NIST Additive Manufacturing Fatigue and Fracture Project: Research Highlights

Nik Hrabe, Ward Johnson, Jake Benzing, Nicholas Derimow Newell Moser, Orion Kafka, Alec Saville

National Institute of Standards and Technology (NIST), Boulder, CO, USA

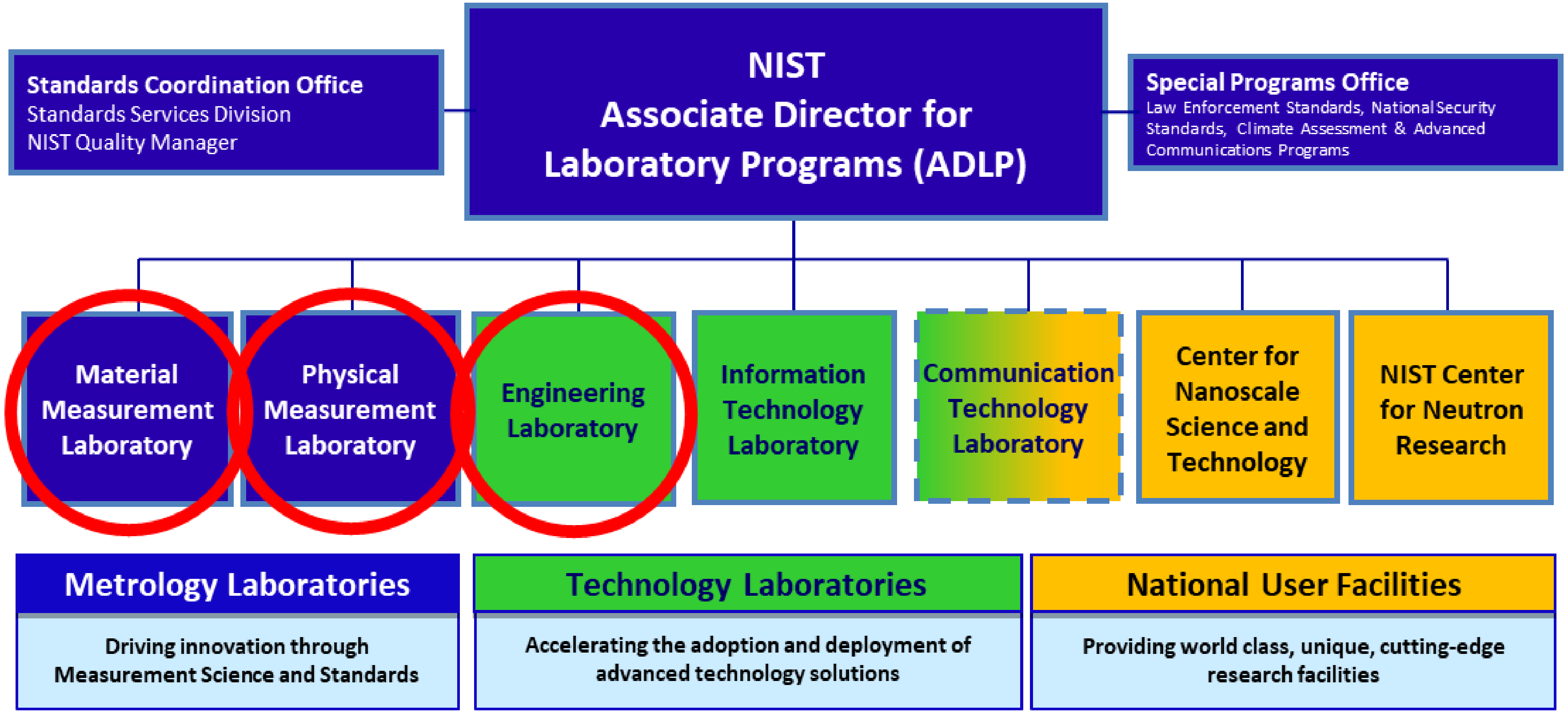
NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY U.S. DEPARTMENT OF COMMERCE

Introduction

- NIST is a national laboratory within the US Department of Commerce
- **MISSION**: To promote U.S. innovation and industrial competitiveness by advancing measurement science, standards and technology in ways that enhance economic security and improve our quality of life.

7 Laboratories make up NIST – ALL are active in AM

3 Laboratories with funded projects in AM



NIST

Introduction

MML

Lyle Levine – Metal Program Lead
Igor Levin – Ceramics Program Lead
Kalman Migler – Polymer Program Lead

Phase Evolution and Corrosion
Mark Stoudt
IN625 delta phase

Fatigue and Fracture
Nik Hrabe
Small-scale mech. testing

Alloy Development
Carelyn Campbell
Co-based AM alloys

X-ray CT
Ed Garboczi
Powder/Pore shape

In Situ Nanomechanics
Jason Killgore
Atomic Force Microscopy

Process Modeling
Jon Guyer
CHiMaD
Phase Field/FEM

Acoustic NDE
Ward Johnson

Synchrotron X-ray
Fan Zhang
Full stress tensors

Extrusion Process
Russell Maier

Cold Sintering Process
Andrew Allen

Process Monitoring & Control – Polymer
Jonathan Seppala

COLLABORATIONCOLLABORATIONCOLLABORATIONCOLLABORATIONCOLL

EL

Shawn Moylan – Measurement Science for AM Program Lead (Metals)

Feedstock and Machine Qualification
Shawn Moylan

In Situ Monitoring
Brandon Lane

Data for Model Validation
Thien Phan

Data Management
Yan Lu
AM Materials Database

Part Qualification
Jason Fox
Surface roughness, XCT, NDE, material properties

AM Control
Ho Yeung
AM Metrology Testbed (AMMT)

Data-Driven Decision Making for AM
Paul Witherell

3D Printed Concrete
Scott Jones

COLLABORATIONCOLLABORATIONCOLLABORATIONCOLLABORATIONCOLLABORATIONCOLLABORAT

PML

Thermal Emittance of Melts and Powders
Sergey Mekhontsev
AMMT - Emissivity

In Situ Metrology
Brian Simonds
Energy Coupling and Spectroscopy

NIST

Additive Manufacturing Fatigue and Fracture Project Summary

Problem Statement

- Metal additive manufacturing (AM) is not used in fatigue and fracture critical applications despite industrial need

Goal

- Enable confident use of metal AM in critical applications through reducing material variability, improving performance, reducing qualification cost, developing appropriate part inspection techniques, and developing necessary standards

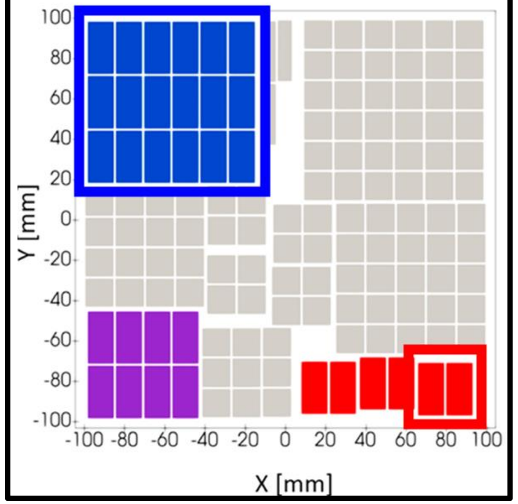
Methodology

- Develop/advance metrological practice for AM-specific performance metrics encompassing the full processing-structure-properties-performance spectrum and the full AM lifecycle
- Develop process and post-process control methods to reduce material variability and improve performance
- Develop new non-destructive evaluation (NDE) techniques that are fast, inexpensive, precise, and capable of inspecting larger parts with complex geometries common in AM
- Develop a rapid qualification framework based on digital twin to reduce cost and time to production
- Develop consensus AM standards with key stakeholders and various standards development organizations

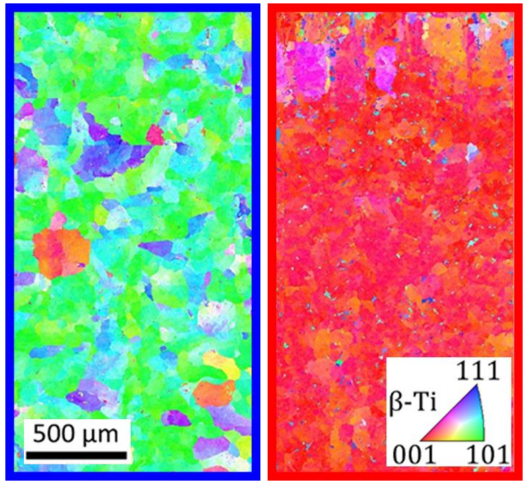
Key Findings and Significance

- Organized workshop that has grown into ASTM International Conference on Advanced Manufacturing, with more than 1,000 annual attendees
- Created NIST Metal AM Powder Consortium, with 11 members as of 2024
- Developed new post-process powder recovery blasting control technique for AM titanium that led to 30x improvement in fatigue lifetime and first-time use in the most critical medical device application (Collaborator: Stryker)
- Developed new process powder reuse quarantining method for AM titanium that led to 15% lower chemistry heterogeneity and part-to-part strength variability and standard ASTM F3592 (Collaborators: UTEP, Sandia)
- **Developed new process-based technique to control crystallographic texture for AM titanium, leading to 40% improvement in fracture toughness and standard ISO/ASTM 52911-3 (Collaborator: AFRL)**
- Developed new post-process heat treatment for AM titanium leading to 100x improvement in fatigue lifetime and revision of standard AMS 7028 (Collaborators: Lynntech, Quintus, 3D Systems)
- Developed new post-process heat treatment for AM Inconel 718 leading to 65% reduction in heat treatment time and 10x improvement in fatigue lifetime (Collaborators: SLM Solutions, Quintus, Sandia)
- Developed a resonant acoustic technique for rapid, inexpensive NDE of AM aluminum, stainless steel, and cobalt-chrome-molybdenum parts (Collaborators: Elementum 3D, Colorado State)

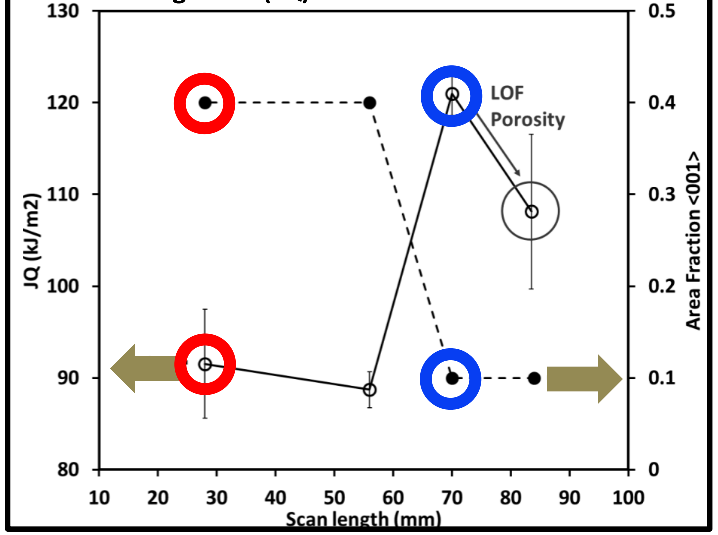
PROCESSING: grouping parts to control scan length (LONG vs SHORT)



STRUCTURE: Scan length affects crystallographic texture (LOW vs HIGH area fraction <001>)



PROPERTIES: 40% improvement in fracture toughness (JQ)



IMPACT: Standardization

ISO/ASTM 52911-3

ISO

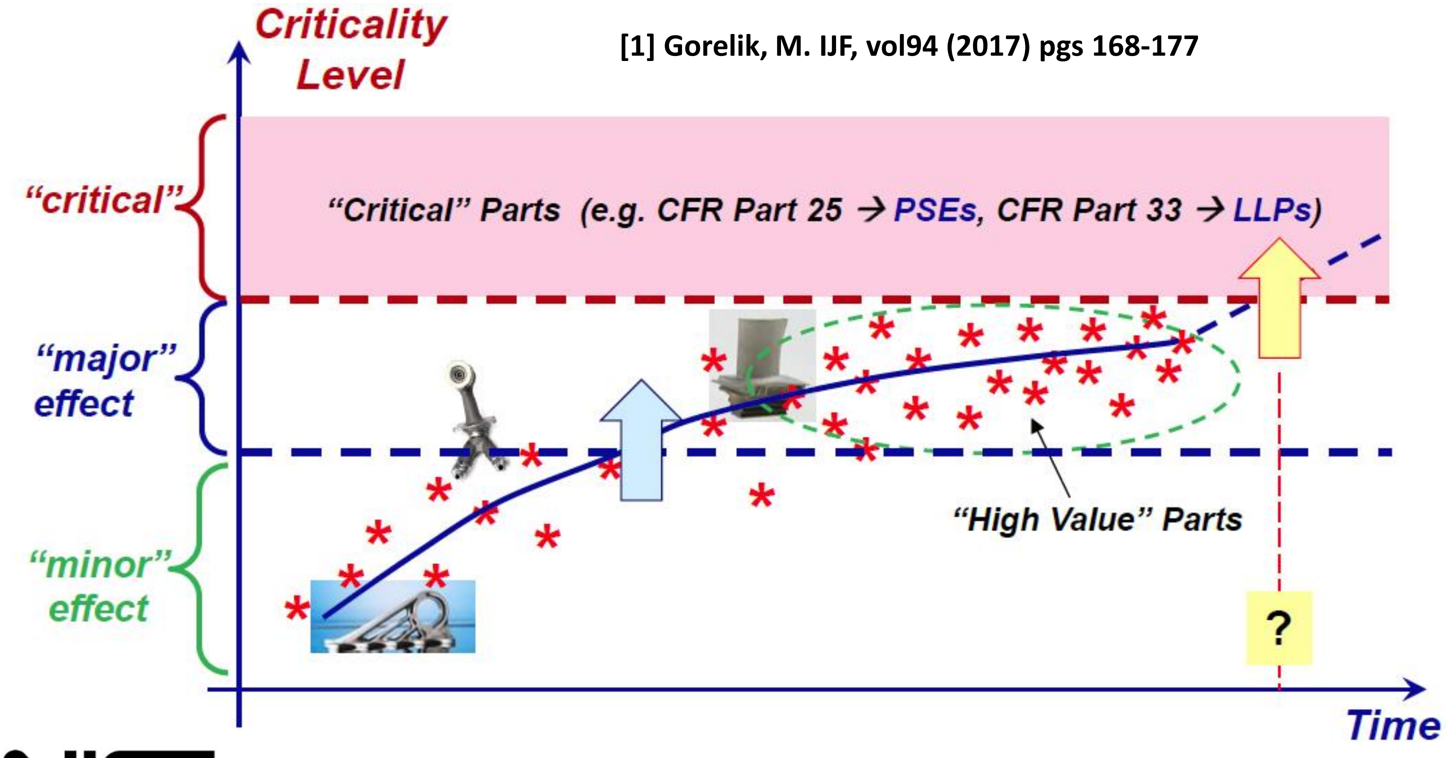
ASTM INTERNATIONAL

NIST

Motivation

- Confident use of metal additive manufacturing (AM) in critical applications is still lacking [1]
- NIST/ASTM workshop [2] identified one of the greatest needs
  - Deeper understanding of processing-structure-properties relationships focusing on fatigue and fracture behavior

[1] Gorelik, M. IJF, vol94 (2017) pgs 168-177



[2] Hrabe, N. et al. NIST Advanced Manufacturing Series 100-4. (2016)

NIST Advanced Manufacturing Series 100-4

Findings from the NIST/ASTM Workshop on Mechanical Behavior of Additive Manufacturing Components

Nikolas Hrabe
Nicholas Barbosa
Material Measurement Laboratory
National Institute of Standards and Technology
Boulder, CO

Steve Daniewicz
Mechanical Engineering Department
University of Alabama
Tuscaloosa, AL

Nima Shamsaei
Mechanical Engineering Department
Auburn University
Auburn, AL

This publication is available free of charge from:
https://doi.org/10.6028/NIST.AMS.100-4

ASTM INTERNATIONAL

NIST National Institute of Standards and Technology U.S. Department of Commerce

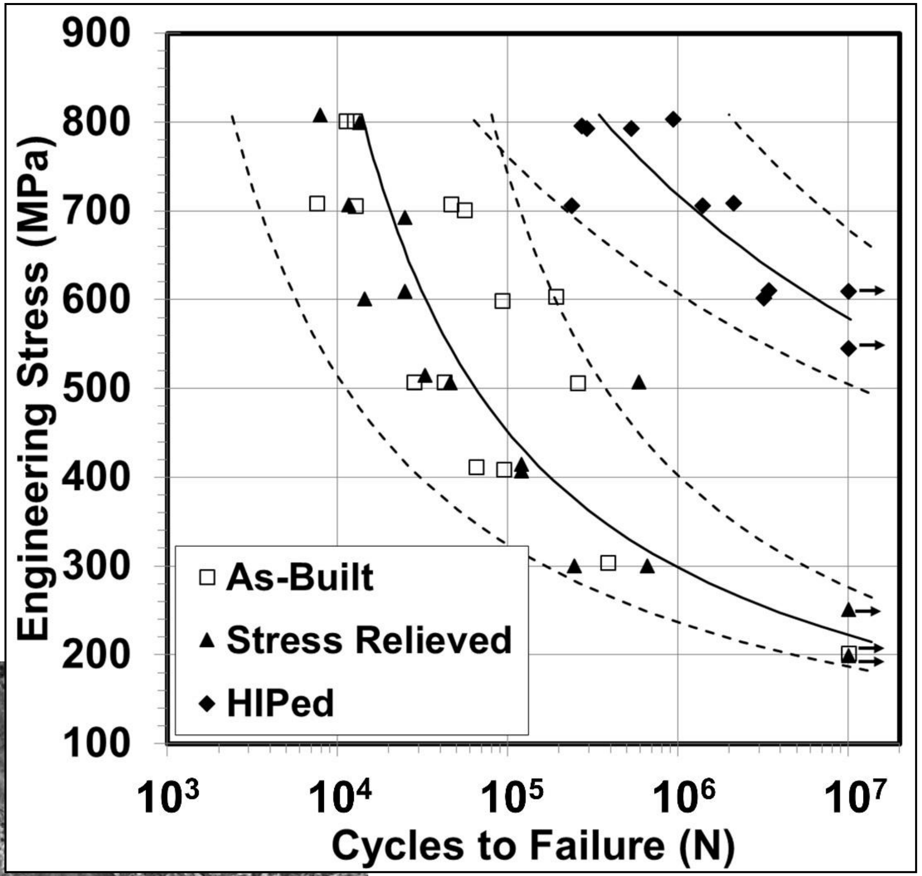
NIST

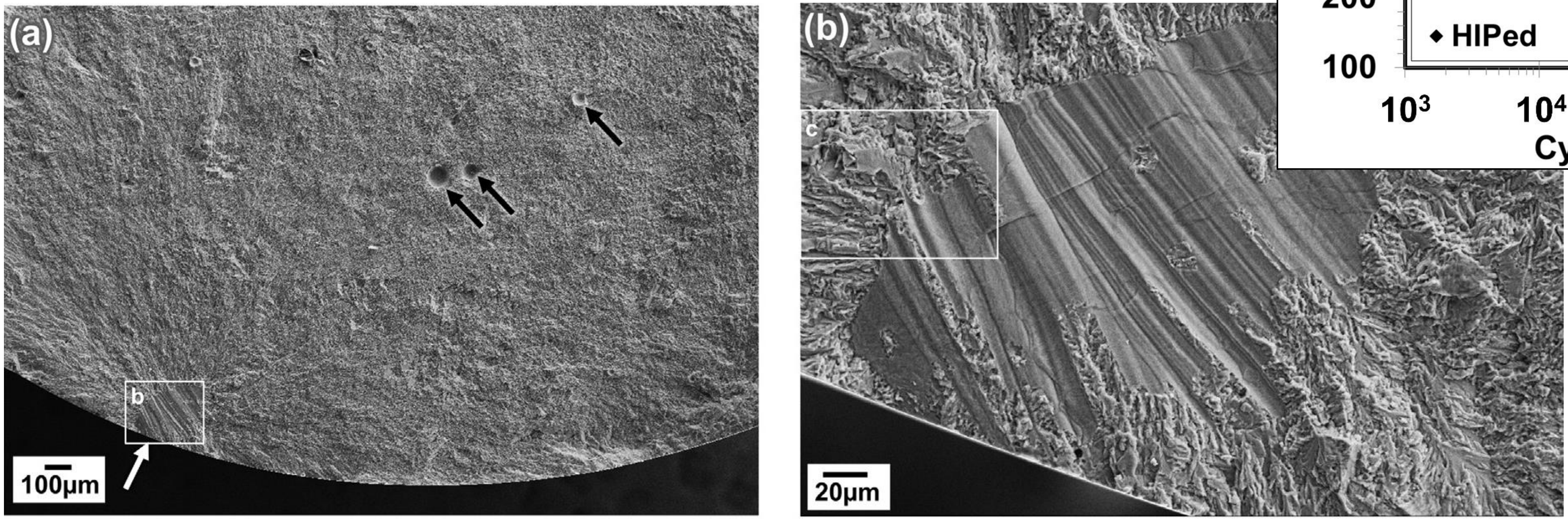
Outline

- Effect of internal defects (porosity)
- Effect of surface defects (surface roughness)
- Effect of microstructure
- Effect of chemistry
- Role of non-destructive evaluation (NDE)
- Role of qualification
- Role of standardization

Effect of internal defects (porosity)

- PBF-EB Ti-6Al-4V, axial HCF, R = 0.1
- Pores cause fatigue crack initiation and lower fatigue lifetime
- Hot isostatic pressing (HIP) closes internal pores and improves fatigue lifetime





NIST MEDICAL MODELING Arcam EBM a GE Additive company Hrabe, IJF, 2017. 94: p. 202-210

Effect of internal defects (porosity)

- **NIST-BAM Workshop** to discuss suitability of probabilistic damage tolerance techniques (e.g. Kitagawa-Takahashi) to predict fatigue performance
- Review paper resultant from workshop

Progress in Materials Science 121 (2021) 100786

Contents lists available at ScienceDirect

Progress in Materials Science

journal homepage: www.elsevier.com/locate/pmatsci

ELSEVIER

PROGRESS IN MATERIALS SCIENCE

Check for updates

Damage tolerant design of additively manufactured metallic components subjected to cyclic loading: State of the art and challenges

Uwe Zerbst[a,*], Giovanni Bruno[a,*], Jean-Yves Buffière[b], Thomas Wegener[c], Thomas Niendorf[c], Tao Wu[c], Xiang Zhang[d], Nikolai Kashaev[e], Giovanni Meneghetti[f], Nik Hrabe[g], Mauro Madia[a], Tiago Werner[a], Kai Hilgenberg[a], Martina Koukolíková[h], Radek Procházka[h], Jan Džugan[h], Benjamin Möller[i], Stefano Beretta[j], Alexander Evans[a], Rainer Wagener[i], Kai Schnabel[i]

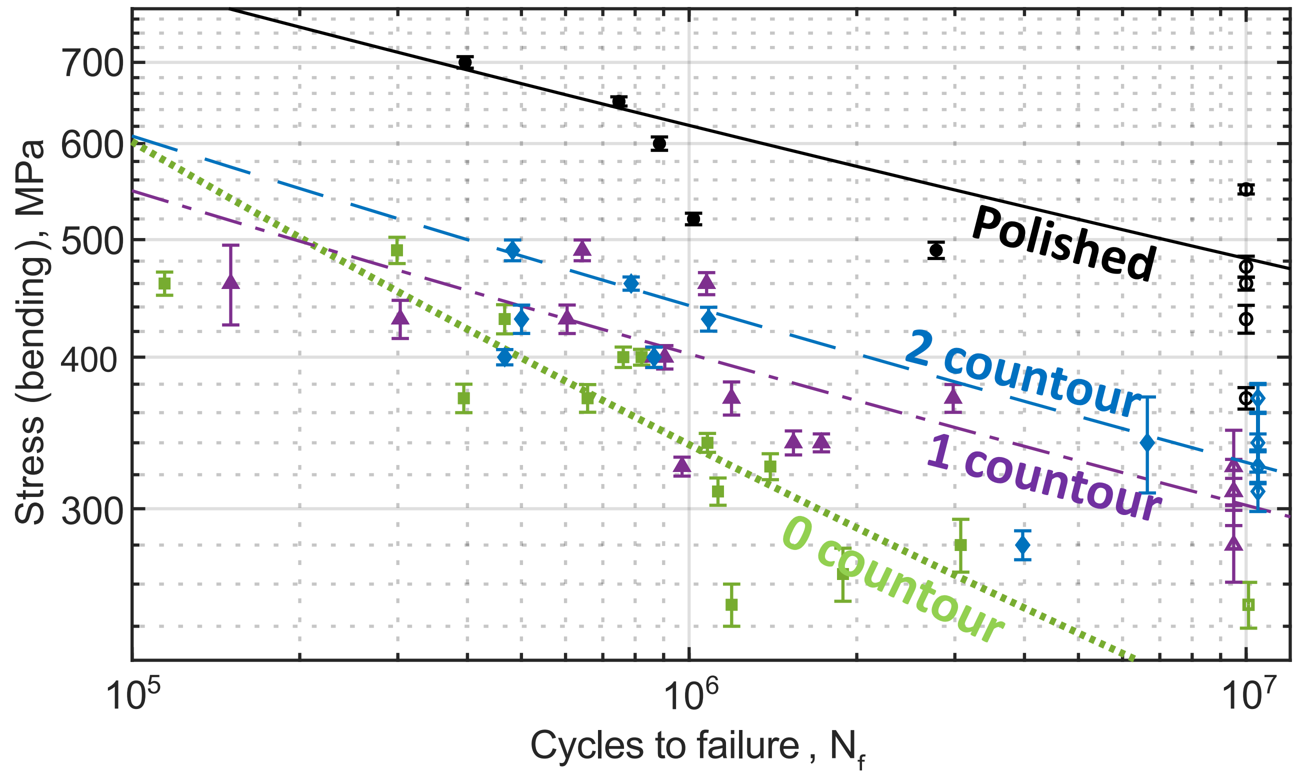
[a] Bundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87, D-12205 Berlin, Germany
[b] INSA-Lyon, F-69621 Villeurbanne, France
[c] University of Kassel, Institute of Materials Engineering - Metallic Materials, Mönchebergstraße 3, D-34125 Kassel, Germany
[d] Coventry University, Priory Street, CV1 5FB Coventry, UK
[e] Helmholtz-Zentrum Geesthacht, Max-Plank-Str. 1, D-21502 Geesthacht, Germany
[f] University of Padova, via Venezia, 1, I-35131 Padova, Italy
[g] National Institute of Standards and Technology (NIST), 325 Broadway, MS-647 Boulder, CO 80305, USA[1]
[h] COMTES FHT, Průmyslová 995, 334 41 Dobřany, Czech Republic
[i] Fraunhofer-Institut für Betriebsfestigkeit (LBF), Bartningstr. 47, D-64298 Darmstadt, Germany
[j] Politecnico di Milano, via La Masa 1, 20156 Milan, Italy

Zerbst (2021) Prog. Mat. Sci., 121, 100786

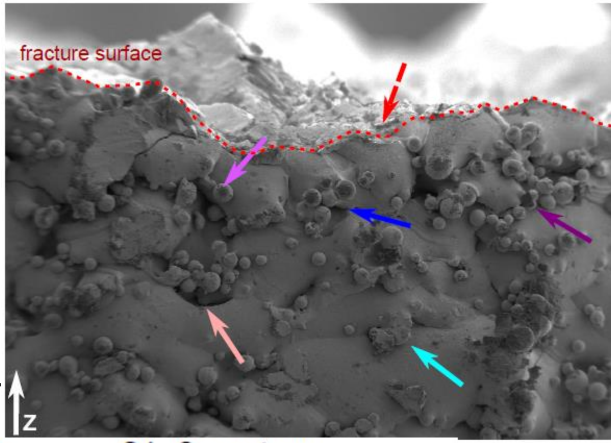
NIST BAM

Effect of surface defects (surface roughness)

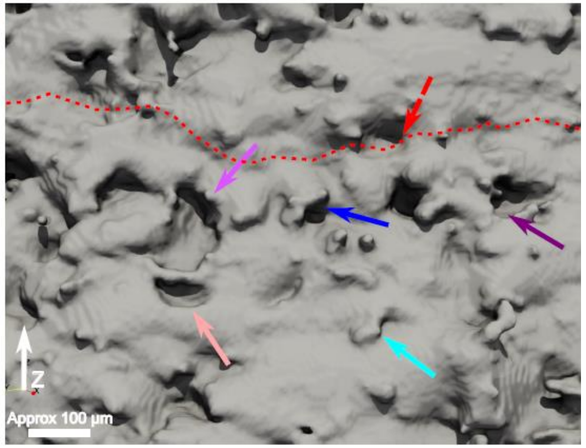
- PBF-L Inconel 718, rotating bending fatigue (RBF), R = -1
- In general, fatigue lifetime improves with reduced surface roughness
- Deepest valley does not always cause crack initiation (microstructure influence?)

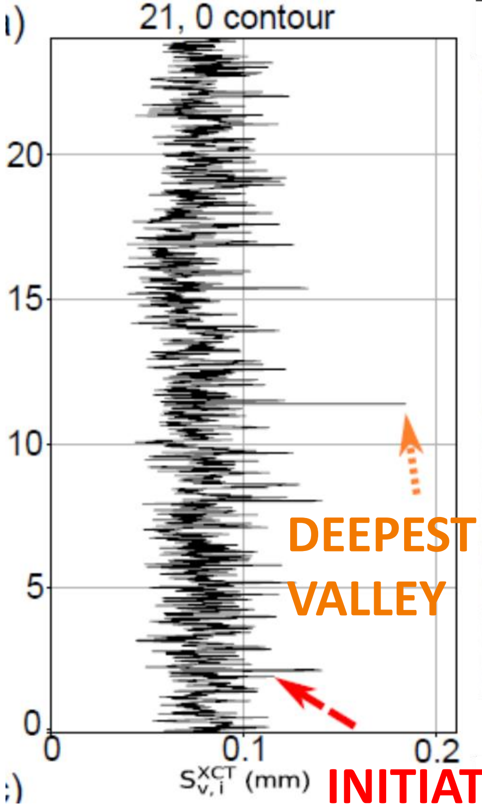


SEM

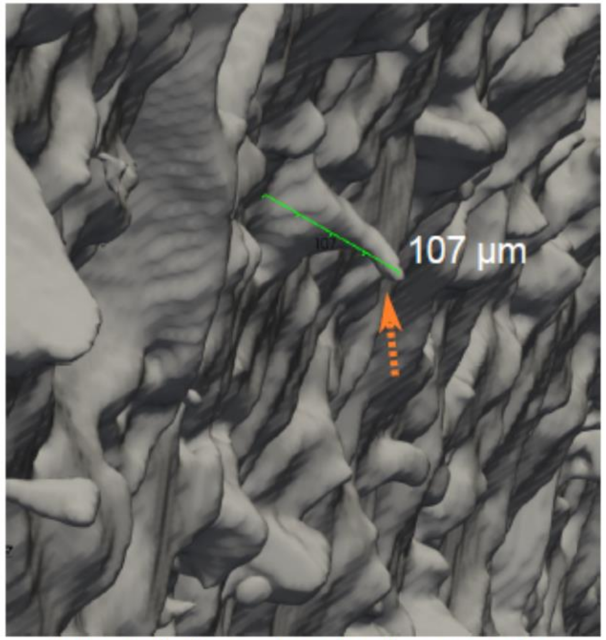


XCT





XCT



Inverted view, showing inner surface

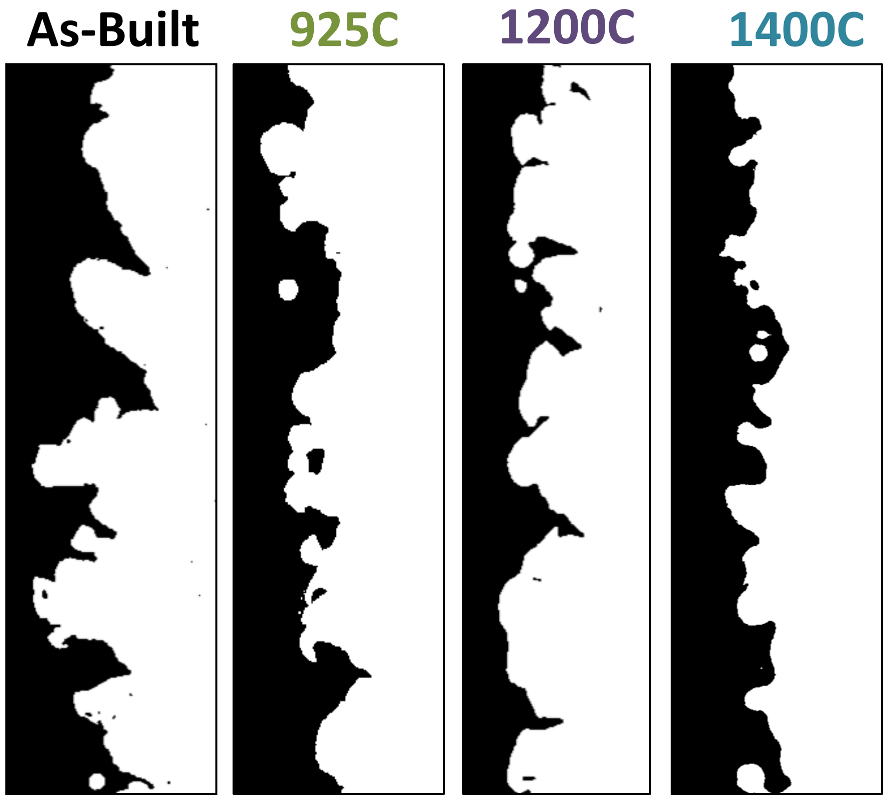
INITIATING SURFACE FEATURE

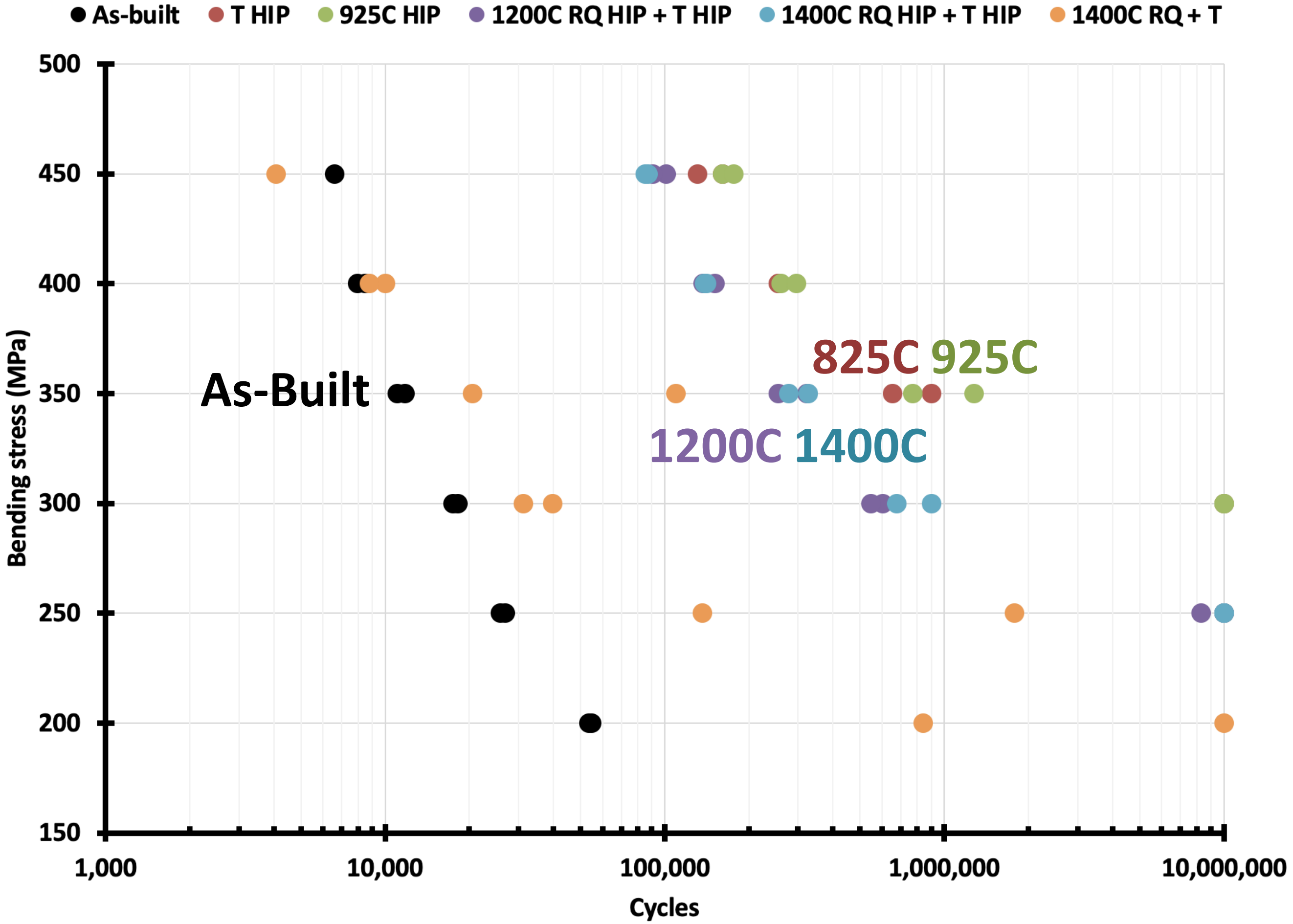
NIST Quintus TECHNOLOGIES SLM SOLUTIONS

Kafka, (2023). *IJF*, 176, 107872

Effect of surface defects (surface roughness)

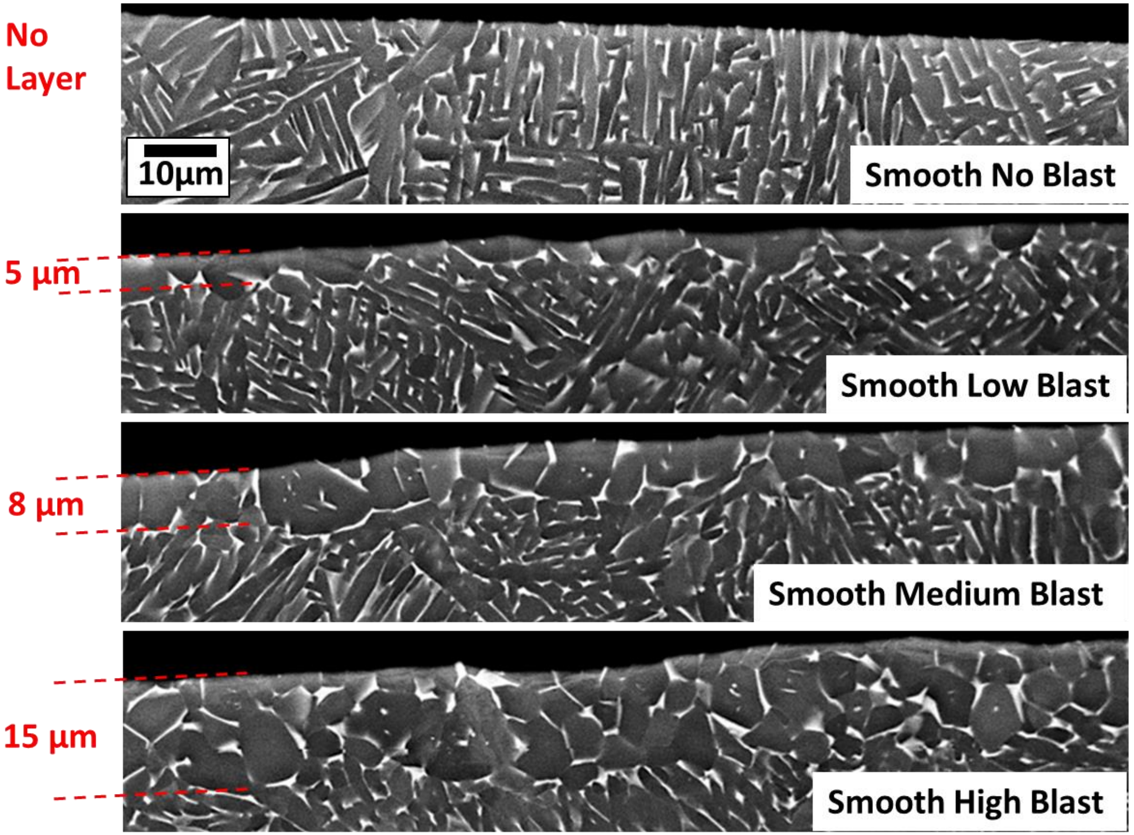
- PBF-L Ti-6Al-4V, RBF, R = -1
- Higher temperature HIP to reduce surface roughness and improve fatigue lifetime





Effect of surface defects (surface roughness)

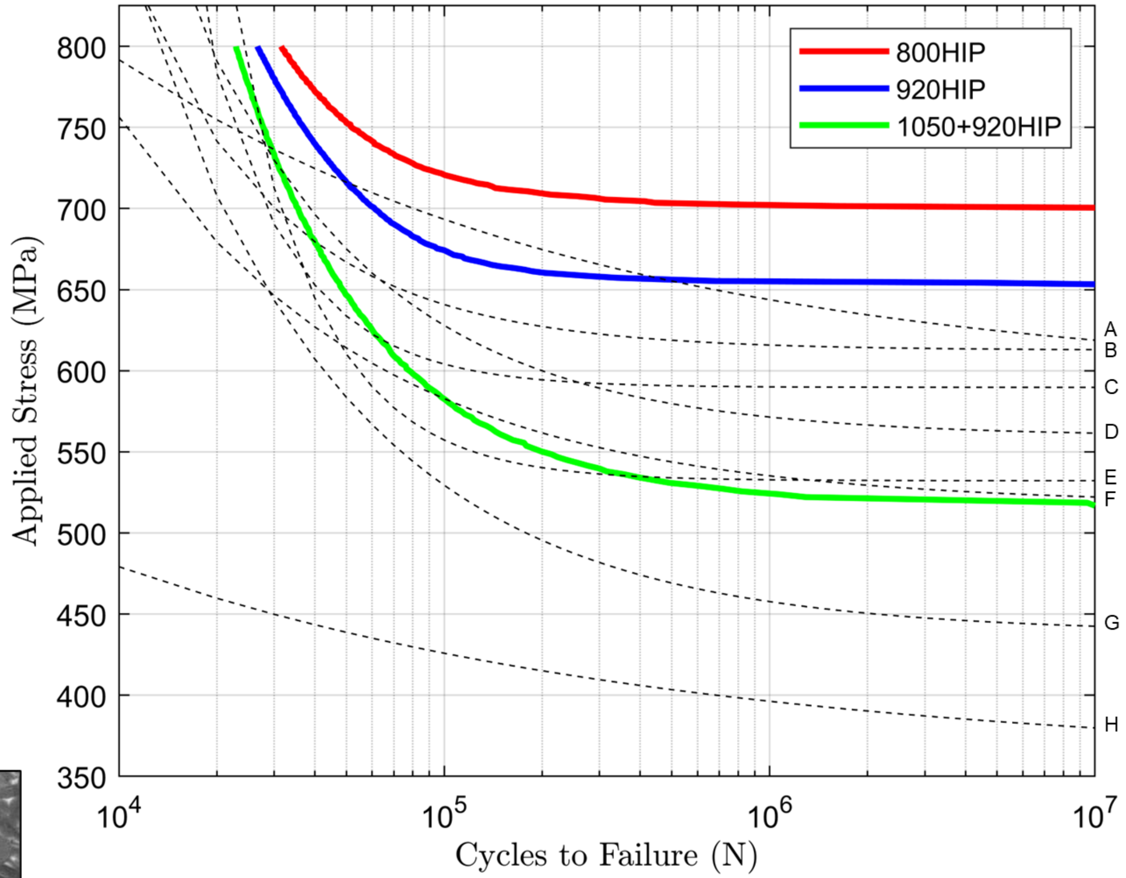
- PBF-EB Ti-6Al-4V, RBF, R = -1
- Controlled powder removal blasting intensity (working distance) to control depth of surface microstructure change (globular, equiaxed) and surface roughness, resulting in significant fatigue strength improvement (**10%**)

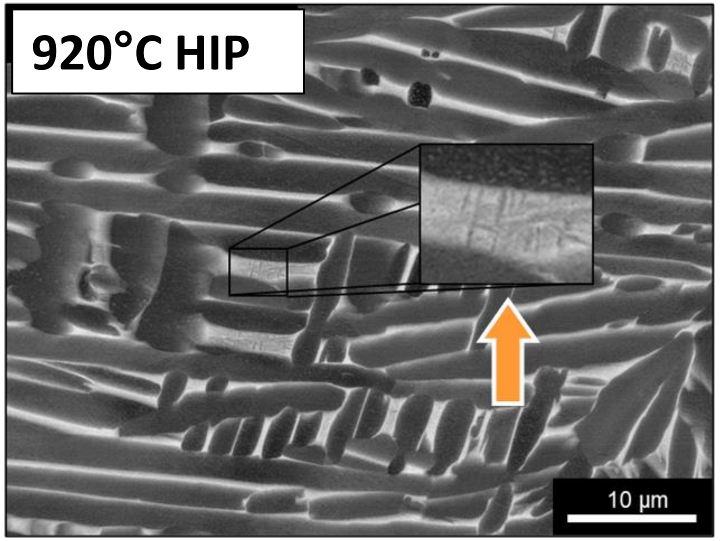


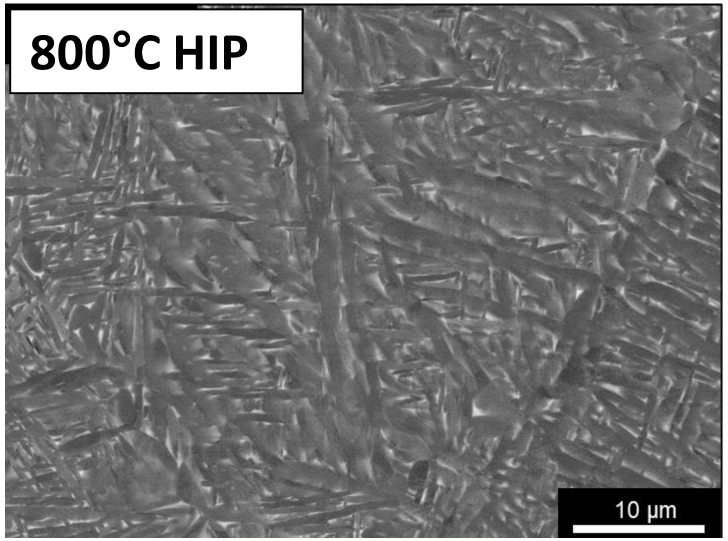
Derimow (2022) IJF, vol159, 106810

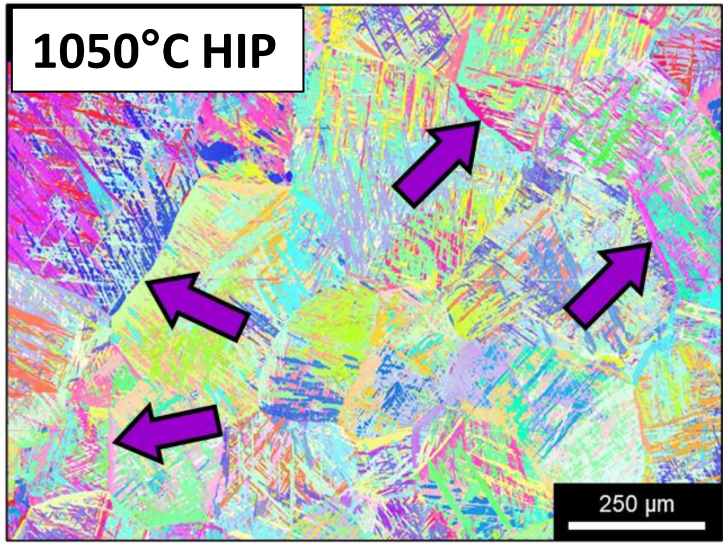
Effect of microstructure

- PBF-L Ti-6Al-4V, RBF, R = -1
- Fatigue behavior of novel HIP treatments
  - 800°C > 920°C due to finer α lath thickness
  - 920°C > literature due to **tertiary α** (100°C/min cooling rate)
  - 1050°C < 920°C due to **grain boundary α** (2000°C/min cooling rate)
- Contributed to AMS 7028 revision currently being balloted







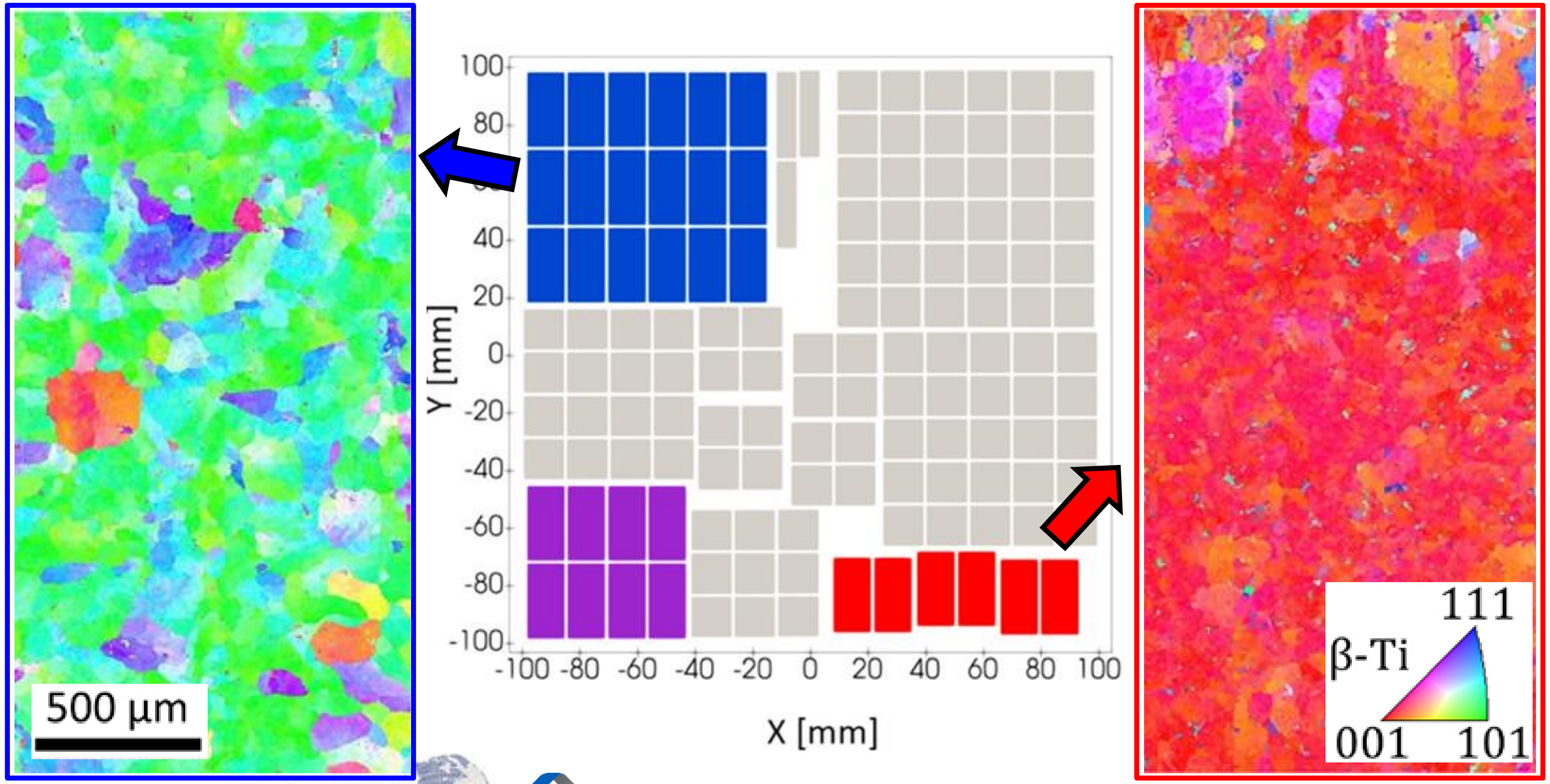


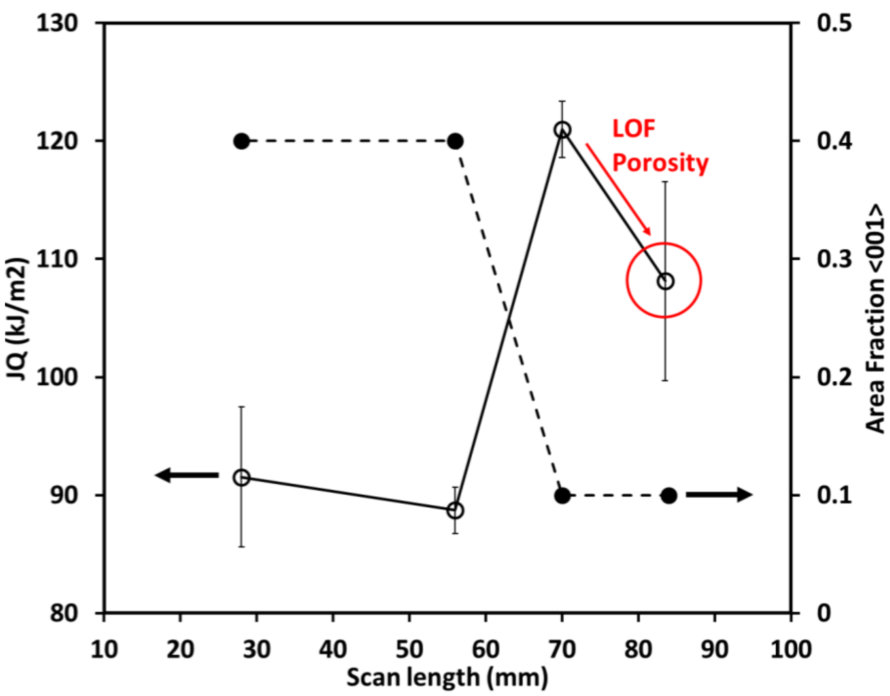
NIST Lynntech Quintus TECHNOLOGIES 3DSYSTEMS

Derimow (2024) *IJF*, in review

Effect of microstructure

- Discovered texture variation in PBF-EB Ti-6Al-4V due to small changes in build layout (scan length) leading to 10% change in YS and **40% change in fracture toughness**
- Developed processing (scan length control) and post-processing (super-β HIP to reset texture) mitigation strategies
- Contributed to ISO/ASTM 52911-3 PBF-EB design guide

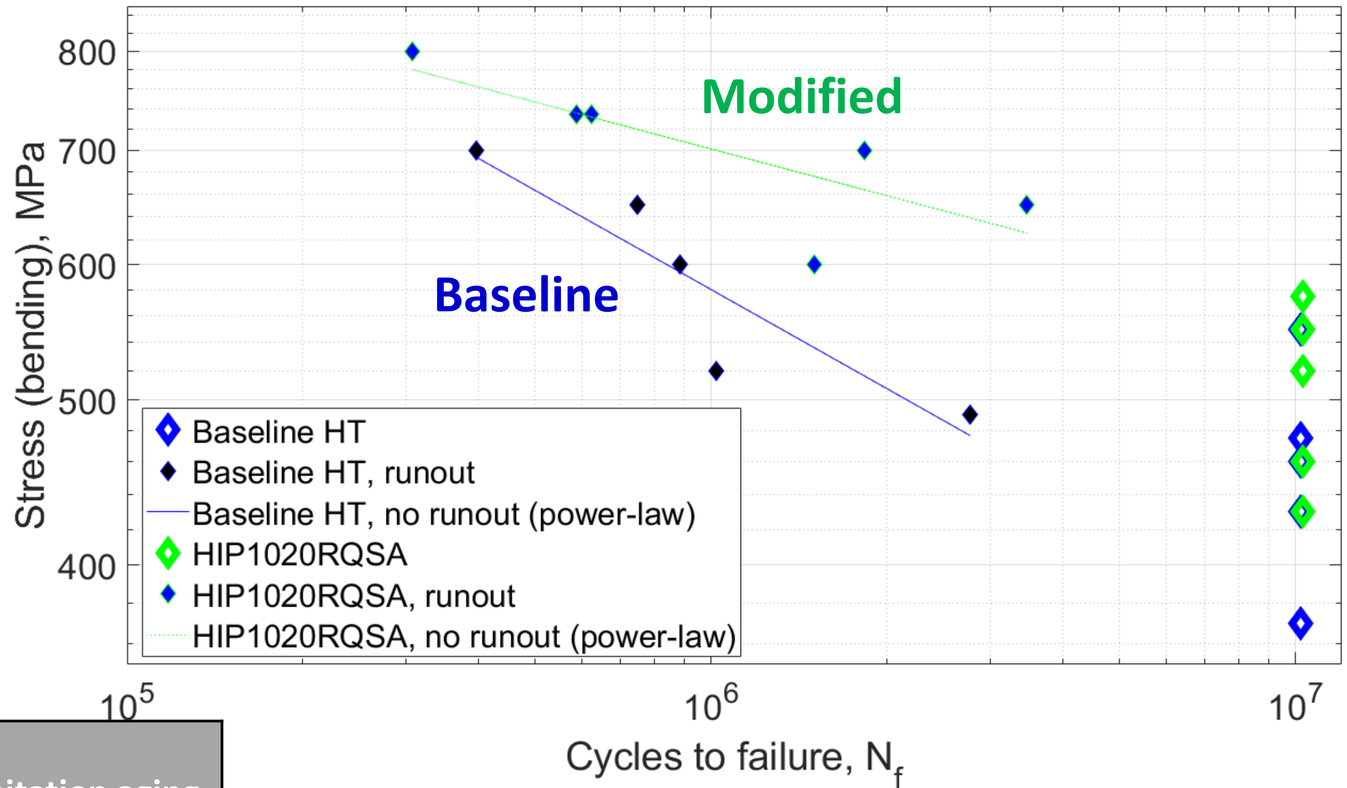




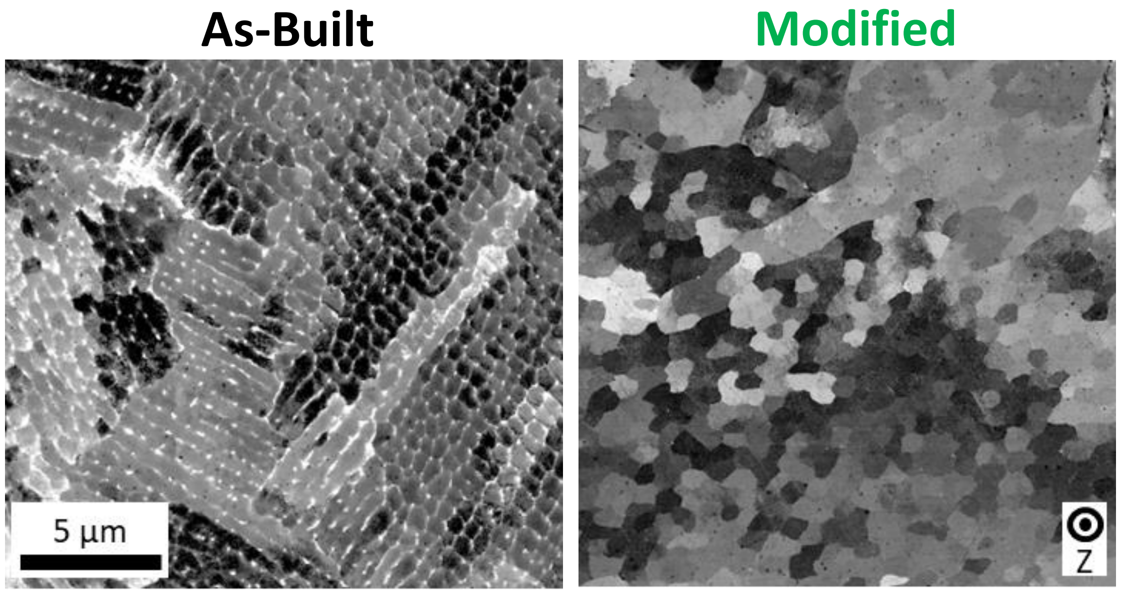
Schwalbach (2022) MSE A, 855, 143853

Effect of microstructure

- Modified HIP for PBF-L Inconel 718
- Reduced heat treatment time (42h→15h) and steps (5→2)
- Lower temperature HIP (1020°C) and combining 3 Baseline steps: stress relief, HIP, and solutionizing
  - Retain as-built sub-grain structure (no/partial recrystallization)
  - No δ, reduced Laves phases
  - Successful pore closure
- Single step aging still achieves desired γ′ and γ′′ precipitates



HIP-HT variant	Stress relief (furnace)	Seal porosity (HIP)	Solution (HIP or furnace)	Precipitation aging (furnace)
Baseline (AMS 2774)	1065 °C, 1.5 h, AC	1150 °C, 4 h, 100 MPa, FC	Vacuum furnace: 1066 °C, 1 h, quench to 95 °C, AC to RT	2-STEP AGING 718 °C, 8 h, FC to 621 °C, hold for additional 10 h
Modified (V4)	-	COMBINE 1020 °C, 0.5 h, 200 MPa, cool to RT at 2,000 °C /min	-	1-STEP AGING 700 °C, 12 h, WQ

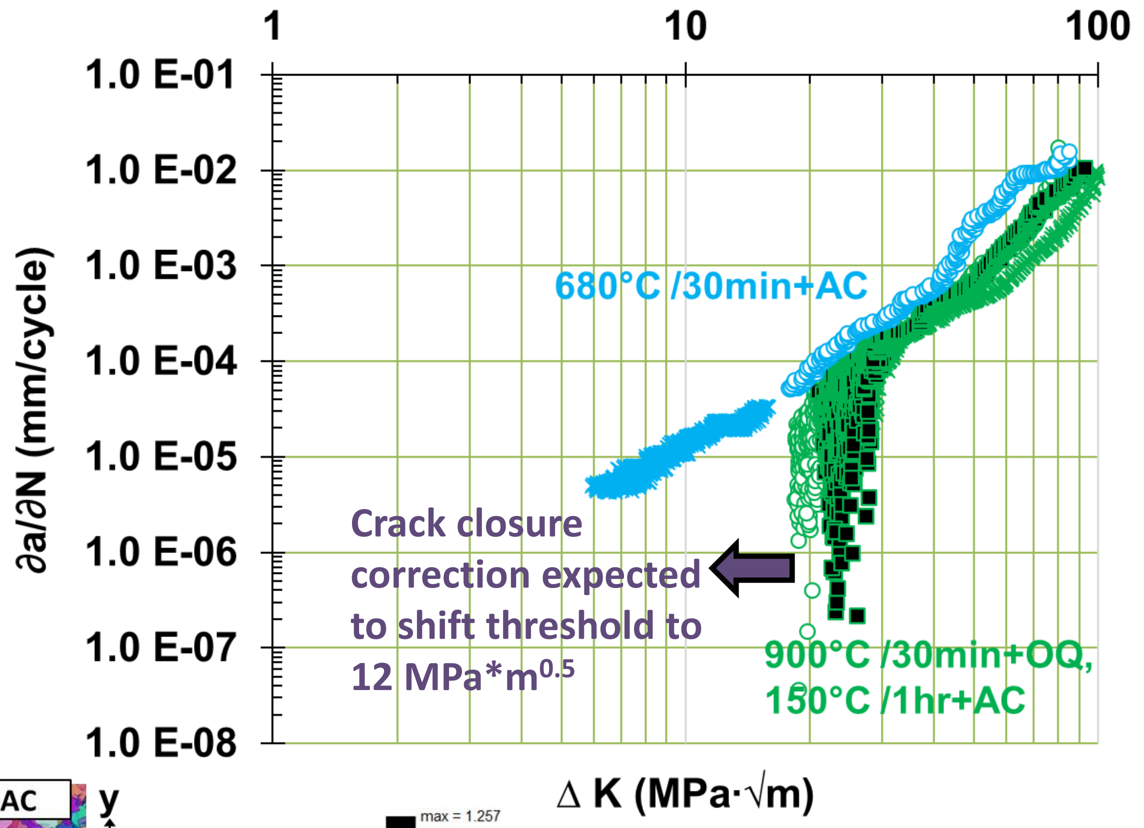


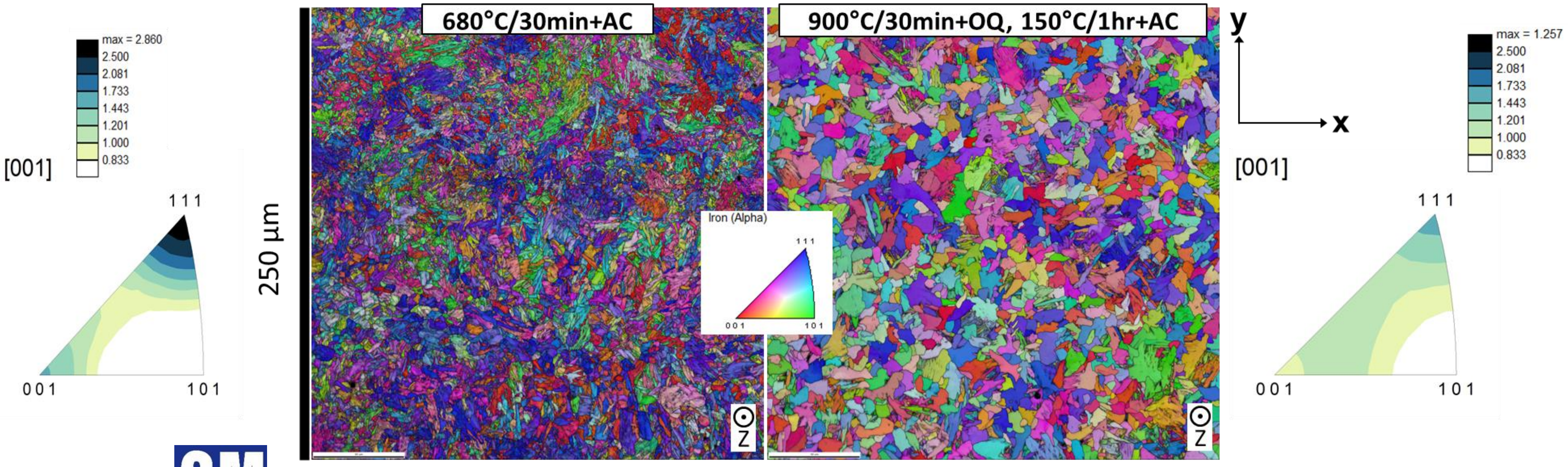
NIST Quintus TECHNOLOGIES SLM SOLUTIONS

Benzing, (2023). *J Mat Proc Tech*, 322, 118197

Effect of microstructure

- **Custom PBF-L automotive steel alloy**
  - Minimize alloy content (0.2C-0.8Mn-1Si wt%)
  - Quench and temper (Q&T) condition [900°C/30min+OQ, 150°C/1hr+AC]
  - Stress Relieved (SR) condition [680°C/30min+AC]
  - No HIP
  - Avoid δ-ferrite phase transformation
- **Q&T condition shows weaker texture and improved fatigue crack growth rate threshold behavior compared to SR condition**

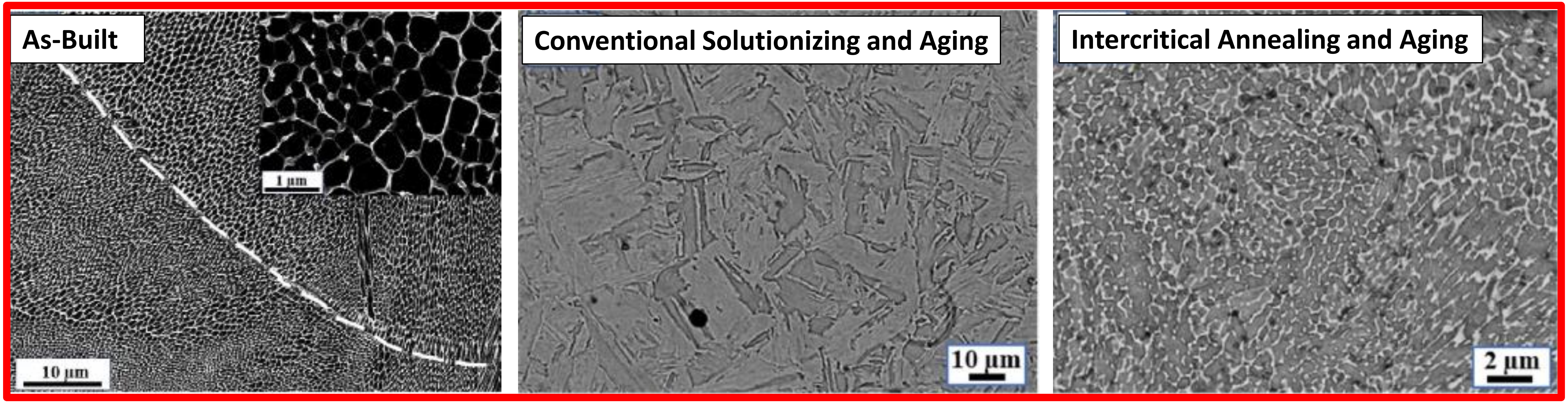




NIST GM eos

Effect of microstructure

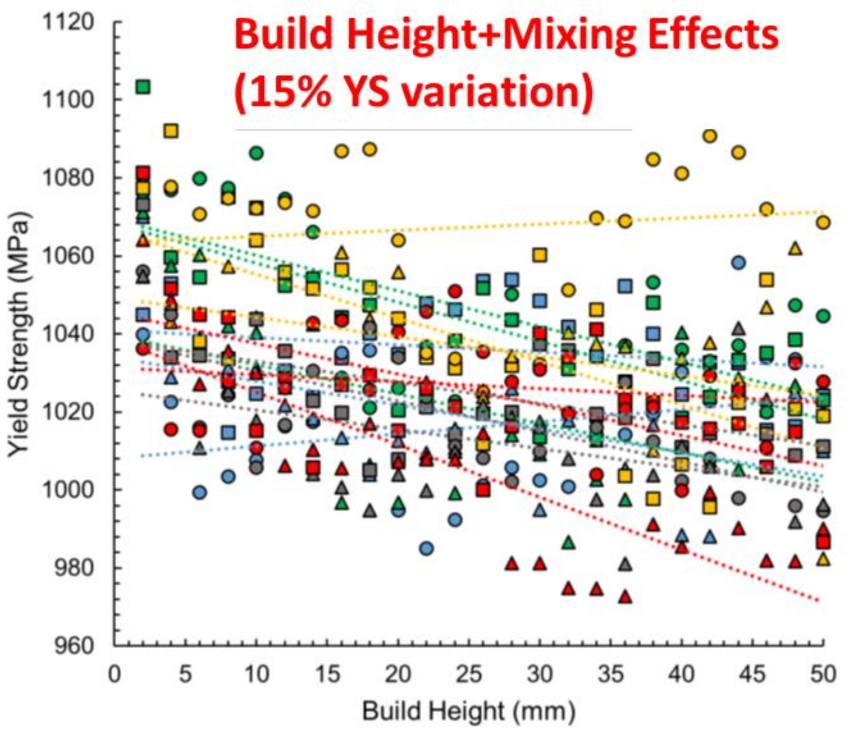
- **M789 cobalt-free maraging steel**
  - Removal of critical mineral leads to 20% strength reduction
- AM rapid heating/cooling promotes nickel partitioning to form metastable austenite (γ) with potential for transformation induced plasticity (TRIP) and improved strength
- Optimize processing and post-process heat treatment to maximize γ
  - Previously demonstrated for **cobalt-containing 18Ni-300 AM maraging steel**
- Mechanical testing at cryogenic (4°K liquid helium) temperatures, and in pressurized hydrogen

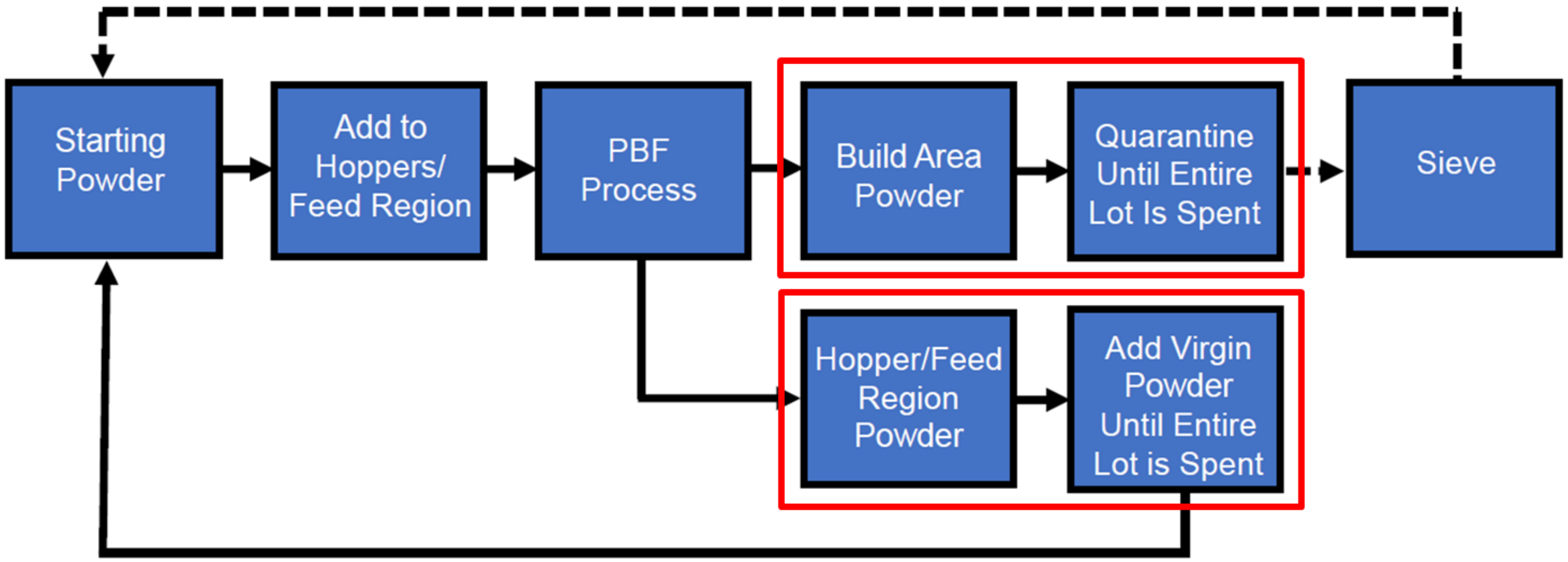


Paul et al. 2022, Mat. Sci. & Eng. A

Effect of chemistry

- Discovered significant chemistry and intra-build strength variation (**15% YS variation**) for PBF-EB Ti-6Al-4V due to current industrial powder reuse (i.e. mixing of powder with different oxygen content)
- Developed mitigation strategy (i.e. **powder quarantining**)
- Contributed to ASTM F3592 guide for PBF powder reuse





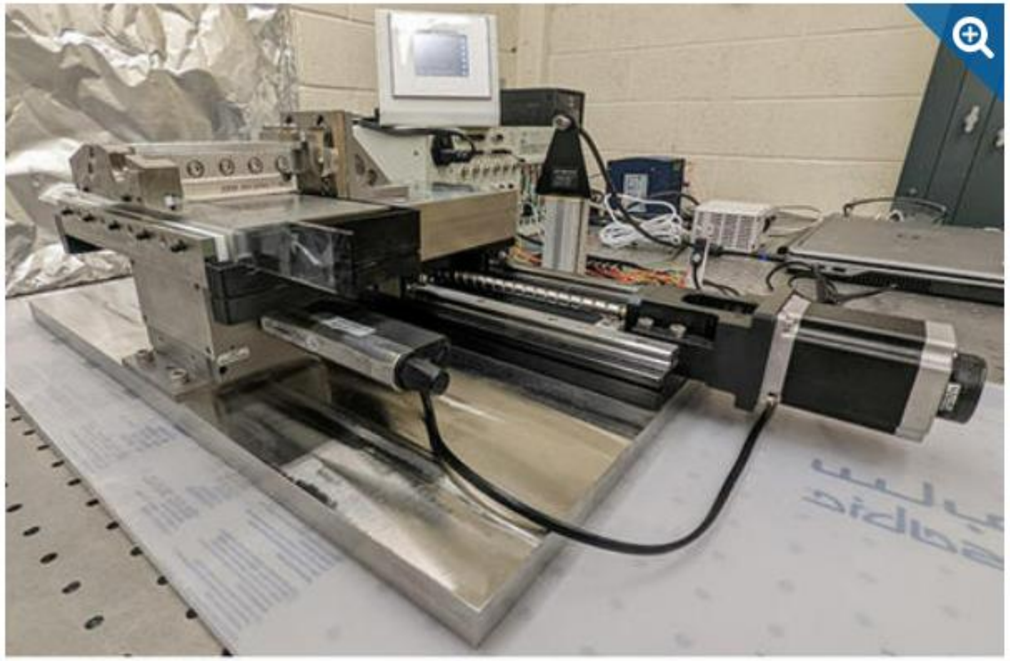
NIST Sandia National Laboratories UTEP AP&C A GE Additive Company

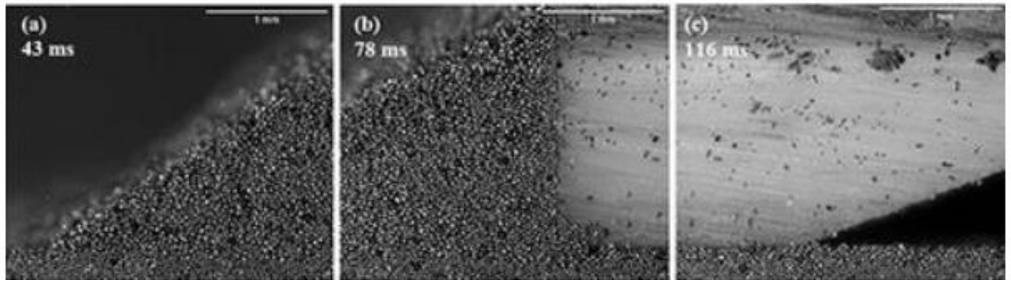
Derimow, MSE-A, 849, 143354 (2022)
Derimow, MSE-A, 848, 143353 (2022)

NIST Metal AM Powder Consortium (MAMP)

- MAMP brings together stakeholders to develop deeper understanding of AM metal powder characteristics, metrics, and measurement techniques, and how they affect various AM processes and resultant materials and components
- Current Challenges
  - Incomplete understanding of powder characteristics, metrics, measurement techniques, and their effect on process, material, and component performance
  - Lack of **prescriptive** standards for effective powder use, re-use, and measurement techniques
  - Inconsistent or undefined repeatability or reproducibility of various powder metrics
  - Lack of common protocols for powder measurement techniques across different equipment manufacturers

NIST Powder Spreading Testbed (PST)



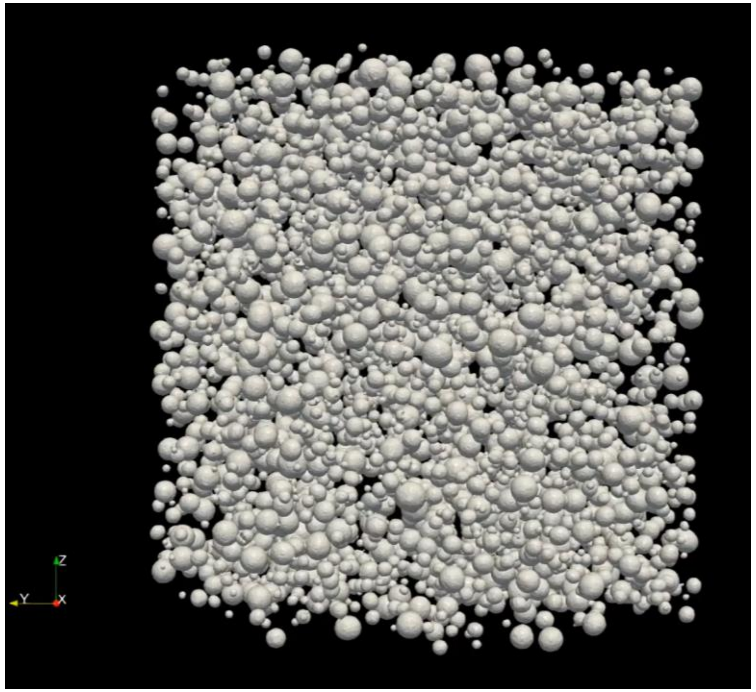


Timelapse Results from PST

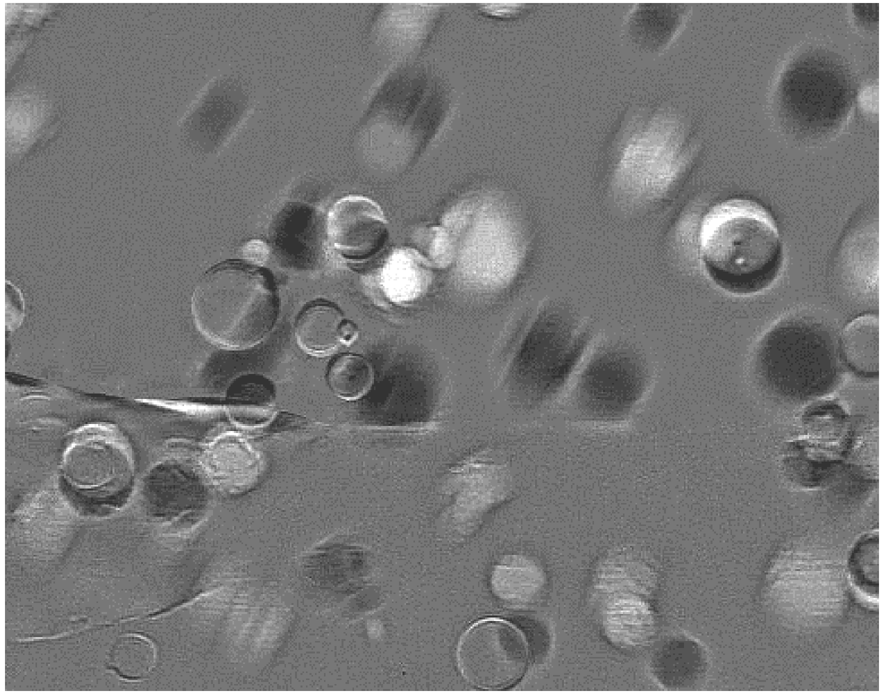
NASA NAVSEA NAVAL SEA SYSTEMS COMMAND Canada NRC·CNRC INMETRO ASTM INTERNATIONAL UNIVERSITY OF LOUISVILLE EXUM SCIENCE | SIMPLIFIED
NIST AP&C A GE Additive Company ELEMENTUM GRANUTOOLS™ GEMCO®

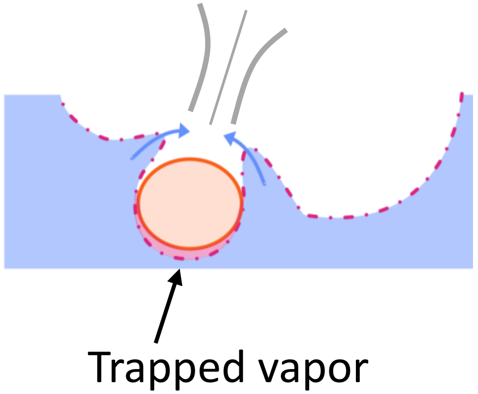
Role of non-destructive evaluation (NDE)

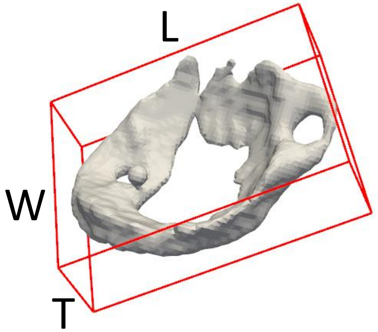
- Developed an (open source) Python library for X-ray CT data processing, called IMPPY3D
- Enables:
  - Dimensional & shape measurements of internal & external defects & features
  - 3D rendering visualization



Garboczi (2020) Add. Manuf., vol 31, 100965



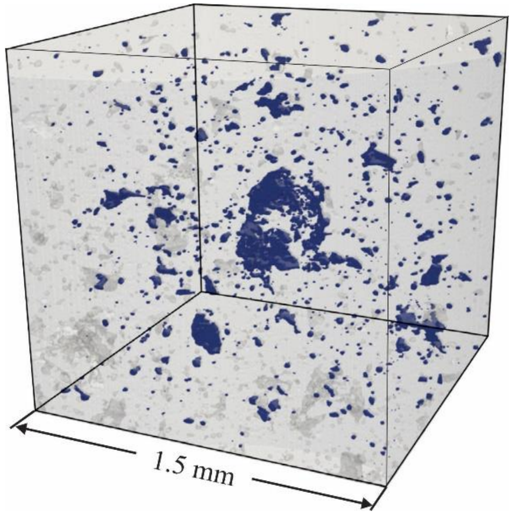




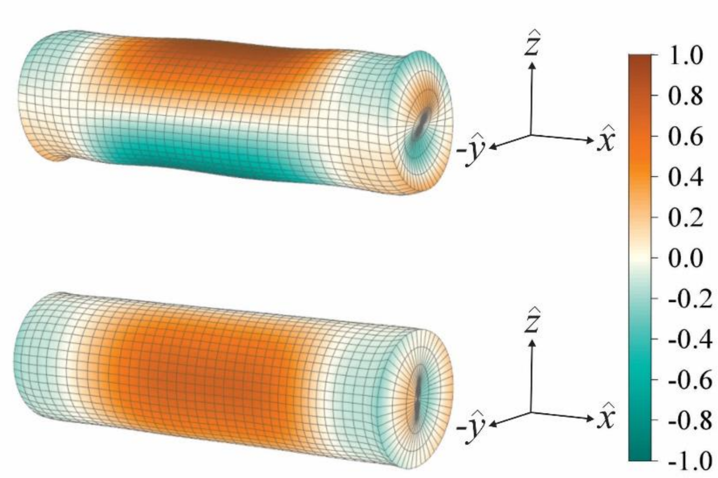
Webster (2023) PNAS Nexus, vol 2, issue 6

Role of non-destructive evaluation (NDE)

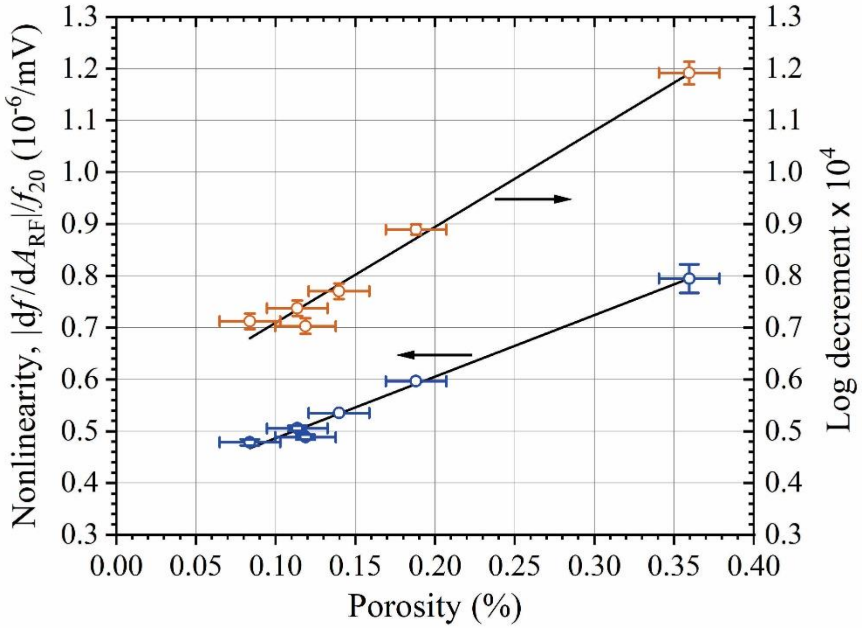
- Developed an innovative acoustic-resonance technique that is sensitive to variations in porosity in AM metals at industrially relevant levels.
- This technique offers a unique set of advantages for industrial post-process AM part inspection, including speed, high precision, low cost, and applicability to complex geometries.



Xray-CT image of pores in AM Al with non-optimal build parameters



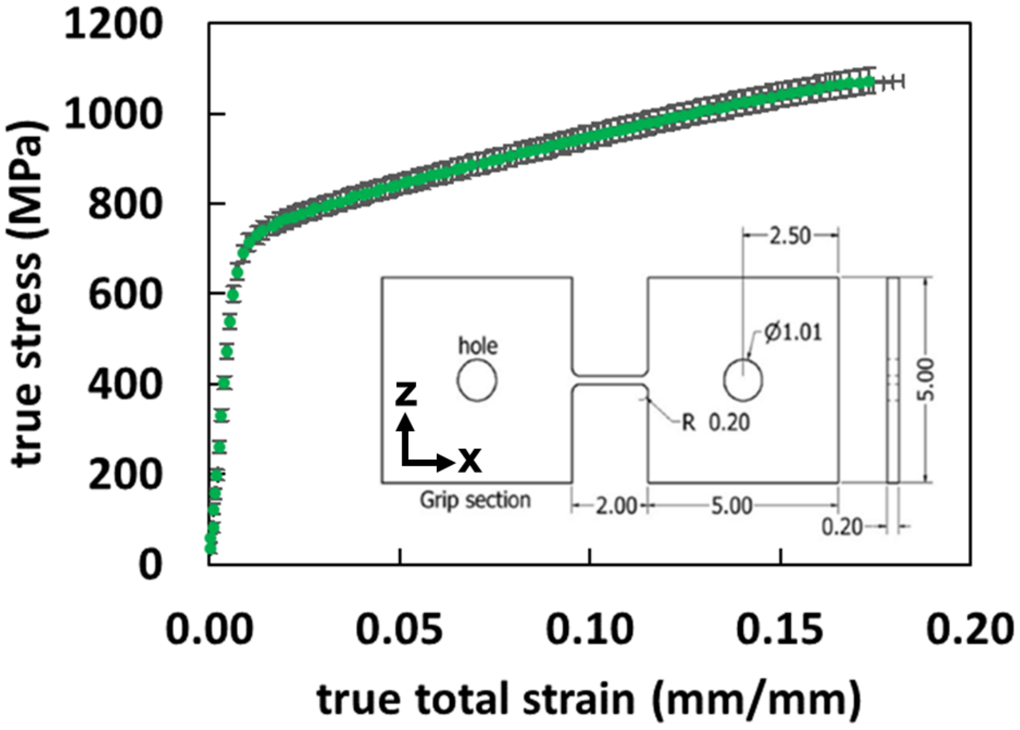
Vibrational displacement patterns of resonant modes near 670 kHz in AM Al cylinders.

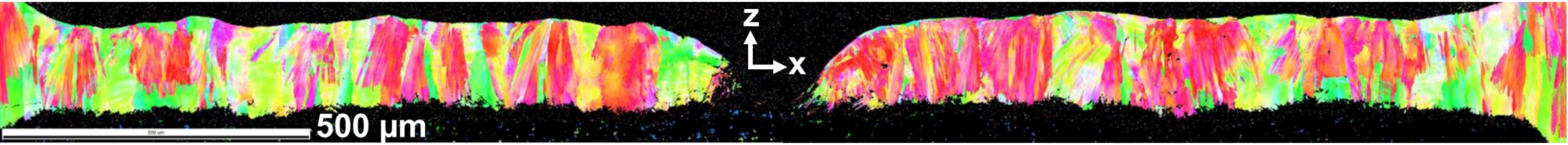


NIST ELEMENTUM Colorado State University Johnson (2023) NDT&E Intl. 135, 102801

Role of qualification

- **"Adoption is limited by qualification"**
  - Quote from 2024 NASEM Workshop on Statistical and Data-Driven Methods for AM
- **Can computational techniques enable rapid qualification?**
  - NASA/FAA/NIST Computational Materials for Qualification and Certification (CM4QC)
  - NIST AM Bench - experimentally supports computational technique development for AM





Kafka (2023) IMMI, 12, 196-209

NIST

Role of standardization

- Documentary standards development requires volunteer experts
  - Many standards development organizations (SDOs) have AM committees/activities
  - Examples: ASTM+ISO, SAE, AWS
- America Makes and ANSI Additive Manufacturing Standardization Collaborative (AMSC)
  - Standardization Roadmap for AM

Opportunities at NIST

- **Undergraduate Students**
  - NIST Summer Undergraduate Research Fellowship (SURF), https://www.nist.gov/surf
- **Graduate Students**
  - Email me to discuss collaboration ideas
  - Guest Researcher status at NIST is possible
- **Postdoctoral**
  - NRC Research Associateship Program (RAP), https://sites.nationalacademies.org/PGA/RAP/index.htm
  - 2yr postdoc with competitive pay (institutions other than NIST available)
  - 10pg proposal developed with potential advisor is main component of application
  - 2 application deadlines: Feb 1 (start date range July-December), Aug 1 (start date range January-June)

Project Website, FREE Publications

QUESTIONS: nik.hrabe@nist.gov