FRACTURE MECHANICS-BASED APPROACH FOR ANOMALY SIZE ACCEPTABILITY OF ADDITIVELY MANUFACTURED METALS

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Abstract: The traditional approach for quantifying material capability generally assumes that material properties in components are fully represented by test bar results. However, this assumption might not always be true for complex additively manufactured components, which may contain anomaly populations different than those expected based on relatively simple-geometry mechanical test coupons.
In this work, we present a fracture mechanics-based approach for definition of anomaly size acceptability limits for AM materials, to augment the traditional building block of fatigue test-based material capability assessments. The fracture mechanics analysis is validated against fractography observations of tested bars and by fatigue tests on bars containing artificially notched coupons.

Keywords: L-PBF; Anomaly; Acceptability; Fatigue; Fatigue Crack Growth

INTRODUCTION

The traditional approach for quantifying material capability consists of mechanical testing of specimens, calculating statistical minima of measured properties, and then using the calculated minimum curves as design allowable.
While minimum fatigue properties of polycrystalline metallic materials are often driven by grain size or melt-related anomalies, this is not the case for AM parts, as most of the variability is explained by the presence of anomalies, and minimum properties are driven by the largest anomaly in the fatigue coupon gage volume [1, 2].
Additionally, complex parts sometimes contain anomalies of sizes and distributions that were not previously expected based on observations recorded during the initial mechanical test coupon campaigns [3]. The expected root cause of the observed discrepancies between test bars (small and of simple geometry) and parts (larger and of more complex geometry) is the role that part size and geometry plays as a key factor in the causes of anomaly populations in additive materials. In addition, the larger volumes associated with parts are more likely to capture occasional and less common deleterious process variations than the relatively small volumes in test bars.
Because the anomaly population of a material appears to be influenced by printed part geometry and size, it is a reasonable conclusion that mechanical capability of parts with different anomaly populations may not be entirely represented by the property curves that were constructed using specimens of simple geometry and correspondingly smaller anomaly populations.

Anomalies in AM materials

Anomalies in AM materials can be distinguished into two main categories, i.e., inherent, and rogue anomalies [4, 5]. As reported in AMC E 515 [6], "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.". Applying the same concept to AM parts, inherent anomalies include all anomalies that are generated by a process in control, i.e., they are repeatable, limited in number and size depending on process quality, and their effects are well known and characterized. Inherent anomalies should generally be conforming to specifications and therefore acceptable.

On the contrary, rogue anomalies include any flaw that is generated by a process out of control, or that fails to meet any of the previously described requirements. Rogue anomalies should generally be considered as nonconformities.

The rest of this paper focuses on inherent anomalies, which can be further distinguished as surface or volumetric. The first category includes anomalies that can only appear in the presence of an outer surface (e.g., the typically large surface roughness as compared to conventional machining, cold laps, and intrusions, surface connected porosity or lack of fusion), while the latter refers to anomalies that may appear anywhere in the volume (e.g, inclusions, porosity, lack of fusion (LoF)).

The necessary steps to obtain parts capable to meet the stringent aerospace quality requirements are optimizing the process, ensuring repeatability, and minimizing anomaly content. Size and frequency of inherent anomalies can be minimized by various means (e.g., process optimization, powder control, machine qualification, design optimization). Furthermore, hot isostatic pressing (HIP) allows closing subsurface porosity and LoF and minimizing their detrimental impact on fatigue strength. On this basis, testing fatigue coupons in the low stress ground (LSG) condition provides fatigue lives comparable with conventionally-manufactured materials [4, 5].

On the contrary, for complex-geometry components, completely removing all surface anomalies or remnants of rough As-Printed (AP) condition is generally difficult and not cost-effective. AP test coupons generally show large fatigue debits compared to LSG allowable, especially when highly stressed surfaces are manufactured in downskin orientation [1, 4]. Non-conventional surface improvement enhances NDT response and may increase fatigue strength by removing surface anomalies. However, the surface usually remains a preferential initiation site as it is for "conventional" materials (e.g., forging).

Anomaly acceptability for fatigue

Most of fatigue variability is driven by the presence of anomalies and their size. The better the coupon quality, the higher the fatigue strength. As-printed material will typically have some anomaly content (e.g., intrusions caused by surface roughness), acting as preferential crack initiation points.

Given that coupons contain anomalies, the minimum design fatigue curves already include the effect of the largest of them. This means that no fatigue debit should be considered for part containing an anomaly smaller than the largest registered in the coupons on which design allowable are based.

This clarifies why rogue anomalies are not acceptable, but inherent (i.e., resulting from a process under control) should be. On this basis, the definition of a robust method for anomaly acceptability becomes a prime necessity.

While x-ray based non-destructive testing (NDT) is capable of detecting many gross flaws, the resolution of most industrial NDT is not fully capable of imaging very thin anomalies, especially of the smaller size range known to still influence fatigue capability [1, 2]. Therefore, destructive analysis of additive material is required to understand the anomaly content of a given volume of material, and repetitious interrogations are required to determine statistical capability of a given additive process to produce material of a known anomaly population that can be tied to a predicted fatigue life. Metallographic inspection of cut-ups has been determined to have adequate resolution to evaluate additive hardware and is the focus of the present review.

DEFINITION OF MATERIAL ALLOWABLE

As described in the Introduction, complete removal of all surface anomalies or remnants of rough AP surface condition is often not a practical option, and this might introduce non-negligible debit to fatigue strength. For this reason, the methodology presented in this paper defines fatigue allowable for Laser Powder Bed Fusion (L-PBF) materials by testing coupons in both LSG and AP conditions. AP test coupons can be specifically designed to include shapes able to characterize most generic orientations of the outer surface of a part.
The AP and LSG test bars are printed with the same process and undergo HIP, so the main reason for the observed fatigue capability difference is that the LSG condition has the surface anomaly population removed.
Both types of coupons are subjected to axial fatigue testing, therefore, applied stress is constant throughout the whole cross-section. This approach is conservative in the presence of anomalies as compared to bending tests, as the coupons is free to fail from the worst-case anomaly, independently of its position in the volume.

Design allowables under fatigue loading are derived by the conservative envelope of test data describing the minimum material properties. Such minima generally correspond to a chosen statistical metric, e.g., as reported in MMPDS [10].
The low cycle fatigue (LCF) capability is built based on strain-controlled fatigue testing, while the high cycle fatigue (HCF) one is based on load-controlled tests.
The number of fatigue cycles for safe-life definition (Ni) are evaluated as the number of cycles necessary to obtain a fatigue failure of the fatigue coupon. The final crack size leading to coupon failure (af) can be measured on the fracture surface and adopted as failure condition for fatigue crack growth (FCG) simulations.

APPROACH FOR ACCEPTABILITY LIMIT DEFINITION

When observed properties of additive materials are measured to be above the average curve, a factor such as grain size is often observed to be limiting mechanical capability when fractography is performed on a tested bar. Conversely, below-average test bar fractography often shows an initiation site associated with a pre-existing material anomaly. The influence of anomalies on fatigue capability seems to also be the most variable factor, contributing to significant scatter in the dataset. Because this work is concerned with parts that are designed using minimum curves, the focus is on control of factors that influence those below-average properties to ensure minima are protected. Therefore, anomaly size is employed as a limiting condition to control and ensure material capability.

To reconcile the expected fatigue properties of a complex geometry part with an anomaly population that might be different than those represented in the published design curves, fracture mechanics is exercised to establish a conservative transfer function between anomaly size and material fatigue performance, for both LCF and HCF loading conditions.

The presence of anomalies might be caused by several factors (e.g., effect of geometry, position on the platform, wall thickness, thermal history, printing parameters, surface orientation). Testing all conditions or destructive evaluation of all parts is unfeasible.
The method selected in this work and reported in the following adopts statistics to verify that anomaly populations are consistent and repeatable, and fracture mechanics applied on worst-case observations to provide robust analytical assessment.
The approach is based on the conservative assumptions of considering any anomaly type as a crack of equivalent area and no crack nucleation time [10].

The emphasis of the fracture mechanics approach is to have selected fatigue design curves consistent with the anomaly or anomaly cluster sizes in the final part. For a stressed part, fatigue failure will initiate at the location where the stress exceeds the local material capability, so selection of fatigue curves must reflect the maximum allowable anomaly content of that part or zone.

The basic idea of the proposed approach is evaluating the largest initial flaw size (IFS) that, if present inside a fatigue bar, would prove conservative with respect to the minimum design curves at any stress condition, thus protecting the design intent.
The capability of a given part or part feature to meet fatigue requirements can be verified by destructive metallographic evaluation and anomaly size evaluation during part manufacturing maturation.

Since the goal is protecting the full range of operative loading conditions that a L-PBF part could possibly be subjected to, the acceptable flaw size (AFS) shall encompass both LCF and HCF types of loads and cover the full range of temperature and applied stresses, including mean-stress effects.

Specimen's life under LCF-based loads can be predicted by adopting standard Linear Elastic Fracture Mechanics analysis tools for fracture mechanics analyses with a range of assumed anomaly sizes. As for HCF, the generally small size of anomalies induced by a process in control might in some cases require the adoption of a short cracks model to increase the accuracy of the simulations without incurring non-conservative assessments. For this reason, a Kitagawa-Takahashi diagram [3] is adopted for modelling a smooth transition from short to long cracks domains. The El-Haddad model [4] is implemented as the most common approach for a simple Kitagawa diagram definition. To account for generic anomaly shape, the $\sqrt{\text{area}}$ parameter proposed by Murakami [5] is selected to describe anomaly size, leading to the modified El-Haddad formulation described in [1, 6] and reported in Eqn. 1, where ΔK_{th} is the crack growth threshold for short cracks as a function of crack size $\sqrt{\text{area}}$, long cracks FCG threshold $\Delta K_{\text{th,LC}}$, and the El-Haddad's size parameter $\sqrt{\text{area}_0}$.

$$\Delta K_{\text{th}}\left(\sqrt{\text{area}}\right) = \Delta K_{\text{th,lc}}\sqrt{\frac{\sqrt{\text{area}}}{\sqrt{\text{area}_0}+\sqrt{\text{area}}}} \quad (1)$$

The measured properties needed for the analysis are:

a) LCF material curves for LSG and as-printed fatigue coupons;
b) HCF material curves for LSG and as-printed fatigue coupons;
c) FCG rate curves and parameters, including $\Delta K_{\text{th,LC}}$ and $\sqrt{\text{area}_0}$.

When a crack size $\sqrt{\text{area}_{\text{th}}}$ is confirmed to be consistent with min. LCF and HCF fatigue properties in the whole range of temperature and operating conditions for the material selected, that size is established as the threshold IFS. Figure 1 provides an example of FCG simulation based on threshold IFS compared with minimum fatigue curve for L-PBF In718, showing that selected IFS provides conservative (longer life) results in both the LCF and HCF regions of the curve.

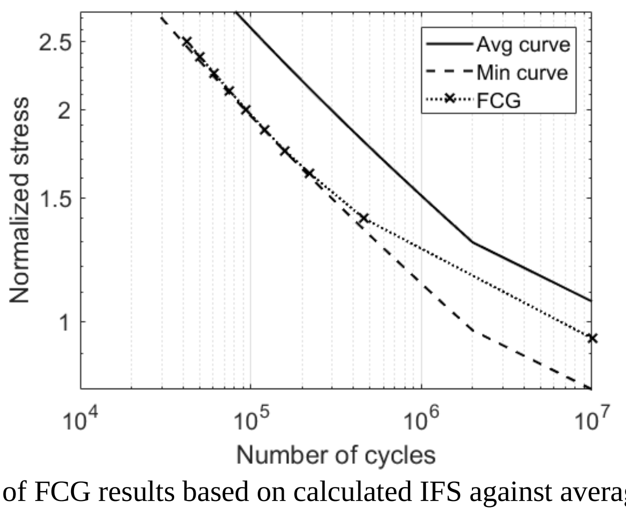

Figure 1: Comparison of FCG results based on calculated IFS against average and minimum fatigue allowable for L-PBF In718 tested at room temperature.

The next step of the approach is identifying an AFS that would provide conservative results when compared to cut-up measurements.

Limitations of cut-ups and rationale for AFS definition

The two main limitations of a cut-up based approach are listed below, complemented by the rational and details of the method that supports its adoption:

1. As any two-dimensional technique, a polished section does not ensure detecting the largest size of a complex-shaped anomaly. Some of the anomalies that can be found in AM parts might be elongated (e.g., LoF) in the out-of-plane direction, so the direct adoption of the anomaly size measured might in some cases prove non-conservative. To cover this, it is conservatively assumed to assign an IFS in terms of crack depth (a) of a semi-elliptical surface crack whose depth is equal to the maximum feret diameter measured, while its surface length 2c along the out-of-plane direction is assumed 10x larger (i.e., shape ratio a/c = 0.2). Although conservative, this assumption protects against any type of anomaly that might be shallow but significantly elongated along the out-of-plane direction, as depicted in Figure 2. In fact, reducing further the a/c ratio does not significantly increase the criticality of the crack (i.e., the K-factor or stress intensity factor (SIF)). Note that the assumption of surface crack is consistent with the evidence of outer surface being the preferential crack initiation location, and conservative compared to internal crack initiation of a crack of similar size from a fracture mechanics perspective.
2. A cut-up based approach only allows investigating part of the overall component material volume. Therefore, the larger the number of metallographic sections investigated the larger the expected maximum anomaly size measured. Therefore, conservatism is introduced on top of the largest measured anomaly size with an "observational factor" providing confidence on the maximum measured size as a function of the number of anomalies measured on representative cut-ups.

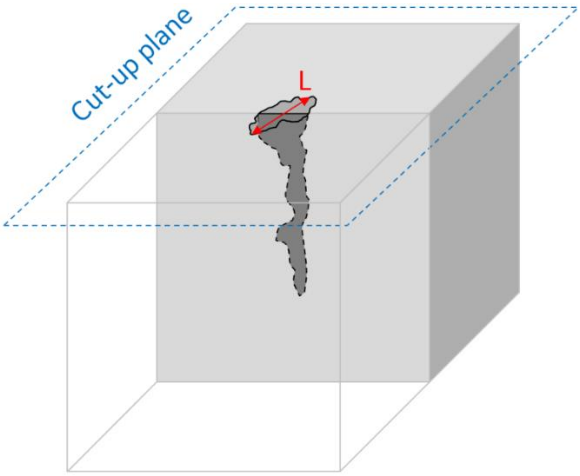

Figure 2: Example of measurement of anomaly size in the case of anomaly elongated perpendicular to cut-up plane.

Figure 3Figure 3 provides a schematic representation of the method adopted to calculate the AFS for cut-up acceptability verification. The AFS derived by applying the shape factor a/c = 0.2 on $\sqrt{\text{area}_{\text{th}}}$ is compared to cut-up measurements increased by the observational factor. The anomaly is deemed acceptable when $L \cdot F \leq a$.

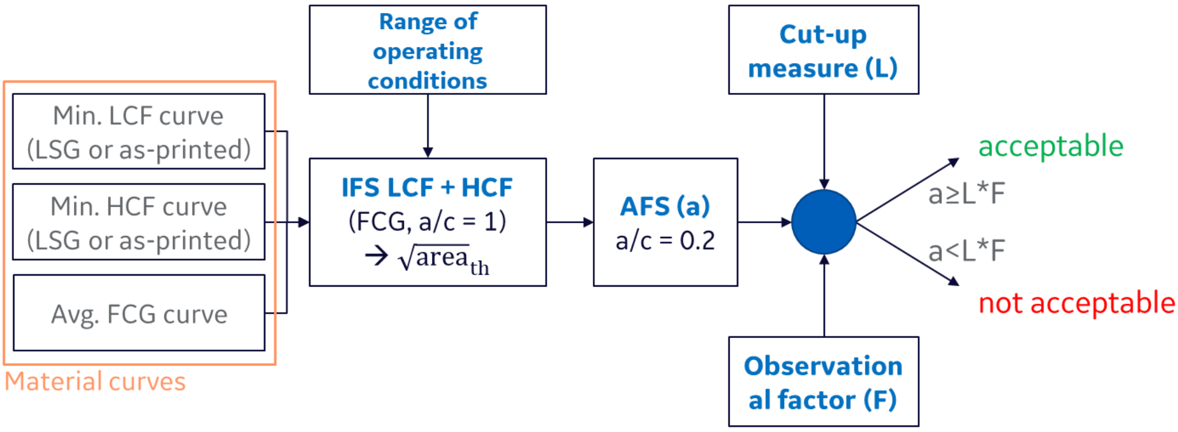

Figure 3: Block diagram summarizing the approach.

Curve derating

For parts found to have anomalies that are larger than the ones common in standard as-printed test bars, debited curves can be created that have a predefined reduction on stress allowable. In this way, it is possible to take advantage of the fracture mechanics-based understanding and calculate the larger acceptable starting flaws that correspond to the reduced minimum curves. This approach can allow the designer the flexibility to tailor product definition within manufacturing capability while maximizing producibility by allowing larger anomaly sizes that still results in parts that meet design requirements. For example, a low-stress feature in a part that may be challenging to print may allow larger anomaly sizes in that zone, keeping design capability but increasing producibility.
Because LSG tested bars likely had smaller anomalies than as-printed bars due to the removal of surface connected anomalies during the machining and surface grinding process, it is also logical to require that parts using the design curves derived from these bars be held to a higher standard and use the smaller predicted allowable initiation site size.
As an example, AFS for L-PBF In718 are reported in Table 1. As it can be seen, the lower fatigue strength of AP material allows for a 50% larger AFS as compared to LSG condition, while 25% and 50% knockdown with respect to AP curve have important increase of the allowable.

Table 1: List of AFS for In718 as a function of curve type and knockdown. AFS data are normalized with respect to the LSG value.

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

VALIDATION

The approach was verified by comparison of calculated AFS against evidence on fracture surfaces of fatigue coupons, and finally validated via a dedicated testing campaign on specimens with predefined crack size.

Verification by AFS comparison with fracture surfaces

The proposed approach targets the definition of largest anomaly size that protects the design intent, i.e., that provides a conservative fatigue life as compared to the minimum design fatigue curves (LCF and HCF).
As discussed in the Introduction, the minimum fatigue properties of AM materials are driven by the largest anomalies contained in the coupons. For this reason, it is expected that the calculated AFS falls in the upper tail region of the distribution of anomaly size that can be measured on the fracture surfaces.

This assumption was verified by analysing the fracture surfaces of the lowest performing fatigue coupons adopted for defining the fatigue allowable of L-PBF In718, Co-Cr-Mo, and A205 alloys in both LSG and as-printed surface conditions. The results confirm that largest anomalies found at the origin of fatigue failure are generally linked to lowest-performing coupons, which are depicted in Figure 4 for three alloys (In718, Co-Cr-Mo, and A205) in LSG and AP surface conditions. As it can be seen, better fatigue properties of LSG coupons can be explained by smaller anomaly size when evaluated in terms of $\sqrt{\text{area}}$.

Table 2 compares measured anomaly size with AFS. The calculated AFS have a size comparable to the largest measured on coupons, but smaller. This confirms the appropriate nature of the approach, since the largest anomaly found in the specimen sets the bar for the minimum curve definition, and the allowable should always be smaller to guarantee that design intent is protected. A205 LSG is the only case in which the maximum anomaly size detected on the fracture surface is smaller compared with the corresponding AFS. This is likely be due to limited fractography data available (11 coupons), and that the cited example did not sit on the calculated fatigue minimum line.

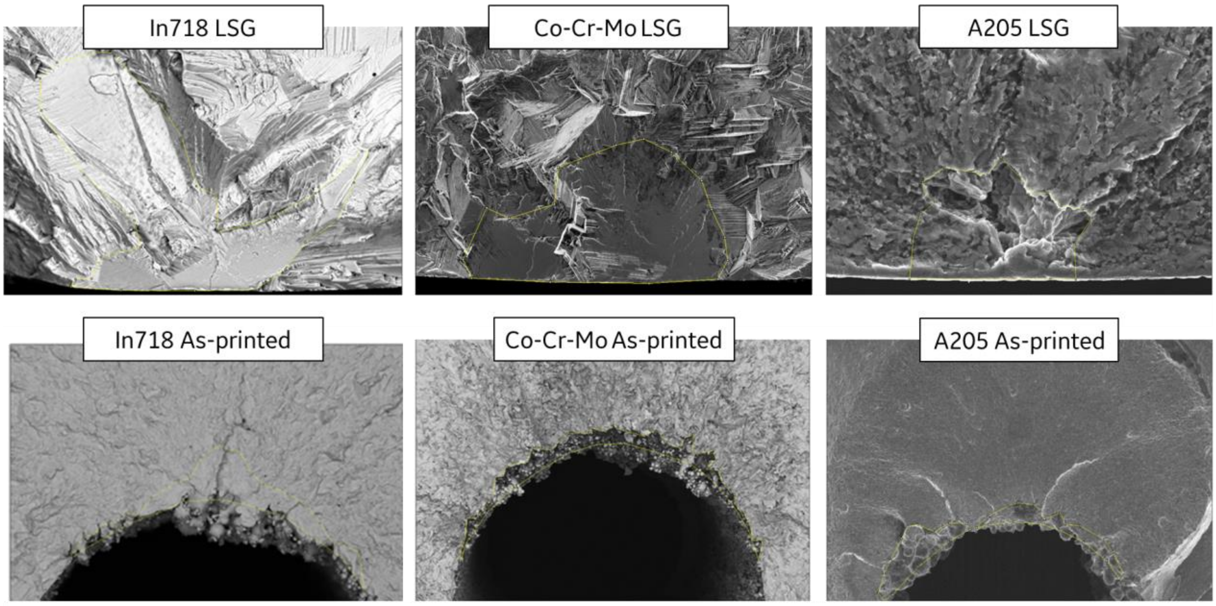

Figure 4: Example of anomaly size measurement on fracture surfaces of LSG and as-printed fatigue coupons.

Table 2: Summary of AFS calculated for three L-PBF materials in LSG and AP surface conditions, and largest anomaly size measured on the fracture surfaces of low-performing fatigue coupons. All values are reported in terms of $\sqrt{\text{area}}$ and normalized with respect to AFS calculated for In718 in LSG condition.

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

<u>Validation via dedicated testing campaign</u>

The conservatism of the approach has been verified by fatigue testing on fatigue coupons containing cracks of size equivalent to the AFS reported in Table 1. The verification was performed targeting AP curves with 25% and 50% knockdown. These conditions were selected to simplify the creation of cracks of predefined size with limited error. Two specimens were tested for both crack sizes.

Fatigue coupons identical to those adopted to derive LCF design curves were manufactured in L-PBF In718. A semi-circular surface notch of 0.254 mm radius was introduced in the gauge volume by precision electro-discharge machining. The coupons were then precracked to develop the target crack size. The accuracy on crack size was verified by potential drop technique as compared to the reference coupon without notch and crack. Postmortem measurement of notch and precracking size provided errors lower than 10% on crack depth and 4% on crack width. Figure 5.a provides an example fractography showing EDM notch and precrack size.

Fatigue tests were performed at room temperature under strain control, at a strain ratio R=0. The maximum applied strain was selected to target fatigue lives of the order of 50.000 to 100.000 cycles. Figure 5: Figure 5.b compares the observed cycles for specimen failure compared to those predicted by FCG simulation. As it can be seen, all tests showed fatigue lives larger than predicted. This confirms the conservatism of the proposed approach. Note that conservatism could be reduced by targeting the most limiting condition as a function of test temperature and applied stress. In fact, AFSs are set to be conservative in the whole range of operating conditions of the material under investigation.

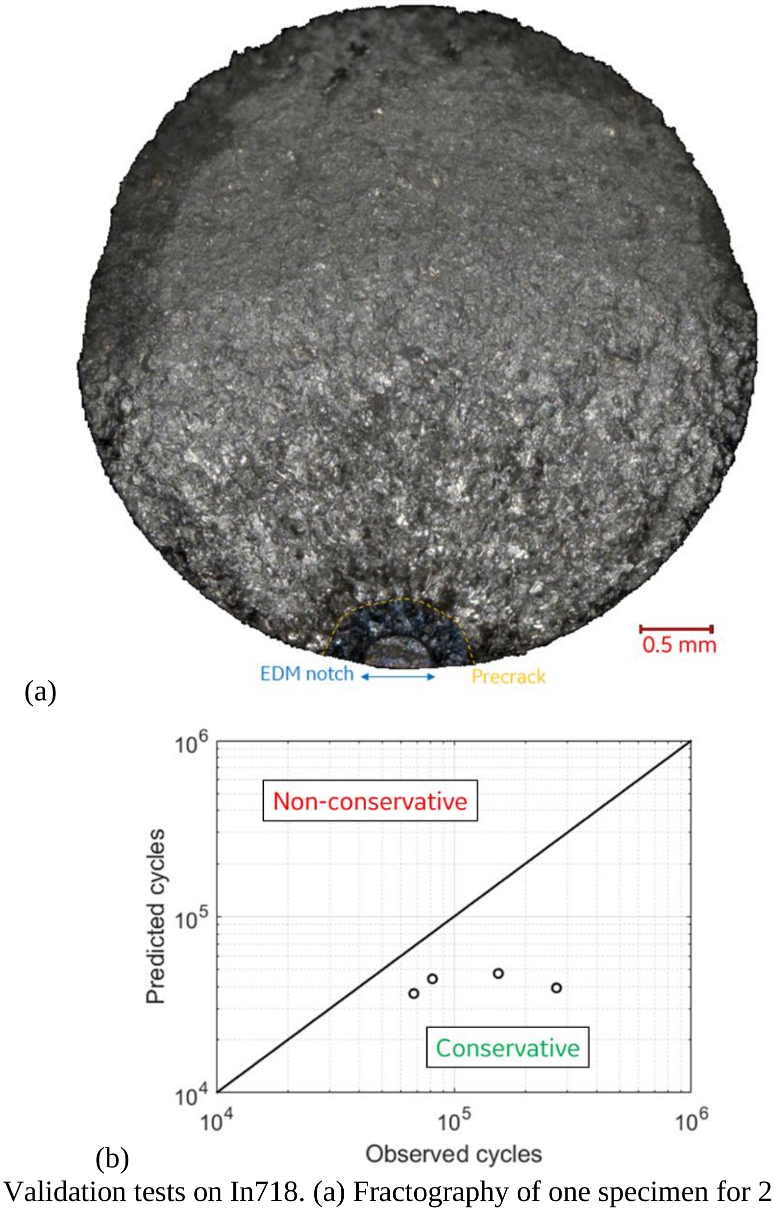

Figure 5: Validation tests on In718. (a) Fractography of one specimen for 25% knockdown verification; (b) Comparison of observed vs predicted life for precracked coupons.

Additional tests are being conducted on L-PBF Co-Cr-Mo, A205, and F357 alloys to verify the approach on multiple materials.

CONCLUSIONS AND PERSPECTIVES

This paper summarized an approach for definition of inherent anomaly size acceptability limits for AM metals based on fracture mechanics, aimed at augmenting the traditional building block of fatigue test-based material capability assessments.
The approach aims at covering safe life limits for inherent anomalies based on the evidence that fatigue strength variability of AM fatigue coupons produced with optimized process and subjected to HIP is driven by the largest anomaly or anomaly cluster falling inside the gauge volume, and that minimum fatigue properties are driven by maximum anomaly or anomaly cluster size on or near the outer surface. Acceptable flaw size limits are conservatively determined as the largest crack size capable to cover by simulation the design intent of the part, i.e., the minimum LCF and HCF design fatigue curves for the whole temperature range the application might require.

The approach includes conservatism on shape and observational factors to cover uncertainties related to cut-up measurements.

To allow flexibility to tailor product definition within manufacturing capability while maximizing producibility, larger anomaly sizes can be allowed by including knockdown factors on fatigue allowables. This enables the possibility to zone parts depending on feature geometry, which gives Design the flexibility to assign a tighter anomaly requirement for a relatively simple geometry that may be capable of meeting that requirement or enlarge acceptability criteria for challenging features that may struggle to achieve limits defined via standard coupons.

Validation of approach conservatism is provided for L-PBF In718 by comparison of AFS with fractographic evidence and by a dedicated testing campaign.

REFERENCES

[1] Beretta, S. and Romano, S. (2017), *Int J Fatigue*, vol. 94, pp. 178-191, 2017.

[2] Romano, S., Brückner-Foit, A., Brandão, A. D., Gumpinger, J., Ghidini T. and Beretta, S. (2018), *Eng Fract Mech,* vol. 187, pp. 165-189.

[3] Romano, S., Beretta, S., Miccoli, S. and Gschweitl, M. (2020), *Structural Integrity of Additive Manufactured Parts,* p. 526–539.

[4] Wells, D. N. (2022). In: *Proceedings of Joint FAA – EASA Workshop on Qualification / Certification*.

[5] Gorelik, M. (2020). In: *NRC Workshop on Advanced Manufacturing Technologies*.

[6] EASA (2020), *Certification Specifications and Acceptable Means of Compliance for Engines (CS-E) Amendment 6*.

[7] Leuders, S., Thöne, M., Riemer, A., Niendorf, T., Tröster, T., Richard, H. A. and Maier, H. J. (2013), *Int J Fatigue,* vol. 48, pp. 300-307.

[8] Pegues, J., Roach, M. D., Williamson, R. S. and Shamsaei, N. (2018), *Int. J. Fatigue,* vol. 116, pp. 543-552.

[9] Yadollahi, A. and Shamsaei, N. (2017), *Int J Fatigue*, vol. 98, pp. 13-31.

[10] Rice, R. C., Goode, R. J., Bakuckas, J. G. J. and Thompson, S. R. (2003). In: *7th Joint DOD/FAA/NASA Conference on Aging Aircraft,* New Orleans, LA.

[11] Romano, S., Patriarca, L., Foletti, S. and Beretta, S. (2018), *Int J Fatigue*, vol. 117, pp. 47-62.

[12] Kitagawa, H. and Takahashi, S. (1979), *Trans. Jpn. Soc. Mech. Eng. A,* vol. 45, no. 399, pp. 1289-1303.

[13] El Haddad, M. H., Smith K. N. and Topper, T. H. (1979), *J. Eng. Mater. Technol, Trans. ASME,* vol. 101, pp. 42-46.

[14] Murakami, Y. (2019), Metal fatigue: effects of small defects and nonmetallic inclusions, Academic Press, 2019.

[15] Murakami, Y. and Endo, M. (1986), *Mechanical Engineering Publications, The Behaviour of Short Fatigue Cracks,* pp. 275-293.