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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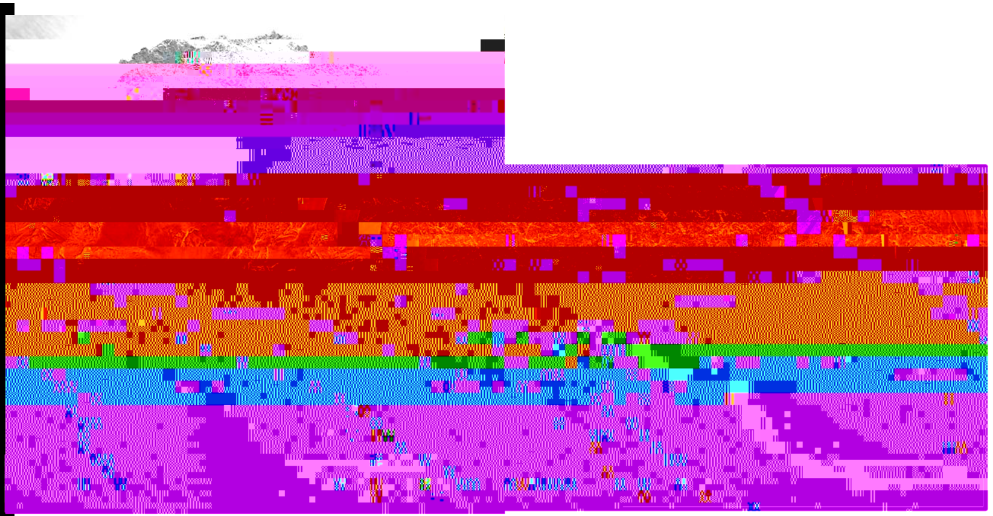
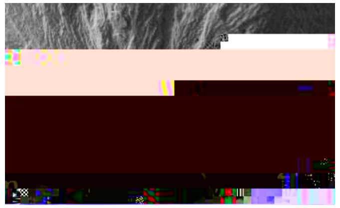
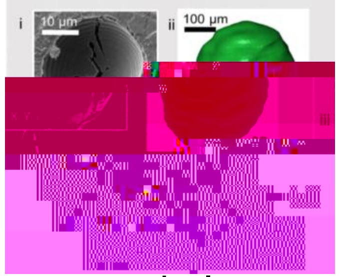
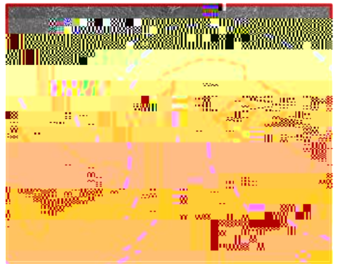




Gas-entrapped pores (GEPs)



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

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

: 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

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

E —

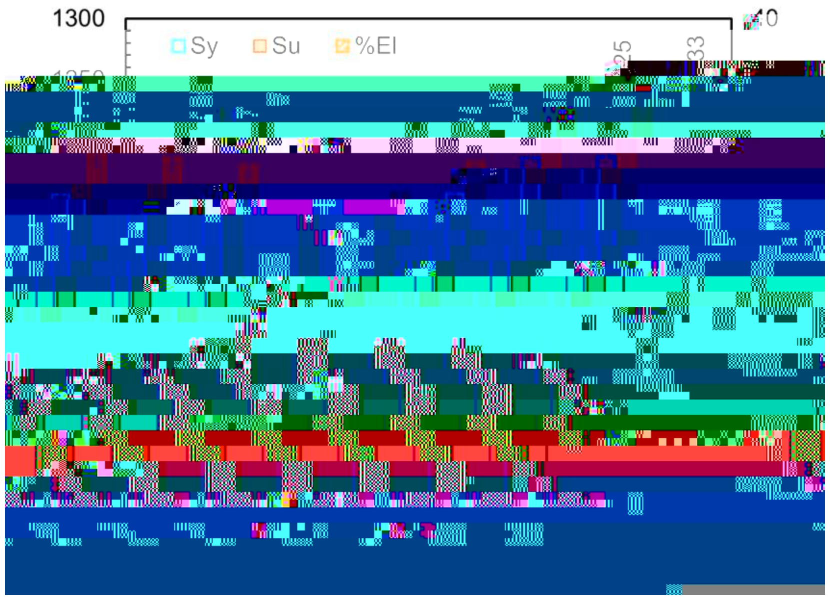
P: Laser power
V: Laser speed
h: Hatch distance
t: Layer thickness

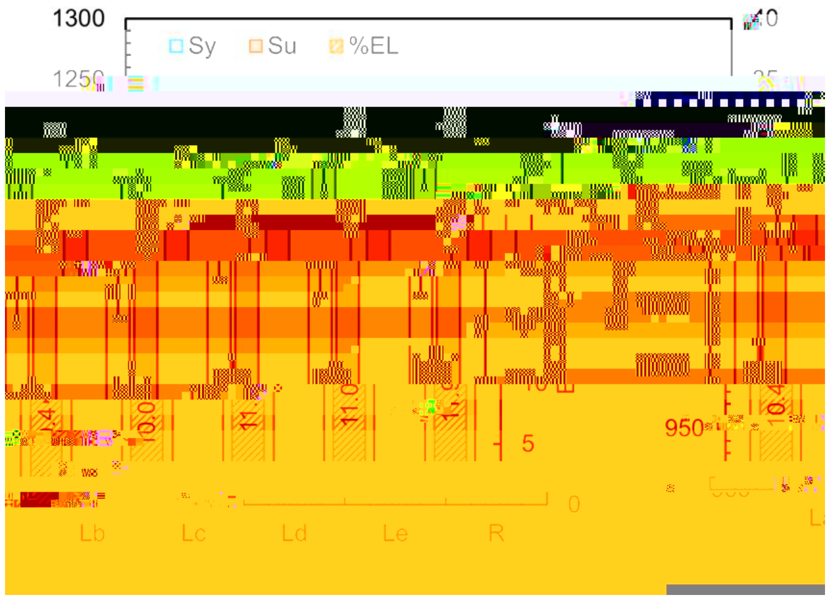
Note: Original plan was to fabricate specimens with 6 sets of process parameters, we fabricated 2 two extra sets (Ld and Le)
X-ray computed tomography (XCT) was performed on vertical fatigue specimens with 5.5 µm voxel size

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





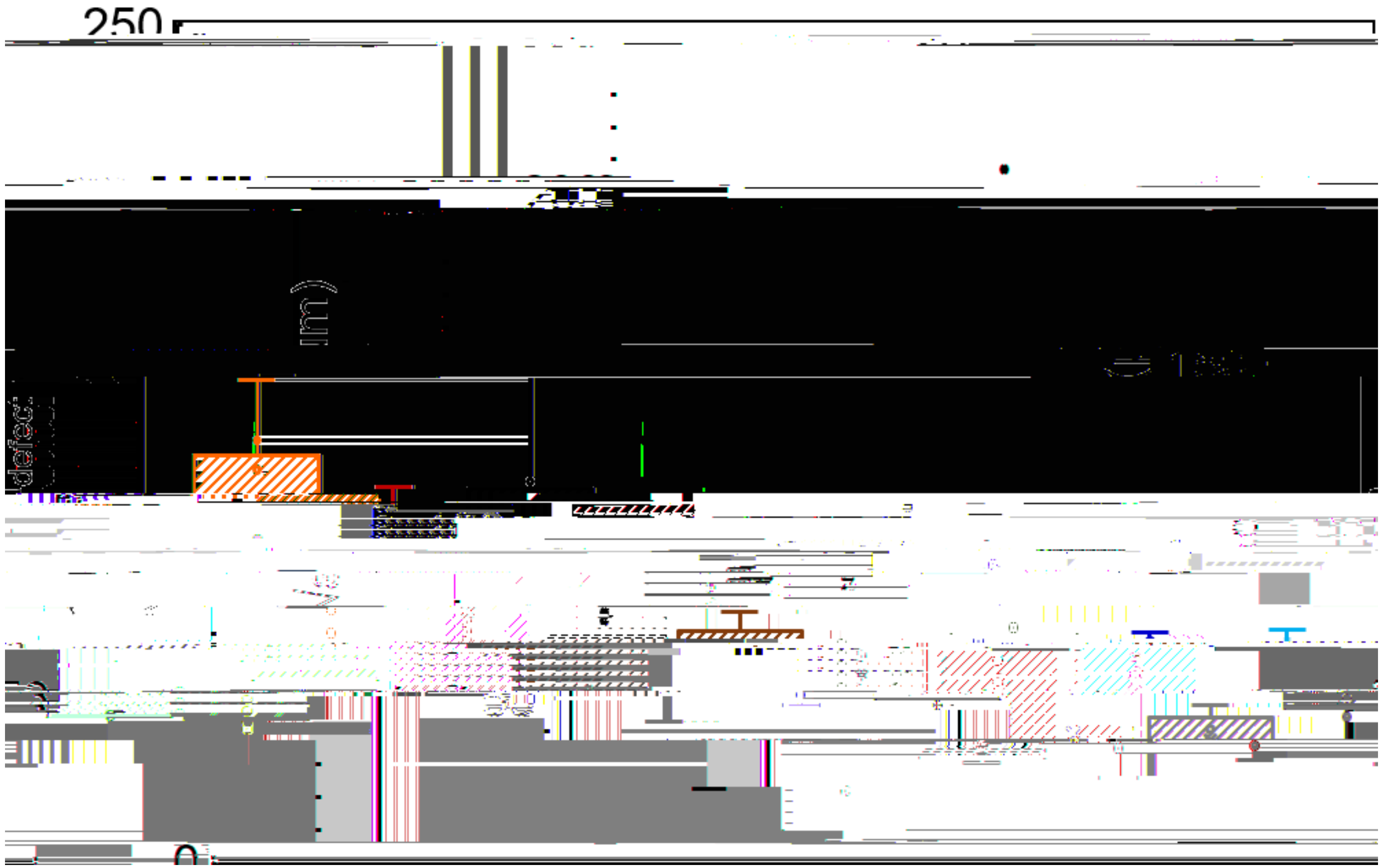
Yield strength (YS) and ultimate tensile strength (UTS) of all specimens were almost comparable

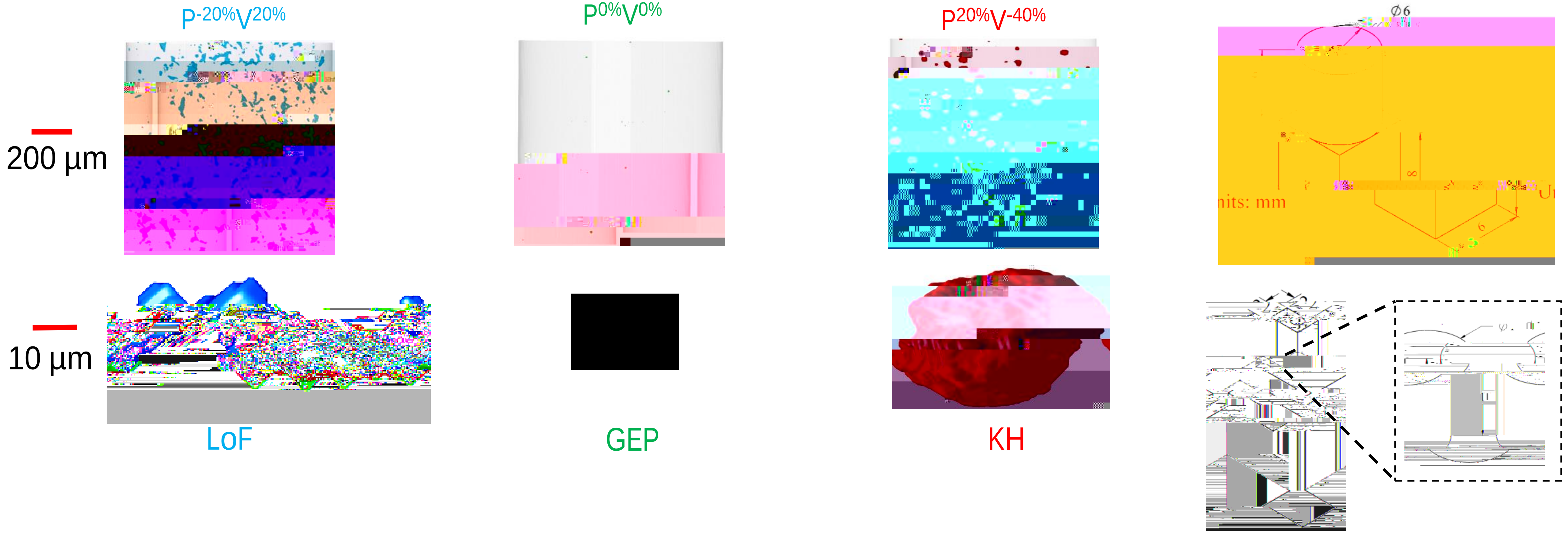
KH specimens had slightly higherslightly

- 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 540 0b3ide exhibited worse ecommended ones

Defect sizes were measured using actual ãarea of the defect

The size of the fatigue crack initiating defects of recommended and KH





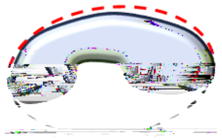
Defects are inherent to the AM process and their morpholoe96 o641 rg2 T14305 0 960 540 reW*n4 reW*n119.16 0 0

Solidity

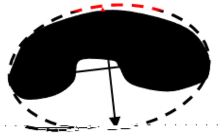
Sparseness

Extent

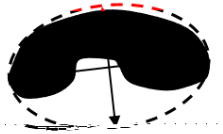
Roundness

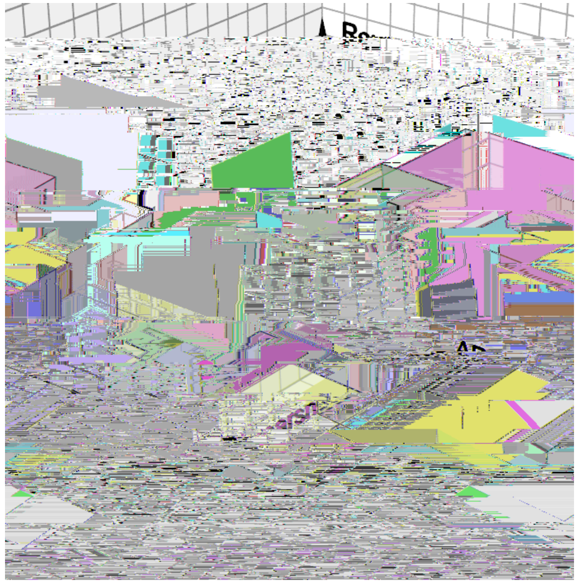


Elongation



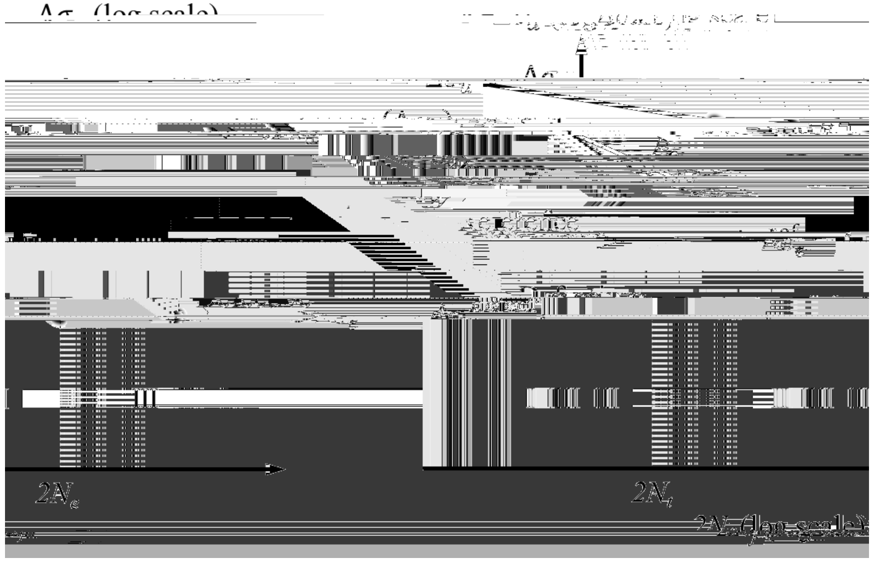
Flatness

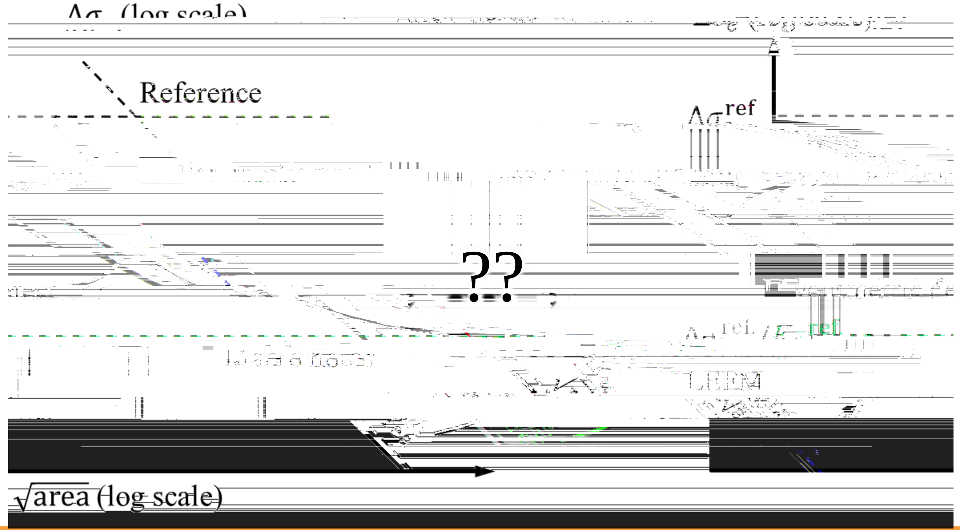




Simultaneous usage of several discriminating parameters can more effectively describe the geometric feature of a defect

Although different defect types have overlaps in all parameters, usage of more parameters can improve the classification accuracy



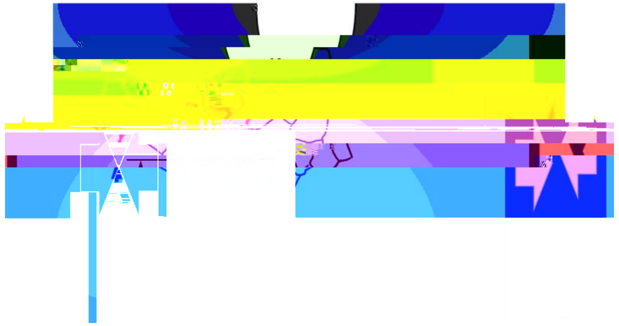


Volumetric/surface defects act as stress risers and can accelerate fatigue crack initiation

Notch-factor approach can account for the effect of volumetric/surface defects

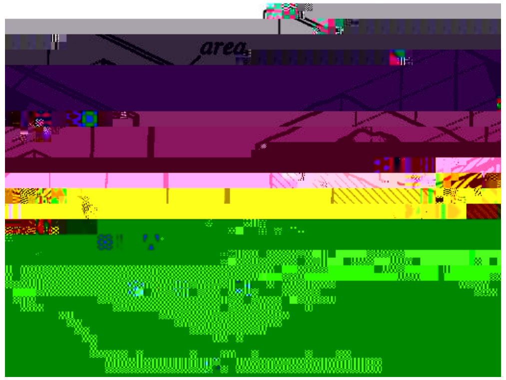
The extremely large defects behave like macro notches.

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



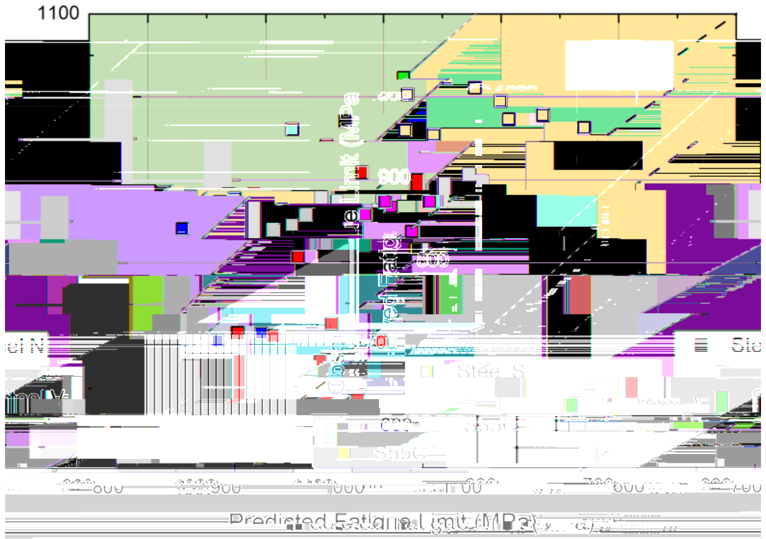
Budynas and Nisbett, . 11 ed., New York, NY, McGraw-Hill Education, 2020.
Yamashita, Murakami, Mihara, Okada, and Murakami, International Journal of Fatigue, , 485-495, 2018.

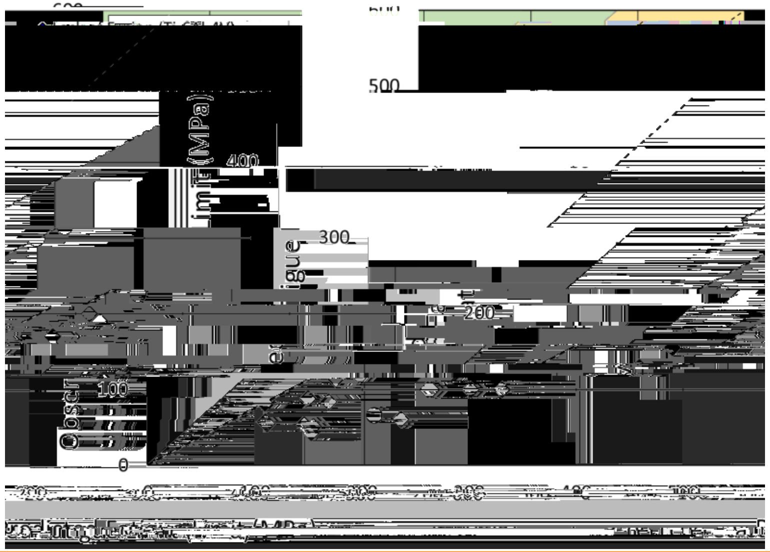
Murakami's defect sensitive fatigue (DSF) model



Surface defects:
Internal defects:

Surface defects:
Internal defects:





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

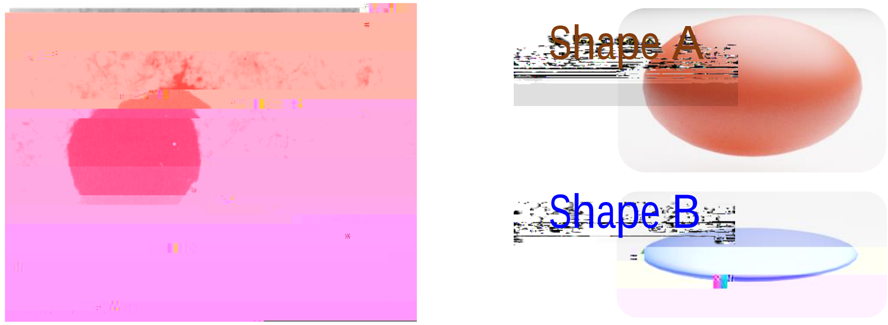
AM materials loaded below fatigue limit are believed to endure indefinitely but are

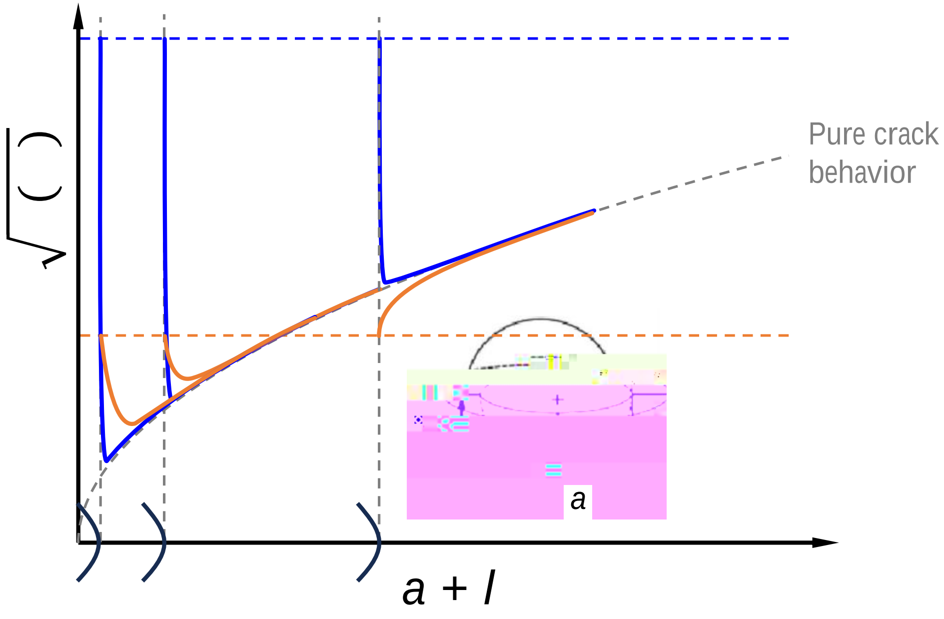
Instead, small cracks initiated from defects can be arrested

The rapidly reducing stress away from defects can cause the effective stress intensity factor range ( ) to first decrease before increasing:

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

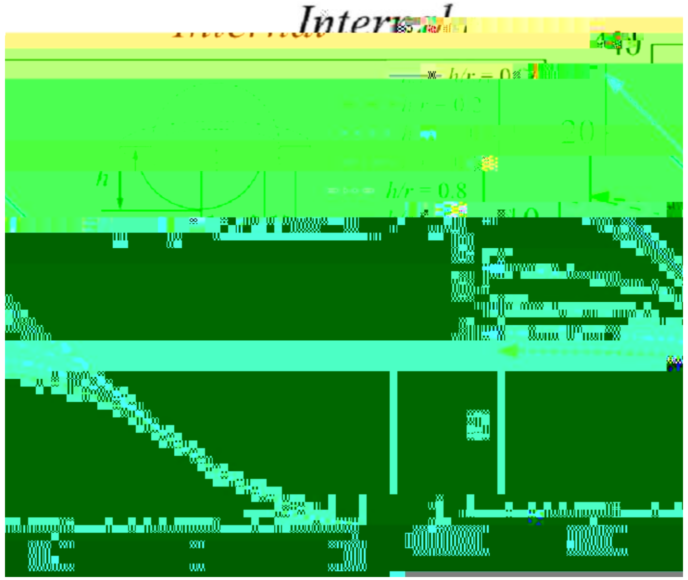
The effects of defectsʹ size, shape, and location are implicitly incorporated in the ʺcrack arrest analysisʺ





How to calculate ( )?

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



√ ;

3D LE-FEA is performed to calculate stress intensity factor of cracks from internal and surface defects

The fatigue life predictions made by the òcrack arrest analysisó are satisfactory

How about surface defects?

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

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

National Center for Additive Manufacturing Excellence (NCAME)