Recent advancements in modeling and testing the fatigue behavior of additively manufactured materials

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ABSTRACT

Additive manufacturing (AM) has revolutionized the production of metal components, enabling the fabrication of highly complex geometries and architected materials with tailored properties. However, ensuring the fatigue reliability of AM parts remains a major challenge, particularly due to defects such as surface roughness, internal porosity, and geometrical imperfections. Recent research has made significant strides in developing robust experimental protocols and predictive models to address these limitations.

This lecture provides an overview of the most recent advancements in modeling and testing the fatigue behavior of AM metallic materials, with a particular focus on lattice structures and miniaturized components fabricated via Laser Powder Bed Fusion (L-PBF). Key developments include the use of extreme value statistics combined with the theory of critical distances (TCD) to quantify the detrimental effects of surface and volumetric defects on fatigue strength, as demonstrated for LPBF Inconel 718 components.

In parallel, the average strain energy density (ASED) criterion has emerged as a promising tool for fatigue life prediction of complex cellular architectures, where classical stress-based approaches fail due to mesh sensitivity and notch-driven failure mechanisms. Innovative multi-scale and image-based modeling strategies, such as the Finite Cell Method and μCT-driven finite element simulations, are also explored. These approaches capture the as-manufactured geometry and allow for accurate, non-destructive prediction of fatigue performance, thus enabling a deeper understanding of how local geometrical imperfections and defect distributions influence mechanical response. Building on this, the role of process-related parameters—such as build orientation and mean stress—has been systematically investigated through experimental campaigns on Ti6Al4V and AISI316L miniaturized struts. These studies revealed pronounced anisotropy and sensitivity to mean stress, particularly at the sub-unit level where failure mechanisms are highly localized. The resulting insights feed directly into data-driven optimization frameworks, which leverage both experimental and modeling data to enhance fatigue life—achieving improvements of up to 24% simply by adjusting the printing orientation.

By integrating statistical, computational, and experimental methods, these advancements pave the way for reliable fatigue design of AM components in safety-critical applications.