National Center for Additive Manufacturing Excellence

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

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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

JAMS

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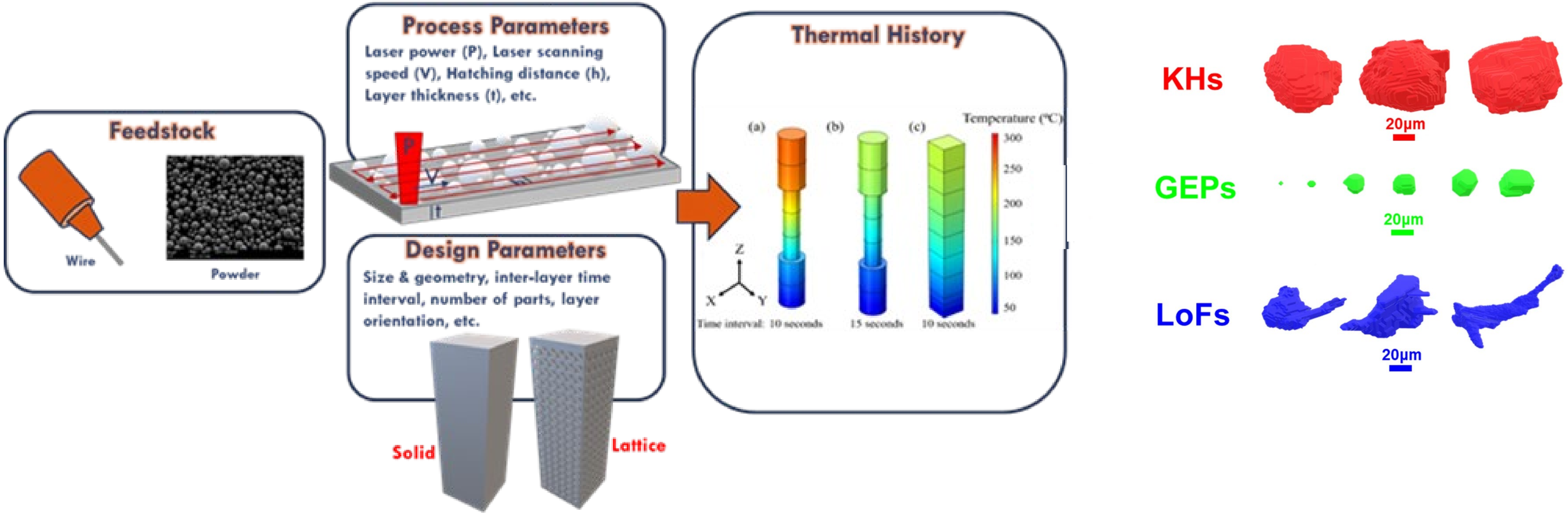
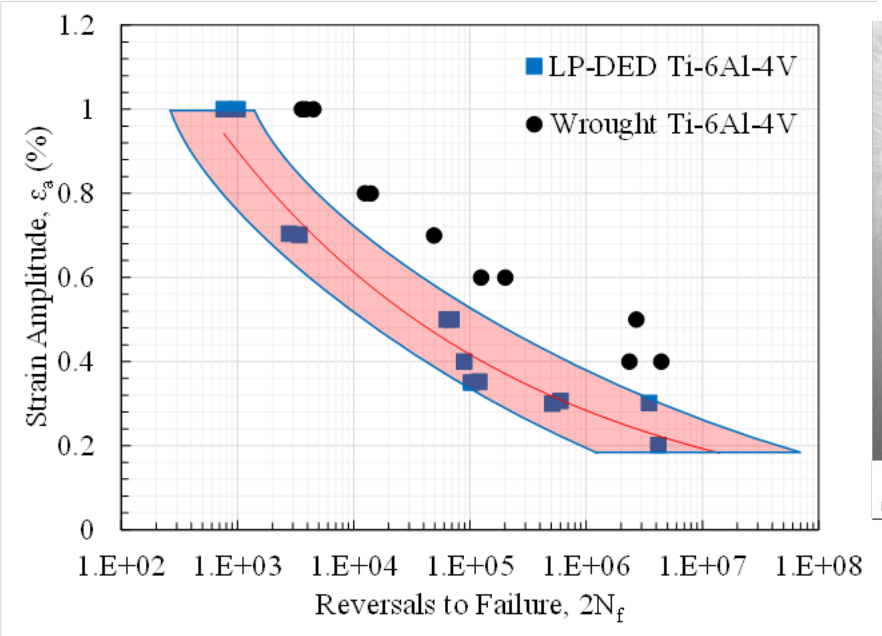
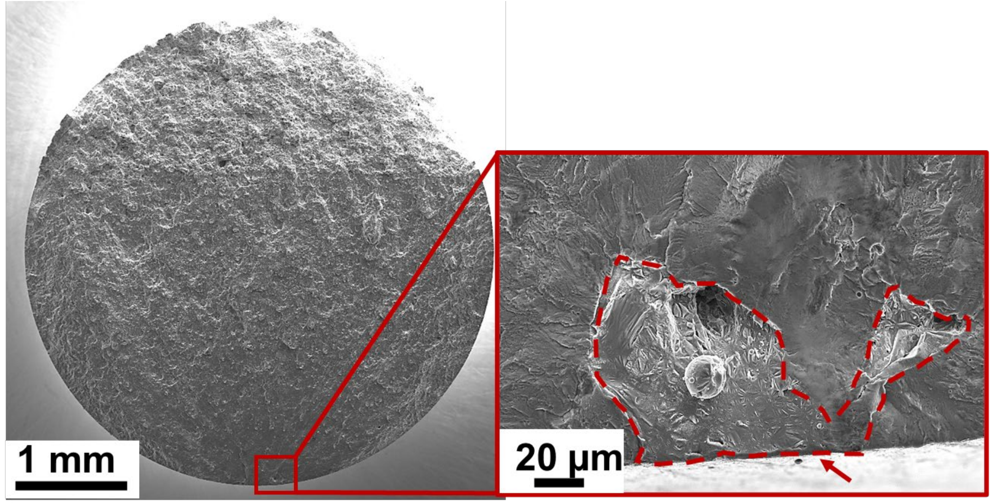
Background



- Low energy density during fabrication results in lack of fusion defects (LoF), and are irregular in shape
- High solidification rates often cause gas-entrapped pores (GEPs) to form, typically appearing as small, spherical voids
- Keyhole pores (KHs) arise from excessive energy density, leading to deep melt pool penetration and pore formation at the bottom, larger than GEPs

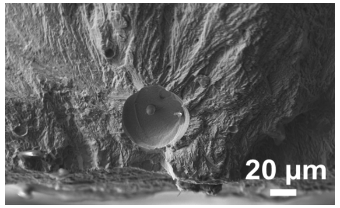
Background



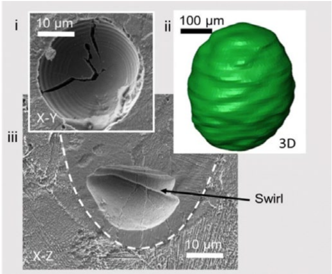


AM defects:

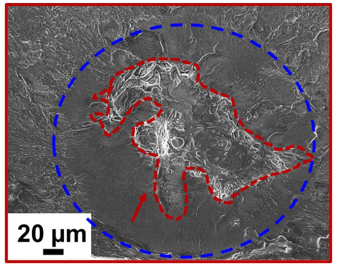
- Significantly reduce and introduce uncertainty to fatigue performance
- Influence of their morphologies are seldom studied
- The difference in their morphologies poses a significant challenge to quantifying their role in fatigue behavior



Gas-entrapped pores (GEPs)



Keyholes (KHs)



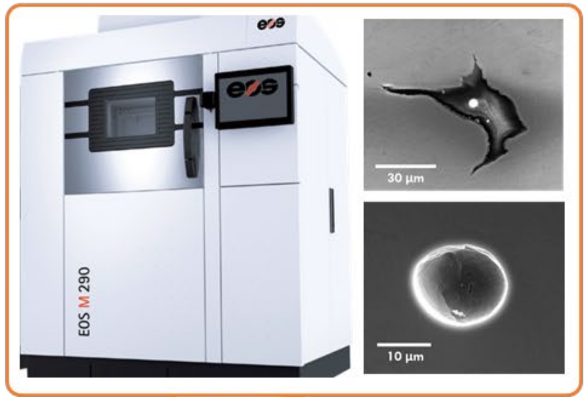
Lack of fusions (LoFs)

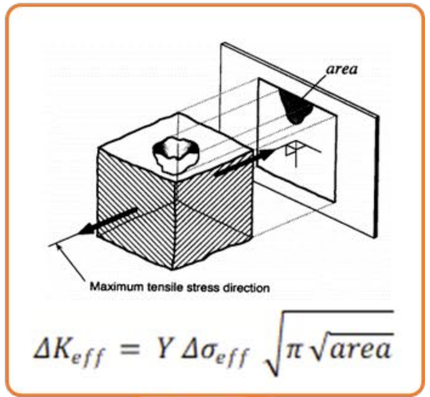
Shamsaei, et al. Int. J. Fatigue, 124: 188-204, 2019.
Snell, et al., Jour. Of. Mater., 72: 101-109, 2020.

Objective & Approach

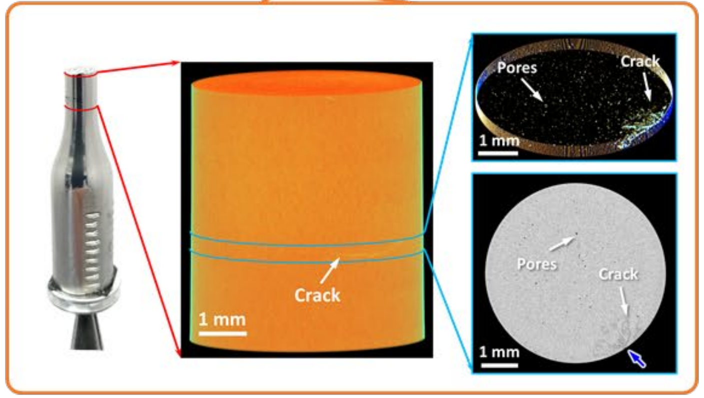
- **Objective**: To quantify the detrimental effect of volumetric defects on mechanical properties of L-PBF Ti-6Al-4V Gr. 5
- **Approach**: Three steps are taken,
  I. Explore process windows by varying laser power, scan speed, and hatching distance
  II. Determine the criticality of volumetric defects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

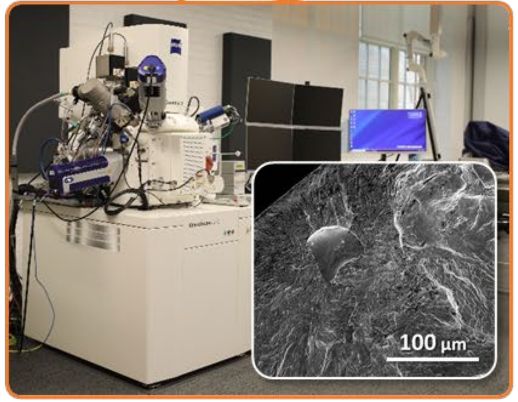
Overall Scope





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

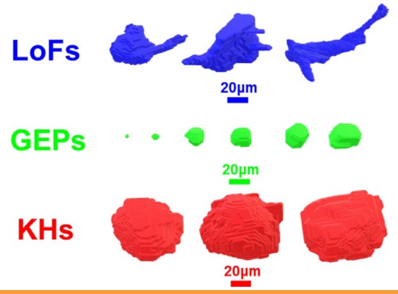
Design of experiments

Designation	Orientation	Process parameters variation (%)			Energy density $E = \frac{P}{vht}$ (J/mm^3)
		P	v	h	
Ua	V, D, H	-20	0	0	44.44
Ub	V, D, H	0	0	20	46.29
Uc	V, D, H	-10	0	0	50.00
Ud	V, D, H	-5	0	0	52.77
Ue	V, D, H	0	0	5	52.91
R	V, D, H	0	0	0	55.55
Oa	V	30	-20	0	90.28
Ob	V	20	-30	0	95.24

U: Underheated set

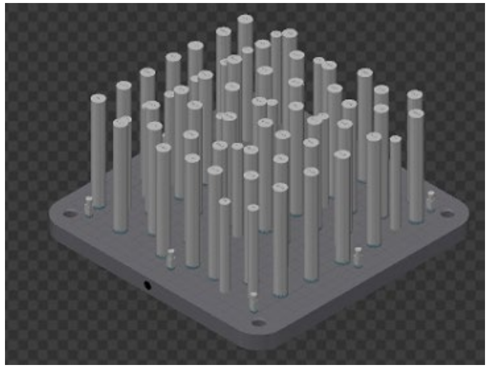
R: Recommended set

O: Overheated set

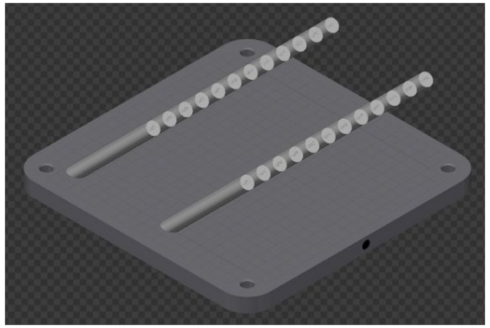


- 240 fatigue (20 x 12) and 100 tensile (20 x 5) specimens were fabricated

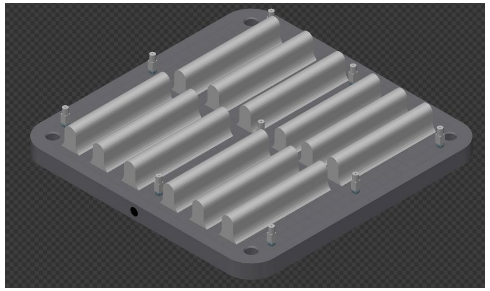
Vertical (V)



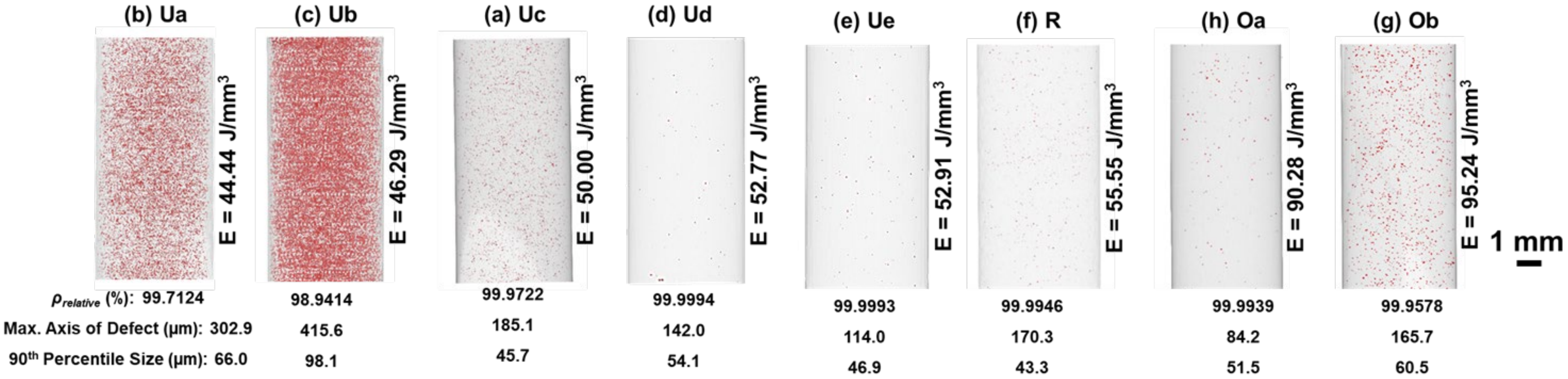
Diagonal (D)



Horizontal (H)



Defect contents: Fatigue specimens



X-ray computed tomography (XCT) was performed on vertical fatigue specimens with 5.5 μm voxel size

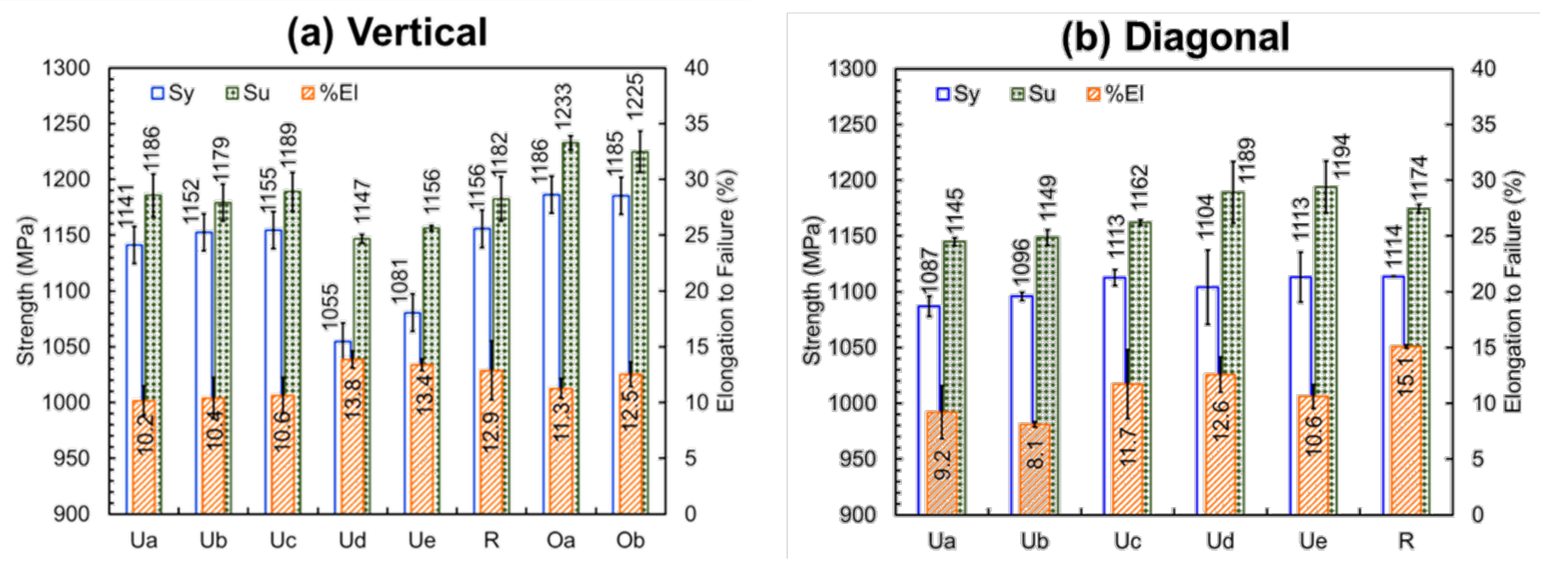
Energy density

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

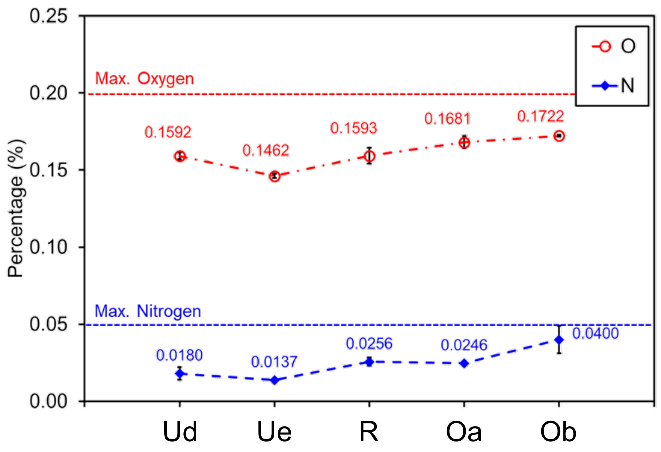
P: Laser power
V: Laser speed
h: Hatch distance
t: Layer thickness

- 240 fatigue (20 x 12) and 100 tensile (20 x 5) specimens were fabricated
  - Lack of fusion (LoF): $P^{-10\%}$ (Ua), $P^{-20\%}$ (Ub), $H^{+20\%}$ (Uc), $P^{-5\%}$ (Ud), and $H^{+5\%}$ (Ue)
  - Keyhole (KH): $P^{+20\%}V^{-30\%}$ (Oa) and $P^{+30\%}V^{-20\%}$ (Ob)
- A comparative analysis of defect morphologies across specimen sets revealed substantial variation in defect size and other relevant features

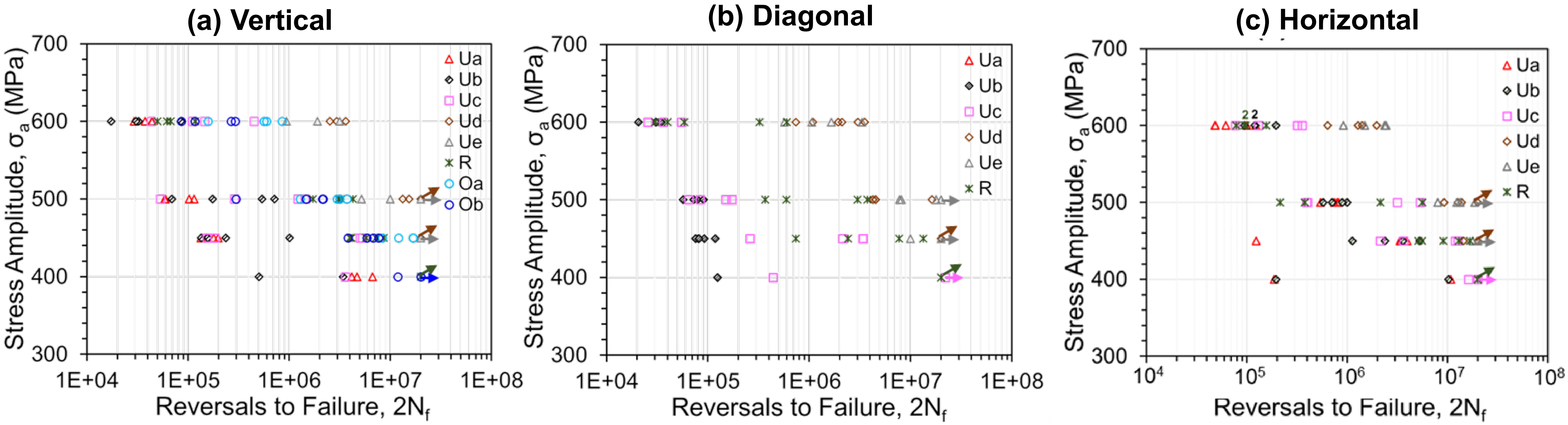
Tensile properties



- Overheated specimens exhibited slightly higher strength than recommended ones, mostly due to higher content of nitrogen
- Defects in underheated specimens negatively impacted the ductility compared to the recommended one, contributing to the early onset of final fracture

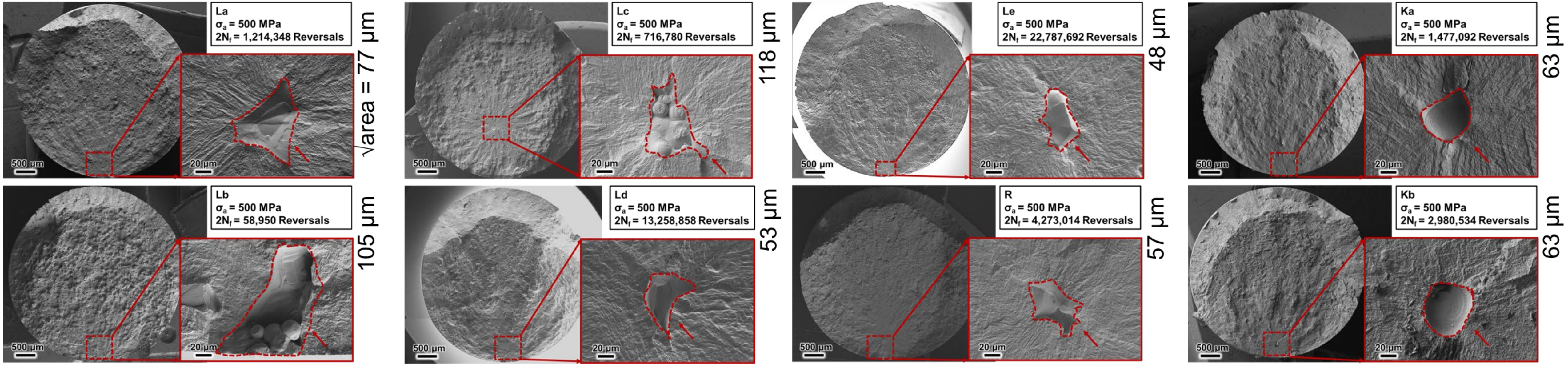


Fatigue behavior



- On average, KH specimens exhibited better fatigue performance than the recommended ones due to both smaller crack initiating defect size than the recommended ones
- Scatter in the fatigue behavior of LoF specimens may be attributed to the variation in the crack initiating defects' morphology and location

Fatigue fractography

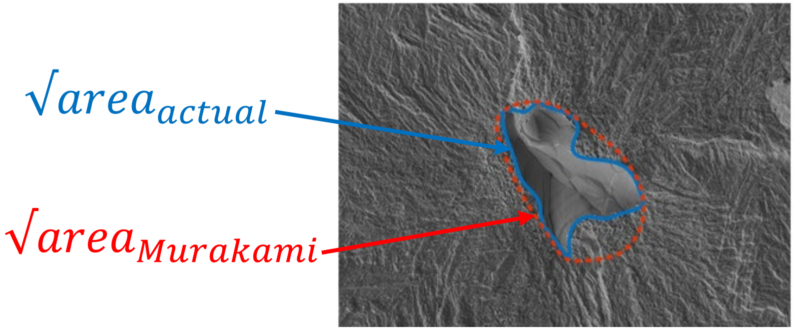


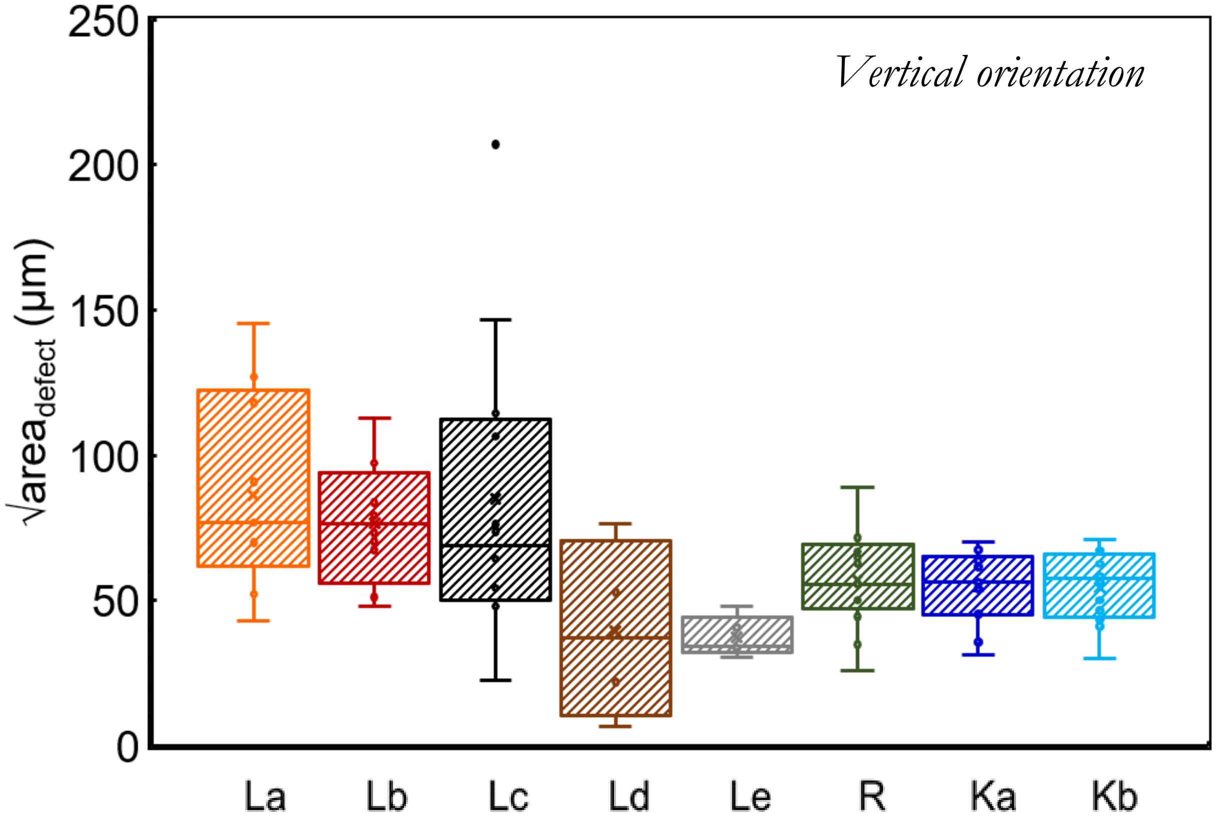
Note: All fractographies are from vertical specimens. √area of crack initiating defects is shown on the top right side of the fractography images

- 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

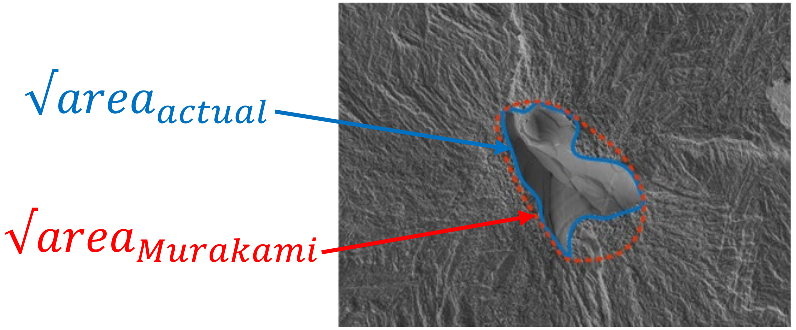
Critical defect sizes

- 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 to some extent

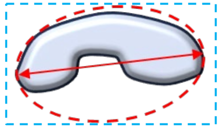




2D morphological features



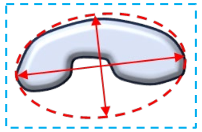
Max. axis



Circularity

$$\psi = \frac{4\pi.\text{Area}}{(\text{Perimeter})^2}$$

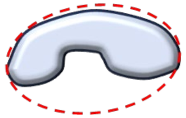
Min. axis



Solidity

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

Roundness

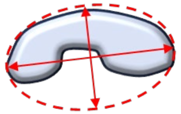


$$\text{Roundness} = \frac{\text{Equiv. dia.}}{\text{Max. axis}}$$

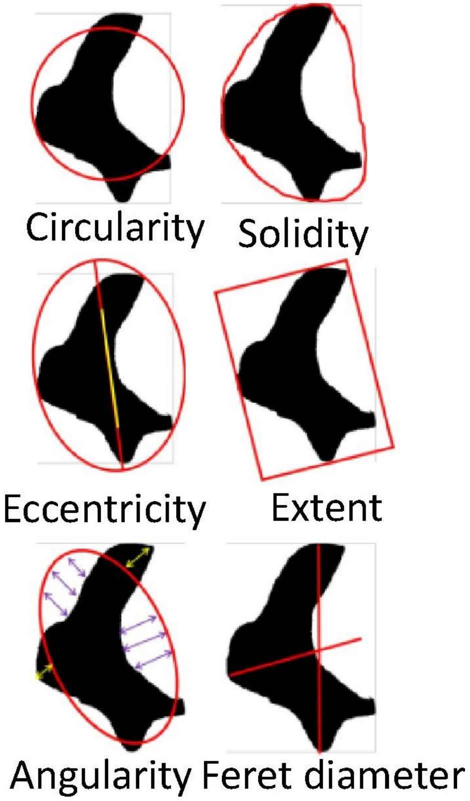
Extent

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

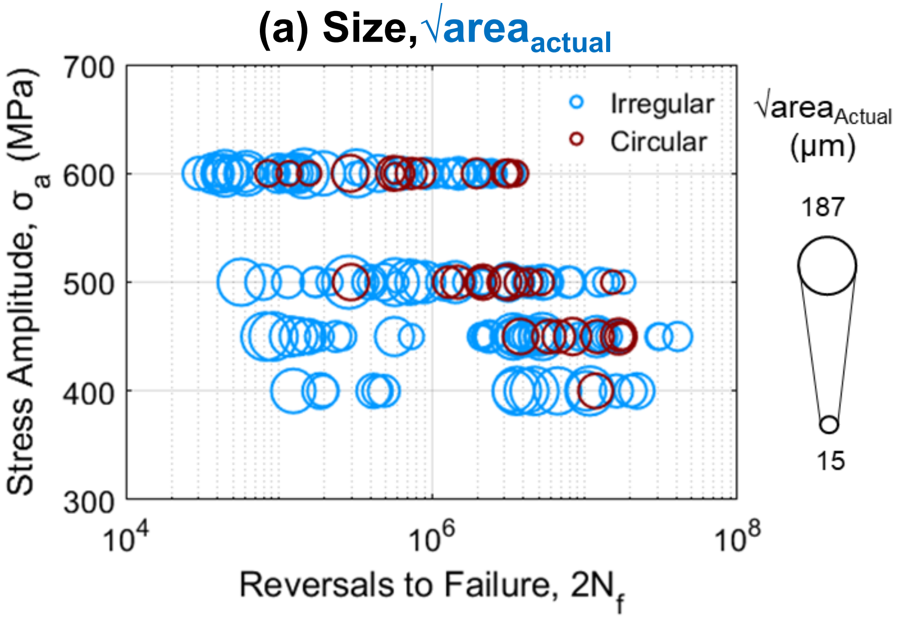
Aspect ratio

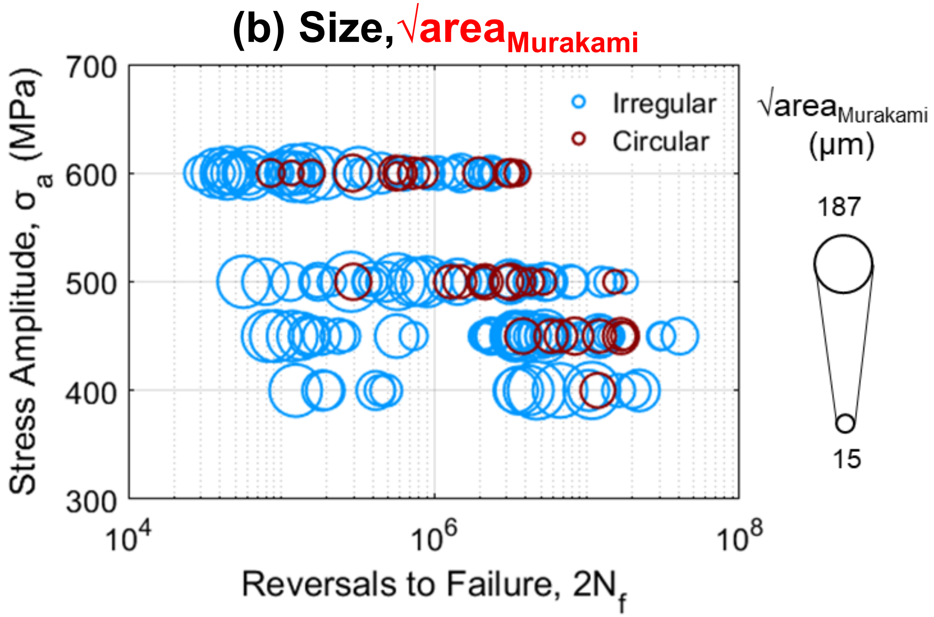


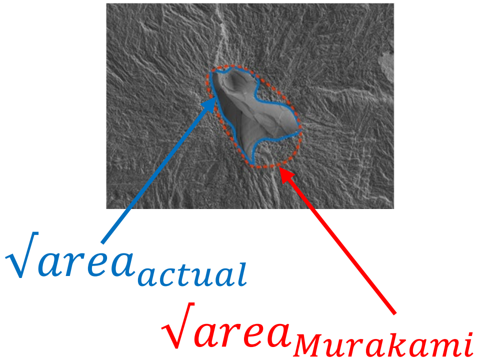
$$\text{Aspect ratio} = \frac{\text{Min. axis}}{\text{Max. axis}}$$



Effect of defect size on the fatigue behavior

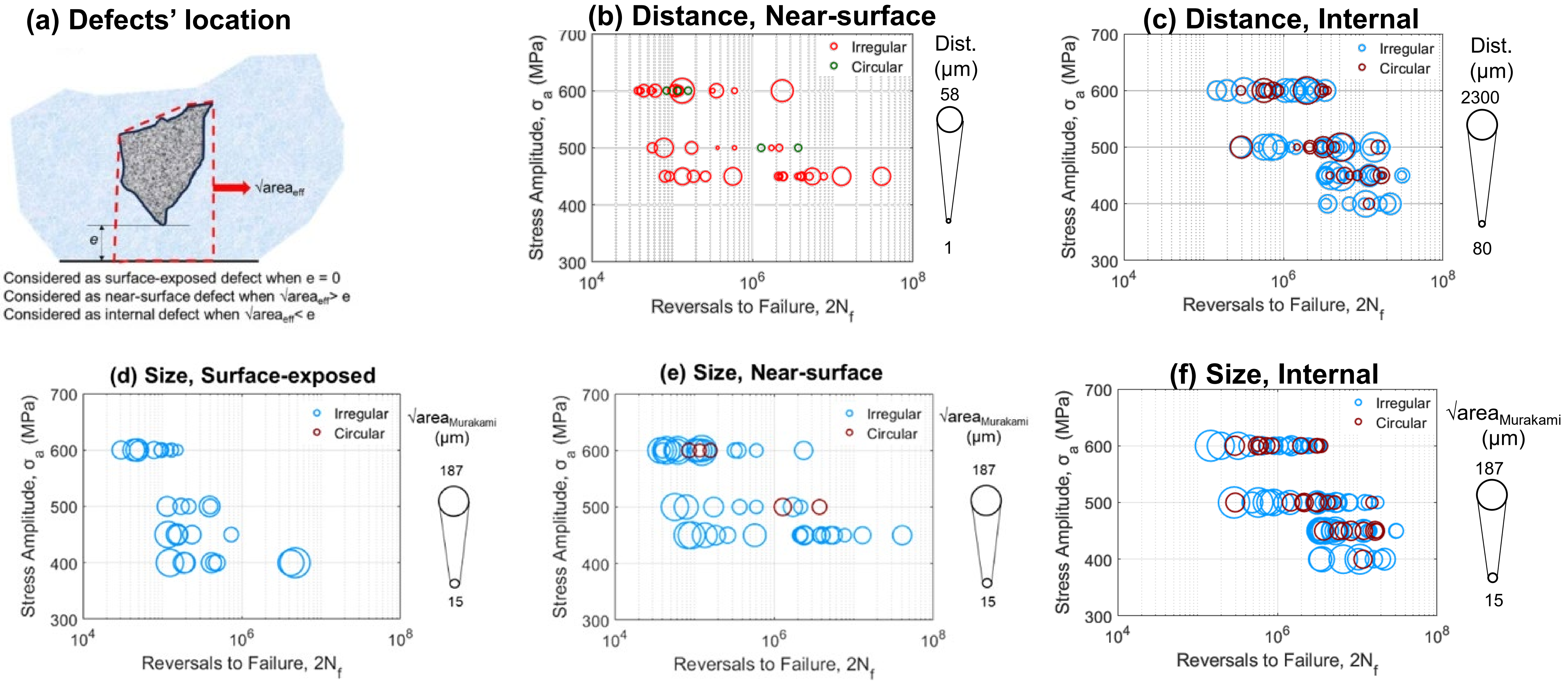




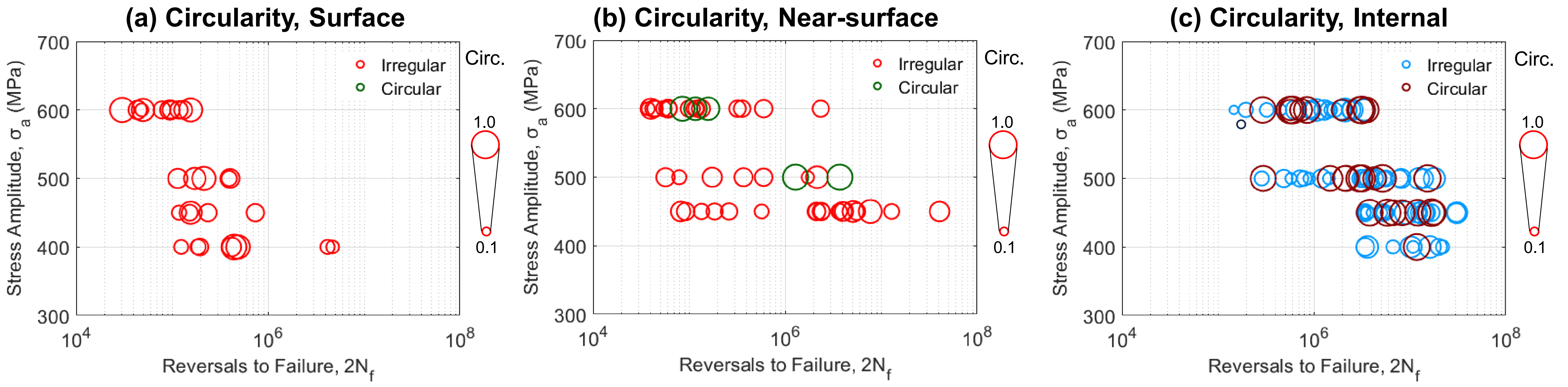


- Size is the most important parameter of a defect influencing the fatigue performance
- Size alone could not explain the order of fatigue lives
- At similar fatigue life, size of circular defects are appearing to be smaller than the irregular ones

Effect of defect location on the fatigue behavior

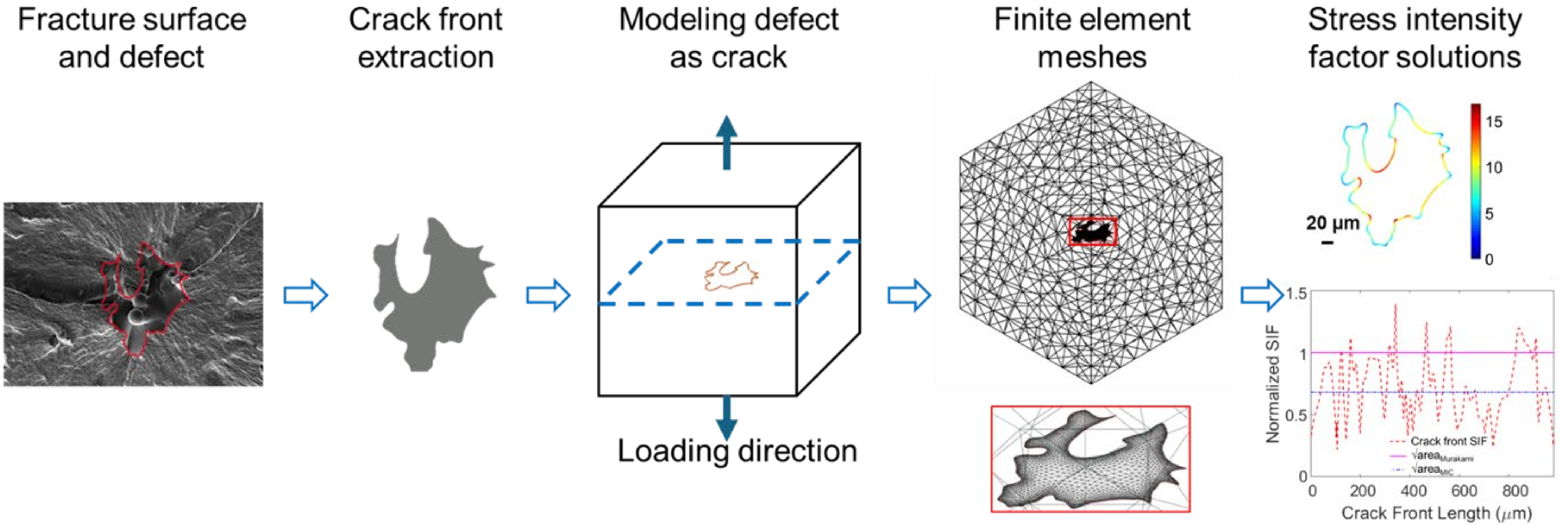


Effect of defect shape on the fatigue behavior



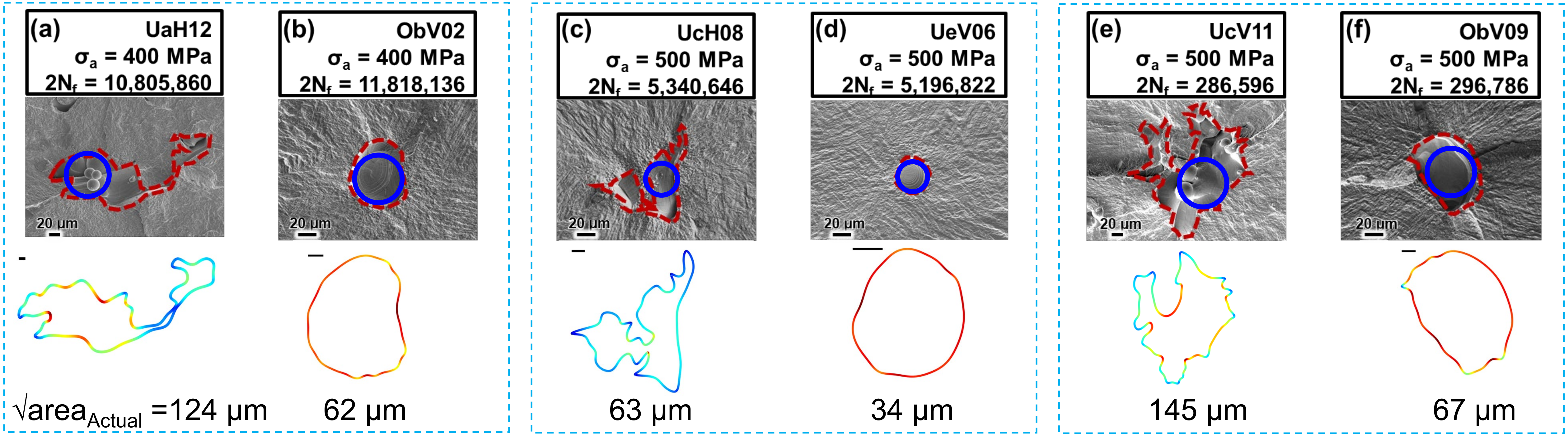
- Circularity alone did not exhibit a clear trend
  - Sub-set of similar sized defects indicated that circular/near-circular defects (i.e., KH/GEP) might be detrimental to the fatigue performance of the surface defects than irregular shaped ones

Numerical analysis procedure



- The crack was modeled as internal crack in an infinite body for simulations
- Size of the crack front element was kept same as that of embedded penny crack of similar size for which the converged stress intensity factor solutions are obtained

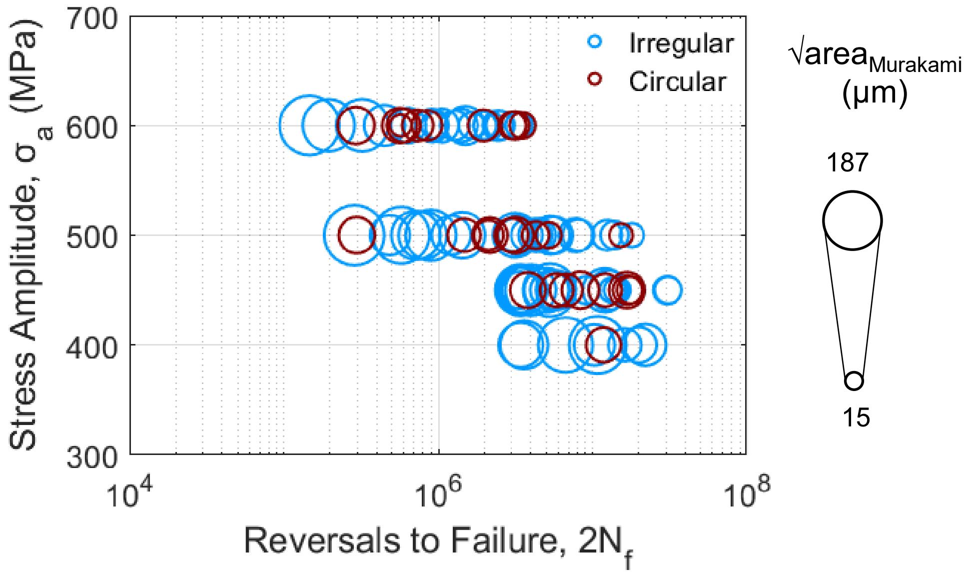
Effect of defect shape on the fatigue behavior



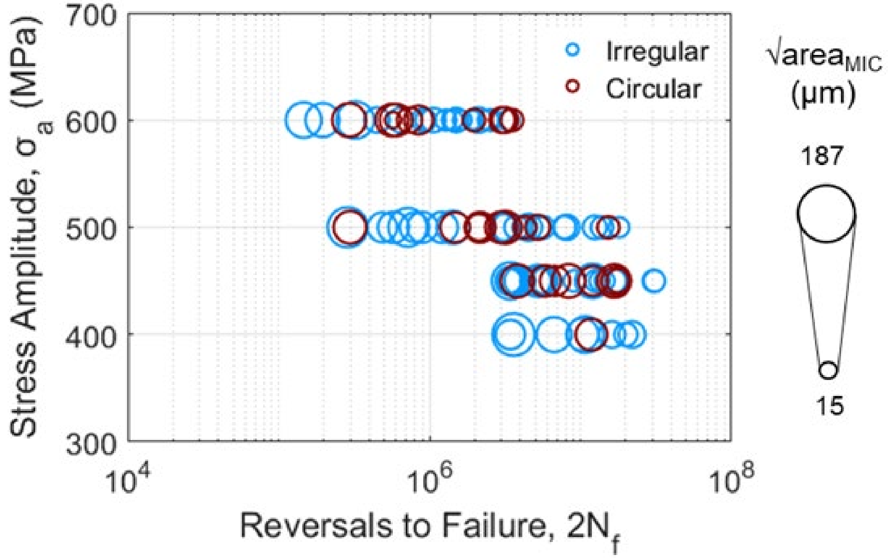
- Circular defects have a contour of uniform SIF, leading to
  - Higher probability of crack initiation
- In irregular shaped defects, SIFs the interior region of the defect, rather than from its sharp features
  - Lower probability of crack initiation compared to circular defects

Effect of defect shape on the fatigue behavior (internal)

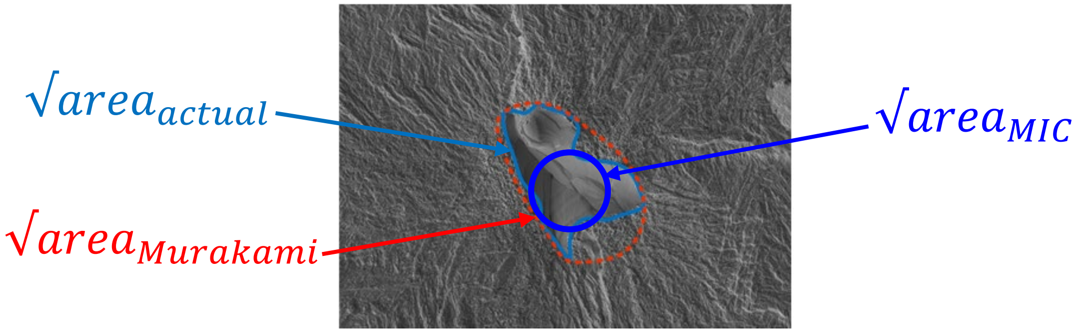
$\sqrt{area}_{Murakami}$



$\sqrt{area}_{MIC}$

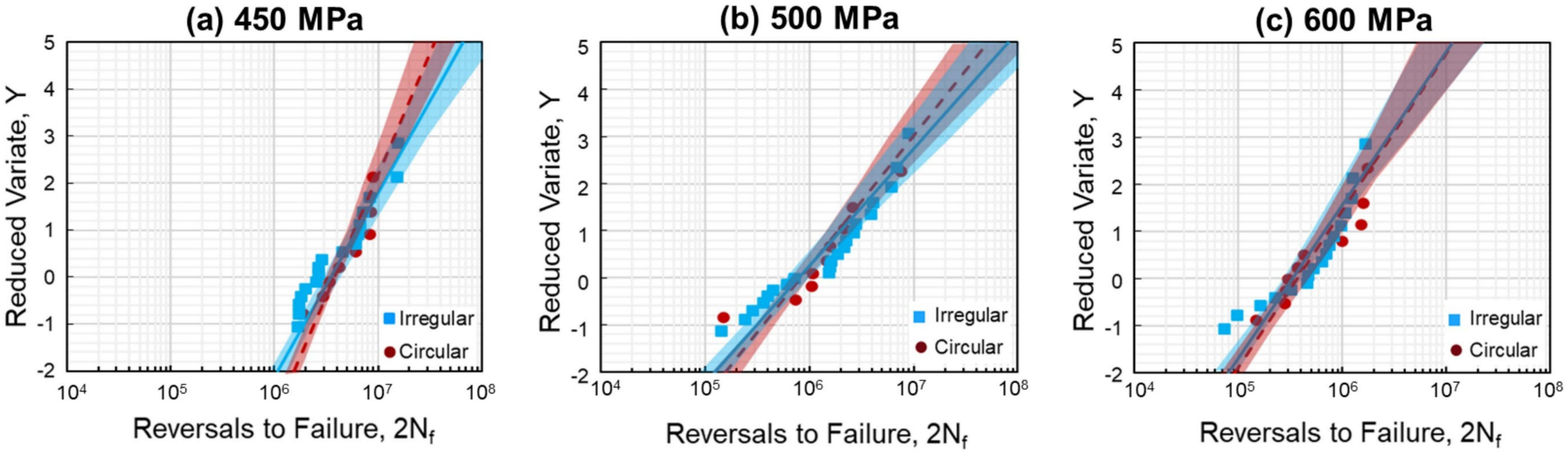


- The fatigue behavior is more consistent when using the $\sqrt{area}_{MIC}$ as defect size
- $\sqrt{area}_{MIC}$ accounts for defect shape as well



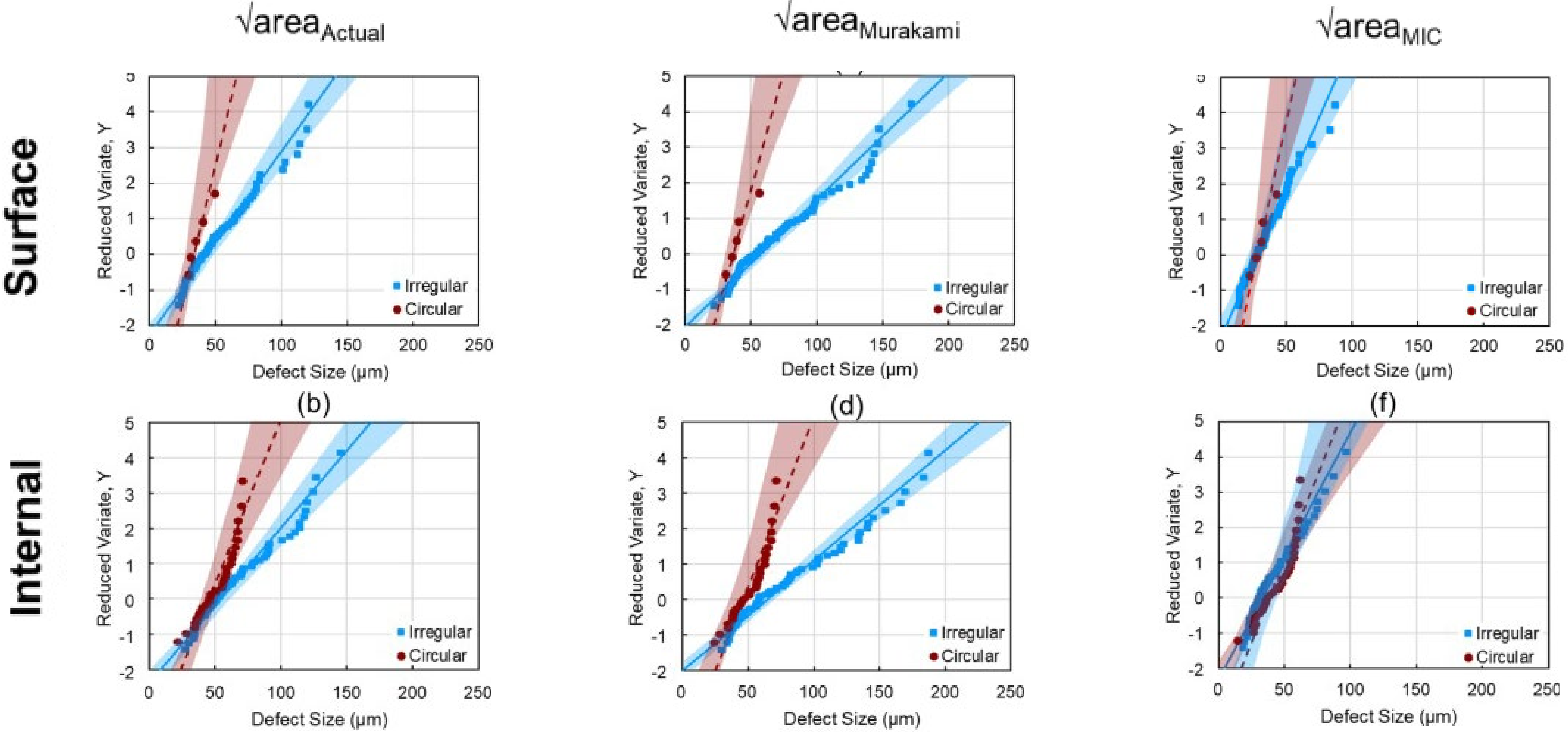
Probability density plots for fatigue life

- Probability density function of largest extreme value distribution using the non-parametric moments method in terms of reduced variate, Yi, $Y_i = -\ln\left(-\ln\left(\frac{i}{N+1}\right)\right)$



- Distribution of circular and irregular defects are identical
- If the defect size measure is appropriate, the probability density plots of both defect types should be identical

Probability density plots for defect size measures



- Distribution of circular and irregular defect sizes are similar when measured using $\sqrt{area}_{MIC}$

Summary

- Defect location significantly influenced the fatigue behavior of AM specimens, with surface defects being more critical than internal ones
- Defect size estimated with the existing approaches could not adequately represent the severity of defects by addressing their shape
- The proposed defect size parameter, $\sqrt{area}_{MIC}$ could account for the effect of defect shape
- Accurate fatigue life predictions were obtained when using the proposed defect size parameter for internal defects

Thank You for Your Attention!

- National Center for Additive Manufacturing Excellence (NCAME)