

## Role of Defect Interaction and Multi-Site Damage in Fatigue Life of Additively Manufactured Metals

Syedmostafa Nasrollahpourshirvani and Aref Yadollahi\*

Department of Mechanical and Civil Engineering, Purdue University Northwest, Hammond, IN,  
46326, USA

\*Corresponding author: Phone: (219) 989-3147, Email: [aref.yadollahi@gmail.com](mailto:aref.yadollahi@gmail.com)

### **Abstract**

Fatigue failure in additively manufactured (AM) metals is heavily influenced by the interaction of closely spaced process-induced defects and multi-site crack growth. In this work, single-crack models were shown to overestimate fatigue life, particularly in low-cycle and mid-life regimes, by neglecting defect interactions. Defect interaction, in this context, refers to the overlapping stress fields and early-stage crack coalescence arising from closely spaced defects. By incorporating nearest neighbor distance analysis and employing a multi-site crack growth framework, fatigue-life predictions aligned more closely with experimental results in these regimes. Multi-crack configurations captured the accelerated failure mechanisms driven by multi-site fatigue damage. This work proposes a defect-based predictive approach that integrates spatial defect data into fatigue-life estimation using a crack-growth based model. The findings highlight the critical need to account for defect proximity and multi-site damage in fatigue modeling to improve performance prediction and support the qualification and certification of AM components for fatigue-critical applications

**Keywords:** Fatigue-life prediction; Fatigue-crack-growth; Fracture; Seeded defects; Multi-site cracking

### **Introduction**

Metal additive manufacturing (AM) has enabled the fabrication of intricate components with minimal material waste and design flexibility [1–4]. Its increasing adoption in aerospace, automotive, and energy sectors is driven by the ability to produce high-performance parts from advanced engineering alloys, such as titanium and nickel-based superalloys. However, despite its advantages, concerns remain regarding the structural integrity of AM components, especially under cyclic loading in fatigue-critical applications [5,6]. Fatigue performance is one of the most critical limitations to the structural reliability and broader adoption of AM parts in highly regulated and fracture-critical industries. While their monotonic properties often approach or match those of conventionally built metals, fatigue life tends to be more variable and less predictable [7–9]. This inconsistency is primarily attributed to process-induced defects such as lack-of-fusion (LOF) flaws and gas porosity which act as initiation sites for fatigue cracks. These defects are strongly influenced by key process parameters, including laser power, scanning speed, and layer thickness [10,11]. Despite significant research efforts on AM process optimization and control, producing a defect-free AM part has not been possible yet. Although hot isostatic pressing (HIPping) is a

powerful means to eliminate porosity and improve a part's fatigue strength, it is ineffective in eliminating all the process-induced defects, e.g., LOF defects, pores filled with inert gas, or pores very near (or open to) the surface [11]. When the microstructure is nearly homogeneous and the residual stresses in an AM part are limited—for instance, by post-fabrication heat treatments or preheating the build plate—variations in size, location, and spacing of defects are the main reasons for the uncertainty and scatter in the AM fatigue data [12, 13].

Numerous studies have explored the influence of defect characteristics on fatigue behavior of AM metals, highlighting the importance of defect size, shape, and distribution in determining crack initiation and propagation mechanisms [14–16]. However, the inherently random formation and distribution of process-induced defects hinder reproducibility and limit the ability to establish clear and systematic correlations between defect morphology and fatigue response. This randomness not only complicates efforts to isolate the role of individual defect features but also allows cracks to initiate from multiple locations and subsequently coalesce, leading to premature failure even in longer life regimes—behavior that differs markedly from conventionally built metals. Internal defects, in particular, can behave differently from surface-connected defects, and their interactions further complicate the development of reliable fatigue life prediction models for AM materials [17–19]. Closing this knowledge gap requires systematic fatigue testing of specimens with intentionally seeded defects of controlled geometry and placement. Such studies were not feasible with conventional manufacturing methods, but the layer-by-layer process and high spatial resolution of metal AM now allow defects to be introduced at prescribed locations. In this study, Inconel 718 is used as a case material to fabricate fatigue specimens containing seeded defects, providing controlled testbeds to examine defect-sensitive fatigue behavior and crack interaction mechanisms. The results are intended to improve predictive models of defect-driven failures and to support the development of qualification strategies and defect-tolerant design methods for AM structural components.

### **Experimental Procedure**

AM specimens of three alloys—17-4 PH stainless steel (SS), Ti-6Al-4V, and Inconel 718—were produced using distinct processing methods for fatigue testing and fatigue life prediction. The 17-4 PH SS specimens were fabricated by laser powder bed fusion (LPBF) and subjected to standard solution annealing and peak-aging heat treatment [29, 22]. Dogbone specimens were prepared for fatigue life testing, and compact tension (C(T)) specimens were produced for crack growth experiments [30]. Ti-6Al-4V specimens were manufactured by laser directed energy deposition (DED-L), followed by annealing at 760 °C for 1 h in argon with subsequent air cooling [20]. Along with dogbone fatigue specimens, C(T) and single-edge-notch bend (SEN(B)) geometries were prepared to evaluate large- and small-crack growth behavior, with crack propagation monitored using back-face strain gauges [23]. For Inconel 718, dogbone specimens with intentionally seeded defects were fabricated via LPBF using optimized parameters. All specimens were heat treated by solutionizing at 980 °C followed by a two-step aging cycle to relieve residual stresses and stabilize the microstructure.

After fabrication, all specimens were polished to achieve uniform surface quality prior to testing. X-ray computed tomography (XCT) was employed to assess process-induced defects in

all specimens. Fatigue and crack growth experiments were performed on a servo-hydraulic load frame under cyclic loading in accordance with ASTM Standards E466 [31], E606 [32], and E647 [33], depending on specimen type. Post-test characterization included fractographic analysis using scanning electron microscopy (SEM) to identify crack initiation sites, propagation paths, and final fracture features.

### **Defect Interaction and Multi-Site Fatigue Damage**

Unlike conventional wrought materials, where a dominant fatigue crack typically initiates from a single critical defect, AM components often contain multiple internal defects of comparable size [22]. These defects are stochastically distributed within the material and can act as independent crack initiation sites under cyclic loading. As a result, fatigue failure in AM metals frequently involves the initiation and propagation of multiple cracks that interact during their evolution. Such crack interactions may occur even without direct physical contact between the crack tips, due to overlapping stress fields that influence local crack driving forces [23].

The phenomenon of crack coalescence—where nearby cracks merge during growth—is particularly critical in AM parts. Experimental and computational studies have shown that when defects are closely spaced, the resulting interaction can significantly elevate the local stress intensity factor, accelerate crack propagation and drastically reduce fatigue life. In this regime, failure is often not governed by the largest single flaw, but by the spatial distribution and proximity of multiple subcritical defects. Figure 1 illustrates the fracture surface from a fatigue-tested specimen of AM 17-4 PH SS, produced via LPBF. The image highlights the coalescence of two independently initiated cracks from adjacent defects, with the dashed line indicating the convergence zone of the two advancing crack fronts [22]. This challenges the applicability of traditional fatigue-life models, which assume isolated crack growth and fail to account for multi-site damage accumulation.

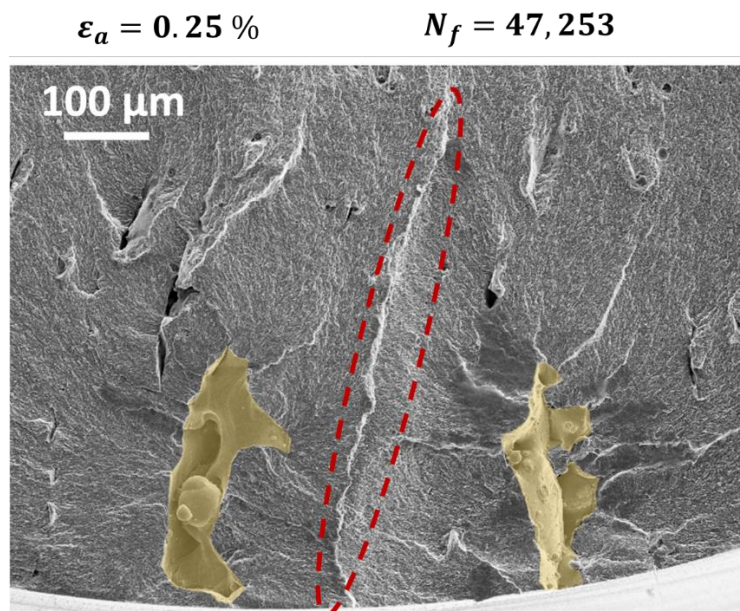


Figure 1. Micrograph of crack coalescence originated from two defects in an LPBF 17-4 PH SS specimen (the dashed line mark demonstrates the location where two approaching crack fronts met).

The early stages of crack growth in AM materials are often dominated by short cracks propagating under microstructural and geometric constraints. These short cracks tend to grow faster and more unpredictably than long cracks due to the absence of a well-established plastic zone and the influence of local heterogeneities [23-27]. In AM materials, this behavior is exacerbated by the anisotropic microstructure and residual stresses introduced during layer-by-layer deposition. Moreover, short crack growth often bypasses classical crack growth thresholds, making it difficult to model using conventional fracture mechanics approaches.

### **Fatigue Life Prediction and Capturing Multi-Site Fatigue Damage**

Reliable fatigue-life prediction remains one of the most challenging aspects of structural integrity assessment for AM metals [22]. Conventional approaches—such as crack growth-based models, defect-tolerant design methodologies, and microstructure-based multistage fatigue (MSF) models—have each advanced our understanding of cyclic damage. Nevertheless, to extend these frameworks to AM alloys, future models must explicitly capture the collective effects of multiple small cracks, defect clustering, and anisotropic microstructures [28].

Crack growth-based models often assume a single dominant flaw and simplify internal defects as sharp cracks present from the first loading cycle, thereby neglecting the processes of crack nucleation and early-stage growth [34]. While this assumption provides conservative estimates in conventional alloys, it limits predictive accuracy for AM materials. To address this gap, models must incorporate the transition from defect nucleation to short-crack growth, as well as the interactions between multiple evolving cracks. Similarly, defect tolerant methods based on Kitagawa–Takahashi diagrams and El-Haddad’s formulation provide insight into non-propagating defect thresholds but fail to incorporate the influence of defect proximity, clustering, or coalescence on the fatigue limit [19]. The MSF model, which decomposes fatigue damage into incubation, microstructurally small crack (MSC), and long crack growth stages, offers a more granular framework. Yet its current form is limited in accounting for defect interaction effects. The inclusion of features such as nearest neighbor distance (NND) has attempted to incorporate defect spatial distribution into life predictions [28]. However, a universal method for computing representative NND values that consider both 3D defect clustering and surface proximity weighting is still lacking. Moreover, none of the current models quantitatively account for the physical mechanisms by which closely spaced cracks alter the local stress field or trigger early coalescence, which can drastically reduce fatigue life. These phenomena cannot be captured by traditional crack-tip stress intensity factor calculations unless multi-defect interaction is explicitly modeled. As a result, models often overpredict fatigue life or fail to capture the observed scatter in AM test data.

Our experimental and modeling results on AM Ti-6Al-4V, fabricated via DED-L, revealed that fatigue-life predictions based solely on the largest detected defect size are sufficient for high-cycle fatigue (HCF) behavior but significantly overestimate life in low-cycle fatigue (LCF) and mid-life regimes due to the neglect of spatial defect interactions [23, 28]. Fatigue-life predictions

were performed using FASTRAN, which is based on the plasticity-induced crack-closure mechanism. Incorporating a multi-crack fatigue modeling approach improved prediction accuracy in these regimes, aligning well with fractographic evidence of multiple crack initiation and coalescence, as shown in Figure 2. NND analysis confirmed that defects frequently occur in close proximity—often within five times their radius—demonstrating a strong potential for interaction and multi-site fatigue damage [28]. These findings underscore the importance of incorporating defect clustering and interaction into fatigue-life prediction frameworks for AM Ti-6Al-4V, especially in the LCF regime where such effects dominate failure behavior.

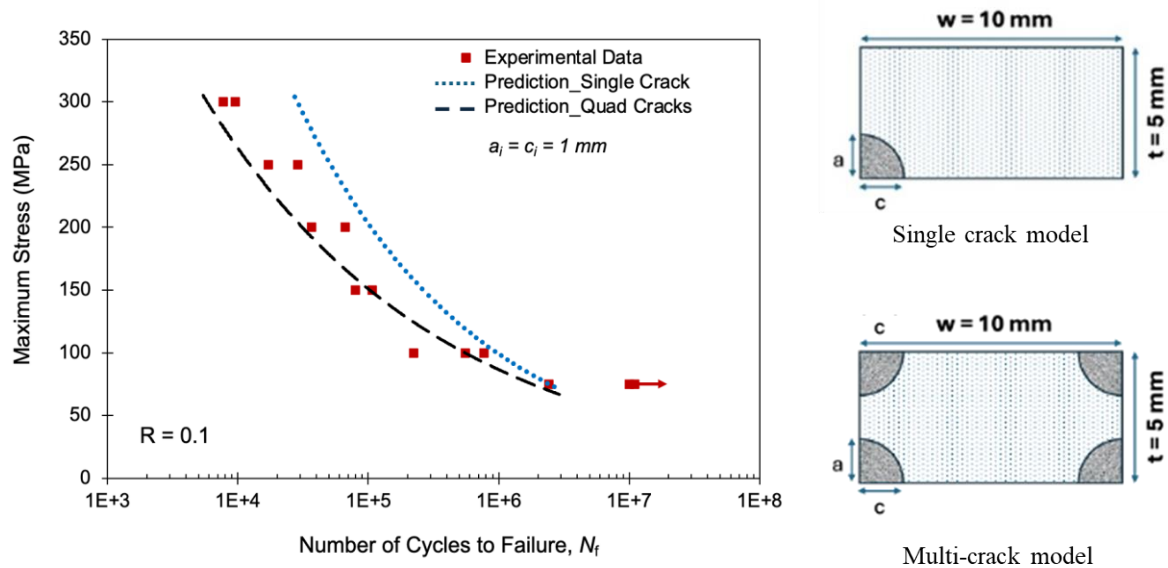


Figure 2. Fatigue-life predictions for DED-L Ti-6Al-4V specimens based on single- and multiple-crack scenarios.

### **Intentionally-Seeded Defects for Fatigue Performance Assessment**

A promising approach to address the challenges associated with defect interaction effects on fatigue behavior involves the fabrication of specimens with intentionally seeded defects using metal AM. The layer-by-layer nature and high spatial precision of techniques such as LPBF enable controlled placement of internal flaws with defined sizes and locations. This capability allows for a systematic investigation into how specific defect configurations influence crack initiation, propagation, and overall fatigue life. Such controlled studies can provide critical data for identifying defect interaction parameters and developing more accurate and physically informed fatigue-life prediction models for AM materials.

In this study, a series of Inconel 718 specimens containing intentionally seeded internal defects were fabricated using an LPBF process to systematically investigate the influence of defect characteristics (i.e., size, location, and spacing) on the fatigue behavior of AM components, as illustrated in Figure 3(a). These seeded defects were strategically embedded at specific locations and varied in both shape and size to replicate typical LOF defects, which are the most critical defect

types observed in AM components. Figure 3(b) shows the XCT image, confirming successful creation of the intentionally seeded defects within the specimen's gauge section.

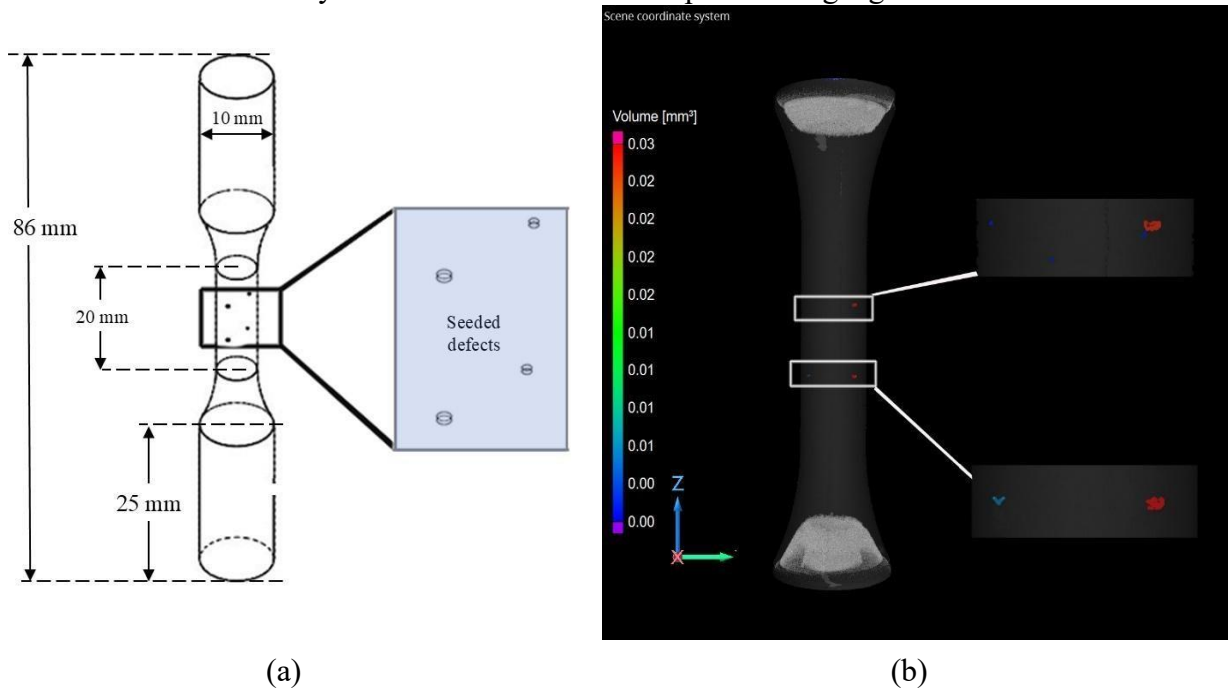


Figure 3. (a) Schematic of the designed Inconel 718 specimen containing intentionally seeded defects within the CAD model, and (b) XCT image confirming their successful formation.

Table 1. Fatigue test results of specimens subjected to different stress levels, as well as crack initiation site characteristics.

Specimen number	Stress (MPa)	Fatigue life	Crack initiation site	
			Largest diameter ( $\mu\text{m}$ )	Distance from surface ( $\mu\text{m}$ )
1	600	1.9E4	467	0
2	600	6.5E4	158 and 71*	120 and 0*
3	500	3.8E4	525	88
4	500	8.9E4	250	101
5	400	5.2E5	197	74
6	400	6.2E5	70.9	0
7	300	2.1E6	446	90
8	200	1.1E6	483	43

\* Multi site crack initiation

Table 1 summarizes the experimental fatigue test results for the investigated specimens. For each specimen, the applied stress level, the number of cycles to failure (fatigue life), and the characteristics of the crack initiation site (i.e. largest diameter and distance from surface) are

reported. Post-mortem fractographic analysis revealed a consistent crack initiation trend, showing that cracks predominantly formed at or near the specimen surface, even when larger seeded defects were located deeper within the material, highlighting the critical influence of surface-adjacent defects in crack nucleation. The severity of these defects was strongly influenced by both their proximity to the free surface and their size. Surface-adjacent defects, particularly those of larger dimensions, resulted in elevated local stress concentrations, which in turn led to accelerated crack initiation and earlier failure under identical loading conditions. The influence of defect size and location is evident in Figure 4, where a specimen containing a larger surface-adjacent defect ( $\sim 525 \mu\text{m}$ ) failed after only  $3.8\text{E}4$  cycles, whereas a smaller defect ( $\sim 250 \mu\text{m}$ ) in a similar location led to failure after  $8.9\text{E}4$  cycles. Both specimens shown in Figure 4 were tested under the same applied stress amplitude of 500 MPa. These results confirm that larger defects near the surface accelerate crack initiation and significantly reduce fatigue life. The correlation between defect size and fatigue performance highlights the critical role of defect control in ensuring the structural integrity of AM components under cyclic loading.

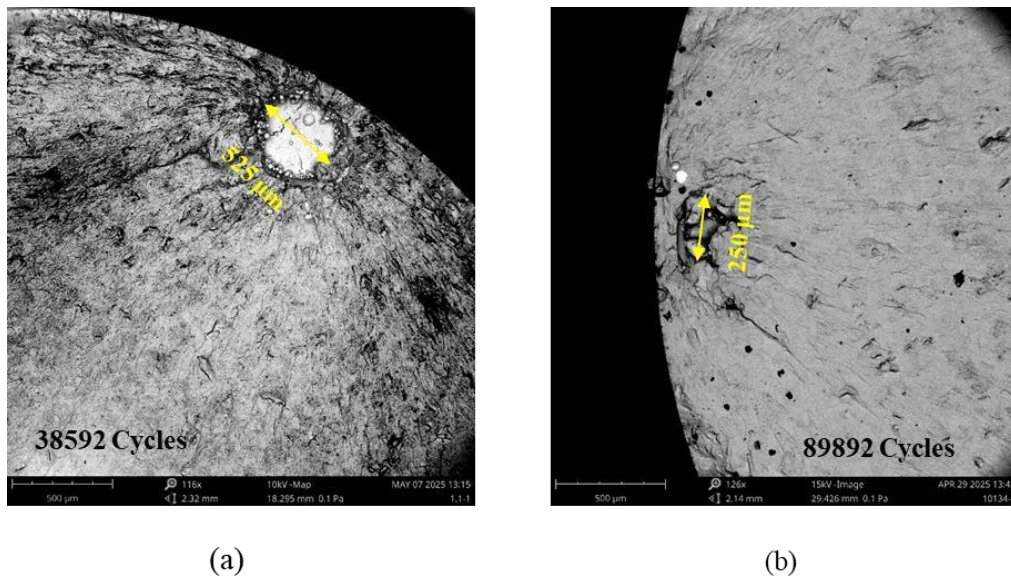


Figure 4. Crack initiation sites observed in two LPBF Inconel 718 specimens tested under a maximum stress of 500 MPa, demonstrating the influence of defect size and location on fatigue life.

The fatigue test results demonstrated that in the presence of multiple defects located on a sample, fatigue behavior is often governed by crack initiation at several defect sites followed by the coalescence of cracks during the propagation phase. This multi-site crack growth behavior was observed more frequently at higher stress levels, suggesting that elevated loading promotes simultaneous crack initiation from multiple defects and accelerates their subsequent interaction. As such, the likelihood of multi-site fatigue increases in the high-stress regime, where the stress intensity is sufficient to activate several defects concurrently. Figure 5 illustrates this phenomenon

by comparing two samples with identical geometries: the sample tested at 500 MPa exhibits clear evidence of multi-site crack growth, whereas the one tested at 300 MPa shows a single dominant crack initiating and propagating to failure. These findings highlight the critical role of applied stress level in influencing both the number of active crack initiation sites and the complexity of the fatigue failure mechanism. This behavior underscores the importance of defect distribution and stress magnitude in fatigue life prediction. It also suggests that traditional single-crack models may underestimate damage in high-stress conditions. Incorporating multi-defect interactions into fatigue assessments can lead to more accurate and reliable design criteria.

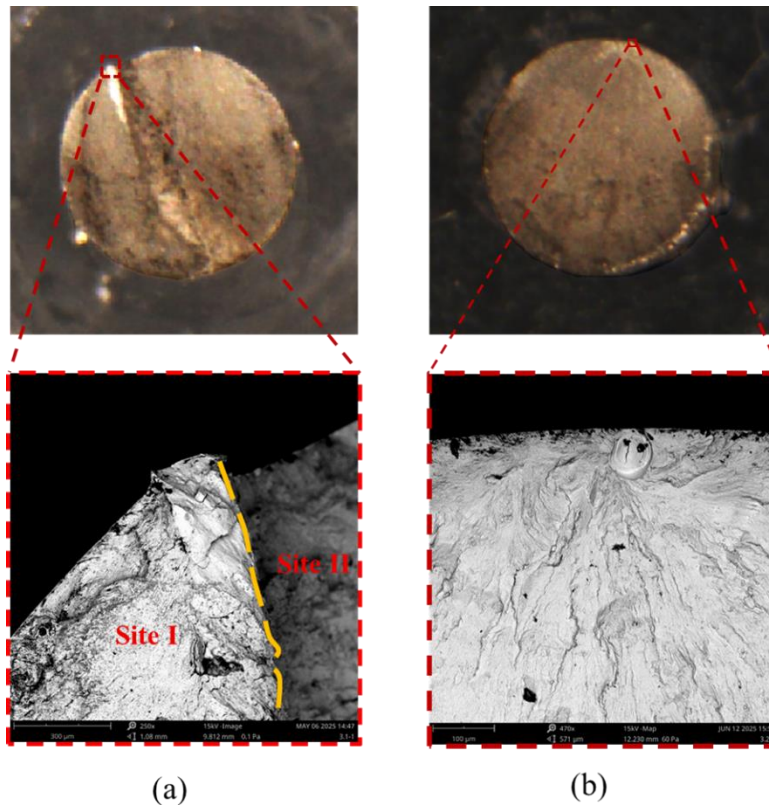


Figure 5. Fatigue fracture surfaces of two LPBF Inconel 718 specimens with identical design, showing (a) multi-site crack growth at 500 MPa, and (b) single-site crack growth at 300 MPa.

### Conclusions

This study highlights the critical role of defect proximity and multi-site fatigue damage in the fatigue performance of AM metals. Traditional fatigue-life prediction models, originally developed for conventionally built metals and based on single-crack assumptions, fail to capture the damage mechanisms observed in AM materials, where the random distribution of process-induced defects plays a central role. The proximity of such defects can strongly influence crack initiation and propagation, while their multiplicity promotes multi-site damage. The findings show that fatigue failure in AM metals—particularly in the LCF and mid-life regimes—is governed not

only by the largest defect but also by the location and spacing of process-induced defects. By incorporating a multi-site crack-growth approach into the plasticity-induced crack-closure model, FASTRAN, the predictive accuracy of fatigue life in these regimes is significantly improved. Experimental validation using intentionally seeded Inconel 718 specimens confirms that closely spaced defects promote early-stage crack interaction and coalescence, especially under high-stress conditions. These insights underscore the need for fatigue models for AM metals that explicitly account for defect spacing and location, rather than considering defect size alone. Such an approach is essential for developing robust qualification criteria and defect-tolerant designs, ultimately enhancing the structural reliability and accelerating the adoption of metal AM in fatigue-critical applications.

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