Computational Materials for Qualification and Certification of Process-Intensive Metallic Materials (CM4QC)

Commonwealth Center for Advanced Manufacturing

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E.H. Glaessgen

NASA Senior Technologist for Computational Materials
NASA Langley Research Center

and

Michael Gorelik

FAA Chief Scientist and Technical Advisor
for Fatigue and Damage Tolerance

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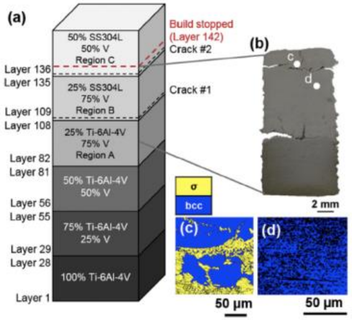
Outline

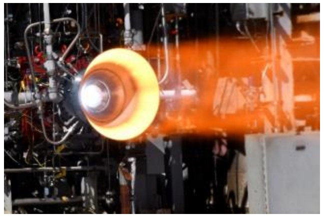
- Evolution of Complexity and Use of Additively Manufactured (AM) Parts
- Some Regulatory Constraints & Opportunities from FAA
- Steering Group Goals, Membership and Operation
- Highlights of the CM4QC Roadmap
- Some Ongoing Related Efforts
- Next Steps

Increasing Complexity of AM Parts

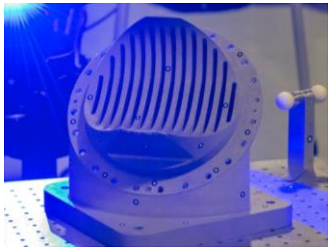
DARPA TRADES Program



Graded Materials
Image: NASA*

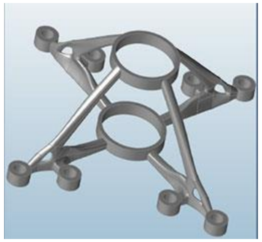


Rocket Engine Components
Image: NASA



Pogo Z-Baffle
Image: NASA

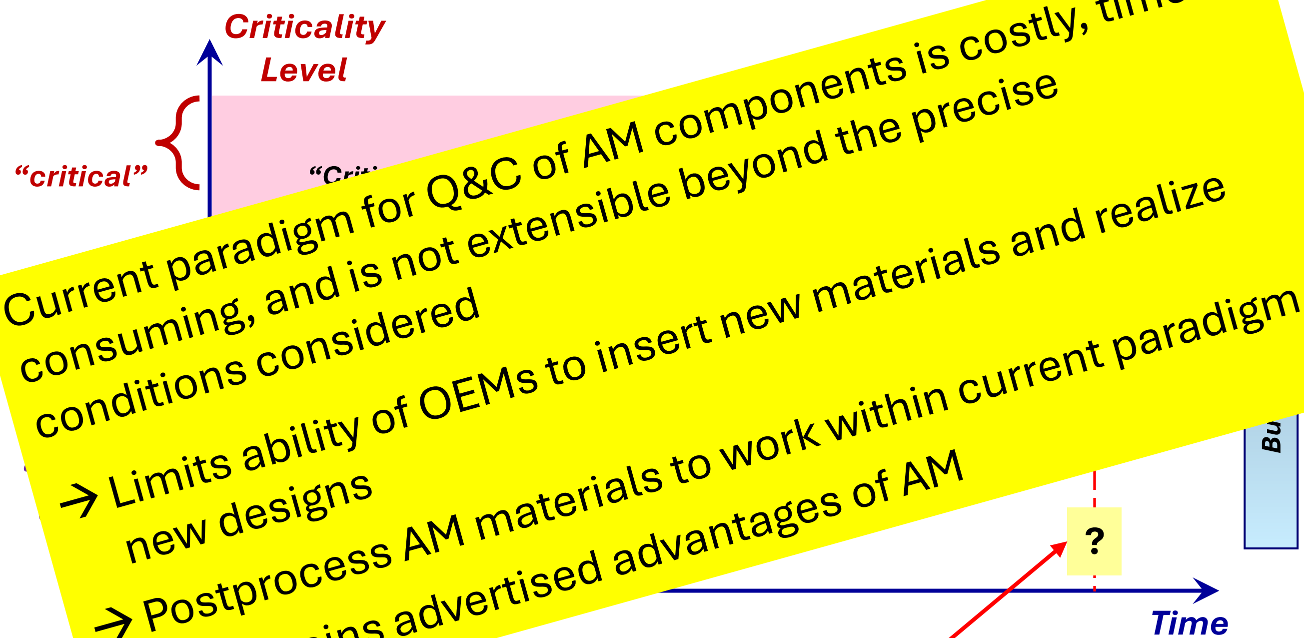
Increasing Complexity



Bracket
Image: NASA

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

Evolution of Criticality of AM Parts



Current paradigm for Q&C of AM components is costly, time consuming, and is not extensible beyond the precise conditions considered

→ Limits ability of OEMs to insert new materials and realize new designs

→ Postprocess AM materials to work within current paradigm

→ Constrains advertised advantages of AM

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

In September 2025, AFRL reported one part design had passed 43 physical iterations without converging on a usable component!

- CFR - Code of Federal Regulations
- PSE – Principal Structural Element
- LLP – Life Limited Part

U.S. Department of Transportation
Federal Aviation Administration

Advisory Circular

Subject: Damage Tolerance and Fatigue Evaluation of Structure

Date: 1/13/2011

Initiated By: ANM-115

AC No: 25.571-1D

Image: NASA

Representativeness of the test specimen

The test article should be full-scale (component or sub-component) and represent that portion of the production aircraft requiring test

Examples of "Model-Friendly" Domains

In the Context of FAA Regulations – 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"

Computational Materials for Qualification and Certification (CM4QC) Steering Group

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 approaches for Q&C of process-intensive metallic materials.
- Identify key considerations and enablers required to increase airworthiness / certifying authorities' acceptance of CM methods used for Q&C of structural or flight-critical process-intensive material (PIM) parts.
- Increase dialogue among the stakeholder organizations and seek opportunities for collaboration.

Membership includes subject matter experts from the aerospace industry, various government laboratories and academia

Steering Group Membership

Industry

- The Boeing Company*
- Lockheed Martin*
- Raytheon / Pratt & Whitney
- General Electric Aviation
- Spirit Aerosystems
- Honeywell Aerospace
- Southwest Research Institute
- Northrop Grumman
- Textron Aviation

Government

- National Aeronautics and Space Administration*
- Federal Aviation Administration*
- National Institute of Standards and Technology*
- Sandia National Laboratory*
- U.S. Air Force Research Laboratory
- U.S. Army Aviation Command
- U.S. Navy Air Systems Command
- Oak Ridge National Laboratory

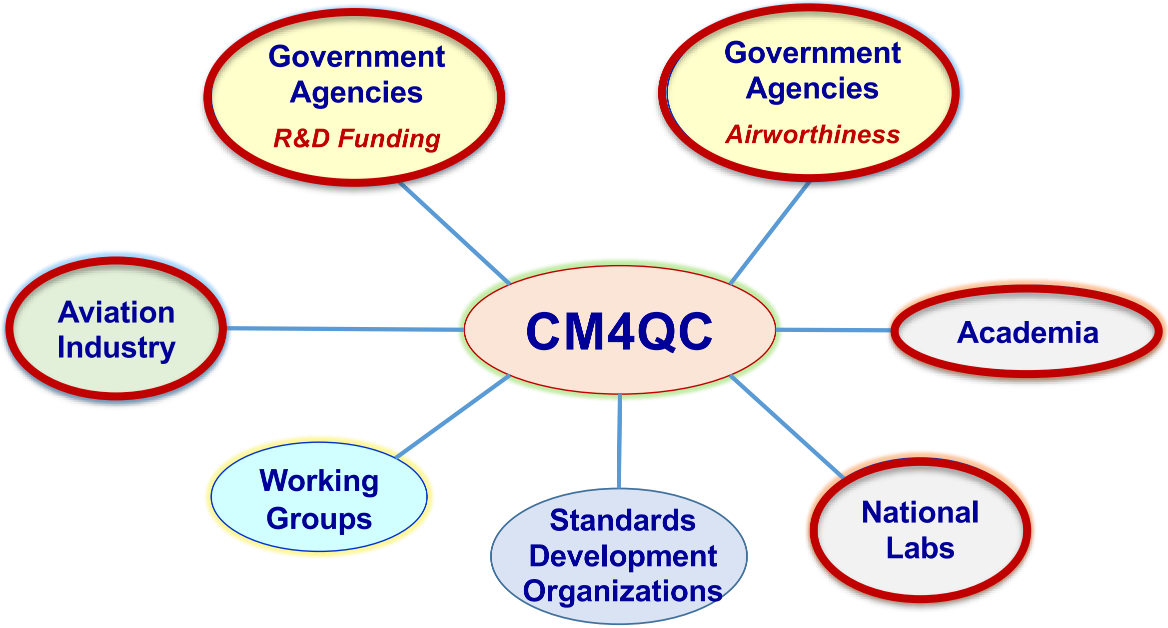
Academia

- Univ Texas San Antonio*
- Carnegie Mellon Univ.*
- Vanderbilt Univ.
- Pennsylvania State Univ.
- Northwestern Univ.

*CM4QC Leadership Team

Operation of the CM4QC Steering Group

- 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)



Initial outcome –
Multi-year implementation plan

CM4QC Membership

*Technology Readiness Level

NASA/TM–20260001729
DOT/FAA/TC-26/10

U.S. Department of Transportation
Federal Aviation Administration

Computational Materials for Qualification and Certification (CM4QC) Strategy Document:

Maturation of Computational Materials Methods for Aviation-Focused Qualification and Certification of Metal Additive Manufacturing (as an Example of Process-Intensive Materials)

Edward H. Glaessgen
Langley Research Center, Hampton, Virginia

Michael Gorelik
Federal Aviation Administration, Scottsdale, Arizona

Corbett C. Battaile
Sandia National Laboratory, Albuquerque, New Mexico

Derrick Lamm
Lockheed Martin, North Bethesda, Maryland

Lyle E. Levine
National Institute of Standards and Technology, Gaithersburg, Maryland

Harry R. Millwater
University of Texas at San Antonio, San Antonio, Texas

Alonso Peralta-Duran
Honeywell Aerospace, Phoenix, Arizona (retired)

Narendran Raghavan
The Boeing Company, Herndon, Virginia

Anthony D. Rollett
Carnegie Mellon University, Pittsburgh, Pennsylvania

Edwin J. Schwalbach
Air Force Research Laboratory, Dayton, Ohio

March 2026

NASA/TM-20260001729

DOT/FAA/TC-26/10

CM4QC Website

https://www.nist.gov/programs-projects/cm4qc

Key Business & Technology Drivers Supporting CM-informed Q&C of AM

C4M QC

From Section 1

Business drivers

- Decreased time and cost of Q&C of AM components
- Expanded design space for a given application offered for AM
- Expanded range of applications including for critical components
- Introduction of economies of scope, beyond existing economies of scale
- Enhanced design-build-test loop with reduced testing

Technology drivers

- Advances, demonstrated successes, increased use/acceptance of CM
- Development of digital twins, data standards and digital enterprise
- Advances in high-performance computing, artificial intelligence and machine learning
- Advances in verification / validation (V&V) and uncertainty quantification (UQ) methodologies and maturation of credibility assurance frameworks
- Increases in the availability of high-quality validation data
- Improvements and increased availability of in-situ and ex-situ measurement systems
- Advances in relevant technical standards and industry best practices

Key Objectives for this Roadmap

From Section 2

Development of a pathway towards Computational Materials-informed Q&C

Detailed Objectives include

- Document industry vision of the future state for the use of CM
- Identify key considerations and enablers required to increase airworthiness and certifying authorities' acceptance of computational methods
- Identify current gaps and key enabling CM capabilities
- Identify R&D investment opportunities
- Develop a framework to evaluate the maturity level of CM simulations
- Initiate a paradigm shift in the aerospace industry's use of CM tools
- Assess the state-of-practice of CM for potential application in Q&C
- Increase dialogue among the stakeholder organizations
- Encourage development of relevant guidance/standards
- Inform academia about training and education gaps

Enabling Industry's Vision for AM

From Section 3

Industry's Vision for AM

- Print *worthy* components anywhere and anytime. Worthiness is dependent on the situational requirements and can refer to airworthiness, cost, or other attributes.
- Expand manufacturing possibilities and emphasizing "economies of scope" operational models
- Reduced lead-time for manufacturing new, complex components
- Reducing the cost for small volume or even single-part production
- Reduced part weights, subassembly part counts, and inventories

&

Lower the barriers to insertion of new materials and new configurations

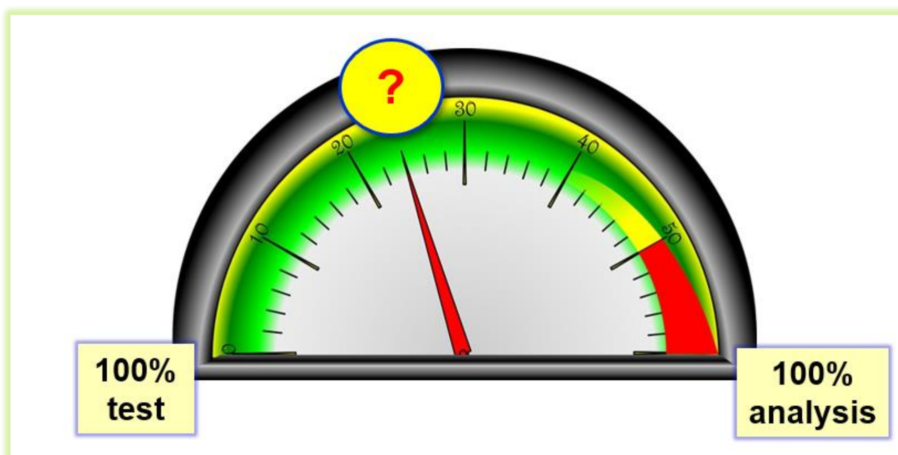
Regulatory Considerations for Acceptance of Computational Materials-informed Q&C

From Section 4

Key drivers

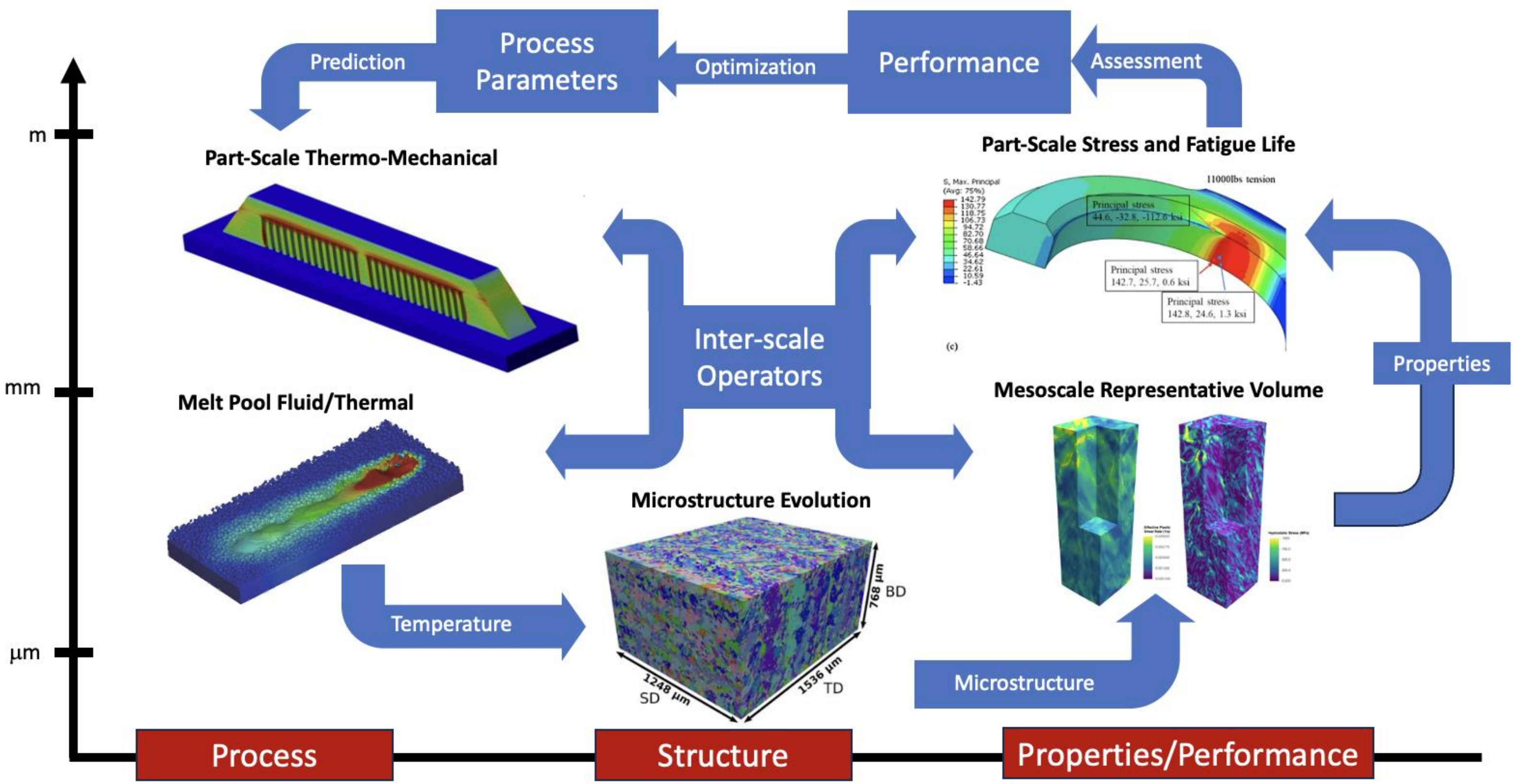
- Gradual reduction in conventional Q&C test matrices
- Optimization of material test matrices informed by CM insights (i.e., obtaining the most valuable information from testing)
- Exploring the corners and fringes of the multi-dimensional process parameters space to fully capture material performance variations
- Understanding process limitations and potential failure modes
- Better understanding of the similitude (or a lack of thereof) between the performance of the test specimens vs. parts

Future State: Balance between Test Data and CM-informed Q&C is Undetermined



Key Computational Materials Capabilities & Enabling Technologies

From Section 5



Process Structure Property/Performance (PSP/P) Modeling Framework

“State of Practice" Assessment of Computational Materials Capabilities

From Section 6

Includes Brief Assessments of:

Process

- Simulation of Powder Flow
- Computational Thermodynamics
- Macroscopic Heat Flow Simulation
- Residual Stress Prediction
- Heat Flow at the Individual Track Level
- Fluid Flow in Melt Pool Simulations

Structure

- Microstructure Simulation

Property/Performance

- Property & Performance Prediction

Key Cross-Cutting Topics

- Computing Capacity
- Data Storage
- Material Properties & Constitutive Models
- V&V and UQ

Validation Metrics

From Section 7

- Validation metrics should be quantitative and objective
- Criteria used by an analyst/designer to accept a model for prediction should be separate from the validation metric itself
- Uncertainties resulting from both computer models and experiments should be considered
- Validation metrics should provide a statistical confidence level associated with the amount of available experimental data
- Validation metrics should also differentiate between models containing greater and lesser amounts of uncertainty
- A metric should have the flexibility of measuring the agreement of prediction and physical observations either at a single setting or multiple settings of controllable inputs over an intended prediction region to assess the global predictive capability.

CM Maturity Assessment Framework*

From Section 8

Maturity Level	Description
1	All underlying models are clearly defined, including inputs, outputs, and application intent. Analytical process is exploratory in nature. Fidelity of predictions are largely unproven. Provides some physical insight, but not yet suitable for adoption in Q&C activities.
2	Proven capability for comparative assessment, ranking, or trending. Experimental validation remains incomplete. Can be used to inform other activities relevant to Q&C.
3	Capability is verified and validated for limited cases. Use is primarily limited to research activities. Impact to industry activities occurs primarily through work where results could be used to inform Q&C activities.
4	Capability is fully verified and validated for industry use cases. Simulation platform is used by industry, but relevance is primarily to research activities, with occasional direct impact to Q&C activities. Results are used primarily to provide guidance and confidence to design and development activities.
5	Simulation platform is widely adopted by industry. Model predictions are directly applicable to Q&C activities.

*Adapted from: B. Cowles, D. Backman, R. Dutton, "Verification and validation of ICME methods and models for aerospace applications," Integrating Materials and Manufacturing Innovation, vol. 1 (2012), pp. 3–18.

Gaps Limiting Maturation and Adoption of Computational Materials in the Q&C Domain (1 of 2)

From Section 9

- Prediction of
  - Process-microstructure relationships (e.g., phases, precipitates, and grain size)
  - Microstructure-property relationships (e.g., mechanical and physical properties, various functional properties)
  - Property-performance relationships (e.g., strength, fatigue life, damage tolerance, durability, and reliability), including critical aspects such as surface finish (including surface particles), defects, complex loading histories, and environmental and temperature conditions
  - Residual stress and distortion
- Build reproducibility
- Nondestructive Evaluation (NDE), including for process development, process qualification, manufacturing, and in-service performance
- Quantitative assessment of performance uncertainty and reliability

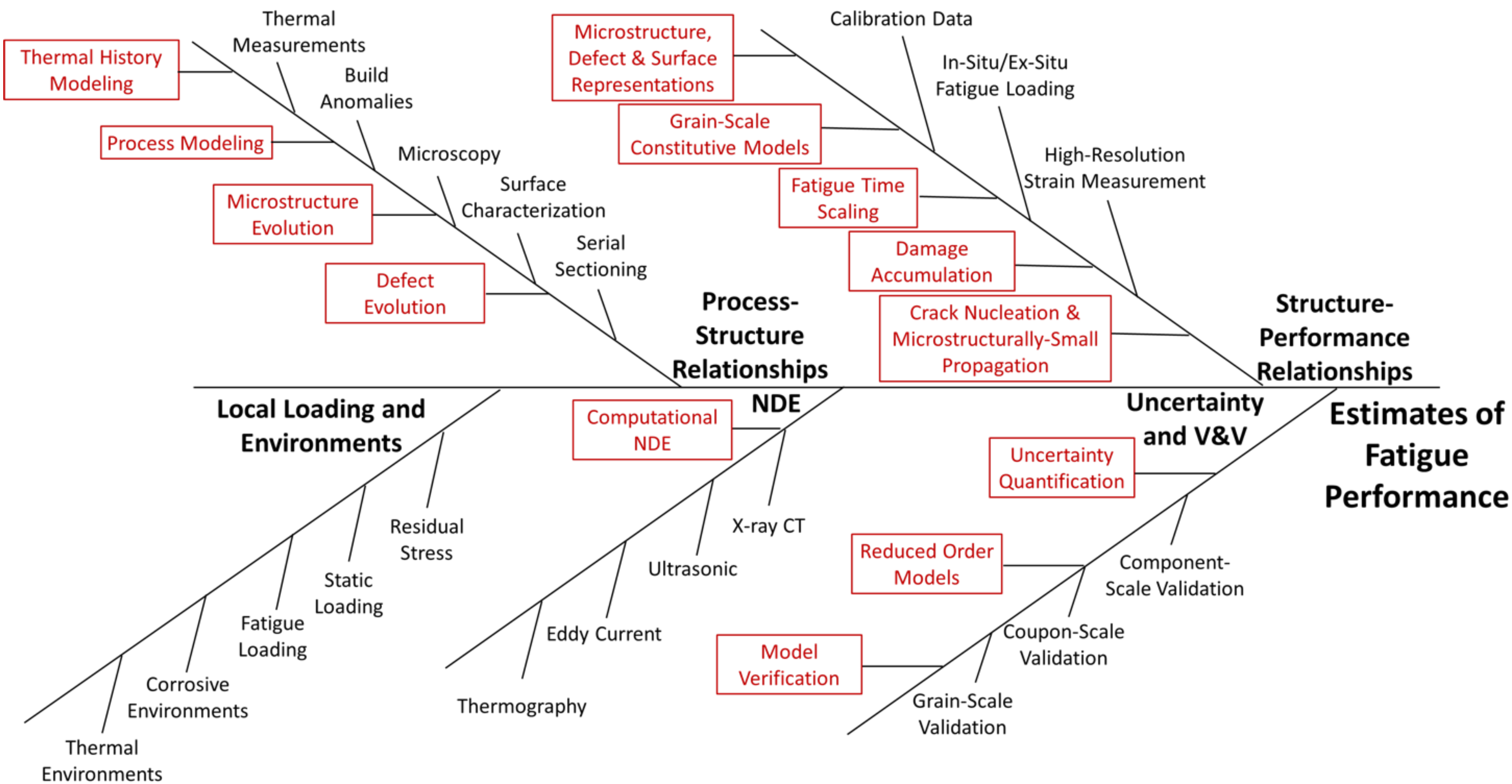
Gaps Limiting Maturation and Adoption of Computational Materials in the Q&C Domain (2 of 2)

From Section 9

- Acceptance by industry and regulatory agencies
  - Incremental with rigorous validation testing
  - Requires trust in models and clear business cases
- Improvements to ease-of-use of software
  - Software must be easy to use and run on laptops or workstations
  - Non-proprietary input/output formats
  - Publicly available validation data such as provided by AM Bench
- Availability of material property data
- Integration of Uncertainty Quantification
- Resources to conduct side-by-side CM-related and conventional Q&C activities, until CM tools are widely accepted as being viable
- Improvements in transitioning non-commercial AM codes to commercial platforms with version control, continued maintenance, linkages, etc.
- Educational improvements leading to increased availability of a CM-informed work force

Inputs and Dependencies that Contribute to Estimates of Fatigue Performance

From Section 9



A Phased Approach for Development of a Capability for Computational Materials-informed Q&C

From Section 10

Near-term (1-5 years)

- Identification of approaches that incorporate existing commercial software including guiding conventional Q&C activities, e.g., designing experiments or guiding testing practices

Mid-term (5-10 years)

- Development of partnerships between aerospace organizations, software vendors, government laboratories, and universities targeting emerging techniques for CM and accelerating their incorporation into commercial tools and Q&C practices
- Includes support from manufacturers and regulators to identify the most critical areas of research

Long-term (>10 years)

- Development of new CM techniques that dramatically expand the capabilities of computational simulations and their application to Q&C
  - Expand the physical fidelity and accuracy of models
  - Focus on methods that dramatically reduce computational expense
  - Exploit highly efficient computing paradigms (e.g., GPUs)

Computational Materials Ecosystem (1 of 3)

From Section 11

How Can CM Augment (Rather than Replace) Existing Q&C practices?

- Investment in CM capability development
- Transition to next-generation AM machines to enable CM-informed Q&C
- Characterization and data practices for calibration, validation, and machine learning
- CM4QC culture
- Development of AM-appropriate regulatory standards
- CM education and workforce development

Computational Materials Ecosystem (2 of 3)

From Section 11

Characterization and Data Practices for Calibration, Validation and Machine Learning

Calibration Data Include

- Material Properties of Molten Materials (Coefficient of Thermal Expansion, Specific Heat, Surface Tension, Viscosity, …)
- Process Parameters (Scan Path, Layer Height, Laser Power, …)
- Microstructure Characteristics (Solid/Liquid Surface Energy, Nucleation Density Solid-Solid, …)
- Material Properties of Solid Materials (Dislocation Density, Grain Size, Precipitate Size, Defect Distributions, …)

Validation Data Include

- Process (Melt Pool Size, Temperature, Distortion, Residual Stress, …)
- Microstructure (Dislocation Density, Grain Size, Precipitate Size, Defects…)
- Properties/Performance (Ultimate Tensile Stress, Fracture Toughness, Creep, Fatigue Crack Growth Rate, Corrosion…)

From Section 11

CM4QC Culture

- Current approaches for Q&C simply do not have procedures for making use of CM results
  - The naïve expectation is that CM predictions may directly replace testing data
- Build a culture in which CM capabilities are used to guide and interpret experiments, development, and testing based on strengths of CM capabilities, while acknowledging their shortcomings

- In the near-term: identify low-risk research activities with a high probability of success for informing Q&C decisions
- Augment rather than replace existing Q&C practices, including:
  - Increasing confidence that material testing is representative of actual components
  - Reducing the total amount of experimental testing while still building the necessary confidence in the results
  - Improving relevance to real components with same amount of testing
  - Reducing variability to improve designs with same amount of testing

DARPA: SURGE

Broad Agency Announcement
Structures Uniquely Resolved to Guarantee Endurance (SURGE)

DEFENSE SCIENCES OFFICE

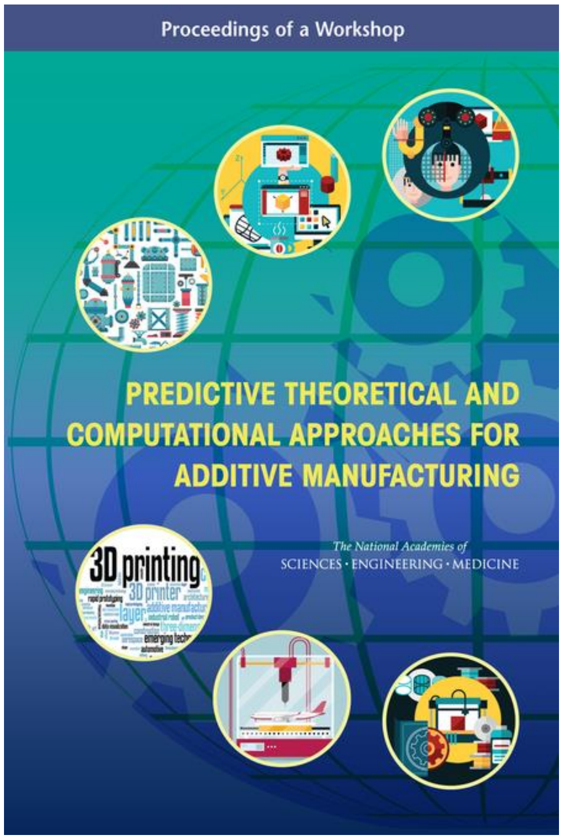
HR001124S0018

April 12, 2024

...aims to rethink the current machine-focused paradigm of part qualification in additive manufacturing (AM)

NIST: AM Bench

The Additive Manufacturing Benchmark Series (AM Bench) was proposed on October 7, 2015

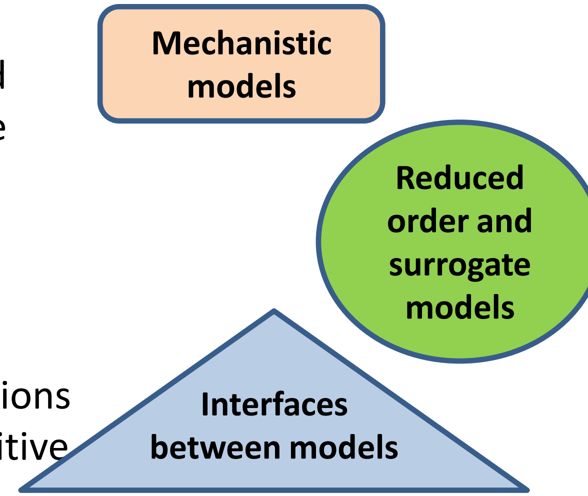


What is AM-Bench?

A continuing series of highly controlled benchmark measurements for additive manufacturing, with modeling challenge problems, and a corresponding conference series

Primary Goal

To allow modelers to test their simulations against rigorous, highly controlled additive manufacturing benchmark test data



AM BENCH 2018

AM BENCH 2022

AM BENCH 2025

AM BENCH 2028

NASA: Space Technology Research Institute (STRI)†

IMQCAM Need, Goal, Digital Twin

- STRI arises from the expense involved in qualifying **safety-critical** 3D printed parts, especially for flight-critical hardware. Motivates physically-based feedstock-processing-microstructure/defect structure-response workflows that predict performance and **fatigue life** based on inputs.
- Central goal of STRI = model-centric workflow that closes the critical gaps between current capabilities and what is necessary for efficient qualification and certification (Q&C) of parts by metals additive manufacturing (MAM), meeting NASA standards.
- The STRI will build and implement a probabilistic †Digital Twin (DT) of the MAM physical asset (actual tasks) as a certifiable surrogate for a model-based Q&C process.
- *Our Digital Twin† Vision:* will virtually represent the entire feedstock-processing-microstructure/defect structure-response to life workflow. Emphasis on end-to-end model system that is responsive to design needs, qualification needs, certification. Less emphasis on numerical avatars (TRL level = 1-3). Reinforced by industry testing and feedback.
- **How will we know that we succeeded? NASA-MSFC+LaRC (& other Centers) use our modeling toolset + industry uses modeling toolset … to build trust & increase confidence in metals-AM with higher speed and lower cost.**
- Is this ICME? Emphatically yes! The difference is the connectivity and VVUQ throughout.

†Institute for Model-Based Qualification & Certification of Additive Manufacturing

ICME – Integrated Computational Materials Engineering

Next Steps for Computational Materials-informed Q&C approaches

Recently completed steps:

- Incorporation of reviewer comments and final edits
- Approval for public release
- Publication of the completed document

Other elements of the *CM4QC Steering Group's* implementation plan:

- Development of a demonstration exercise (what is possible today, what are the biggest and most important capability gaps). Led by NIST.
- IMQCAM STRI
- Socialization and outreach to
  - The aviation industry and corresponding certification authorities
  - Funding agencies and government research laboratories
  - Academia
  - Relevant consortia, professional societies & standards organizations
  - Non-profit organizations
- Development of best practice guides
- Application / adaptation of the framework to other industry sectors and other PIM technologies

Summary

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Questions: Please contact us at…

Ed Glaessgen
e.h.glaessgen@nasa.gov

Michael Gorelik
Michael.Gorelik@faa.gov

CM4QC Website