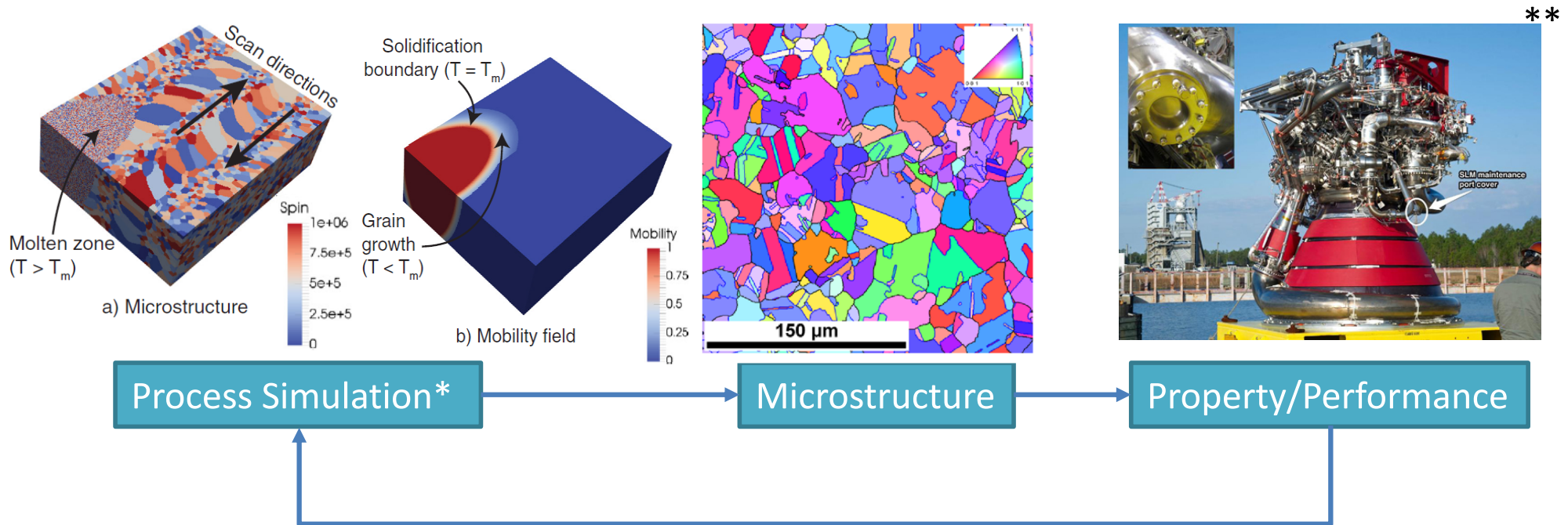
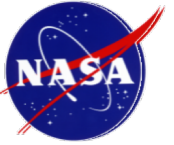


**

Combined DXR and Near-IR Movie

Image: *Argonne National Lab, **Tao Sun (APS)

Process-Structure-Property Linkage



**Image: NASA/Marshall Spaceflight Center

*T.M. Rodgers et al./Computational Materials Science 135 (2017) 78–89

FAA Perspectives

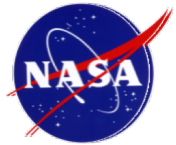
Computational Materials

- Material Performance
 - Next Gen Durability & Damage Tolerance (D&DT)
- Material Processing

Future Directions

- ARMD Vision 2040 Roadmap
- ARMD Rapid Manufacturing Workshop

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



NASA/CR—2018-219771



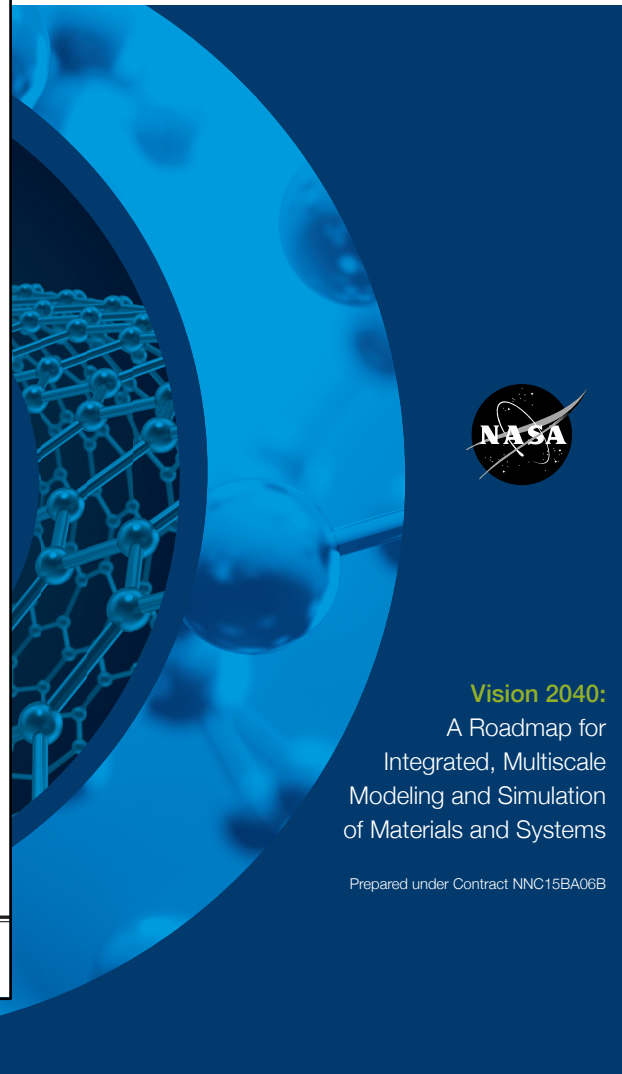
Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems

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

*Jared Kusters and Jack Holmes
Nexight Group, Silver Spring, Maryland*

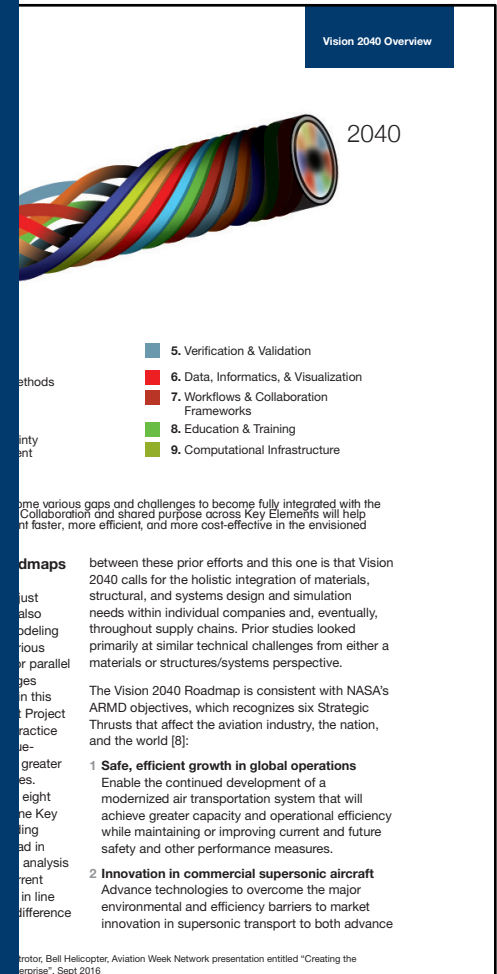
NASA/CR-2018-219771

March 2018



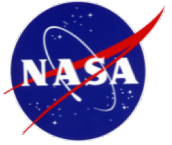
Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems

Prepared under Contract NNC15BA06B



NASA/CR—2018-219771

12



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

Executive Summary

Forthcoming

Compilers: Jonathan Ransom (LaRC), Ed Glaessgen (LaRC), and Brian Jensen (LaRC)
Reviewers: Sean Swei (ARC), Tim Risch (AFRC), James Zakrajsek (GRC), and Joyce Dever (GRC),
Michelle Ferebee (LaRC)

National Aeronautics and
Space Administration



NASA Langley Research Center 1917-2017

A Storied Legacy, A Soaring Future

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