



Computational Materials for Qualification and Certification of Additively Manufactured Materials

E.H. Glaessgen
NASA Senior Technologist for Computational Materials

NASA Langley Research Center
Hampton, VA 23681

TACP Showcase
2-4 February 2021



Short Bio: Ed Glaessgen

TACP - Transformational Tools & Technologies Project

Education - B.S./M.S. Mechanical Engineering, U Tulsa
Ph.D. Engineering Mechanics, VA Tech

Experience – Rockwell International (1989-1991), VA Tech (1991-1996),
NASA LaRC (1996-1999-present)

- NRC Post-doc
- Aerospace Technologist
- Assistant BH of Durability, Damage Tolerance & Reliability
- Chief Engineer for Structures and Materials

Current Position – NASA ST for Computational Materials

Expertise/Contributions

- Debonding/Delamination of Composite Materials
- Mechanics of Textile Composites (Progressive Failure, Stitching)
- Fatigue and Fracture of Metals
- Digital Twin
- Computational Materials (PSPP relationships, Next-Gen Durability and Damage Tolerance)





Outline



TACP - Transformational Tools & Technologies Project

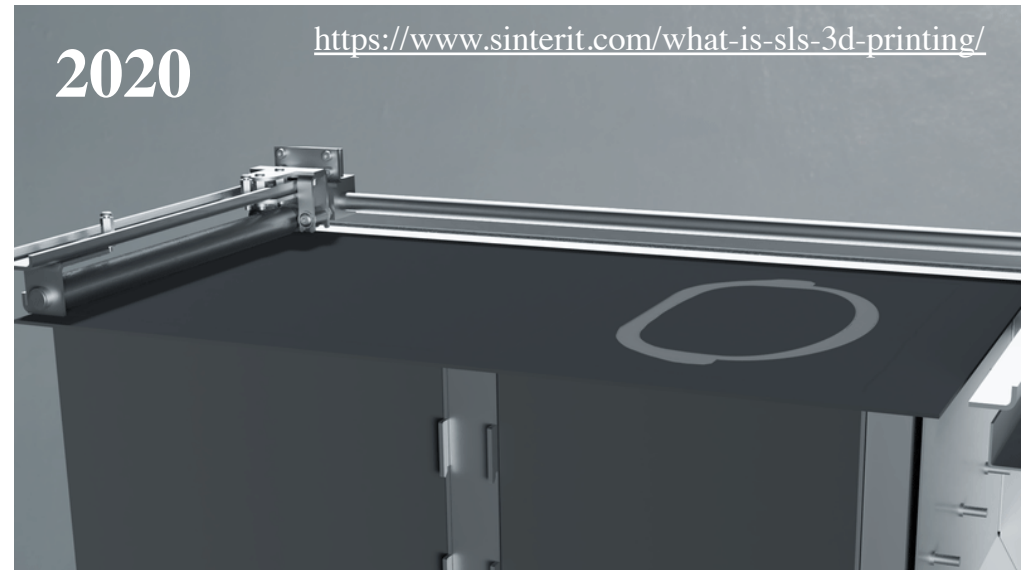
- Additive Manufacturing (AM) Opportunity Space
- Qualification and Certification
- Engagement with the Community
- TACP's Complementary Investments
 - ❖ ULI - Ecosystem for Qualification of AM Processes
 - ❖ TTT - Design and Certification of AM Materials and Structures
- Concluding Remarks



Evolution in 3D Metals Printing*



TACP - Transformational Tools & Technologies Project



Main change since the 1970s has been our ability to control the powder and to control the (fiber) laser beam. This has enabled 3D shapes to be printed.

Advantages of additive manufacturing include the **ability to produce complex parts with new functionalities**, dramatically reduce the number of parts and secondary joining steps in complex assemblies and reduce overall manufacturing time.

Revenue forecast for AM is \$35B in 2024[†].



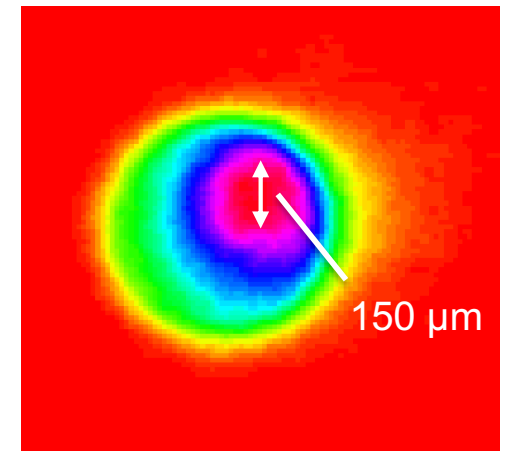
Laser - Powder Bed Fusion (L-PBF) Process



TACP - Transformational Tools & Technologies Project



**



In-situ Thermal Image
of Melt-Pool

Dynamic X-Ray Radiography of L-PBF

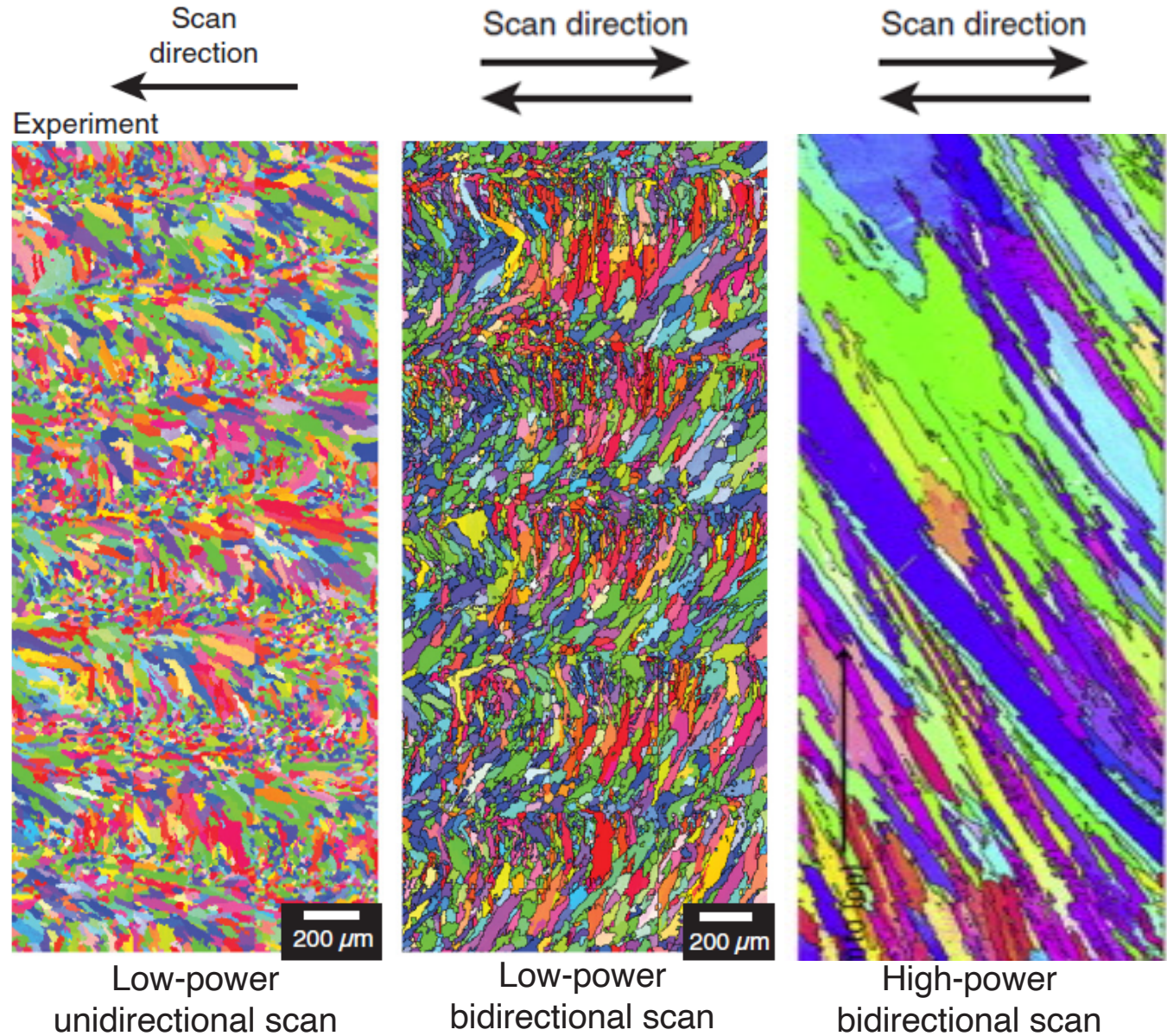


*

Advanced Photon Source (APS) at
Argonne National Laboratory

AM Microstructure*

TACP - Transformational Tools & Technologies Project



Material:
Inconel 718

Process: L-PBF



AM Offers Unprecedented Potential (e.g., DARPA TRADES Program*)



TACP - Transformational Tools & Technologies Project

Transform design by exploring new math/algorithms to:

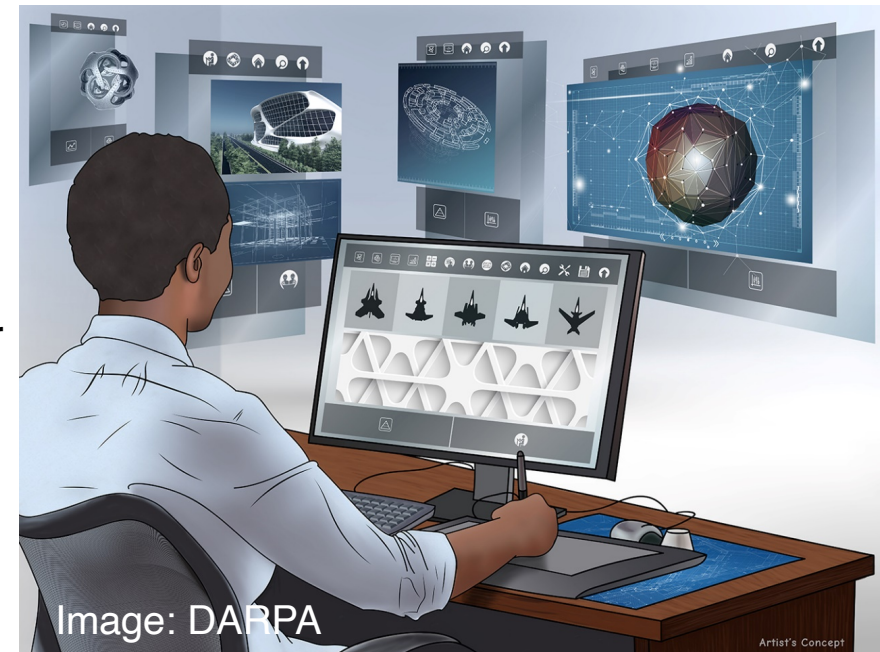
- Harness the tidal wave of new materials and fabrication methods coming our way and enable new designs that are unimaginable today.

Vision

- Advance the foundational mathematics and computational tools required to generate and better manage the enormous complexity of design.
- TRADES intends to develop engineering tools to address design representation, analysis, and synthesis.

Goals

- TRADES technologies will allow designers to more easily navigate the design space to discover non-intuitive yet realizable designs that **fully leverage new materials and advanced manufacturing approaches**, ultimately showing a way forward for future design systems and processes.





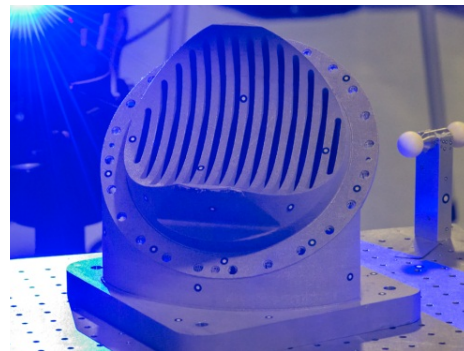
Increasing Complexity of AM Parts



TACP - Transformational Tools & Technologies Project



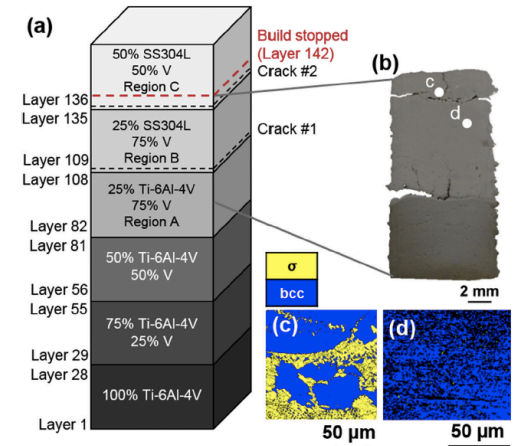
Fuel Injector
Image: GE



Pogo Z-Baffle
Image: NASA



Topology Optimized Bracket
Image: AutoDesk



Graded Materials
Image: JPL*

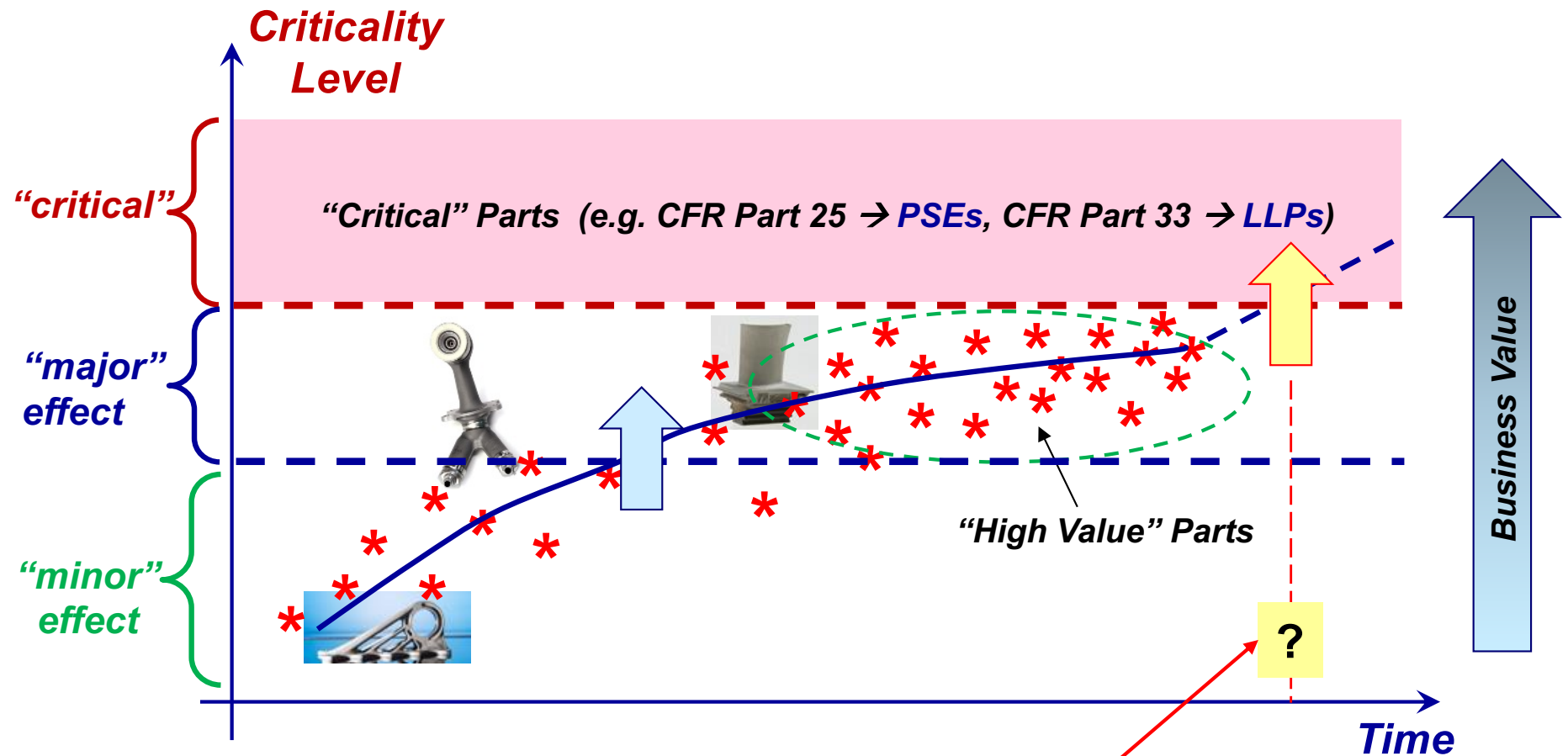
Increasing Complexity

*Bobbio *et al.* (2018) *J. Alloys and Compounds*, **742** 1031



Evolution of Criticality of AM Parts*

TACP - Transformational Tools & Technologies Project



Transition to “safety-critical” applications in aviation will occur sooner than initially expected



Examples of “Model-Friendly” Domains*



TACP - Transformational Tools & Technologies Project

Reference to Title 14 CFR Parts 25 (Airframe) and 33 (Engines)

- 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”





Community Guidance



TACP - Transformational Tools & Technologies Project

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

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

NASA/TM-2021-
NIST/publication info
FAA/publication info



NIST



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

*E.H. Glaessgen
NASA Langley Research Center, Hampton, Virginia*

*L. Levine, P. Witherell, A. Donmez
National Institute of Standards and Technology, Gaithersburg, Maryland*

*M. Gorelik
Federal Aviation Administration, Scottsdale, Arizona*

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

*R. Barto
Lockheed Martin Advanced Technology Laboratories, Cherry Hill, New Jersey*

*C.C. Battaile
Sandia National Laboratories, Albuquerque, New Mexico*

*H. Millwater
University of Texas at San Antonio, San Antonio, Texas*

*G.J. Nanni
Bell, Fort Worth, Texas*

February 2021

NASA/TM-2021-



Computational Materials for Qualification and Certification (CM4QC) Steering Group



TACP - Transformational Tools & Technologies Project

The **primary goals** of this Steering Group are to

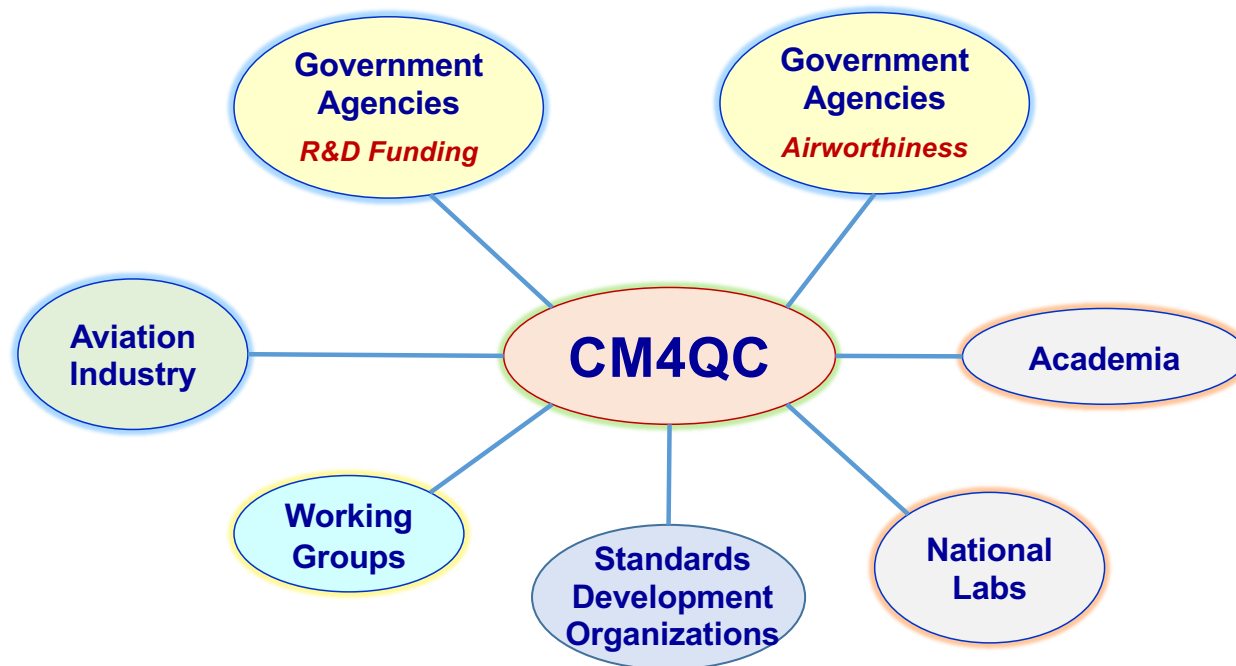
- Provide **coordination for and focus to investments** made by U.S. industry and the U.S. government toward development of computational materials-based (CM) approaches for qualification and certification (Q & C) of process intensive metallic materials (PIM).
 - Initial focus is on laser powder bed fusion (L-PBF)
 - Subsequent consideration of wire directed energy deposition (DED) and powder DED.
- Identify key considerations and enablers required to **increase airworthiness / certifying authorities' acceptance of computational methods** use for Q&C of structural or flight-critical PIM parts.
- **Increase dialogue among the stakeholder organizations**, develop a common understanding of the state-of-the-art of CM in the Q & C domain including related gaps and challenges.
- Seek opportunities for **sharing capabilities, methods, tools, codes, best practices and discussion of regulatory considerations**.



Operation of the CM4QC Steering Group

TACP - Transformational Tools & Technologies Project

- Working Group 1: Understanding industry priorities / timeline and key regulatory implications (High TRL)
- Working Group 2: Strategies for maturation and transition of Research to Engineering (Mid TRL)
- Working Group 3: Development of required computational materials and measurement capabilities (Low TRL)



**Expected initial outcome –
Draft of multi-year implementation plan (late CY2021)**



TACP Complementary Investments



TACP - Transformational Tools & Technologies Project

**Carnegie
Mellon
University**

NASA University Leadership Initiative at Carnegie Mellon University on Development of an Ecosystem for Qualification of Additive Manufacturing Processes and Materials in Aviation
(6 universities, 2 small businesses)

Focused on development of defect-based process maps that guide AM production machine settings to minimize or eliminate those manufacturing defects.

→ **Process Windows**



Transformation Tools and Technologies Project's effort on Design and Certification of Advanced Manufacturing-Based Materials and Structures

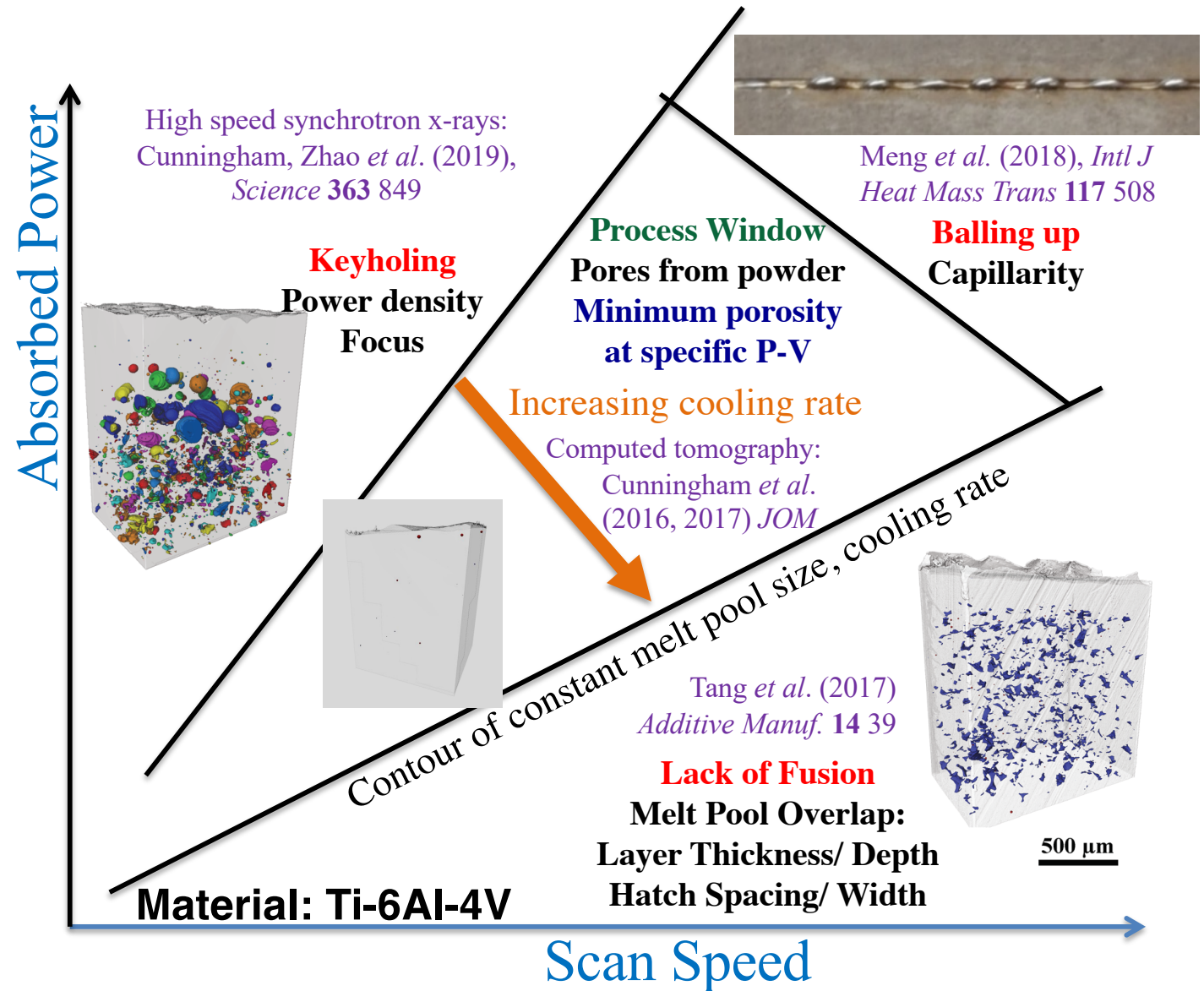
Focused on understanding the effect of processing on evolution of material microstructure and defects and the resulting effects of those defects on lifecycle performance

→ **Microstructurally-Informed Durability and Damage Tolerance**

Process Window: Porosity*

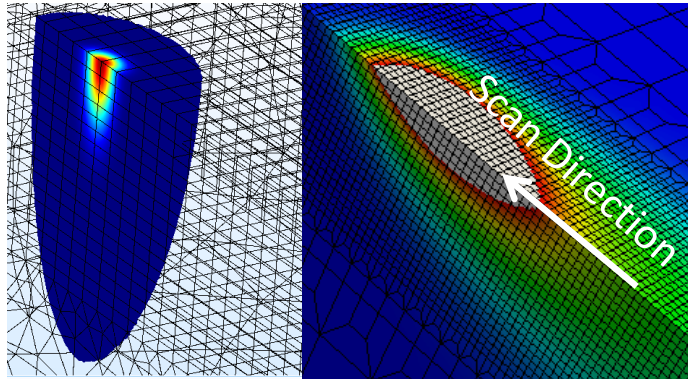
TACP - Transformational Tools & Technologies Project

- Note the sharp increase in porosity predicted in the lower right (lack of fusion) and upper left (key-holing).
- Key-holing: excessive power density
- Lack-of-fusion: geometry of melt pool relative to layer depth & hatch spacing
- Capillarity causes “balling up”; complicated by fluid flow behind the heat source



*A.D. Rollett, NASA Aeronautics Research Mission Directorate's University Leadership Institute on Development of an Ecosystem for Qualification of Additive Manufacturing Processes and Materials in Aviation

Simulation of AM Processes

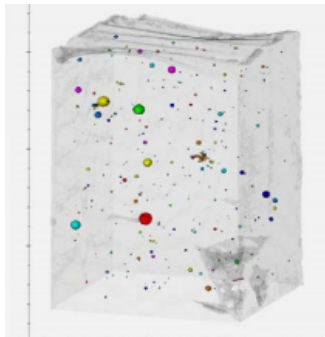


Thermal Modeling



*Simulation of Microstructure
& Defect Evolution*

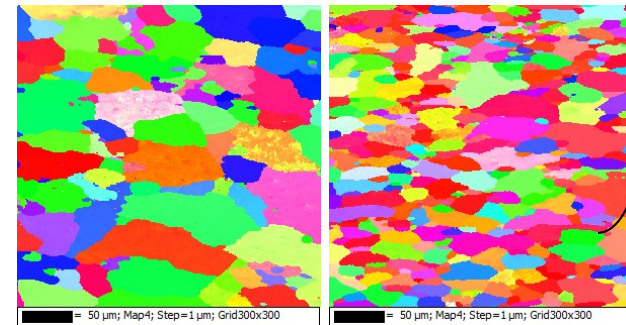
Microstructural Characterization



Inherent porosity



Inherent cracks

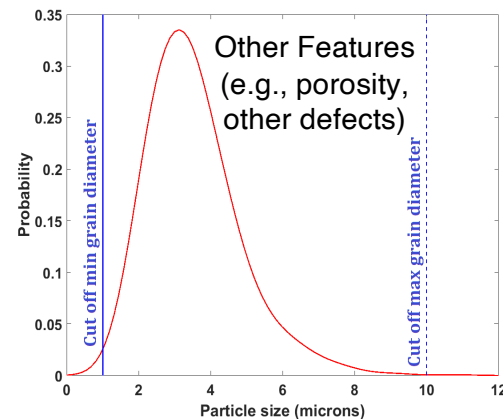
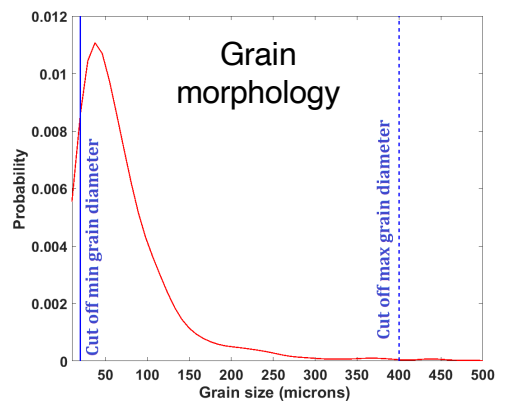


Morphology

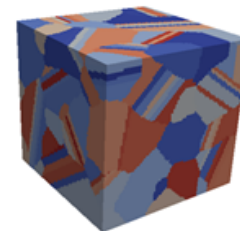
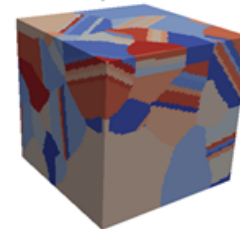
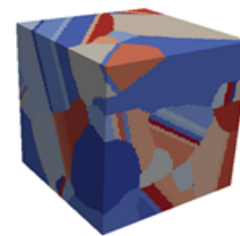
Physics-based simulation and high-fidelity characterization of AM processing provide input to microstructure performance simulations

FEA Simulations Consider Representative Microstructures Developed from Processing Simulation and Characterization Data– Capture Microstructural Details and Responses*

Combined simulation and characterization to consider microstructure variability**

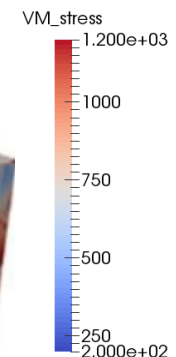
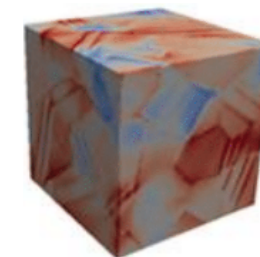
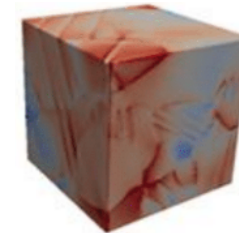


Microstructure instantiations for FEA#



100-1000 independent simulations

FEA Simulations#

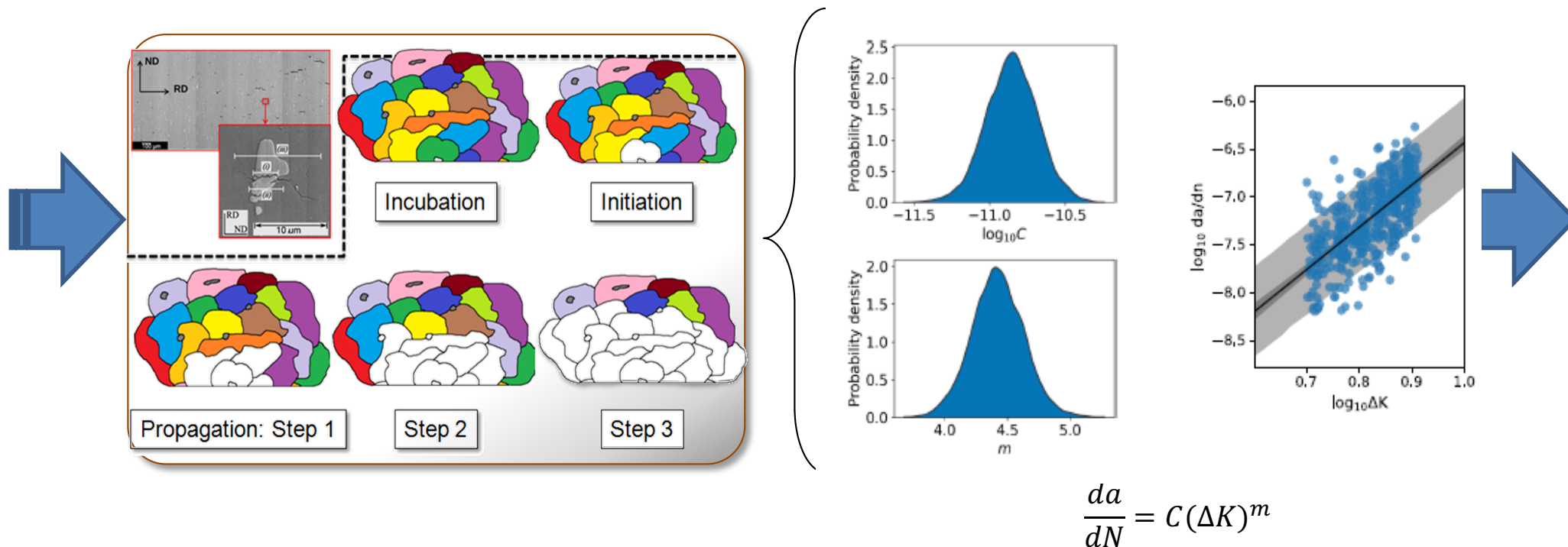


Finite element simulations account for variability in microstructure

Transition from Microstructurally Small Crack Growth Estimates to Engineering Codes

$$N_{failure} = N_{incu} + N_{init} + N_{MSC} + N_{MLC}$$

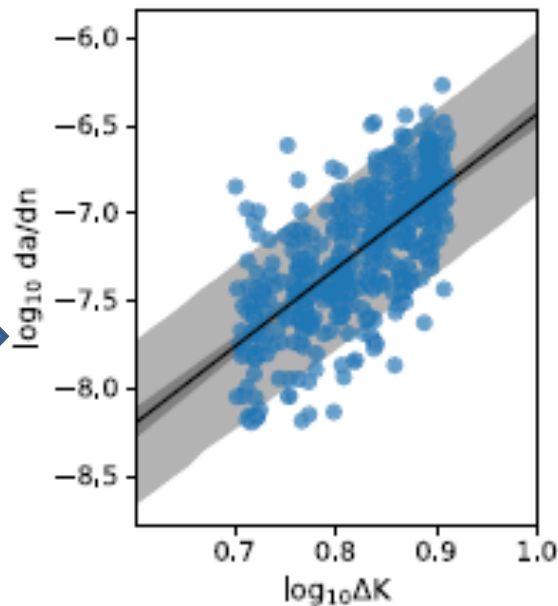
*Fatigue Crack Growth Material Parameter Distributions**



Nondeterministic prediction of fatigue life considering effects of microstructure

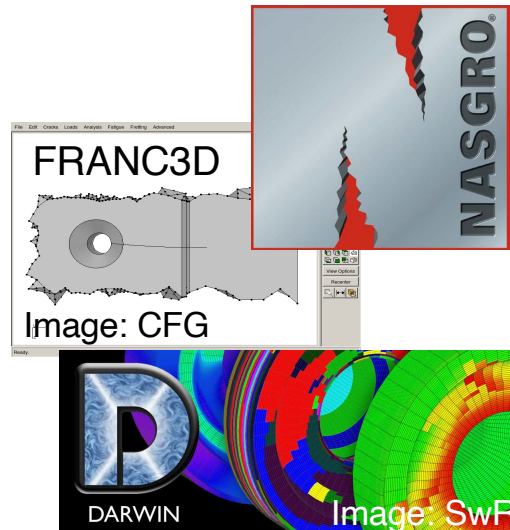
Microstructurally-Informed D&DT of Fracture-Critical Components

Microstructure-Informed Variability in Crack Growth Rates

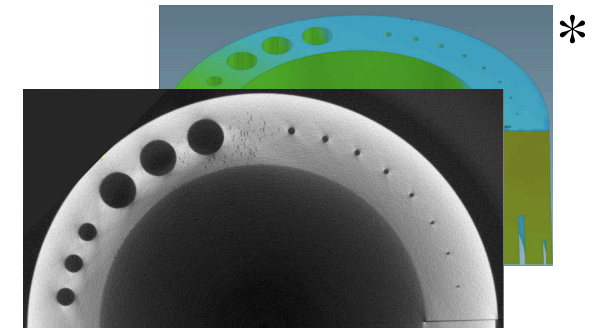


$$\frac{da}{dN} = C(\Delta K)^m$$

Embed these Relationships within Engineering Codes

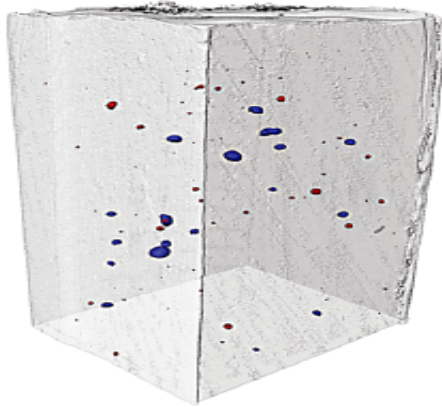


Component Level Inputs

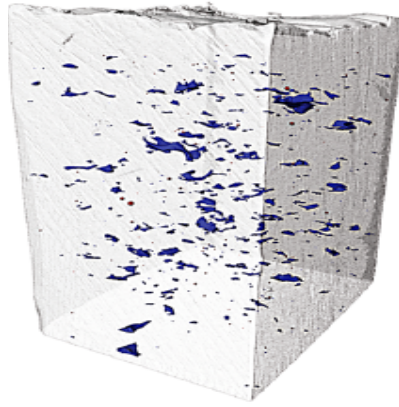


Apply microstructurally-informed D&DT simulation to determine distribution in fatigue life of fracture-critical AM components with variable microstructures

Types of Defects in L-PBF Process



***Keyhole Porosity**



***Lack of Fusion (LoF) Porosity**

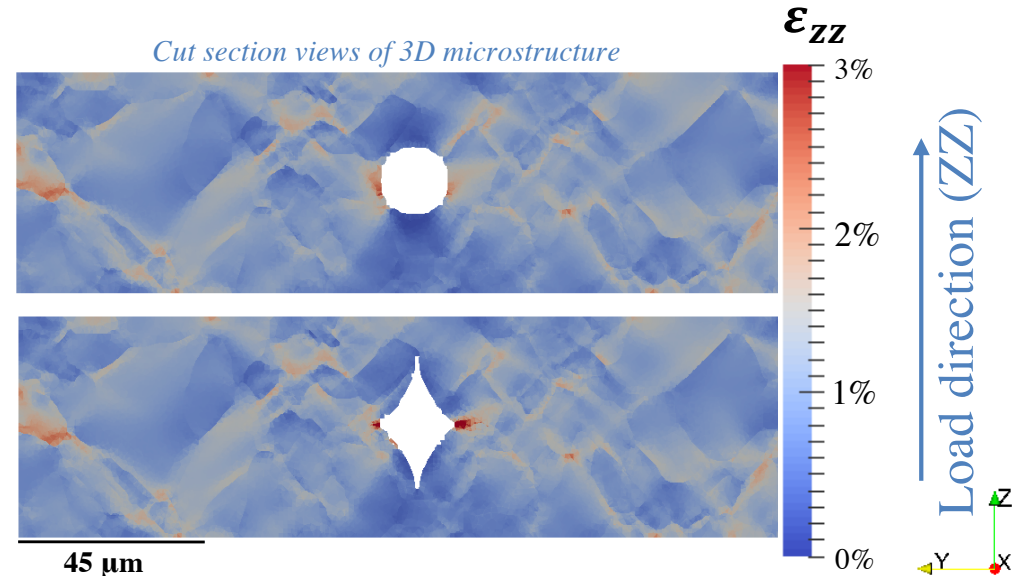
Other types of defects :

- Microcracking
- Entrapped gas pores
- Oxide induced pores
- Surface roughness
- Balling

Other parameters

- Proximity to free surface
- Local neighborhood
- Residual stress

Strain Localization



- Surrounding microstructure is the same in both cases
- Pore volume fraction is the same in both cases
- Global strain applied: 1%

Observation: Strain localization is more intense for LoF pore with sharp corners compared to the idealized keyhole pore of the same volume



Summary



TACP - Transformational Tools & Technologies Project

- Additive manufacturing (AM) offers unprecedented design flexibility and enormous potential economic impact but with increased material variability
- Use of AM parts in critical applications is evolving rapidly and necessitates new approaches to Q&C
- FAA requirements provide entry points for computational materials simulation if supported by testing
- Continued extensive engagement with the community across the TRL scale
- Complementary TACP research is aimed at development of needed capabilities for Q&C