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Fracture mechanics-based approach for anomaly size acceptability of additively manufactured metals

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Simone Romano, Andrew C. Perry, Francesco Sausto, Apostolos Karafillis

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Presenter and co-authors

Dr. Simone Romano
Advanced Lead Engineer
Life Methods

Dr. Andrew C. Perry
Principal Engineer
Materials Science and Engineering

Dr. Francesco Sausto
Scientist
Life Methods

Dr. Apostolos Karafillis
Chief Consulting Engineer
Mechanical components

Agenda

– 01 **Anomalies in AM materials**

– 02 **Motivation and scope**

– 03 **Approach for acceptability limit definition**

– 04 **Limitations of cut-ups and rationale for AFS definition**

– 05 **Overview of the approach**

– 06 **Curve derating**

– 07 **Validation**

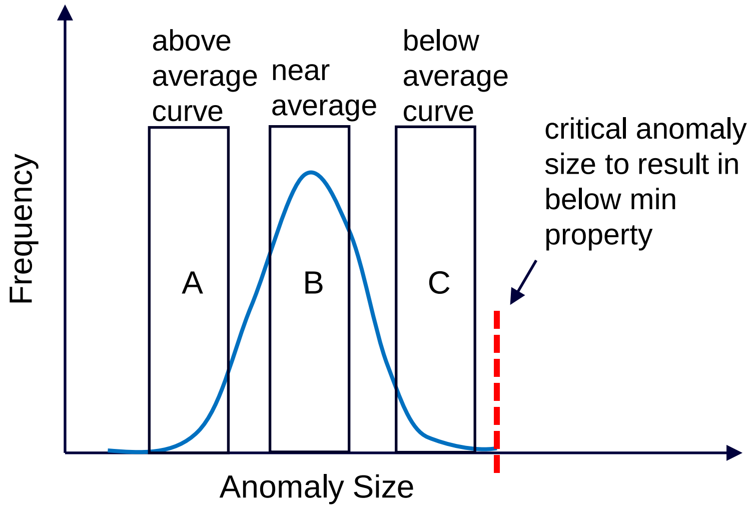
– 08 **Conclusions and perspectives**

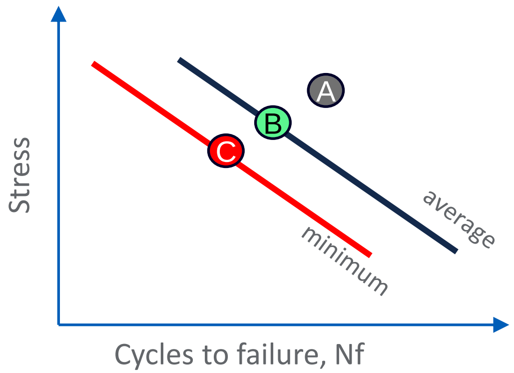
Anomalies in AM materials

Inherent anomalies, produced within process control limits

Examples:

- Bulk porosity,
- Surface connected porosity
- Downskin features





Allowed inherent flaw size must be consistent with fatigue design curve

Unusual/Rogue Flaws, produced outside of process control limits

Examples:

Lack of Fusion Due to

- Dropped vectors
- Short feeds
- Process interruption
- Support failure
- Recoater interaction

Thermal Stress Cracking

Unusual flaws can be addressed by defect tolerant design, process parameter control, process monitoring, and NDT inspection

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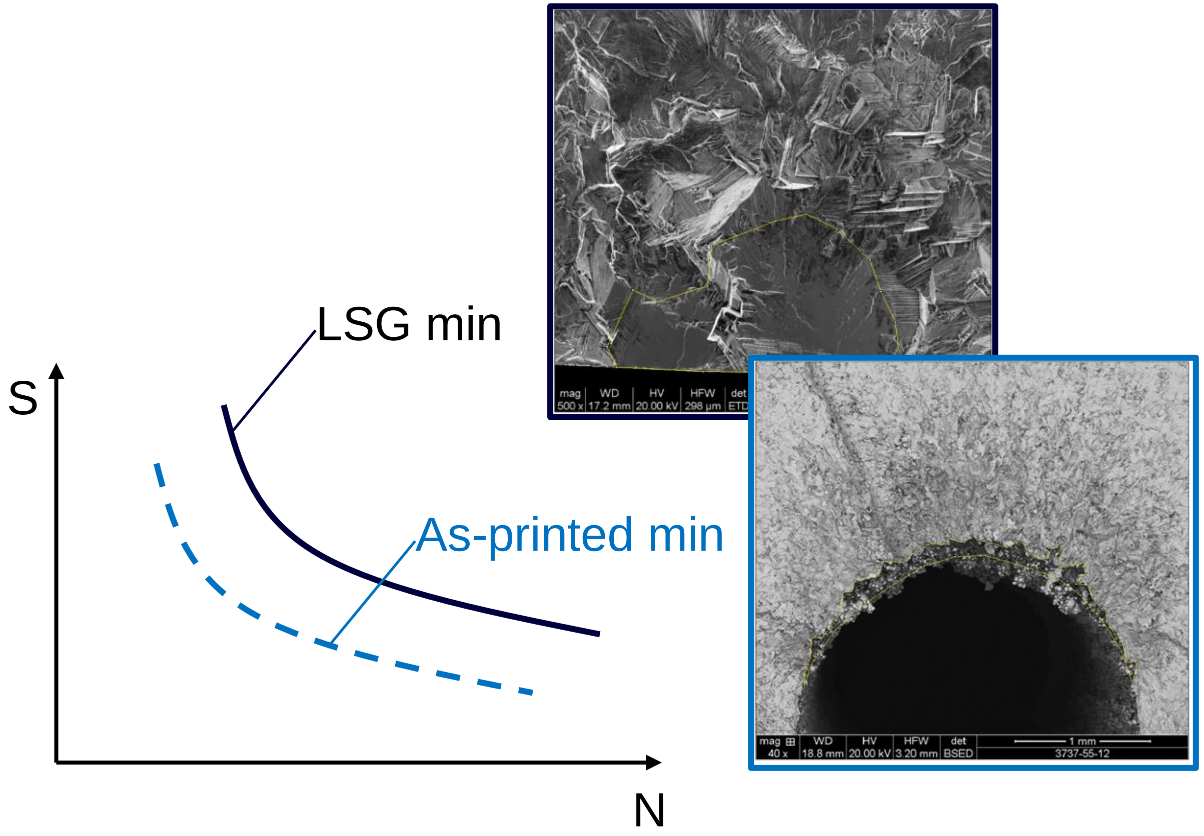
Motivation and scope

- **Initiation life** evaluation based on fatigue (LCF, HCF) tests → effect of small *inherent anomalies* (i.e., output of a process under control) included in min design curves
- An anomaly smaller than those embedded in the fatigue specimens does not introduce debit to the min curve
- Inherent anomalies (accounted by design) shall be acceptable. Acceptability size depends on specimens' quality (i.e., smaller for LSG than for as-printed)

Need for definition of acceptability limits in material specs



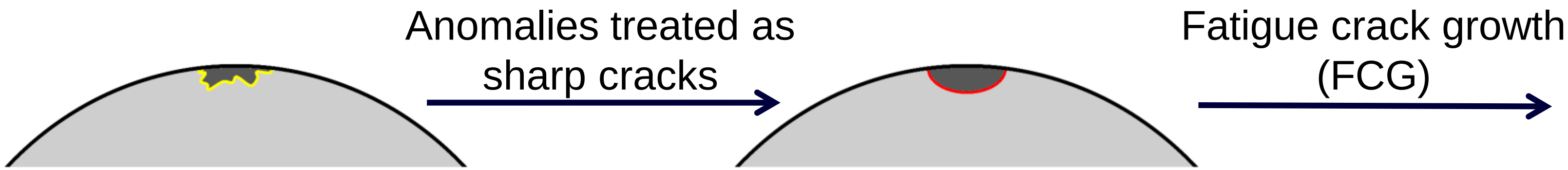
AMC E 515, "Some construction techniques, such as welding or casting, contain inherent anomalies. Such anomalies should be considered as part of the methodology to establish the Approved Life. Fracture mechanics is a common method for such assessments."

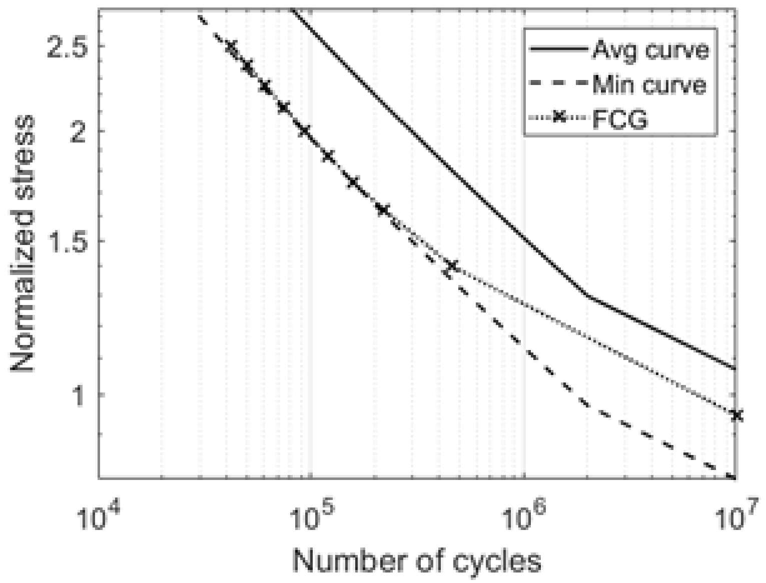
Scope: definition of acceptability limits for inherent anomaly size of AM metals based on fracture mechanics, aimed at augmenting the traditional building block of fatigue test-based material capability assessments.

Approach for acceptability limit definition

Curve minima are controlled by largest anomaly → acceptable flaw size is the largest crack that doesn't grow to failure before design intent based on minimum material curve.

Testing all conditions is unfeasible, fracture mechanics provides a robust transfer function between anomaly size and fatigue performance and covers cases when anomaly population in parts differs wrt tested coupons.



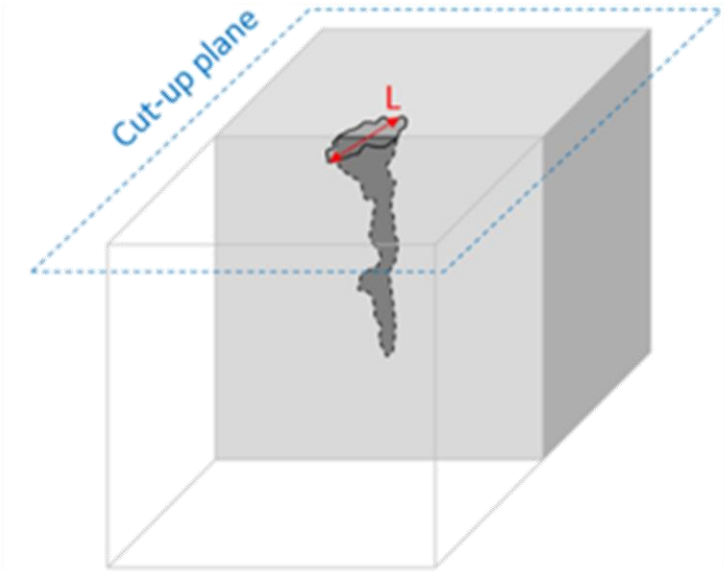


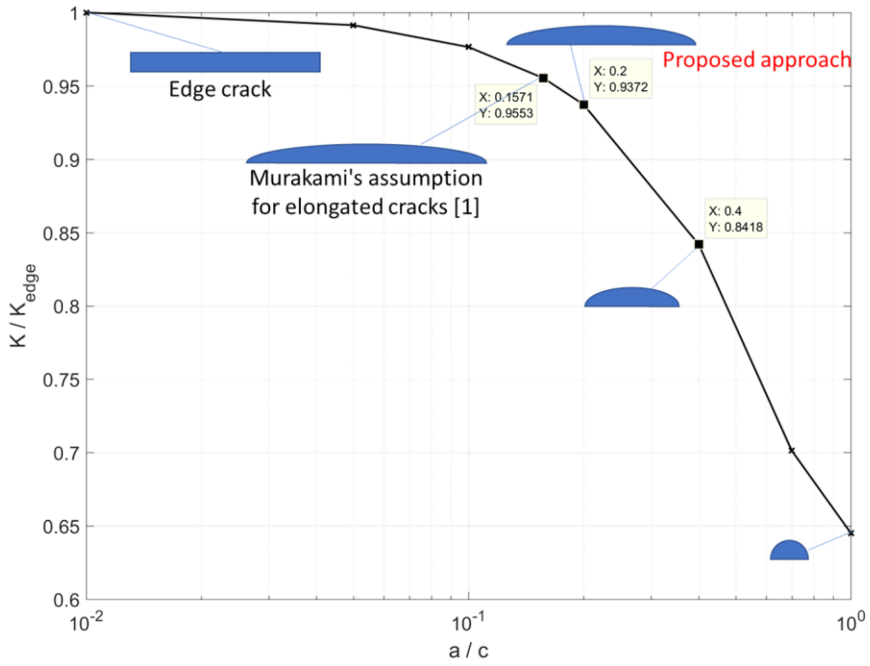
Short cracks model included via Kitagawa-Takahashi diagram (El-Haddad's formulation with Murakami's $\sqrt{\mathrm{area}}$ parameter):

$$\Delta K_{\mathrm{th}}(\sqrt{\mathrm{area}}) = \Delta K_{\mathrm{th,lc}} \sqrt{\frac{\sqrt{\mathrm{area}}}{\sqrt{\mathrm{area}_0} + \sqrt{\mathrm{area}}}}$$

Limitations of cut-ups and rationale for AFS definition

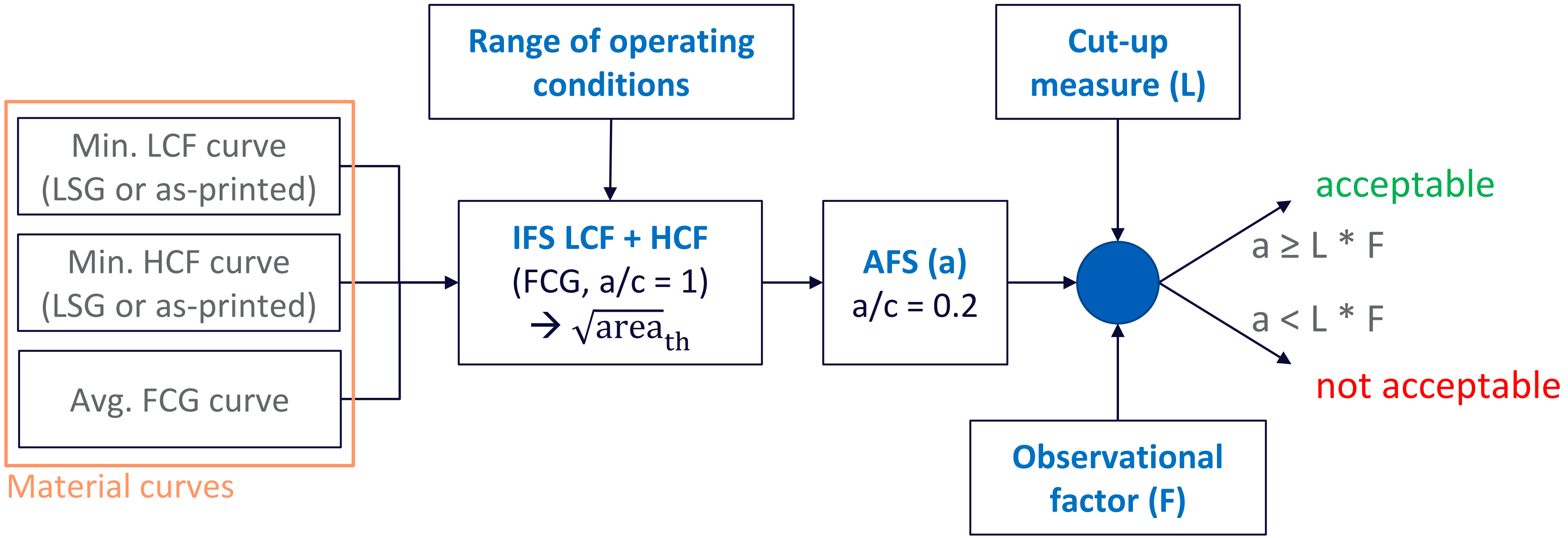
1. **Observational factor:** only small part of volume can be investigated by cut-ups. Conservatism shall be introduced on largest measured size to cover uncertainty. → factor based on number of indications measured on representative coupons.
2. **Anomaly shape:** 2D techniques do not ensure detecting the largest size of complex-shaped anomalies → conservative assumption of 10x larger dimension along the out-of-plane direction (shape ratio a/c = 0.2)





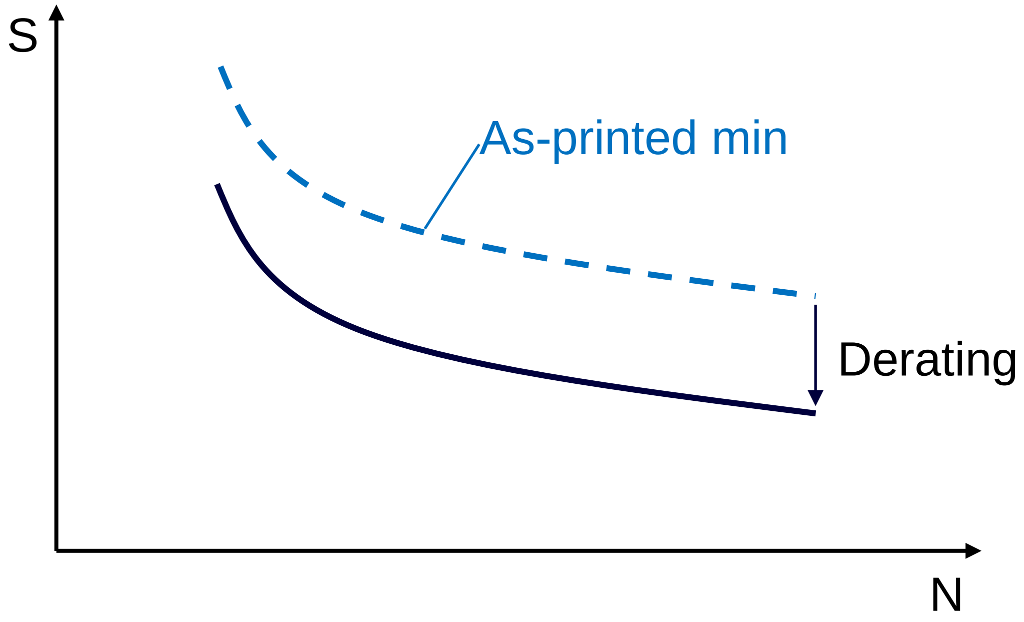
[1] Murakami, Yukitaka. *Metal fatigue: effects of small defects and nonmetallic inclusions*. Academic Press, 2019.

Overview of the approach



Curve derating

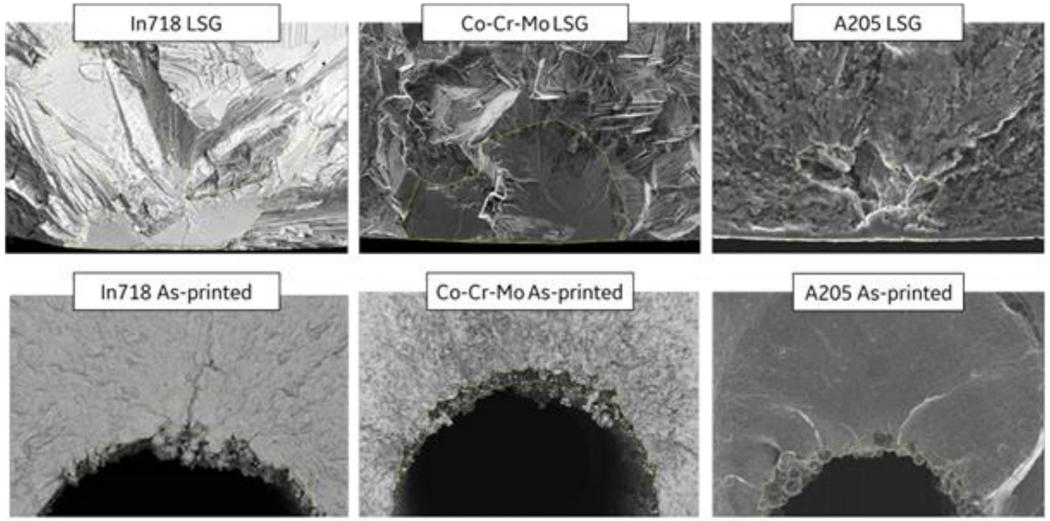
- Parts might contain anomalies larger than those common in test bars, thus limiting part life with respect to the design fatigue curve.
- Designers need the flexibility to tailor product definition within manufacturing capability while maximizing producibility → a low-stress feature that may be challenging to print may allow larger anomaly sizes.
- This is achieved by defining a fracture-mechanics based approach for fatigue curve derating.



Curve type	$\sqrt{\text{area}}$ normalized
LSG	1.00
As-printed	1.50
As-printed -25%	2.75
As-printed -50%	5.00

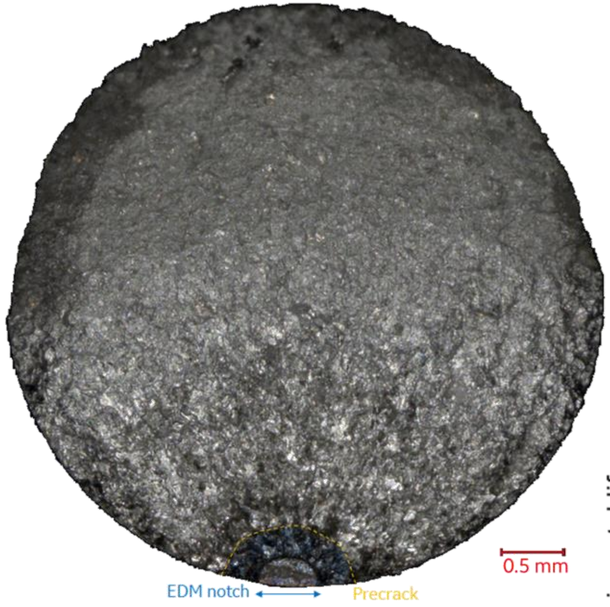
Validation

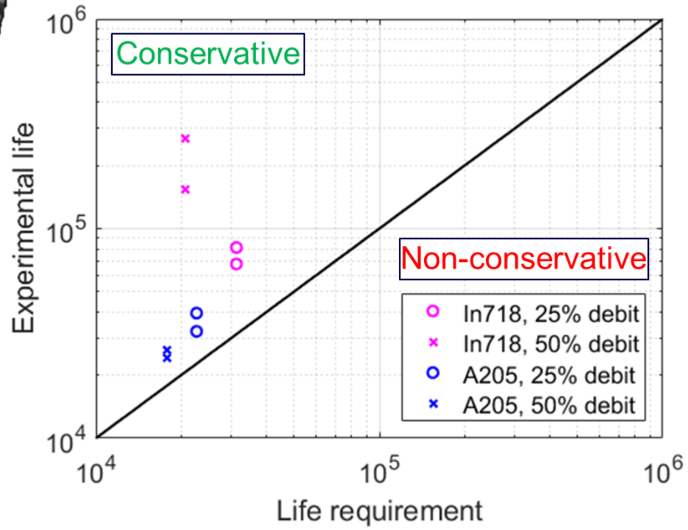
- Calculated AFSs consistent with size of anomalies at the origin of fatigue failure



Material	Surface condition	AFS normalized	Max anomaly size normalized
In178	LSG	1.00	1.66
	AP	1.50	2.15
Co-Cr-Mo	LSG	0.50	0.68
	AP	2.10	2.24
A205	LSG	1.30	0.90
	AP	1.80	2.17

- Fatigue tests on pre-cracked coupons confirm the conservatism of the approach





Conclusions and perspectives

- An approach for definition of **anomaly size acceptability limits** for AM metals based on **fracture mechanics** has been presented, aimed at augmenting the traditional building block of fatigue test-based material capability assessments.
- The approach covers **safe life** limits for **inherent anomalies**.
- Acceptable flaw size limits are conservatively determined as the largest crack size capable to **cover by simulation the design intent** of the part (min LCF and HCF design fatigue curves).
- Conservatism on shape and observational factors to **cover uncertainties related to cut-up** included.
- To allow flexibility to tailor product definition within manufacturing capability while **maximizing producibility**, larger anomaly sizes can be allowed by including knockdown factors ("**derating**") on fatigue allowables.
- **Validation** of approach conservatism is provided for L-PBF In718 and A205 by comparison of AFS with fractographic evidence and by a dedicated testing campaign.

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simone.romano@avioaero.it