Factors Affecting Qualification/Certification:

Evaluating the Criticality of Inherent Anomalies/Defects on the Fatigue Behavior of LB-PBF Ti-6Al-4V Gr. 5

National Center for Additive Manufacturing Excellence (NCAME)

AUBURN UNIVERSITY

JAMS Technical Review
August 26, 2021

Federal Aviation Administration

JAMS
Joint Centers of Excellence for Advanced Materials

A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

CECAM
center of excellence for composites and advanced materials

Introduction

- **Project Title:** Factors Affecting Qualification/Certification - Evaluating the Criticality of Inherent Anomalies/Defects on the Fatigue Behavior of Additively Manufactured Materials
- **Principal Investigator:** Nima Shamsaei

  (See next slide for complete list of participants.)
- **FAA Technical Monitor:** Kevin Stonaker
- **Source of matching contribution:** Faculty time and use of equipment

Project team

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NCAME Project Team
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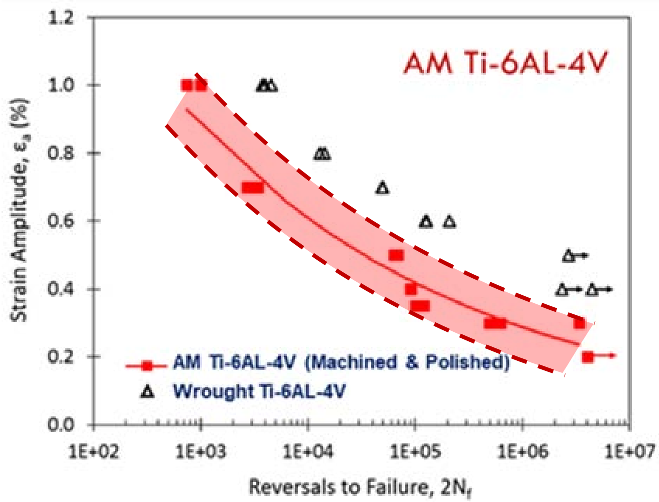
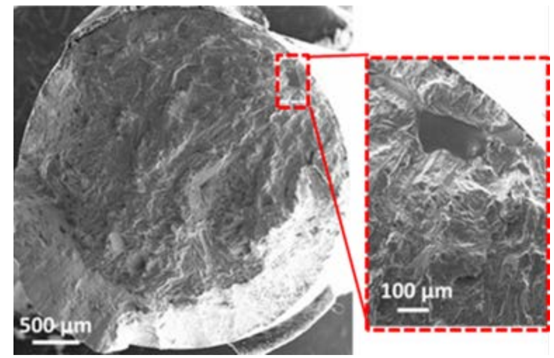
Aleksandr Vinel (Indus. Sys. Engr.)
Jia Liu (Indus. Sys. Engr.)

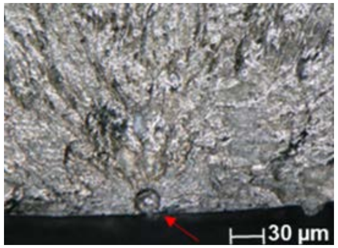
Background



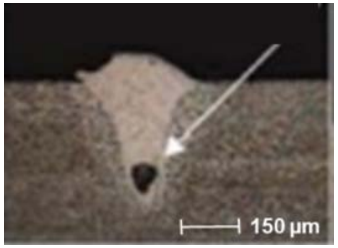


AM defects:

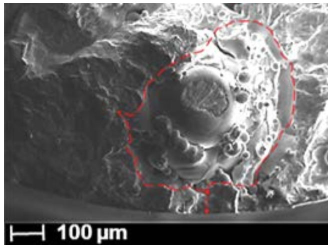
- Significantly reduce and introduce uncertainty to fatigue performance
- Pose great challenge for qualification/certification of AM parts



Gas-entrapped pores (GEPs)



Keyholes (KHs)

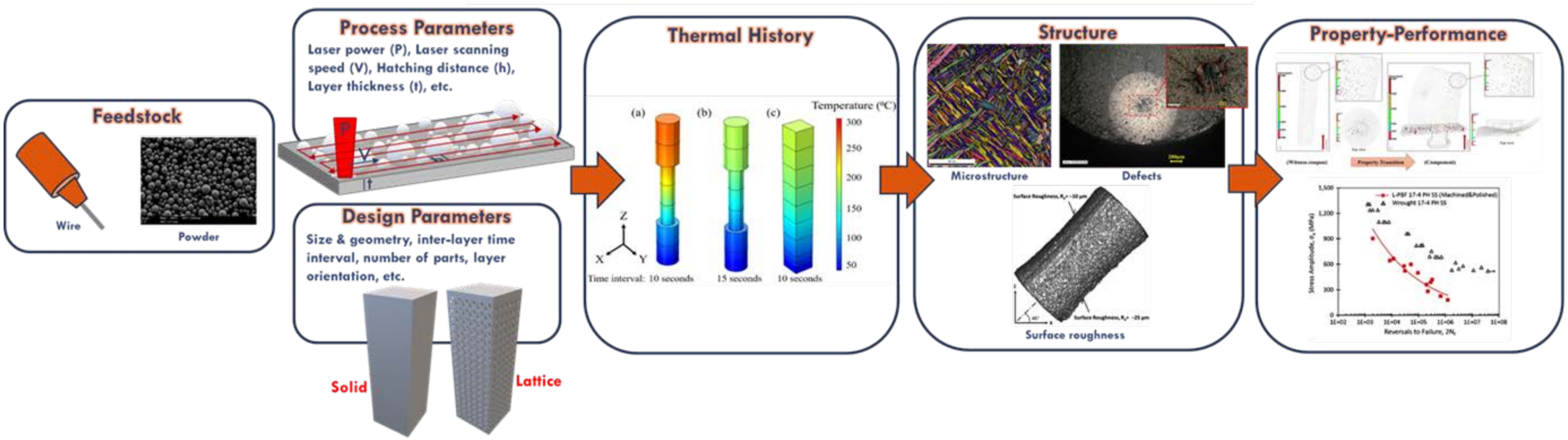


Lack-of-fusions (LoFs)

Shrestha et al., Addit. Manuf., 28 (2019) 23-38. // Nezhadfar et al., Int. J. Fatigue, 124 (2019) 188-204. // Gong et al., SFF Symposium, (2014) 256-267.

Challenge

- Significant data is needed to statically quantify the mechanical behavior of materials and generate materials allowables in support of qualification
- AM has virtually infinite combinations of feedstock, process, and design parameters, which influence micro-/defect-structure
- Knowledge on defect-criticality may be beneficial in decoupling the fatigue properties from the explicit consideration of process/design parameters – if defect information is known



Objective & approach

Objective: To quantify the detrimental effect of volumetric defects on mechanical properties of LB-PBF Ti-6Al-4V Gr. 5

Approach:

I. Explore process windows by varying laser power and scan speed

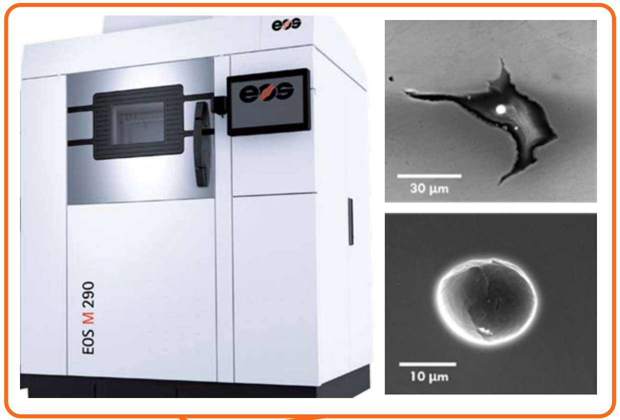
II. Determine the criticality of volumetric defects on mechanical performance using specimens seeded with different defect types

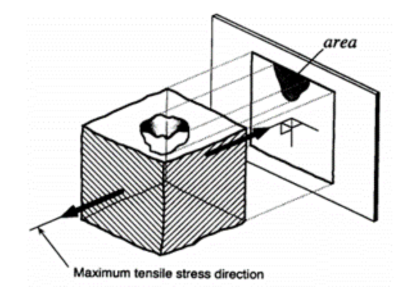
III. Calculate the fatigue performance debit associated with defects

IV. Evaluate the effectiveness of X-ray CT at two resolutions in capturing the fatigue critical defects *(specimens will be provided to external collaborators for examining other NDE techniques)*

V. Take advantage of machine learning and simulations wherever applicable

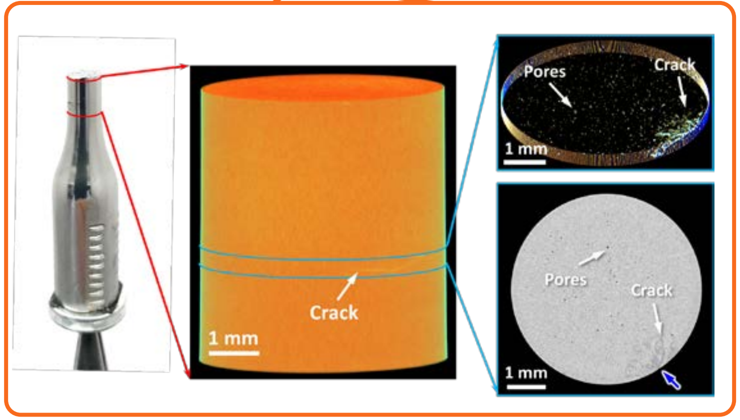
Overall scope

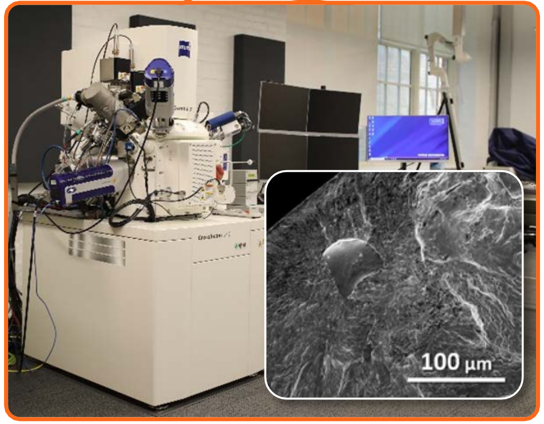




$$\Delta K_{eff} = Y\,\Delta\sigma_{eff}\sqrt{\pi\sqrt{area}}$$

- Defect seeding (Fabrication)
- Defect detection (NDI)
- Mechanical testing
- Fractography
- Defect criticality





Deliverables

- Reliable classification criteria for various defect types
- Definition of process window using laser power and scan speed according to a suitable printed material quality metric
- Quantitative knowledge on the criticality of volumetric defects on mechanical properties
- Data on the effectiveness of X-ray CT at two different resolutions in capturing the fatigue critical defects

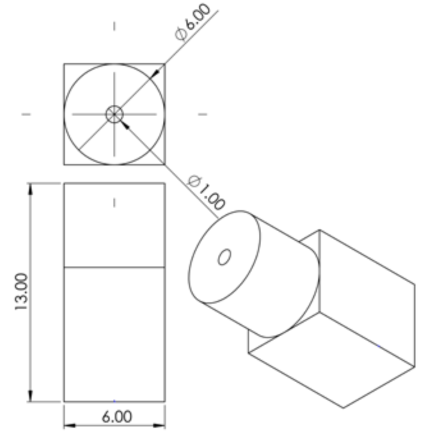
Project tasks

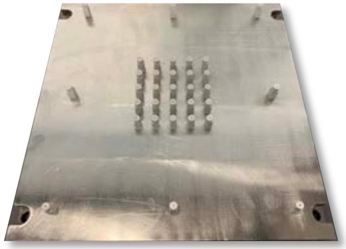
- **TASK 1: Literature Review & Design of Experiment**
  - Collect information from literature, equipment OEMs, FAA AM team, and steering committee and finalize the DoE
  - Generate the process window for LB-PBF Ti-6Al-4V Gr. 5
- **TASK 2: Fabrication**
  - Fabricate all specimens with different types/levels of defects
- **TASK 3: Non-destructive Inspections**
  - Perform multiple non-destructive inspections and compare the results
- **TASK 4: Mechanical Testing & Fractography**
  - Conduct tensile, fatigue, and high strain rate fracture tests and perform fractography
- **TASK 5: Defect Criticality Analysis**
  - Utilize machine learning to identify the most critical features of defects
- **TASK 6: Establishing Defect Structure – Fatigue Relationship**
  - Employ, calibrate, and validate a defect sensitive fatigue model to capture the effects of defects on fatigue behavior
- **TASK 7: Final Report**

DoE to classify volumetric defects and define process window

Defects and process window

- Classify defects and define process window for LB-PBF Ti-6Al-4V Gr. 5
    - Fabricate XCT witness coupons
    - Individual parameter adjustments:
        - Scanning speed: up to +/- 30% of the recommended 1300 mm/s at 10% interval
        - Laser power: up to +/- 30% of the recommended 280 W at 10% interval
    - Geometry designed for easy XCT scan (Scanning only central cores to exclude skin-related defects)
    - Combined high/low resolution scans to classify defects (GEPs, KHs, vs. LoFs) and identify suitable parameters to induce each type





All coupons are placed in the center of build plate

EOS recommended process parameters for LB-PBF Ti-6Al-4V Gr. 5

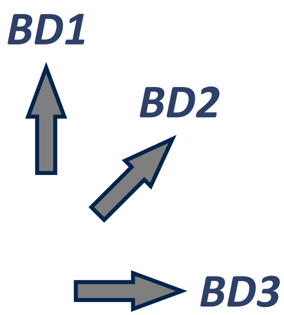
Laser power	*Scan speed*	*Hatch spacing*	*Layer thickness*	*Layer rotation angle*
280 W	*1300 mm/s*	*120 µm*	*40 µm*	*67 °*

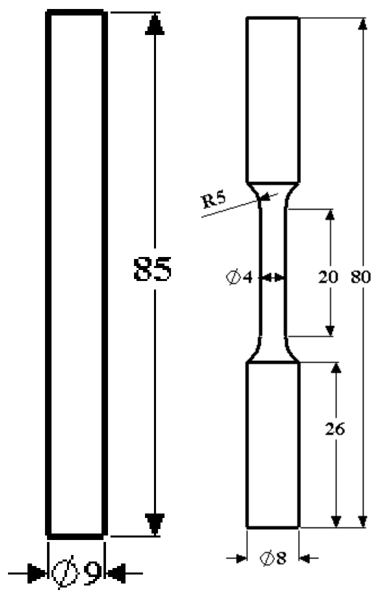
DoE to determine the criticality of defects on mechanical performance

Fabrication (tensile)

- Fabrication of specimens with different types of defects

Tensile Specimens (ASTM E08):





Vertical: 56
Diagonal: 16
Horizontal: 16

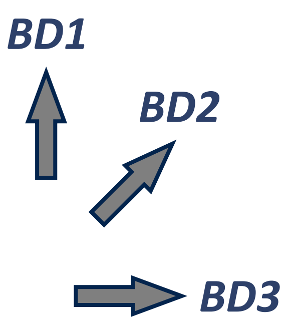
104 spec. total

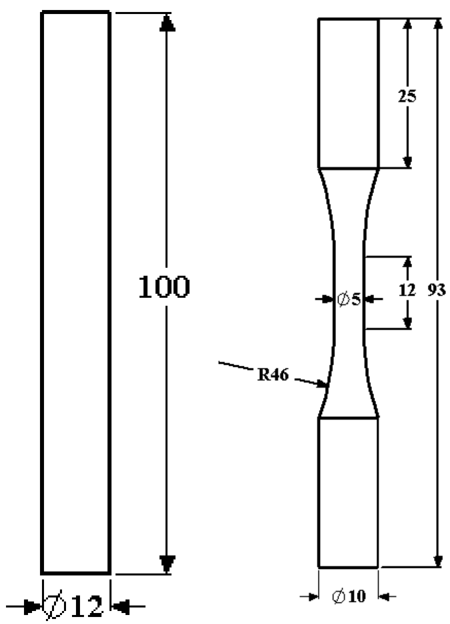
- Defect types:
  - Vertical specimens: KHs (2 sets), LoFs (2 sets), GEPs (1 set)
  - Horizontal specimens: LoFs (2 sets)
  - Diagonal specimens: LoFs (2 sets)
- All specimens to be stress relieved
- All dimensions are in mm

Fabrication (axial fatigue)

- Fabrication of specimens with different types of defects

Axial Fatigue Specimens (ASTM E466):





Vertical: 105
Diagonal: 30
Horizontal: 30

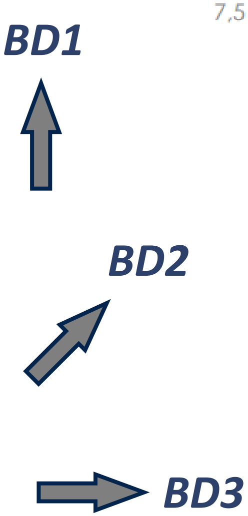
165 spec. total

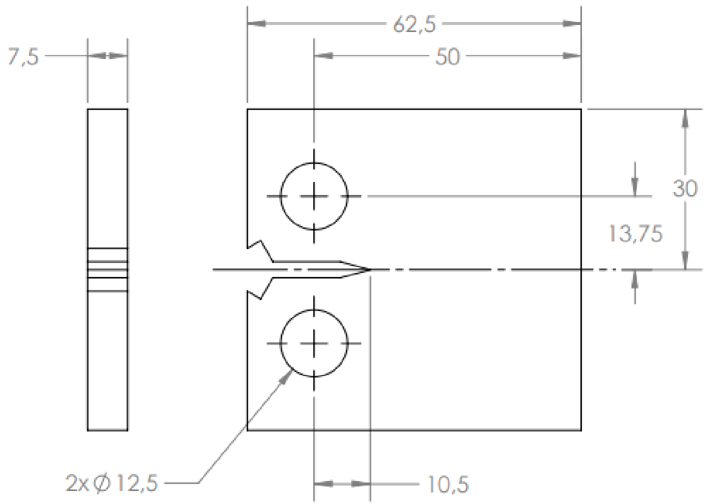
- Defect types:
  - Vertical specimens: KHs (2 sets), LoFs (2 sets), GEPs (1 set)
  - Horizontal specimens: LoFs (2 sets)
  - Diagonal specimens: LoFs (2 sets)
- All specimens to be stress relieved
- All dimensions are in mm

Fabrication (crack growth)

- Fabrication of specimens with different types of defects

Fatigue crack growth (FCG) specimens (ASTM E647):





Machined geometry

Vertical notch: 16
Diagonal notch: 16
Horizontal notch: 20

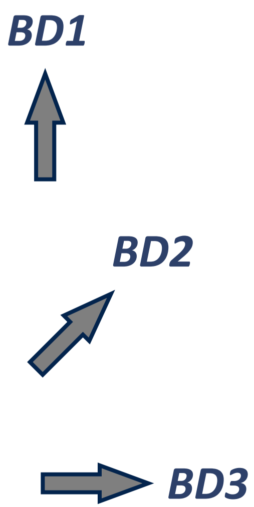
52 spec. total

- Defect types:
  - Vertical notch spec.: LoFs (1 set) and GEPs (3 sets)
  - Horizontal notch spec.: KHs (1 set), LoFs (1 set), and GEPs (3 sets)
  - Diagonal notch spec.: LoFs (1 set) and GEPs (3 sets)

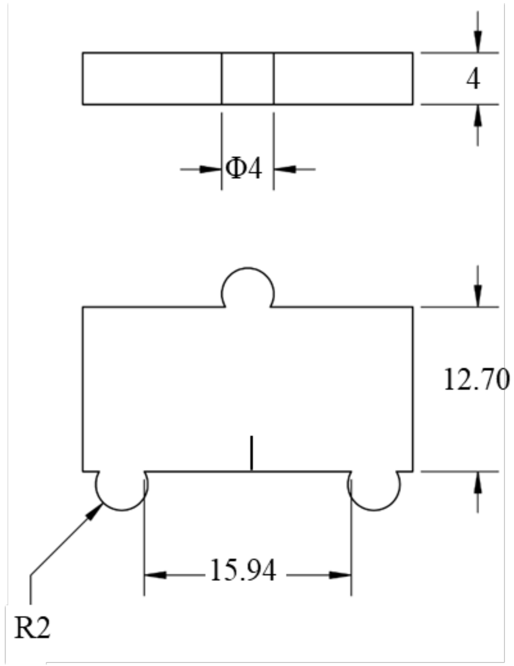
- All specimens to be built oversized and machined to the final dimensions
- All specimens to be stress relieved
- All dimensions are in mm

Fabrication (high strain rate fracture)

- Fabrication of specimens with different types of defects



Vertical notch: 25
Diagonal notch: 10
Horizontal notch: 10



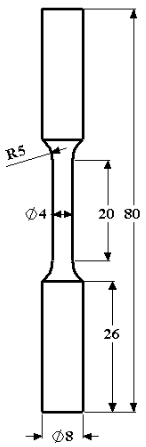
45 spec. total

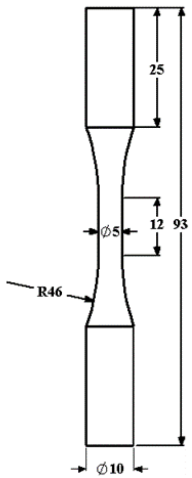
- Defect types:
  - Vertical notch spec.: KHs (2 sets), LoFs (2 sets), GEPs (1 set)
  - Horizontal notch spec.: LoFs (2 sets)
  - Diagonal notch spec.: LoFs (2 sets)

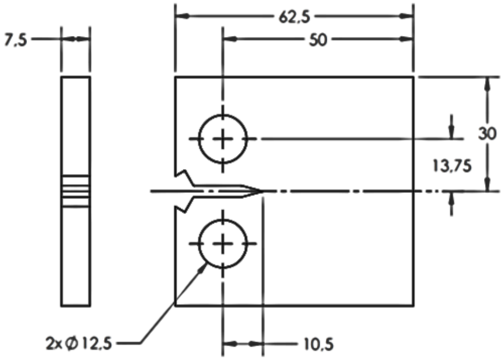
- All specimens to be stress relieved
- All dimensions are in mm
- Edge notch: 5 mm
- Root radius: ~100 micrometers

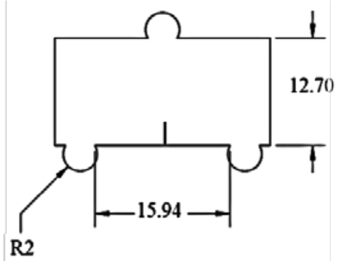
Mechanical testing and fractography

- Tasks 4.1-4.2 Mechanical Characterization & Fractography









Tensile:
- ASTM E08
- 6 tests per set based on defect types

Axial Fatigue:
- ASTM E466
- Force controlled
- Stress levels (R = -1): 500 MPa, 600 MPa, and 700 MPa
- 4 tests per stress level, per defect type

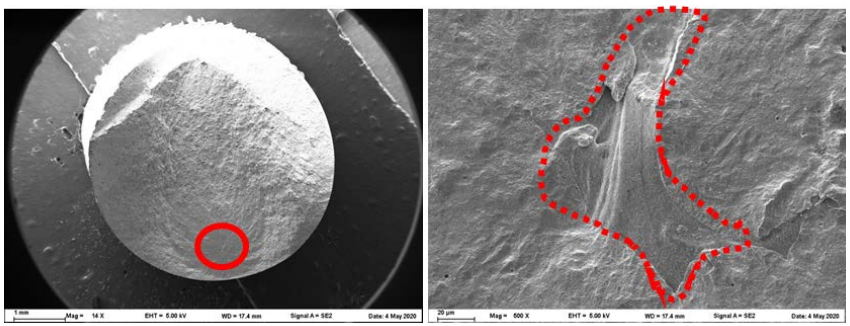
Crack Growth:
- ASTM E647
- Load ratio R = 0.1, 0.4, 0.7 for GEPs spec.
- Load ratio R = 0.1 for LoFs and KHs spec.
- 3 tests per set based on defect type and notch orientation

High-Strain Rate Frac.:
- Edge notched 3-point bend fracture
- Strain-rate ~1000/sec
- Optical measurements (DIC, high-speed photography)
- 3 tests per set based on defect types

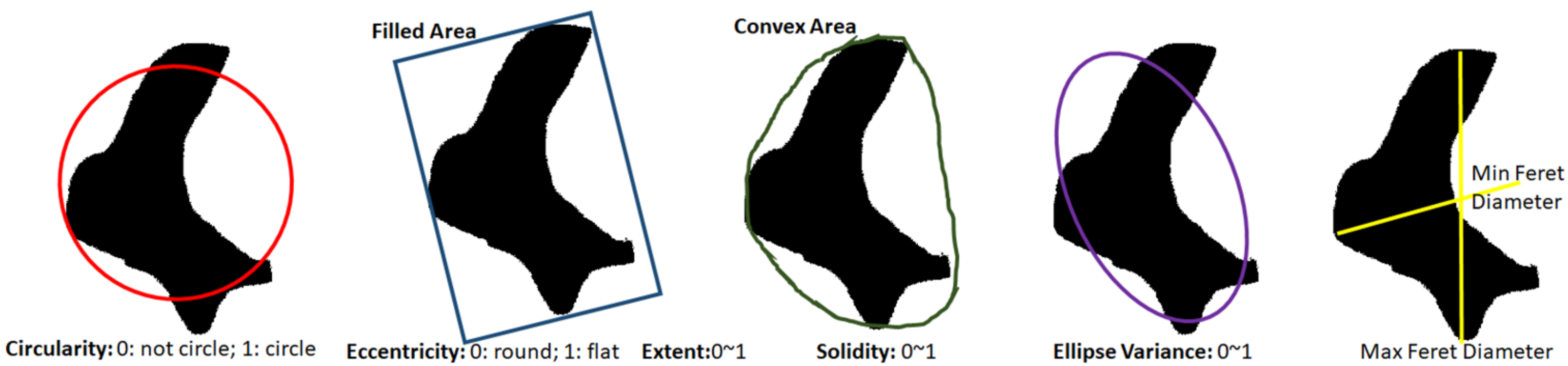
Study to analyze criticality of defects on mechanical performance

Machine learning based defect criticality

- Extract shape descriptors of defects from fractography images (2D) and XCT data (3D)
- Quantify characteristics of defects, e.g., roundness, sharpness, irregularity, etc.



Conditions	Size	Shape
Process Parameters	Area Perimeter Equivalent Diameter Major Axis Length Minor Axis Length Filled Area Convex Area Max Feret Diameter Min Feret Diameter	Circularity
Strain/Stress Levels		Eccentricity
		Extent
Property (tensile, fatigue, fracture)		Solidity
		Ellipse Variance

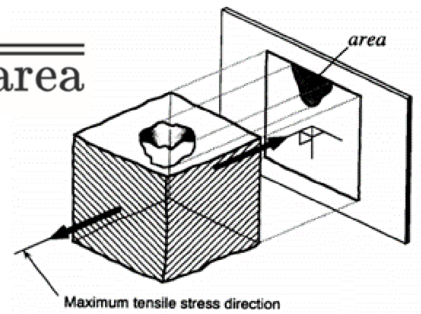


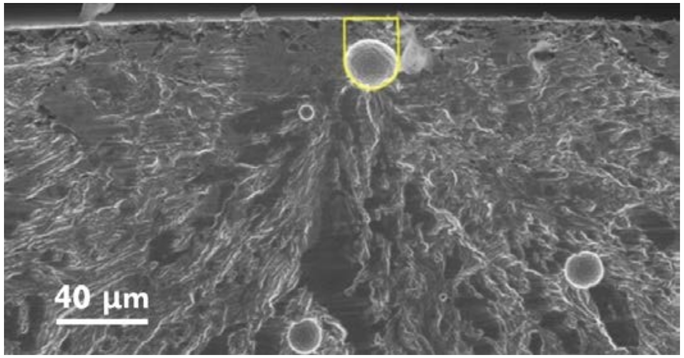
Fatigue modeling

- Murakami's defect sensitive fatigue (DSF) model treats volumetric defects as cracks

$$\Delta K = Y \Delta\sigma \sqrt{\pi \sqrt{\text{area}}}$$

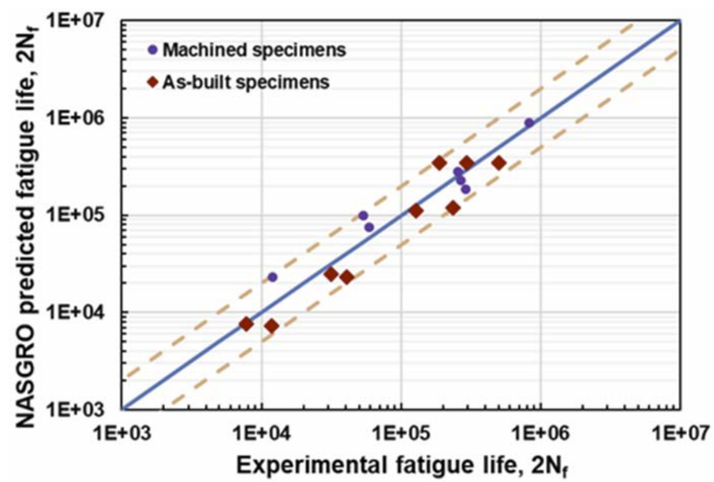
Surface: $Y = 0.65$
Internal: $Y = 0.5$





- Fatigue life is an integration of crack growth rate from initial crack size to critical crack size

$$\frac{da}{dN} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{max}}{K_C}\right)^q}$$

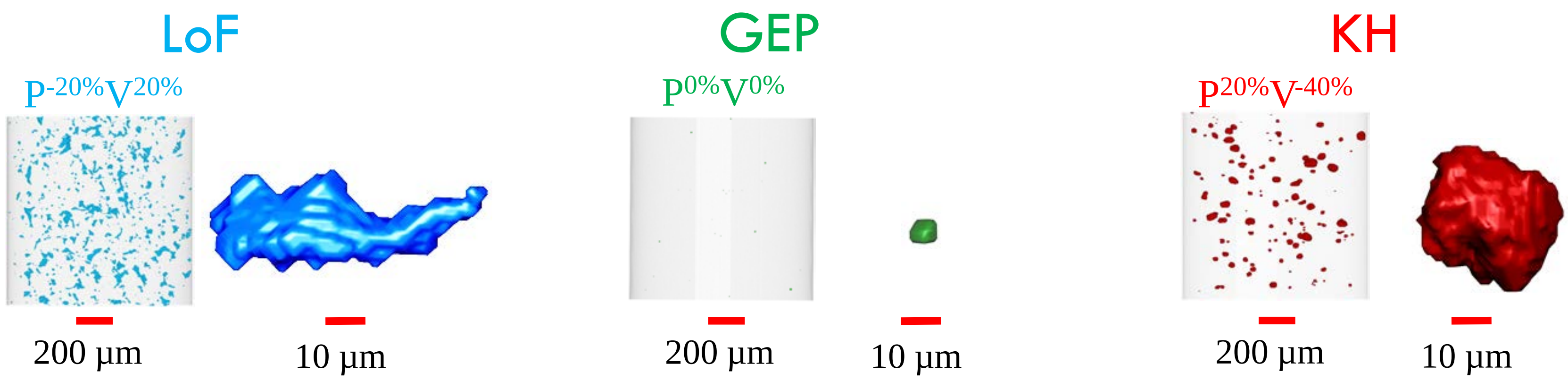


- Murakami's DSF model is simple to use and relatively accurate

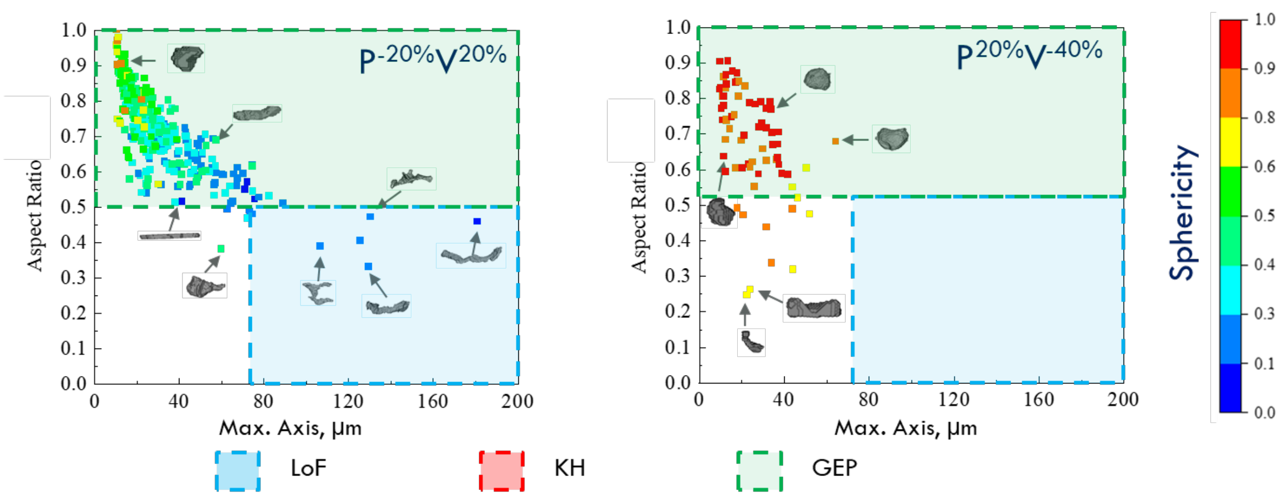
Romano, Nezhadfar, Shamsaei, Seifi, and Beretta, Theor. Appl. Fract. Mec., 106 (2020) 102477.

Preliminary results

Defect classification – state of art

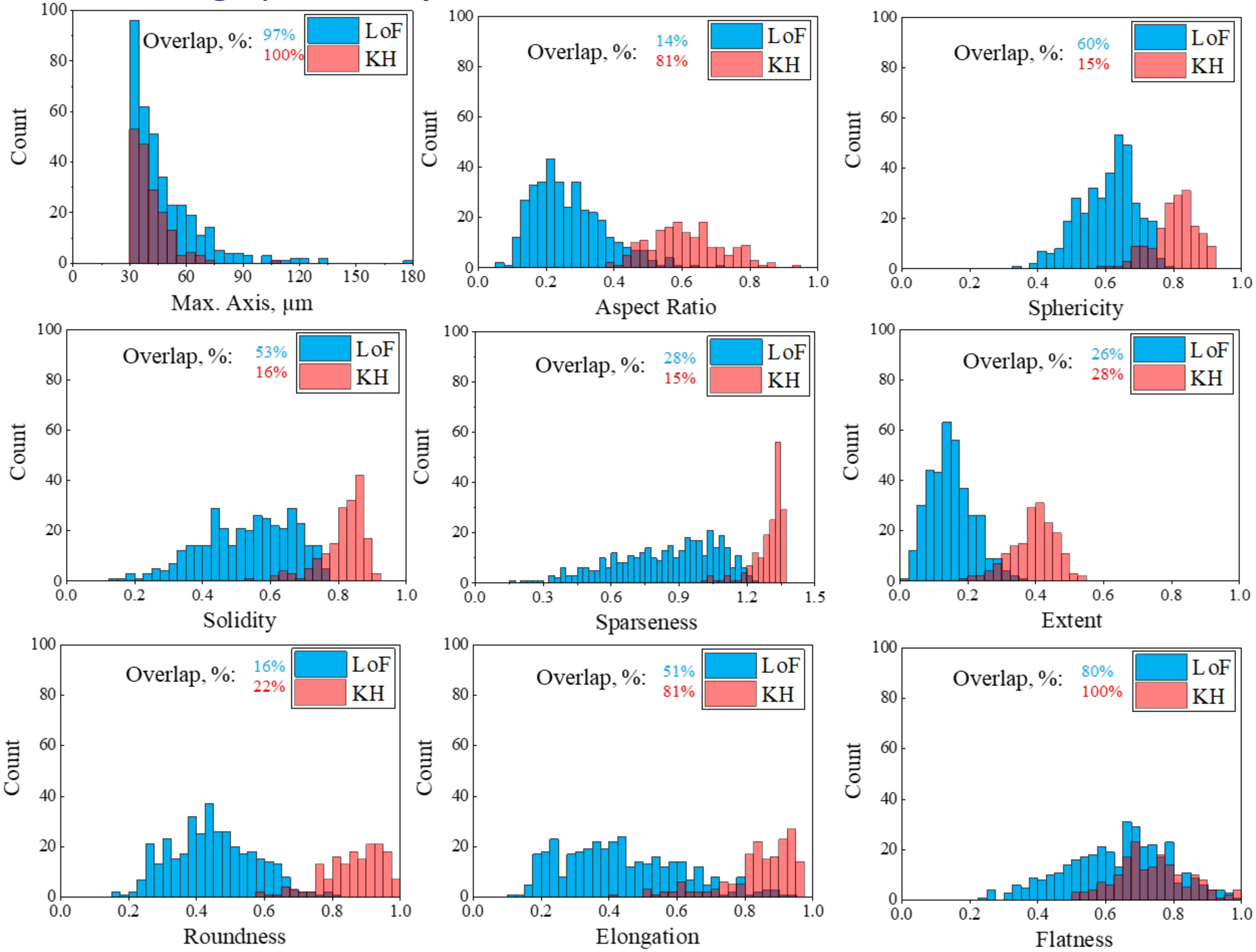


- **State of art:** using up to **three parameters** (size, aspect ratio, and sphericity) and draw "hard" boundaries with each
- An example from literature: LoF: Size > 75 µm, AR < 0.5; GEP: AR > 0.5



Defect classification – NCAME approach

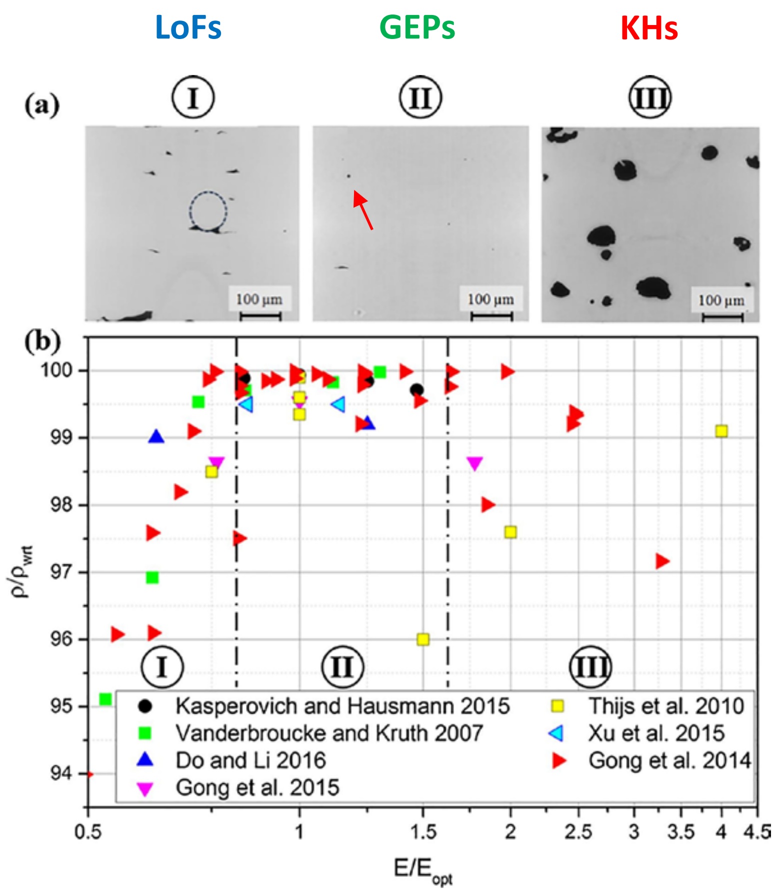
- Using up to **nine parameters** and **manual decision tree**



Use of only 4 parameters and decision tree resulted in **98.7% accuracy**

Process window definition – state of art

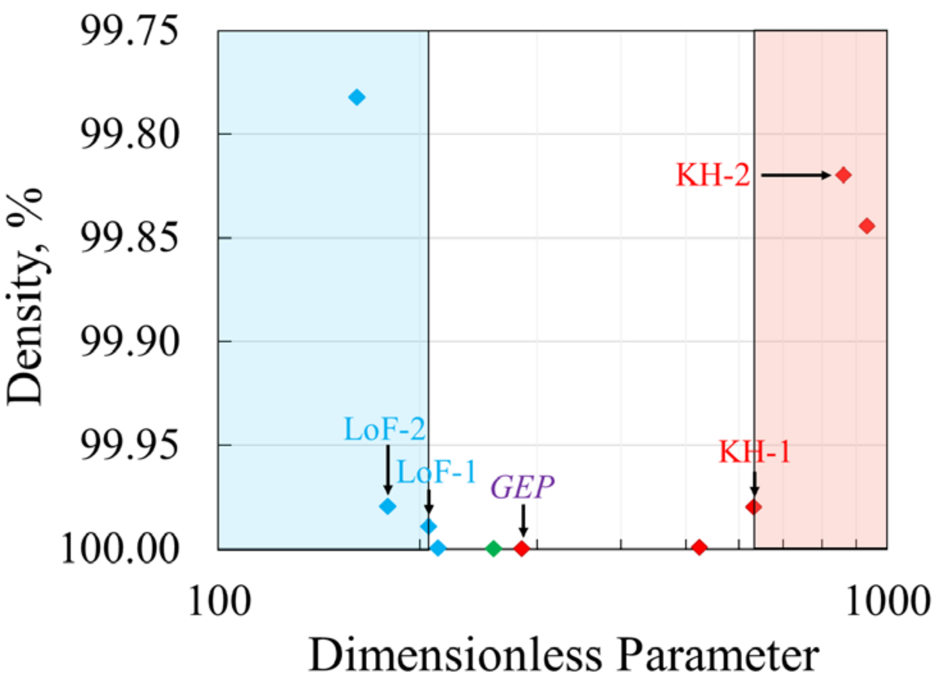
- **State of art:** using only relative density as the fabrication quality indicator.
- Although relative density is easy to measure, it may:
  - ➢ not represent fatigue properties well;
  - ➢ not be sensitive to process parameters near boundaries;
  - ➢ not be relevant as most modern LB-PBF machines can achieve >99.9% density.



Pegues et al., Inter. J. Fatigue, 132 (2020) 105358.

Next step

- Identify combinations of laser power and scan speed to induce 5 different levels of defects:
  - GEP: $P^{10\%}V^{0\%}$
  - LoF: $P^{-20\%}V^{0\%}$ and $P^{0\%}V^{20\%}$
  - KH: $P^{20\%}V^{-30\%}$ and $P^{20\%}V^{-40\%}$



- Start mechanical testing and fractography

- Data on defect classification is planned to be fully analyzed and become available to the public by the end of 2021