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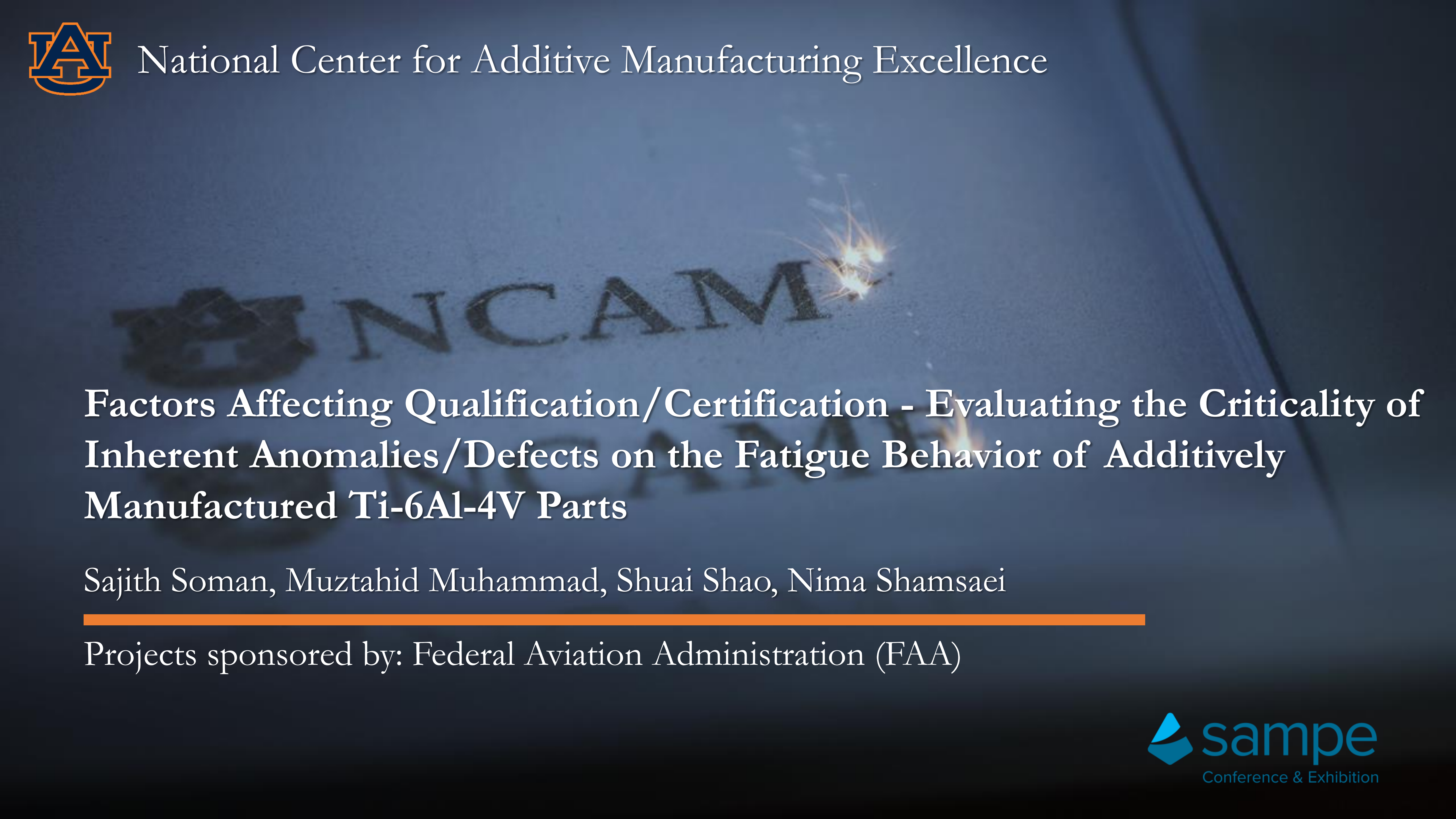

Factors Affecting Qualification/Certification - Evaluating the Criticality of Inherent Anomalies/Defects on the Fatigue Behavior of Additively Manufactured Ti-6Al-4V Parts

Sajith Soman, Muztahid Muhammad, Shuai Shao, Nima Shamsaei

Projects sponsored by: Federal Aviation Administration (FAA)

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Introduction

- **Project Title:** Factors Affecting Qualification/Certification - Evaluating the Criticality of Inherent Anomalies/Defects on the Fatigue Behavior of Additively Manufactured Ti-6Al-4V Parts
- **Principal Investigator:** Nima Shamsaei

(See next slide for complete list of participants)

- **FAA Technical Monitor:** Kevin Stonaker
- **Source of matching contribution:** Faculty time and graduate research assistant tuition

Federal Aviation Administration

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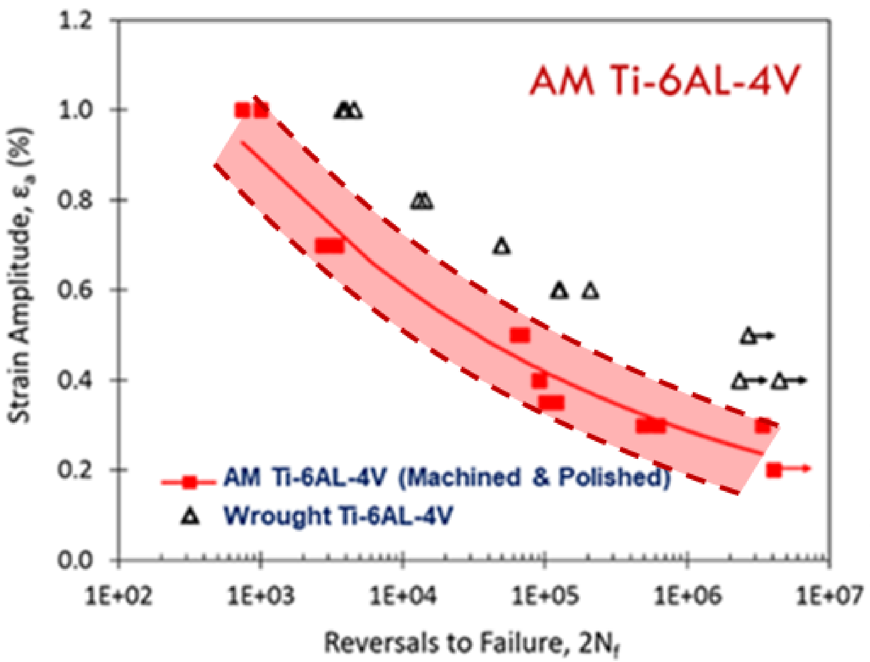
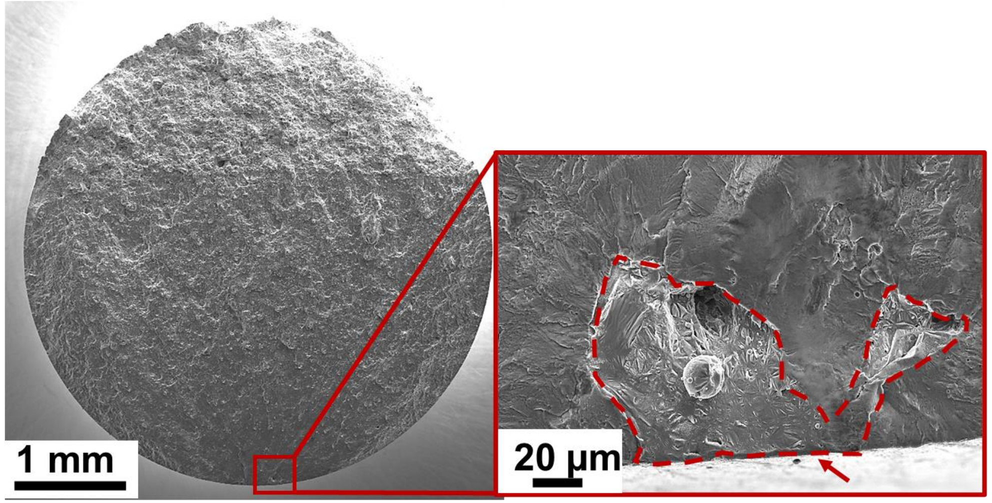
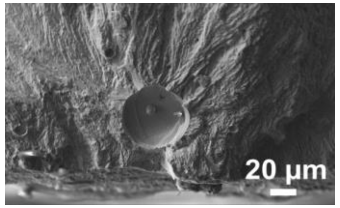
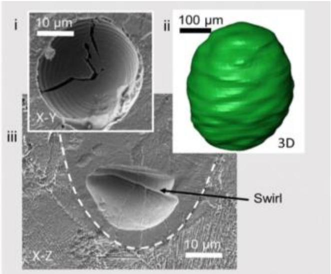
Background



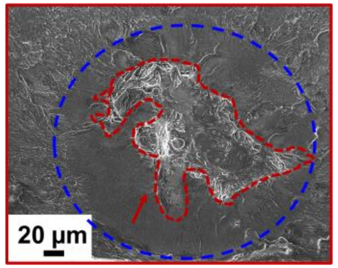




Gas-entrapped pores (GEPs)



Keyholes (KHs)



Lack of fusions (LoFs)

AM defects:

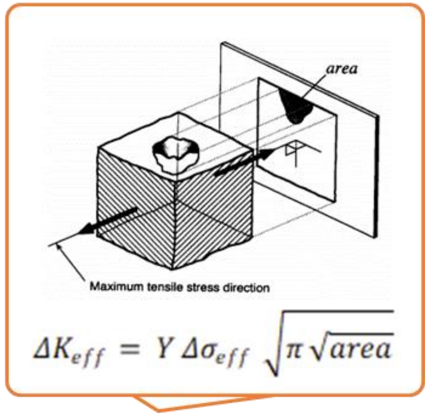
- Significantly reduce and introduce uncertainty to fatigue performance
- Pose great challenge for qualification/certification of AM parts

Muhammad, Nezhadfar, Thompson, Saharan, Phan, & Shamsaei, Int. J. Fatigue, 124 (2019) 188-204
Snell, Tammas-Williams, Chechik, Lyle, Hernandez-Nava, Boig, Panoutsos, & Todd, JOM 72 (2020) 101-109

Objective & Approach

- **Objective**: To quantify the detrimental effect of volumetric defects on mechanical properties of L-PBF Ti-6Al-4V Gr. 5
- **Approach**: Three steps are taken,
  I. Explore process windows by varying laser power, scan speed, and hatching distance
  II. Determine the criticality of volumetric defects on mechanical performance using specimens seeded with different defect types
  III. Take advantage of machine learning and simulations wherever applicable

Overall Scope



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

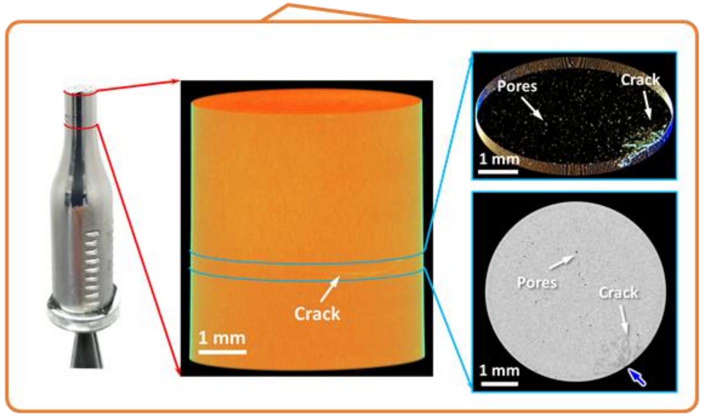
Defect seeding (Fabrication)

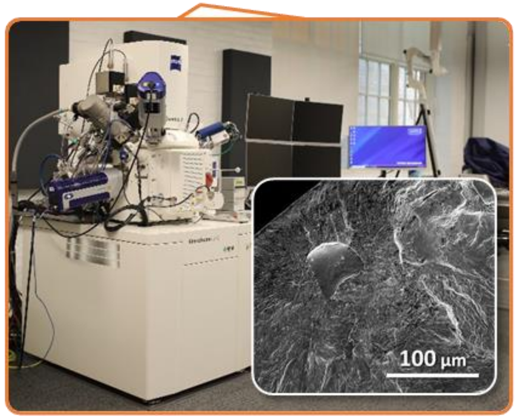
Defect detection (NDI)

Mechanical testing

Fractography

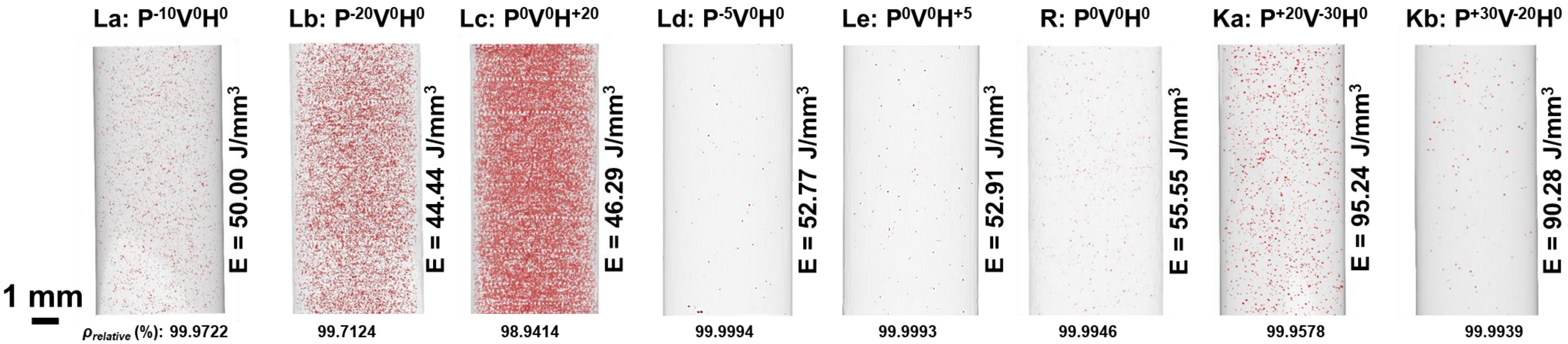
Defect criticality





- AP&C Ti-6Al-4V Grade 5 powder (15-53 µm) was used as feedstock

Defect Contents: Fatigue Specimens



Energy density

$$E = \frac{P}{Vht}$$

P: Laser power
V: Laser speed
h: Hatch distance
t: Layer thickness

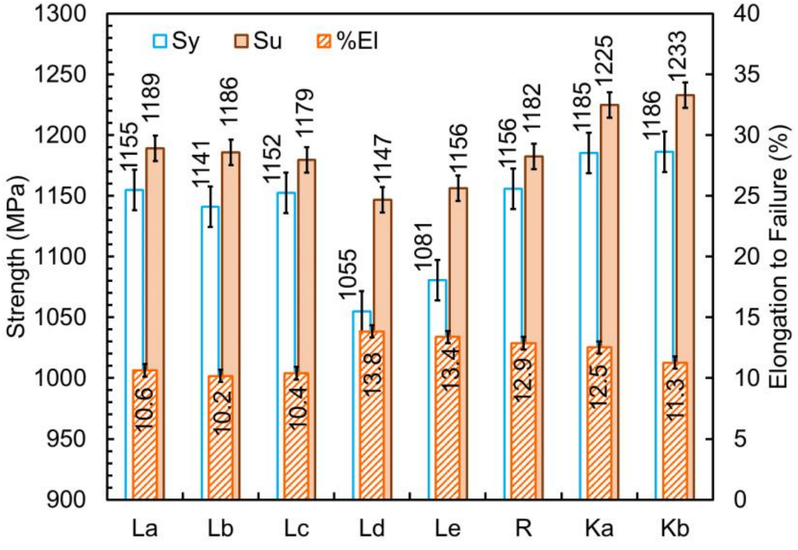
Note: Original plan was to fabricate specimens with 6 sets of process parameters, we fabricated 2 two extra sets (Ld and Le)
X-ray computed tomography (XCT) was performed on vertical fatigue specimens with 5.5 µm voxel size

- 240 fatigue (16 x 15) and 96 tensile (16 x 6) specimens were fabricated
  - Lack of fusion (LoF): $P^{-5\%}$, $P^{-10\%}$, $P^{-20\%}$, $H^{+5\%}$, and $H^{+20\%}$
  - Keyhole (KH): $P^{+30\%}V^{-20\%}$ and $P^{+20\%}V^{-30\%}$
- KH specimens were fabricated only in vertical orientation, while the recommended (R) and LoF ones were fabricated in vertical, diagonal, and horizontal orientations

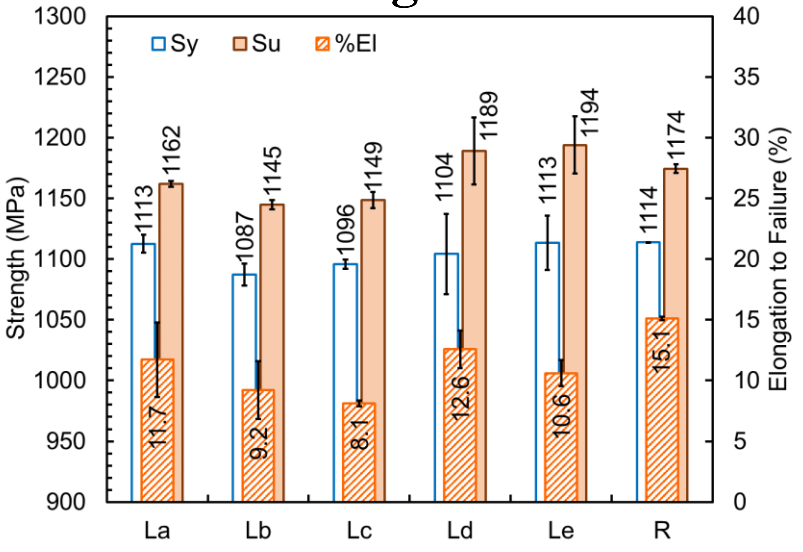
Unpublished data, written permission required before dissemination

Tensile Properties

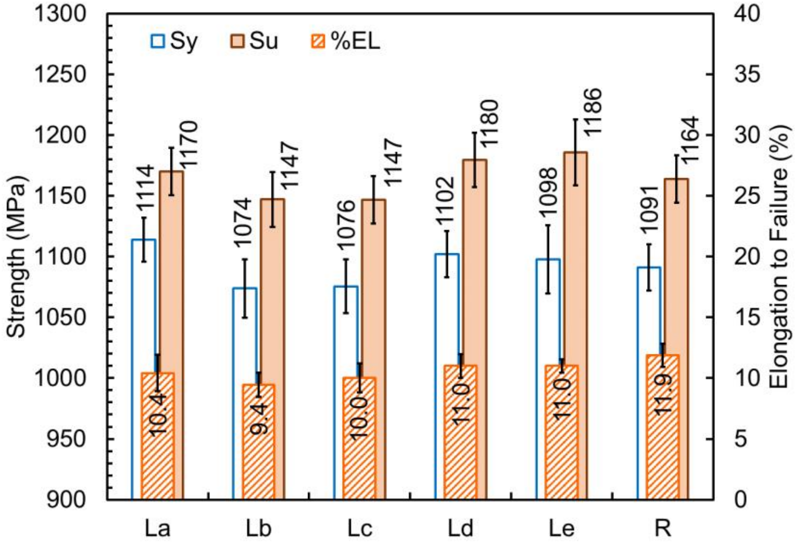
Vertical



Diagonal



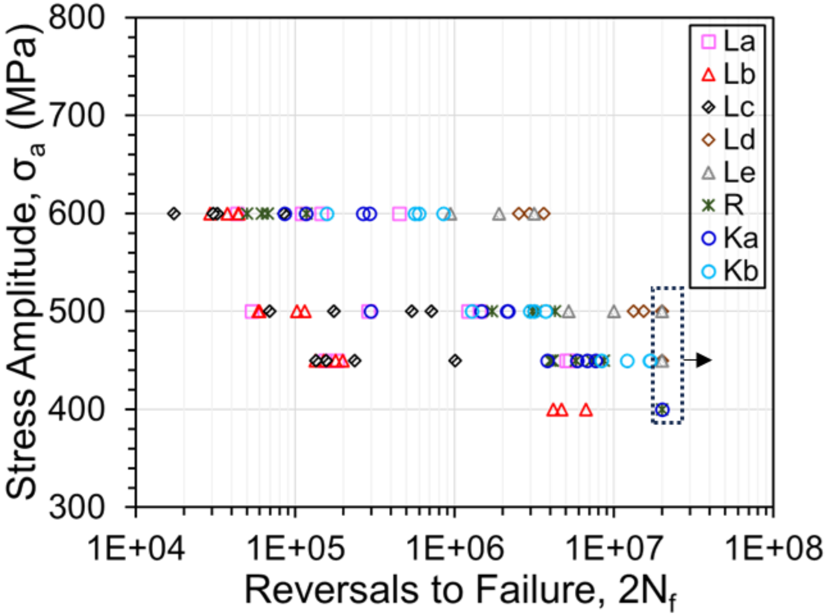
Horizontal

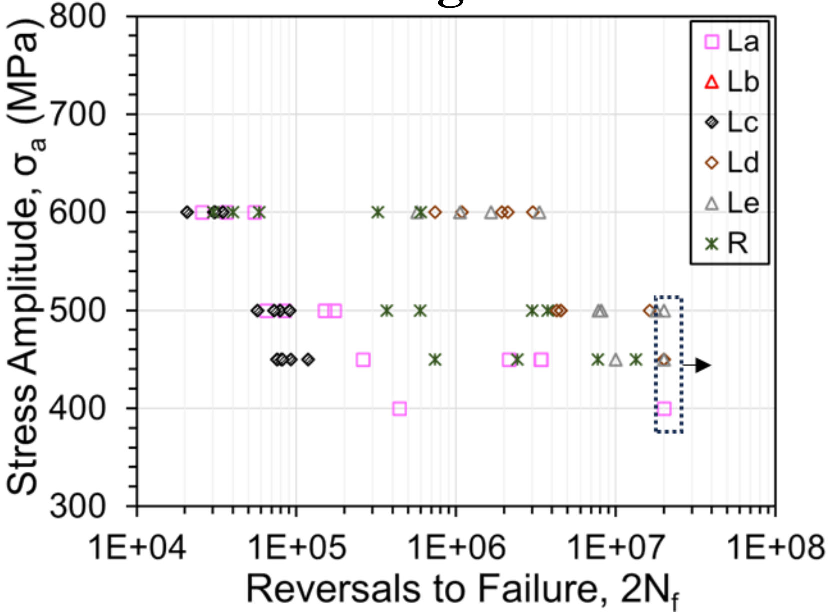


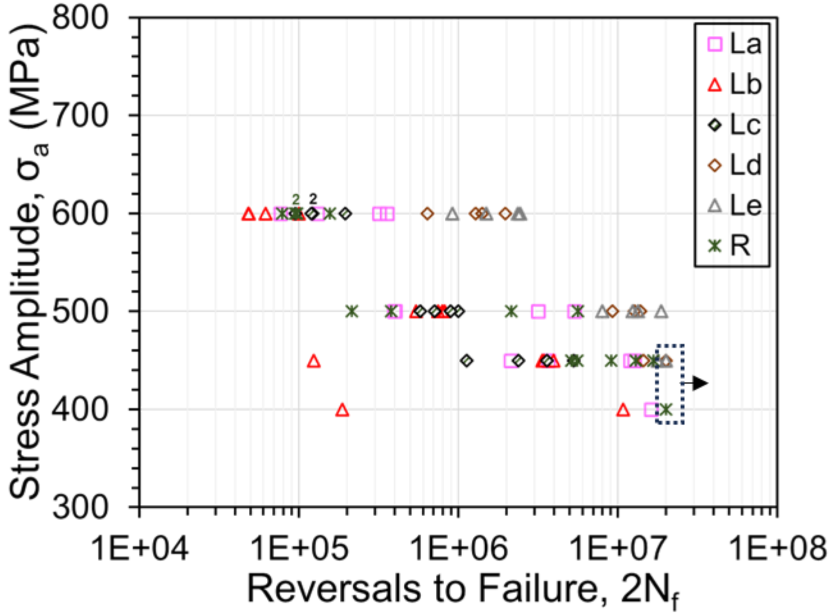
Note: 5 tensile specimens were tested for each condition

- Yield strength (YS) and ultimate tensile strength (UTS) of all specimens were almost comparable
- KH specimens had slightly higher strengths which might be attributed to the higher oxygen and/or nitrogen content due to excessive energy input during fabrication (please see back up Slide 32 for chemical analysis)
- LoF specimens with higher defect content (Sets La, Lb, and Lc) had lower ductility due to larger number and larger size of defects causing an early failure

Fatigue Performance


Vertical

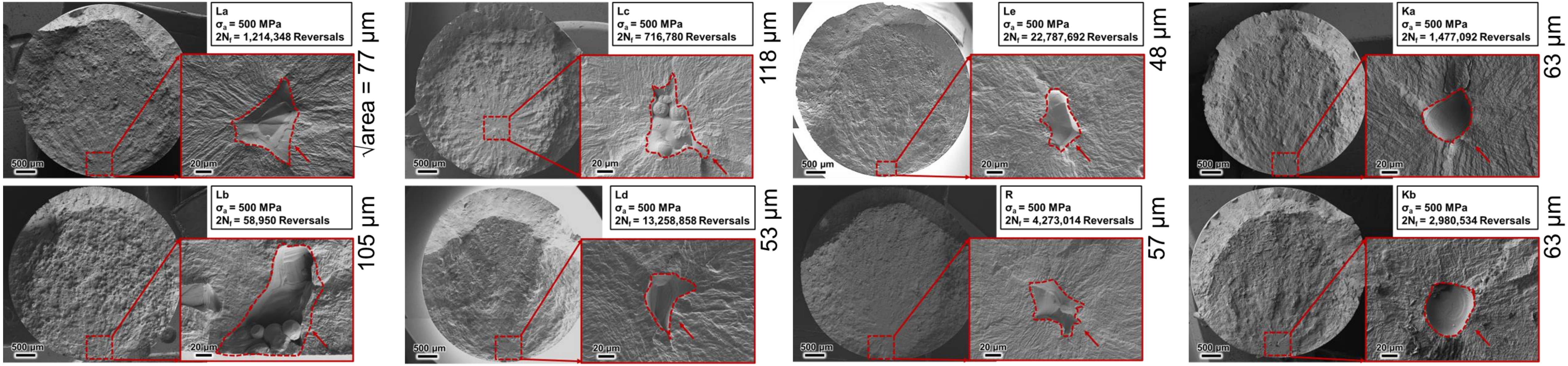

Diagonal


Horizontal

- Fatigue specimens were tested all the way until final fracture
- In vertical orientation, KH specimens exhibited better fatigue performance than recommended ones
- Fatigue lives of LoF specimens had more scatter than KH ones due to wide variation in shape, size, and location of the crack initiating defects
- LoF specimens with higher defect content (Sets La, Lb, and Lc) exhibited worse fatigue performance for vertical and diagonal orientations

Unpublished data, written permission required before dissemination

Fatigue Fractography

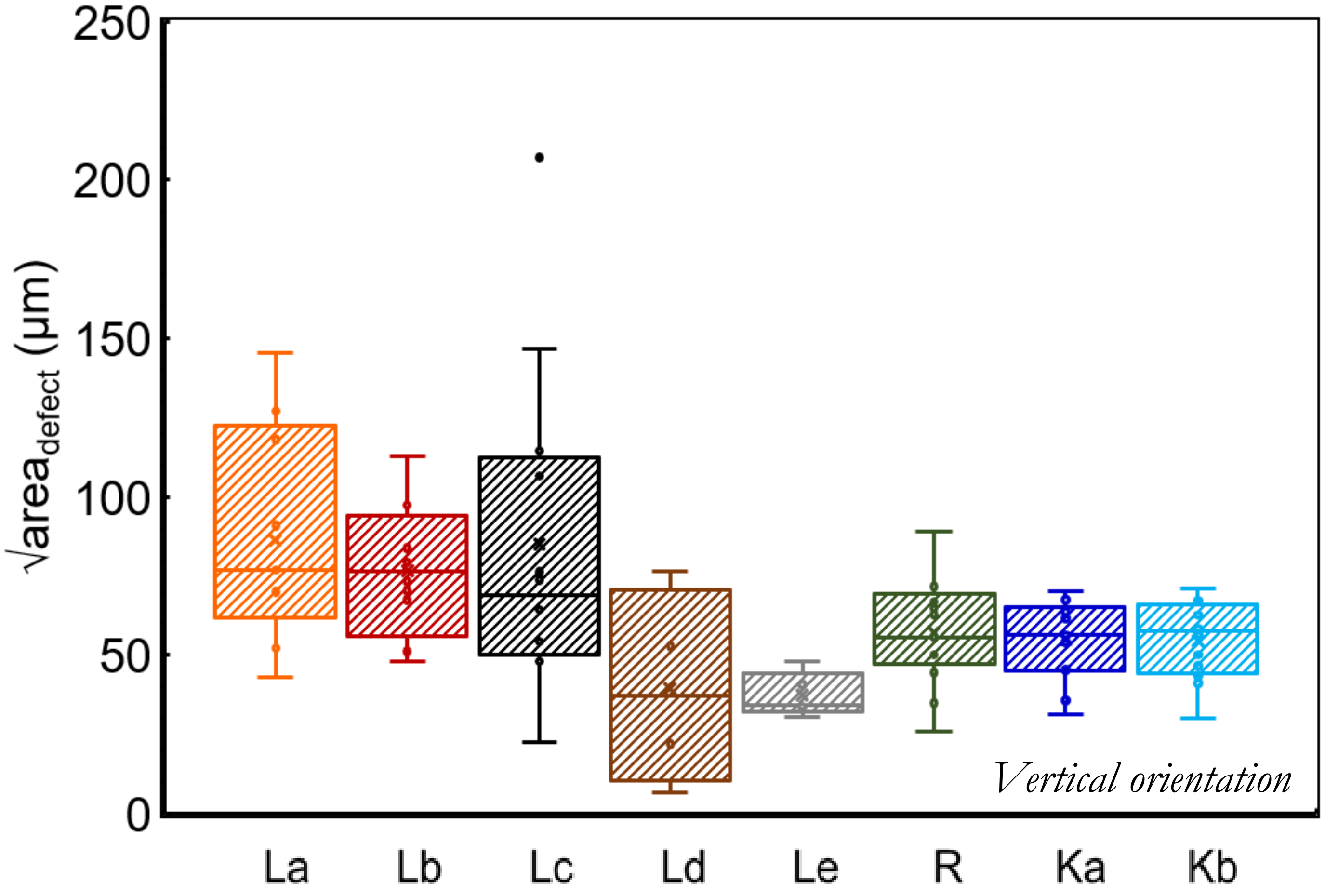


Note: All fractographies are from vertical specimens. √area of crack initiating defects is shown on the top right side of the fractography images

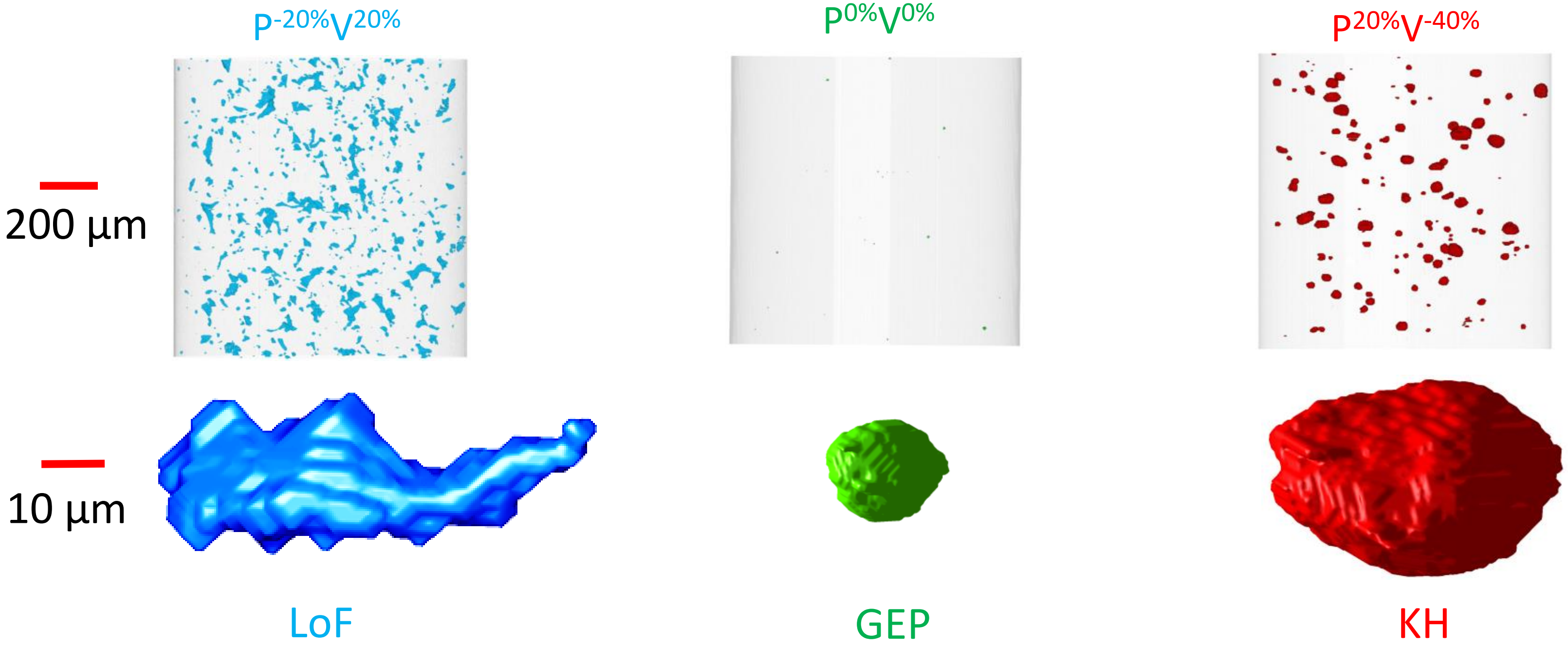
- LoF specimens:
  - All fatigue cracks, except for some in Ld and Le sets, initiated from either internal or surface LoF defects
  - Fatigue cracks for Ld and Le specimens initiated from mostly internal LoF defects and rarely from KH defects
- Recommended specimens: all fatigue cracks initiated from internal or surface LoF defects
- KH specimens: fatigue cracks initiated mostly from KH defects and rarely from LoF defects, located internally or at surface

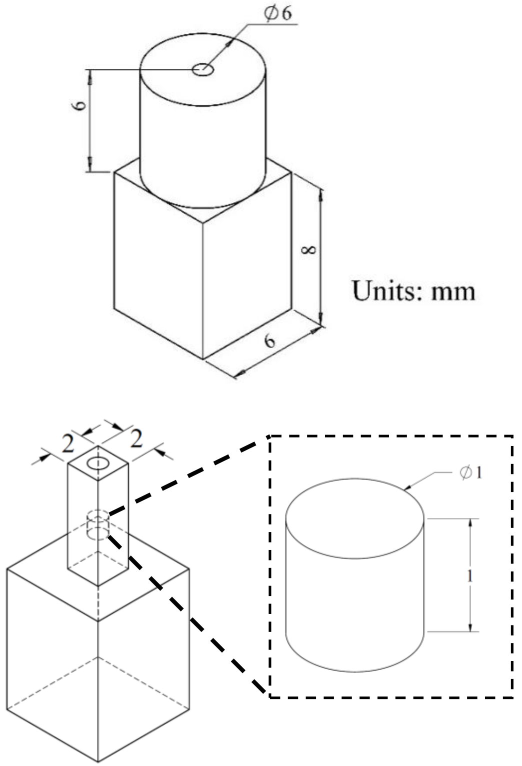
Fatigue Behavior

- Defect sizes were measured using actual √area of the defect
- The size of the fatigue crack initiating defects of recommended and KH specimens were comparable
- Mean √area of the crack initiating defects of LoF specimens with higher defect content (LoF sets a, b, and c) were significantly larger compared to recommended and KH specimens
- Size of the defects explained the order of fatigue life



Typical Volumetric Defects in AM Metallic Materials





- Defects are inherent to the AM process and their morphology is sensitive to processing conditions
- Three common defect types are typically seen: LoFs, GEPs, and KHs

✓ How to quantify the geometric features of defects in an AM part and how to classify defects?

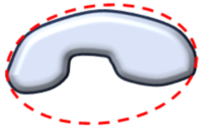
Shamsaei & **Shao** et al., Nature Communications, 13: 6369, 2022.

Alternative Approach: Utilizing Additional Parameters

Solidity

$$\text{Solidity} = \frac{\text{Volume}_{\text{object}}}{\text{Volume}_{\text{convex hull}}}$$

Sparseness

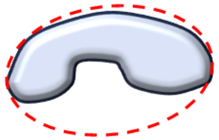


$$\text{Sparseness} = \frac{\text{Volume}_{\text{object}}}{\text{Volume}_{\text{ellipsoid}}}$$

Extent

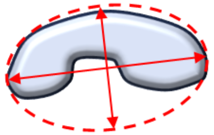
$$\text{Extent} = \frac{\text{Volume}_{\text{object}}}{\text{Volume}_{\text{bounding box}}}$$

Roundness



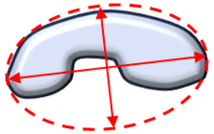
$$\text{Roundness} = \frac{\text{Equiv. dia.}}{\text{Max. axis}}$$

Elongation

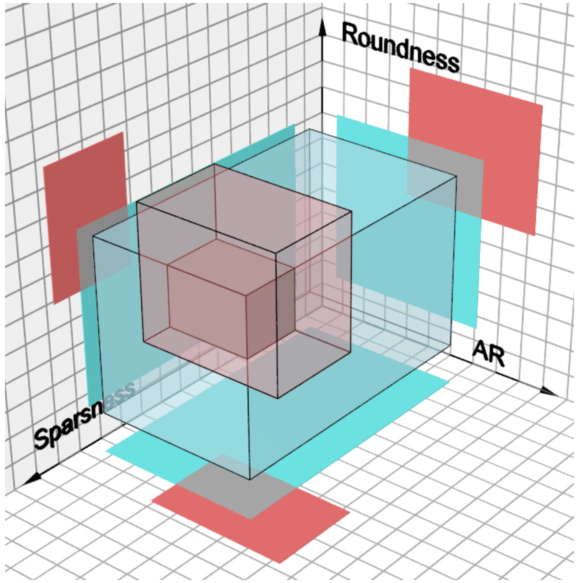


$$\text{Elongation} = \frac{\text{Med. axis}}{\text{Max. axis}}$$

Flatness

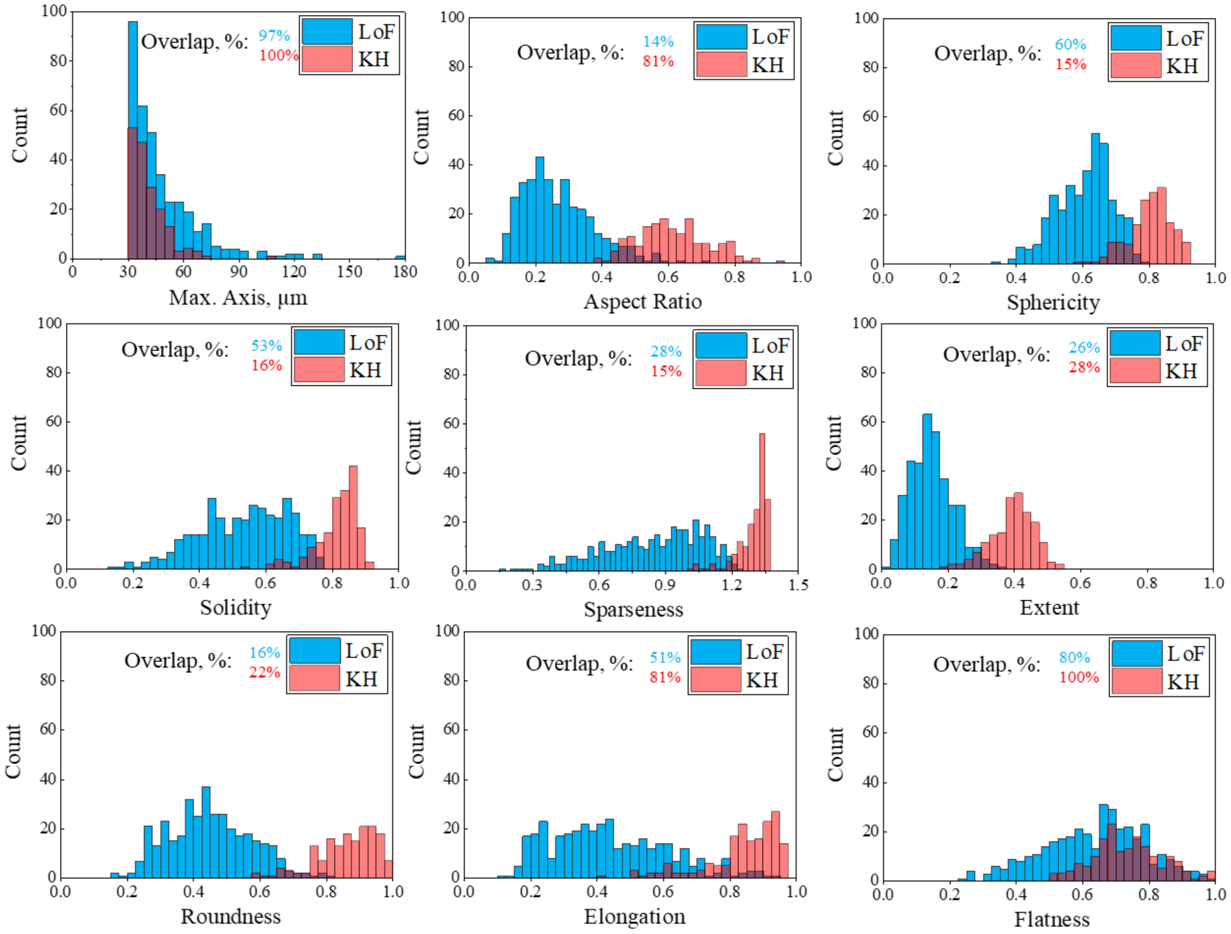


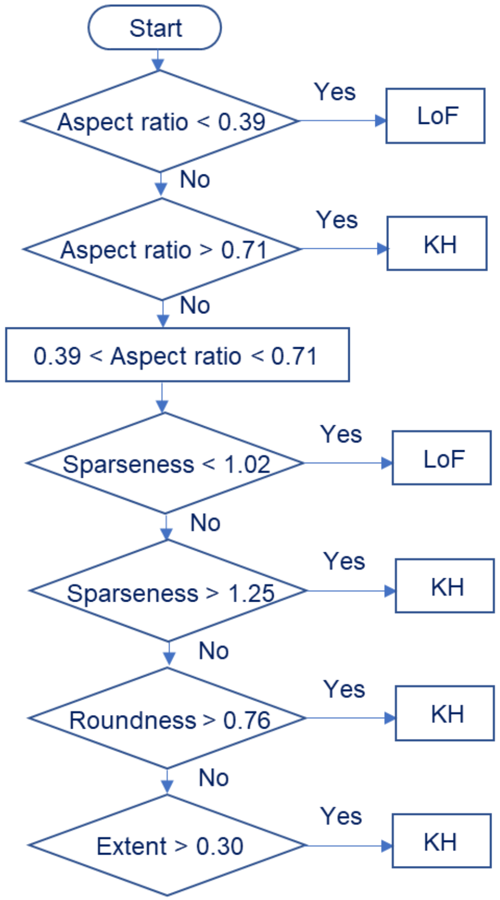
$$\text{Flatness} = \frac{\text{Min. axis}}{\text{Med. axis}}$$



- Simultaneous usage of several discriminating parameters can more effectively describe the geometric feature of a defect
- Although different defect types have overlaps in all parameters, usage of more parameters can improve the classification accuracy

Alternative Approach: Decision Tree





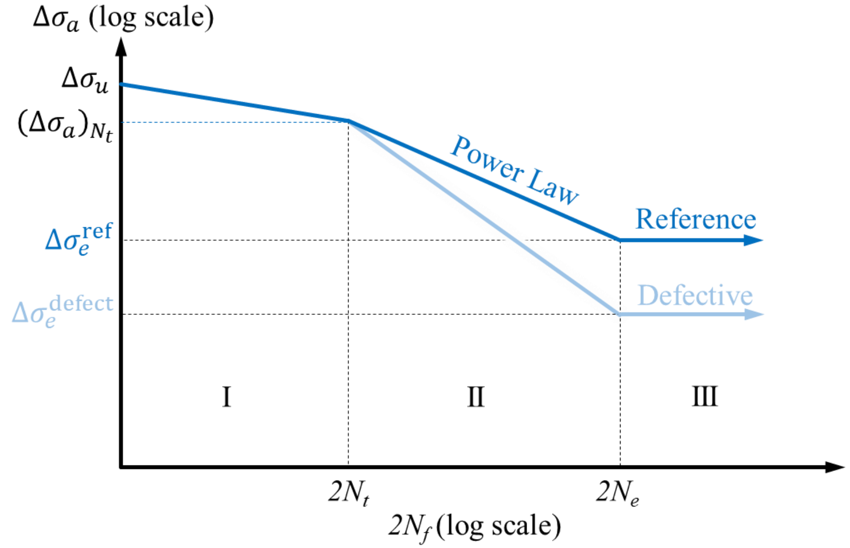
Accuracy

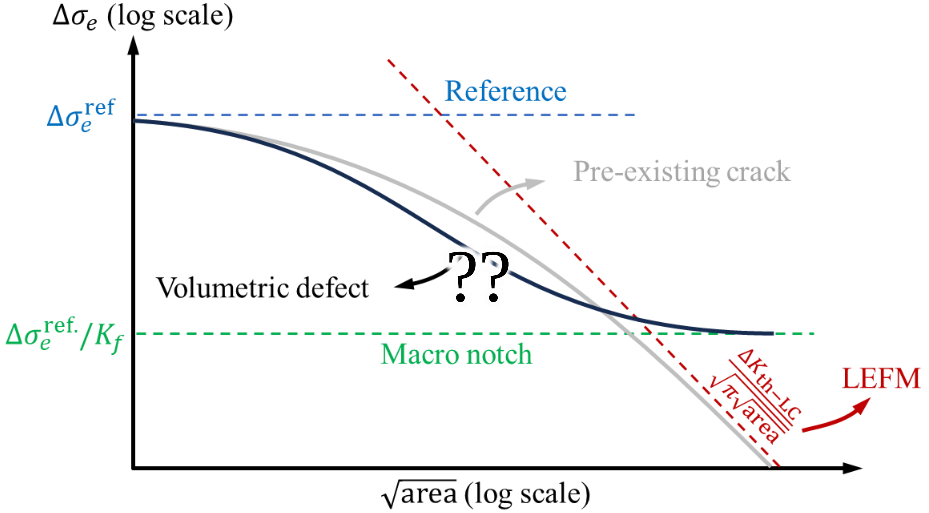
- ☐ Aspect ratio and sparseness: 93.1%
- ☐ Adding roundness (3 parameters): 98.0%
- ☐ Adding extent (4 parameters): 98.7%
- ☐ Including other parameters does not improve the accuracy

✓ What kinds of volumetric defects are more detrimental to fatigue performance?

Shamsaei & **Shao** et al., Nature Communications, 13: 6369, 2022.

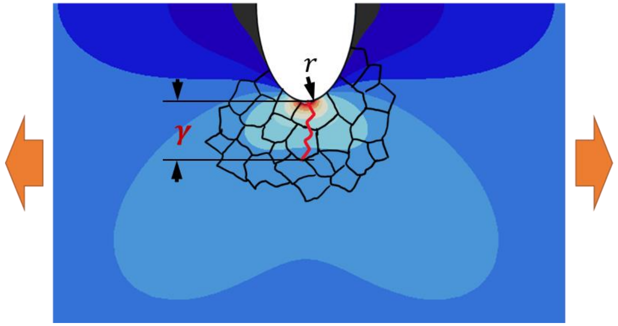
Role of Volumetric/Surface Defects on Fatigue





- Volumetric/surface defects act as stress risers and can accelerate fatigue crack initiation
- Notch-factor approach can account for the effect of volumetric/surface defects
- The extremely large defects behave like macro notches.

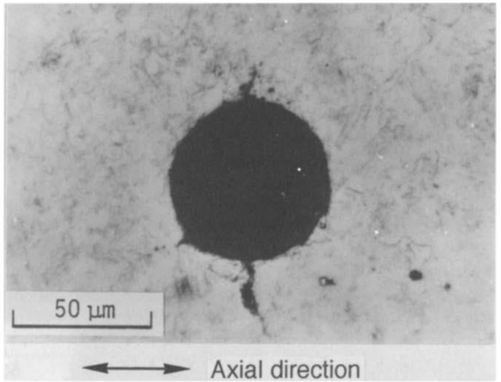
✓ How to calculate the effect of defects of different sizes and shapes?

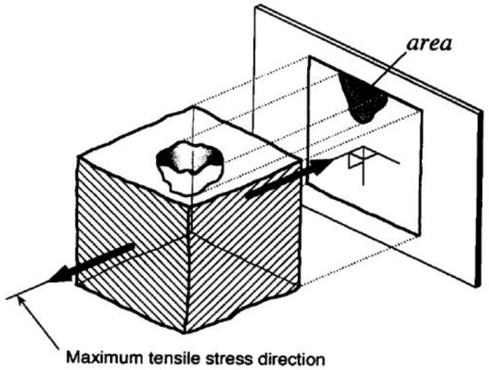


Budynas and Nisbett, *Shigley's Mechanical Engineering Design*. 11 ed., New York, NY, McGraw-Hill Education, 2020.
Yamashita, Murakami, Mihara, Okada, and Murakami, International Journal of Fatigue, **117**, 485-495, 2018.

Existing Defect-sensitive Fatigue Models

- Murakami's defect sensitive fatigue (DSF) model



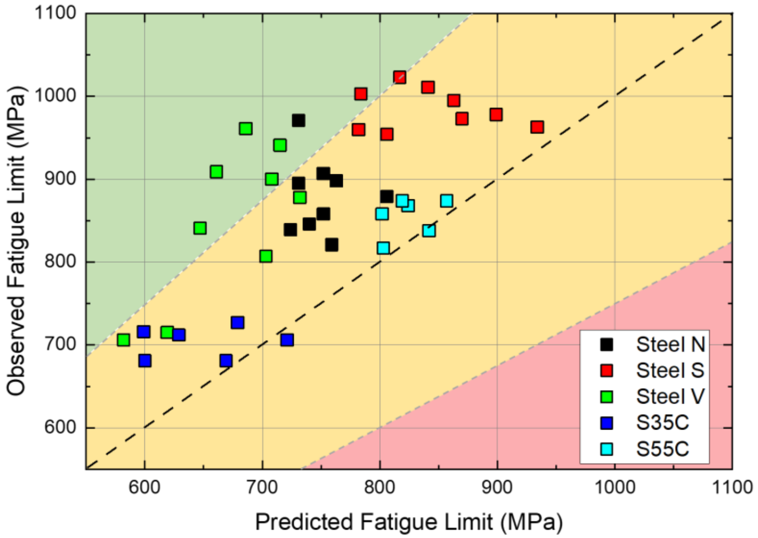


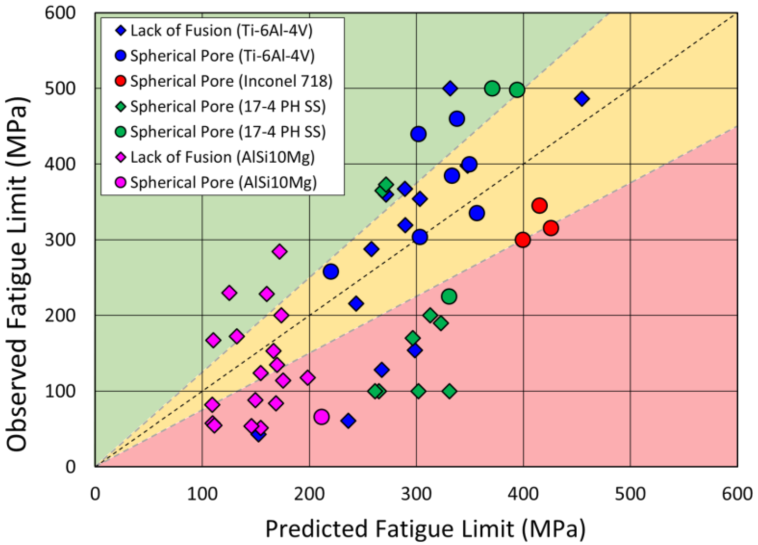
$$\Delta K = Y\Delta\sigma\sqrt{\pi\sqrt{area}}$$

Surface defects: $Y = 0.65$
Internal defects: $Y = 0.50$

$$\sigma_e = C\frac{HV + 120}{\sqrt{area}^{1/6}}$$

Surface defects: $C = 1.43$
Internal defects: $C = 1.56$





Y. Murakami, 2019, Metal fatigue: effects of small defects and nonmetallic inclusions, 2nd Ed., Academic Press, London, UK.
Shao and **Shamsaei**, et al., Current Opinion in Solid State and Materials Science, Vol. 26 (2), 100974 (2022)

Modeling the Effect of Volumetric Defects

- AM materials loaded below fatigue limit are believed to endure indefinitely but are **rarely crack-free**
- Instead, small cracks initiated from defects can be arrested
- The rapidly reducing stress away from defects can cause the effective stress intensity factor range (ΔK_{eff}) to first decrease before increasing:

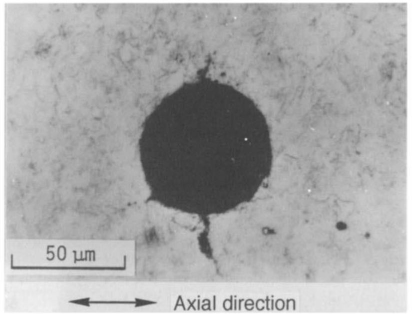
$$\Delta K_{\text{eff}} = K'(l)\Delta\sigma\sqrt{\pi(l+l_0)}$$

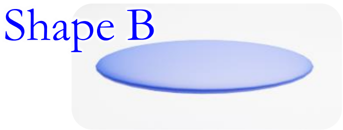
- The fatigue limit of a defect-laden material can be calculated:

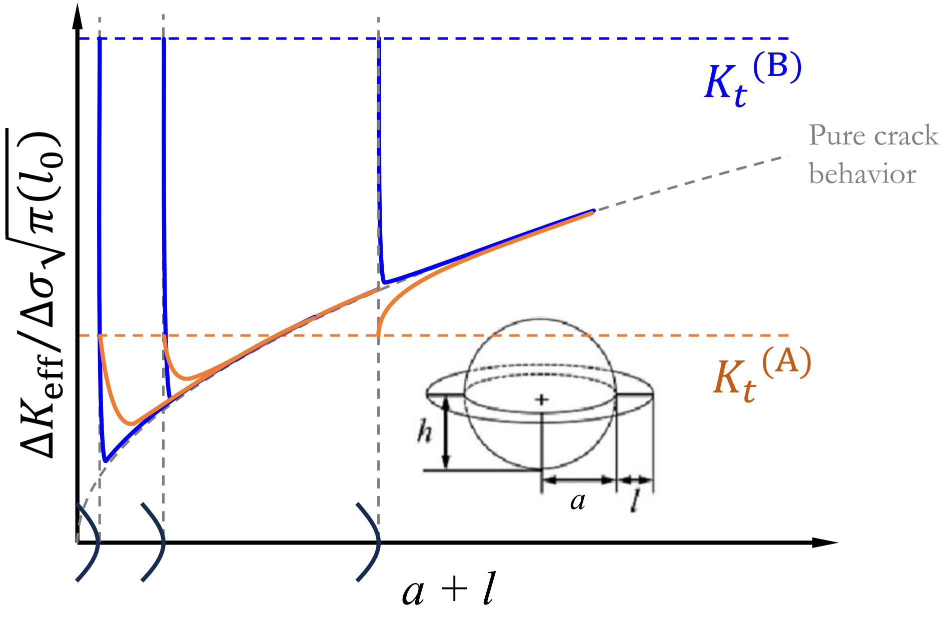
$$\Delta\sigma_e^{\text{defect}} = \frac{\Delta K_{\text{th-LC}}}{\min\left[K'(l)\sqrt{\pi(l+l_0)}\right]}$$

- The effects of defects' size, shape, and location are implicitly incorporated in the "crack arrest analysis"

✓ How to calculate $K'(l)$?

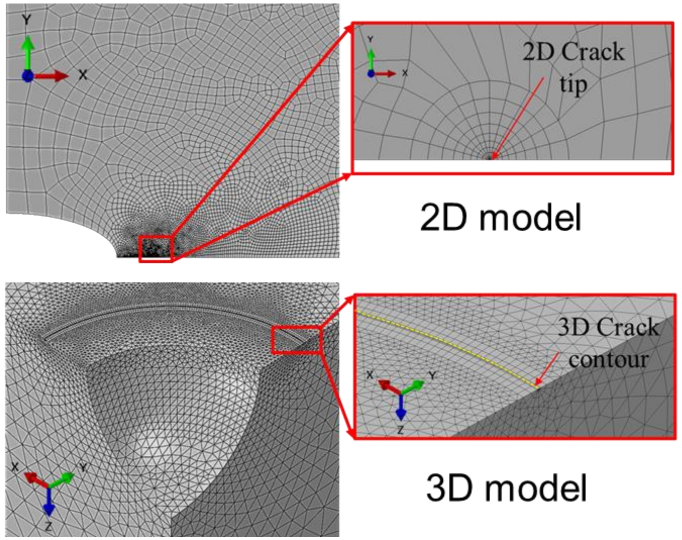


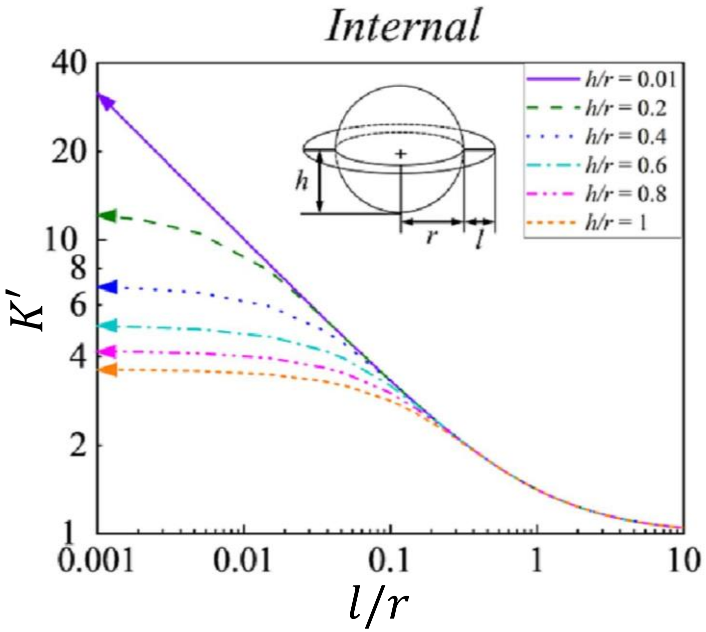




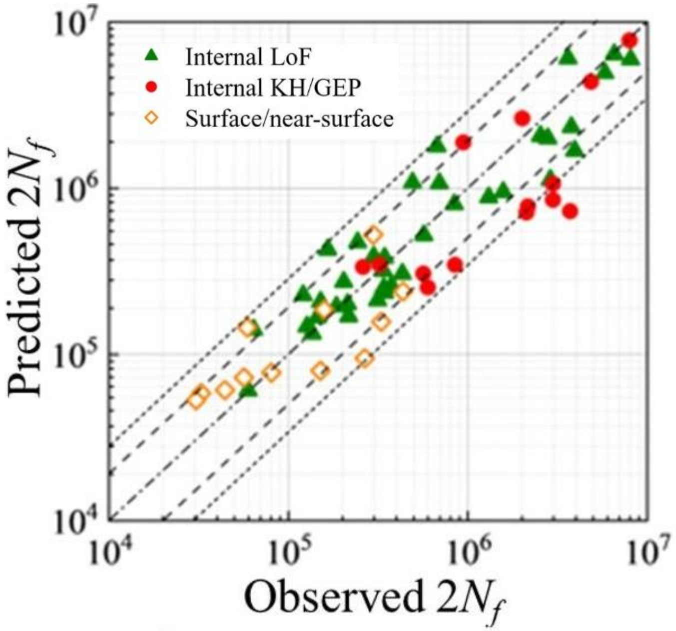
Shao & **Shamsaei** et al., Eng. Fract. Mech. 285 (2023) 109298.
El Haddad et al., Eng. Fract. Mech. 11 (1979) pp. 573-584.

LE-FEA of Cracks Initiated from Defects





$$\Delta K_I = K' F_\infty \Delta\sigma\sqrt{\pi l};\ F_\infty = 2/\pi$$



- 3D LE-FEA is performed to calculate stress intensity factor of cracks from internal and surface defects
- The fatigue life predictions made by the "crack arrest analysis" are satisfactory

✓ How about surface defects?

Shao & **Shamsaei** et al., Eng. Fract. Mech. 285 (2023) 109298.

Summary

- KH specimens exhibited better fatigue performance than recommended ones due to smaller crack initiating defect sizes
- LoF specimens exhibited more scatter in fatigue life due to differences in crack initiating defect sizes and their morphologies
- A morphological parameter alone could not explain the scatter in fatigue life
- Larger defects, located at or near surface, were more detrimental to the fatigue performance
- LoF defects had higher stress gradients, which could lead to more rapid reduction of driving force for cracks as they propagate away from the defect and induce crack arrest more easily
- More analysis will be performed to determine fatigue critical morphological features of defects in future

Thank You for Your Attention!

- National Center for Additive Manufacturing Excellence (NCAME)