

PREDICTION OF FATIGUE LIFE IN SLM 316L STAINLESS STEEL: THE IMPACT OF RATCHETING AND BUILD ORIENTATION

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1. Introduction

Low-cycle fatigue (LCF) is characterized by material degradation under cyclic loading with significant plastic strain amplitudes, typically leading to failure below 10^4 cycles. Unlike high-cycle fatigue, LCF is driven by macroscopic cyclic plasticity, which can occur even at stress levels below the initial yield strength in materials prone to cyclic softening. LCF is especially important in industries with severe cyclic loading, such as aerospace and power generation. In the field of additive manufacturing (AM), specifically Laser Powder Bed Fusion (LPBF), the fatigue behavior is further complicated by the inherent anisotropy of the layer-by-layer build process. Previous study [1] has confirmed a significant influence of build orientation on the mechanical properties of 316L stainless steel (SS 316L). It was observed that while the XY orientation (horizontal) exhibits the highest ductility and fatigue resistance, the Z orientation (vertical) is characterized by the lowest plasticity and the fastest damage evolution. While the orientation effect is well-documented, most existing models focus on fully reversed loading ($R=-1$). However, real-world components often operate under non-zero mean stress, leading to ratcheting.

This paper extends the previous research by incorporating new experimental data on ratcheting behavior, specifically focusing on the critical Z-orientation. The objective is to verify a damage accumulation rule, recently proposed by the authors [2], which accounts for the interaction between

cyclic softening and ratcheting-induced damage to improve fatigue life predictions for AM materials.

2. Experimental Data

The specimens were fabricated using LPBF technology. The powder feedstock and process parameters were kept consistent with the previous study [1] to ensure comparability.

2.1 Cyclic stress-strain curve

The experimental data from research [1] were re-evaluated to determine the cyclic stress-strain curves (CSSC) using scripts developed in Python [3,4]. Based on Fig. 1, it is evident that the ZX45 orientation has the smallest hardening exponent (slope in the log-log plot), indicating a lower amplitude of plastic strain for a given stress amplitude compared to the other orientations up to approximately 450 MPa. In this range, the XY orientation exhibits the lowest plastic strain amplitude. The orientation of the specimen axis during printing significantly affects the CSS curve shape. The corresponding fatigue life (S-N) curves for all three orientations are detailed in [1].

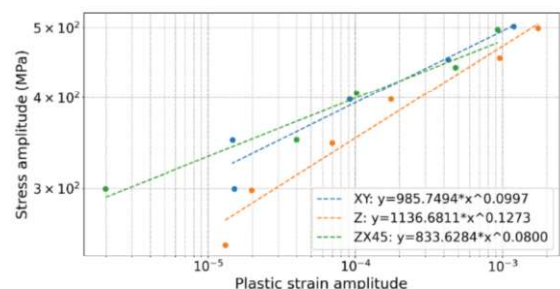


Fig. 1. CSSC for three build orientations [1].

2.2 Ratcheting tests

The new experimental campaign involved LCF tests with non-zero mean stress to investigate ratcheting. The SS 316L exhibits significant cyclic softening and a sensitivity to plastic strain accumulation when subjected to mean stress. An impact of the mean stress sign on the ratcheting rate and fatigue life was observed (Fig. 2).

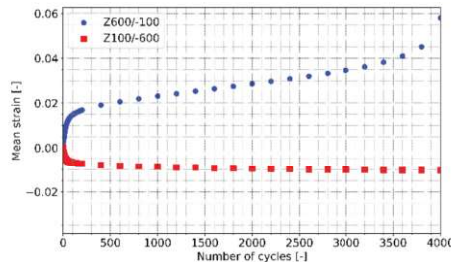


Fig. 2. Comparison of ratcheting evolution for a stress amplitude of 350MPa and a mean stress of ± 250 MPa.

It is well known that the vertical build orientation (Z-axis) represents the "worst-case scenario" due to presence of pores in the critical cross-section. The ratcheting curves provide further confirmation of this, as the accumulation of negative axial strain under compressive mean stress appears to suppress damage evolution, potentially due to pore closure. In contrast, tensile mean stress leads to rapid strain accumulation and significantly shorter life.

3. Fatigue Life Prediction

Fatigue life predictions were based on the Smith-Watson-Topper (SWT) parameter [2]. Three distinct approaches were used to assess the impact of different phenomena:

1. SWT_CSSC model: A standard approach based on stabilized mid-life data. The cyclic stress-strain curve (CSSC) from Section 2.1 was used to define the material state.

2. N_f p_SWT_transient: A linear damage accumulation method that accounts for the transient cyclic behavior. This approach performs a cycle-by-cycle analysis, tracking the unique stress/strain amplitudes and mean stress for each individual cycle as the material softens.

3. N_f p_SWT_ratcheting: The most advanced approach, which incorporates the ratcheting-sensitive damage accumulation rule recently proposed by Halama et al. [2]. This model accounts for the additional damage caused by the progressive accumulation of plastic strain, which is typical for AM alloys under non-zero mean stress.

4. Conclusions

Fig. 3 compares experimental and predicted fatigue lives. The standard SWT_CSSC approach significantly overestimates life below 10^4 cycles. Including transient effects improves results, but the ratcheting-based damage rule [2] provides the best correlation, especially for the Z-orientation specimens which exhibit the shortest lives.

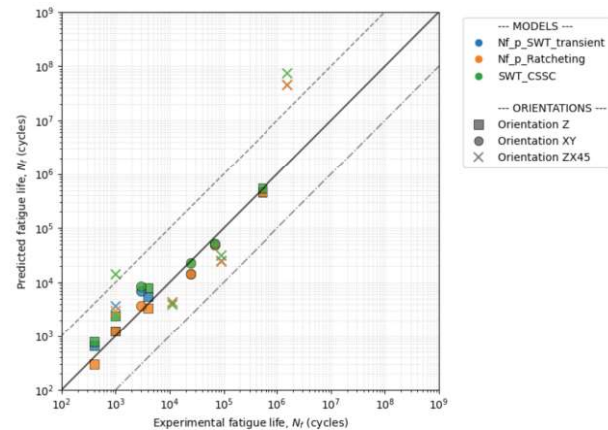


Fig. 3. Experimental vs. predicted fatigue life.

At $N_f > 10^4$, all models converge as ratcheting becomes negligible. Incorporating ratcheting-induced damage is crucial for accurate life prediction of LPBF 316L stainless steel in the LCF regime under non-zero mean stress. Future research will focus on advanced cyclic plasticity modeling to accurately capture the ratcheting response.

Acknowledgments

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