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Machine Learning-assisted Detection and Extreme Value Characterization of Critical Defects in PBF-LB parts via XCT

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Volumetric defects in laser powder bed fused (PBF-LB) parts can critically affect their fatigue performance. X-ray micro-computed tomography (XCT) is widely used for the inspection of additively manufactured parts, enabling non-destructive evaluation-informed assessment of components. It is particularly suited for detecting volumetric defects, whose largest occurrences can be described through an extreme value distribution for probabilistic assessment.

Although XCT enables volumetric defect detection, its effectiveness is limited not only by physical resolution but also by data post-processing, particularly image segmentation. These limitations lead to defect underestimation, non-detection, and resolution-induced fragmentation of complex morphologies such as lack-of-fusion defects, ultimately compromising defect-based fatigue assessment.

To address these challenges, this study evaluates the influence of different segmentation methods (Otsu, Triangle, and U-Net) on defect detectability and sizing accuracy through probability of detection (PoD) and sizing error analyses across XCT scans with varying voxel sizes. A machine learning framework is employed to identify interactions among fragmented defects, coupled with a 3D convex hull approach to reconstruct physically meaningful defect sizes. The results show that Otsu often underestimates defect size and misses critical defects at larger voxel sizes, whereas Triangle and U-Net, especially when combined with ML-based interaction, significantly improve PoD and reduce sizing errors.

The analysis is then extended beyond detection to quantify the impact of characterization uncertainty on defect populations. PoD and sizing error are systematically integrated into extreme value statistics (EVS), including block maxima and peak-over-threshold approaches, to evaluate how detection limitations affect defect size distributions. The results demonstrate that conventional threshold-based segmentation can lead to significant underestimation of defect distributions at coarse resolutions, whereas ML-enhanced approaches improve defect representation and reduce false negatives.

By integrating non-destructive evaluation, machine learning, and statistical modelling, this work establishes a robust pathway toward defect-informed and reliability-driven design of PBF-LB components, supporting their safe adoption in critical engineering applications.

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