THE PROCESS OF DAMAGE ACCUMULATION FOR CONSTRUCTION MATERIALS PRODUCED USING ADDITIVE MANUFACTURING TECHNOLOGIES

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Abstract

This study presents the results of fatigue investigations performed on additively manufactured austenitic stainless steel 316L produced using the Laser Powder Bed Fusion (LPBF) technique. Fatigue tests were conducted under axial tension–compression loading for three different stress ratios: R = −1, −0.5, and 0. The primary objective of the research was to evaluate the influence of the stress ratio on fatigue life and to assess the applicability of the Smith–Watson–Topper (SWT) parameter in describing the fatigue behavior of LPBF-manufactured material. Based on the experimental results, S–N fatigue curves were constructed for each loading condition, and corresponding analytical equations were determined to describe the relationship between stress amplitude and the number of cycles to failure. From these equations, load levels were calculated for three selected fatigue life ranges and subsequently correlated with the SWT parameter, enabling a comparative analysis of the combined effects of maximum stress and strain amplitude on fatigue damage evolution. In addition to mechanical testing, fracture surface analyses were carried out using scanning electron microscopy (SEM). The findings provide valuable insight into the fatigue performance of additively manufactured 316L stainless steel under different mean stress conditions and contribute to a better understanding of fatigue assessment methods for metallic materials produced by additive manufacturing technologies.

Keywords: Additive manufacturing, austenitic stainless steel 316L, Stress Ratio Factor, cycle asymmetry ratio, uniaxial tension-compression

1. INTRODUCTION

Additive manufacturing (AM) technologies, in particular laser powder bed fusion (L-PBF) have gained significant attention due to their ability to fabricate complex and customized geometries of components with reduced material waste [1,2]. AM processes are associated with the presence of defects emerging in the manufacturing process. These defects include lack-of-fusion voids, gas porosity, unmelted particles and surface irregularities. All these defects can act as stress concentrators and significantly reduce fatigue life [3,21,5]. In comparison with conventionally manufactured materials, AM components exhibit higher variability in fatigue behavior due to the stochastic nature of defect formation. The interaction between defect size, morphology and location has been shown to influence crack initiation mechanisms with larger and more irregular defects leading to earlier crack nucleation and reduced fatigue strength [2,4,5]. Austenitic stainless steel 316L has emerged as one of the most widely studied alloys because of its excellent corrosion resistance and good mechanical properties. This material has found out broad industrial applicability in sectors such as biomedical, aerospace and energy industries. Despite these advantages the fatigue performance of additively manufactured 316L components remains a critical concern limiting their widespread structural application [1,2, 4,5]. The available literature provides insufficient information on the behavior of this material under experimental conditions involving different cycle asymmetry ratios. Therefore, the aim of this study is to investigate the fatigue behavior of additively manufactured 316L stainless steel in uniaxial tension-compression tests under varying cycle asymmetry ratios.

2. DESCRIPTION OF MATERIALS AND METHODS

Specimens for fatigue tests were manufactured using powder of stainless steel 316L. The specimens were produced using the EOS M280 system in a nitrogen atmosphere by the LPBF (Laser Powder Bed Fusion) process. For LPBF process, default parameters supplied by EOS were applied. The specimens with geometry shown in **Figure 1a)** were built along the Z-azis on a platform pre-heated to 40 °C. Specimens were cleaned by micro-blasting using glass beads with diameter of 90 – 150 µm at a low flow pressure of 300 kPa (Blast 2 Softline K1 device, FerroECOBlast) without any further machining.

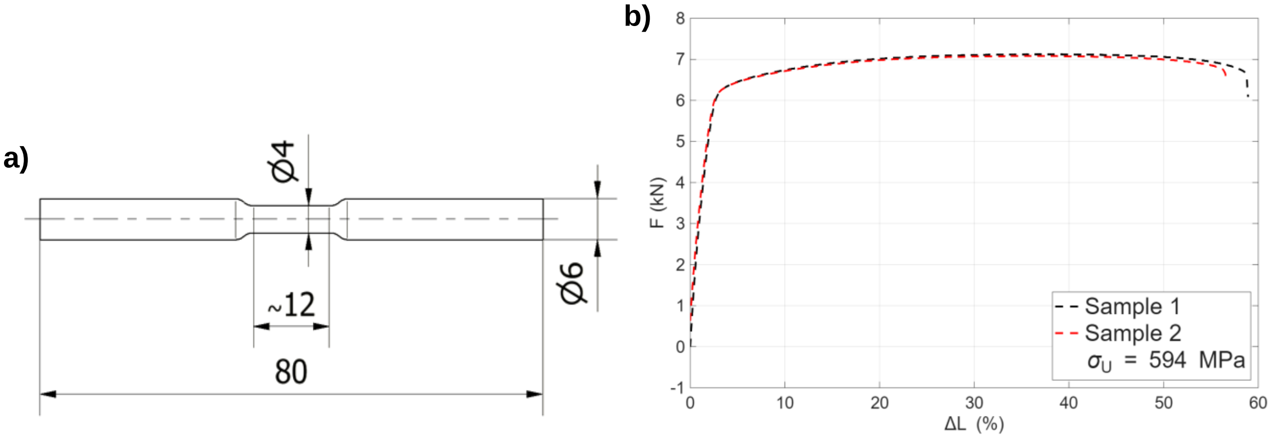

Figure 1 a) Specimen geometry, b) Tensile test of 316L material

An instron Electro Puls E10000 testing system with maximum load capacity of 10 kN was used for fatigue tests. Uniaxial tension-compression tests controlled by force with constant frequency of ~5 Hz were performed under sinusoidal loading with constant amplitude for cycle asymmetry ratio R = -1. For R = -0.5 and R = 0 test were performed under sinusoidal loading with constant amplitude including mean load values. With changes in the R ratio, the contribution of mean stress is as follows $\sigma_m = 0$ for R = -1; $\sigma_m = 1/3\ \sigma_a$ for R = -0.5; $\sigma_m = \sigma_a$ for R = 0. The fatigue tests were conducted until the specimen fractured or the system lost its stiffness. The Smith-Watson-Topper (SWT) parameter, expressed as a fatigue indicator was applied in [6]. In performed uniaxial low-cycle fatigue tests under fully reversed strain-controlled loading conditions, authors investigated relationship between fatigue damage and number of cycles to failure. The SWT parameter is defined as:

$$SWT = \varepsilon_a \cdot \sigma_{max} \quad (1)$$

where:

ε_a - strain amplitude (-) and σ_{max} - maximum stress (MPa)

The study [7] used the SWT mean stress correction model to assess the fatigue life of maraging steel MS1 specimens at various cycle asymmetry ratios. This approach allowed for comparison between literature data for R = -1 and experimental results obtained for R = 0. The SWT mean stress correction is given by:

$$\sigma_{ar} = \sigma_{max}\sqrt{\frac{1-R}{2}} \quad (2)$$

where:

σ_{ar} - equvalent stress amplitude for cycle asymmetry ratio R=-1 and R - cycle asymmetry ratio (-)

3. RESEARCH RESULTS

The tensile test curves for two specimens are shown in **Figure 1b)**. The stress-strain response is initially linear. After reaching the maximum load, there is a significant increase in deformation occurs while the load remains approximately constant until fracture. This indicates that the material exhibits pronounced ductile behavior.

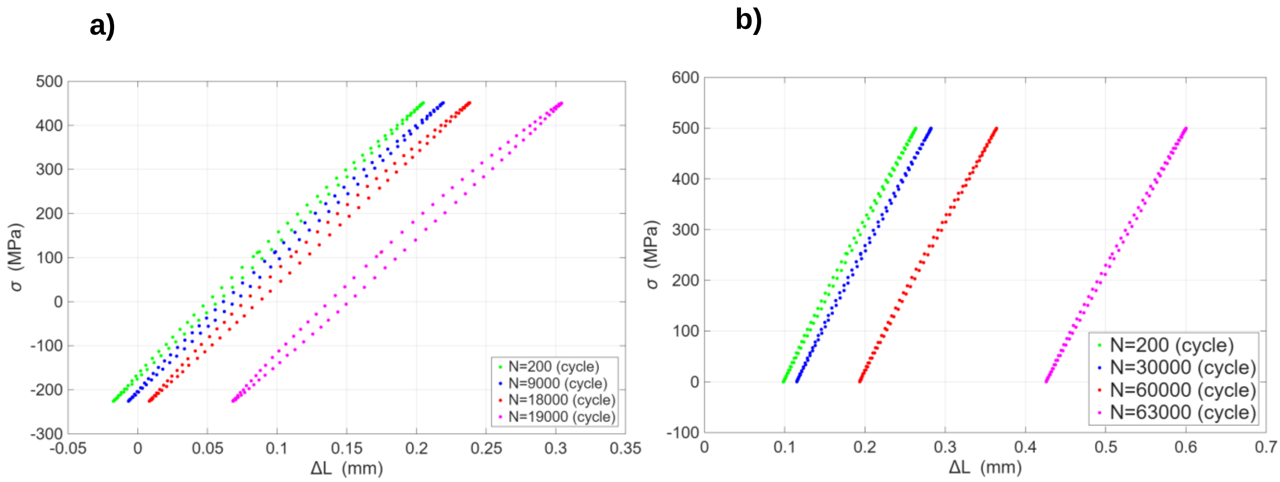

Figure 2 Hysteresis loops with cycle asymmetry ratio R and stress amplitudes: a) R = −0.5, σ_a = 330 MPa, b) R = 0, σ_a = 250 MPa

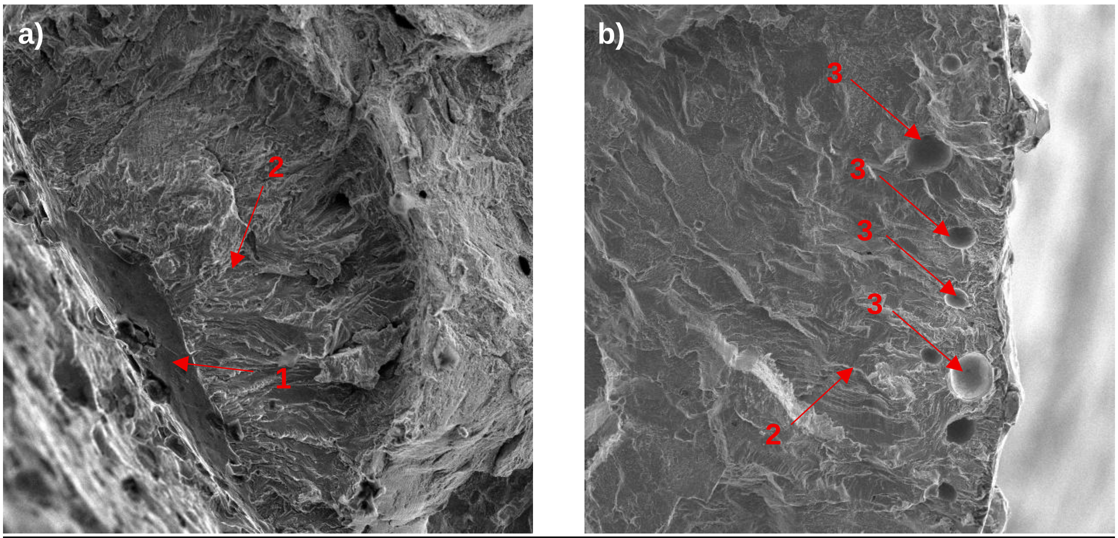

Figure 3 Fracture surface of the samples a) R=0, σ_a = 250 Mpa, b) R=-0.5, σ_a = 270 Mpa, where 1 - unfused boundary, 2 - fatigue striations, 3 - voids

The stress-displacement curves obtained for different cycle asymmetry ratio are presented in **Figure 2.** The results in all cases exhibit an approximately linear relationship between load and displacement, indicating a predominantly elastic response. As the number of cycles increases, the curves shift toward higher displacement values for similar load levels. This behavior suggests a gradual reduction in stiffness of specimen. Changing value of the cycle asymmetry ratio from -1 to 0 higher differences in displacement values were observed. As presented in **Figure 3** most of the fracture propagation was caused by defects like lack of fusion or voids. The relationship between fatigue life N and the maximum applied stress σ_{max} representing the results from the conducted experiments for different cycle asymmetry ratio is presented in **Figure 4a).** In **Figure 4b)** are presented S-N curves obtained from experimental data in logarithmic scale of stress amplitude σ_a and fatigue life N with correlation ratio over 0.9. For R = -1, the range of fatigue life was 1.4 x 10^4 – 2 x 10^5

with applied stress of 220 – 370 MPa. With the appearance of mean load for R = -0.5 the stress amplitude σa was 270 – 330 MPa with mean load σm equal to 90 – 110 MPa. Observed range of fatigue life was 1.9 x 10^4 – 8.9 x 10^4 cycles. For similar values of stress amplitude σa at R = -1 and R = -0.5 it is observed that the fatigue life is similar which is observed in **Figure 4b)** as the S-N lines are close to each other. While the first two cycle asymmetry ratios yield similar results, increase in mean load in R = 0, decrease fatigue life, where σ_a is 180 – 250 MPa and mean load is equal to the values of σ_a. Fatigue life is of 5.1 x 10^4 to 2.4 x 10^5 cycles. In this study, the classical, historically oldest model, which is described in detail in article [8], is used to generate the basic S–N curves. Fatigue curves are expressed using logarithmic functions, as in equation (3). The S-N curves based on experimental data obtained for additively manufactured 316L stainless steel samples are presented in **Table 1.**

$$\log(\mathrm{N}) = \mathrm{b} + \mathrm{a}\cdot\log(\sigma) \tag{3}$$

where:

N - number of cycles

a and b - equation parameters

σ - stress amplitude

Table 1 Equations describing S–N curves for 316L material at different cycle asymmetry ratios

Cycle asymmetry ratio	Equation
R = -1	$\log N = -5.263 \log\sigma + 17.76$
R = -0,5	$\log N = -6.536 \log\sigma + 20.85$
R = 0	$\log N = -4.33 \log\sigma + 15.13$

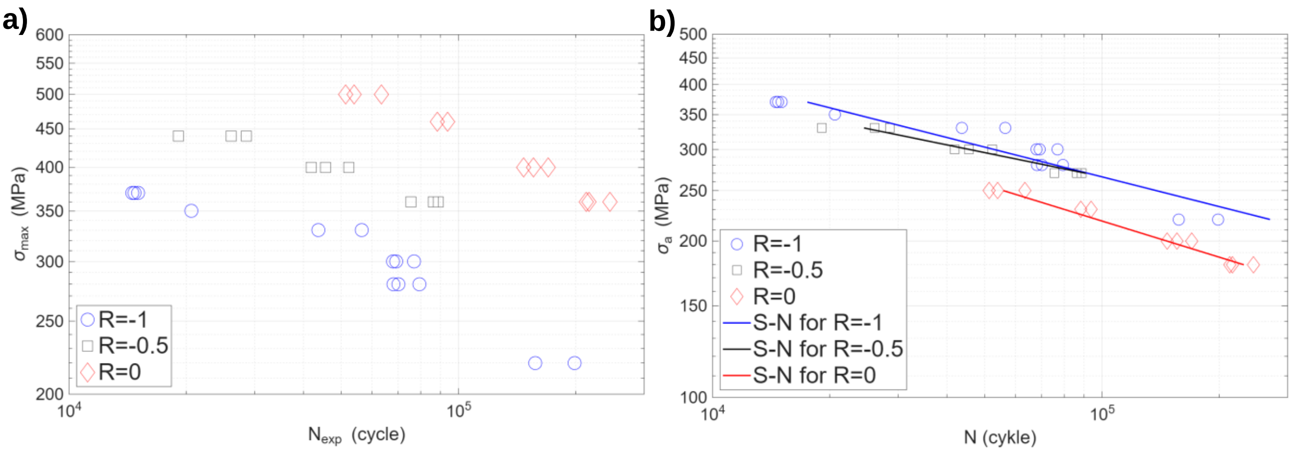

Figure 4 a) comparison of experimental tensile results for different cycle asymmetry ratios; b) S–N curves according to equations presented in **Table 1**

4. STRESS RATIO FACTOR APPROACH

In [9], R. Pawliczek and G. Gasiak introduced a model used to determine the material sensitivity factor to cycle asymmetry *ψ* as a function of the number of cycles to failure, based on results obtained from experimental fatigue test. The model relies on the Haigh diagram and assumes simplified linear relationship between the stress amplitude σ_a and the mean stress σ_m. The calculated parameter values showed good consistency with experimental data with exception of one loading case that involved mean stress. This observation suggests that even a small mean stress component can affect the process of damage accumulation. For limiting amplitudes of normal stress, the following relationship is used:

$$\Delta\sigma = \Delta\sigma_{-1} - 2\psi_\sigma \sigma_m \qquad (4)$$

$$\psi_\sigma(N) = \frac{2\Delta\sigma_{-1}(N) - \sigma_0(N)}{\sigma_0(N)} \qquad (5)$$

where: $\psi_\sigma(N)$ - material sensitivity factor to cycle asymmetry for a given number of cycles to failure,

$\Delta\sigma_{-1}(N)$ - stress amplitude under cyclic bending/tension at the number of cycles to failure and

$\sigma_0(N)$ - maximum stress under pulsating cycles in bending/tension for a given number of cycles to failure.

To analyse the influence of cycle asymmetry ratio on variation of the S-N characteristics (**Table 1**), three fatigue life levels were considered 5 x 10^4; 1 x 10^5 and 1.5 x 10^5 cycles to failure. Based on the corresponding equations, values of the stress amplitude were calculated, and according to the previously described model ψ, appropriate mean stress values were assigned for R = -0.5 and R = 0. Obtained results are presented in **Figure 5a)** together with the equations describing curves for selected stress ratios. The theoretically determined fatigue points closely coincide with linear regression curves and curve equations shown in **Figure 5a)** are almost identical to those reported in **Table 1**.

Figure 5b) shows the relationship between normalized mean stress (σ_m/σ_u) and normalized stress amplitude (σ_a/σ_{AT}) using previously determined points. An analysis of points corresponding to different values of the cycle asymmetry coefficient R proves that an increase in the value of R (shift toward more positive stress states) results in a decrease in fatigue strength. This indicates that the presence of tensile stresses without compressive components accelerates the initiation and progression of fatigue damage. The regression lines reflect the distribution of experimental data points, although slight deviations are visible at higher mean stress values. The differences between applied models are particularly noticeable in the middle and higher ranges of mean stresses. It is noticeable that equation (2) predicts slightly higher values of amplitudes compared to equation (2). In comparison to regression curve of equation (2), the equation (4) is a linear model and in many cases leads to more conservative estimates.

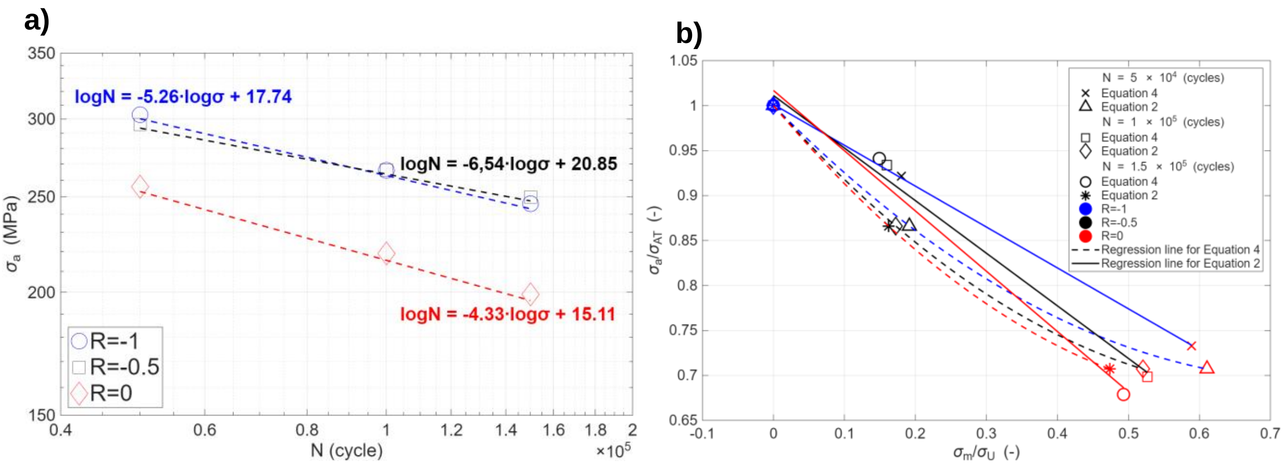

Figure 5 a) Fatigue life N versus estimated stress amplitude for the assumed fatigue lives, b) Normalised Haigh diagram

Table 2 Comparison of experimental and calculated values of the material sensitivity factor to cycle asymmetry

N (cycles)	ψ_{exp}	ψ_{cal}	***Relative error (%)***
$5 \cdot 10^4$	0.2492	0.182	26.97
$1 \cdot 10^5$	0.2254	0.216	4.17
$1.5 \cdot 10^5$	0.1901	0.236	24.15

Table 2 summarizes the comparison between the experimental values of the sensitivity factor to cycle asymmetry and those calculated using equation (5). As can be observed, experimental values are decreasing with increase in fatigue live. With the sensitivity factor obtained using equation (5) where values are increasing as the number of cycles is increasing. It can be seen, that for the highest value of cycles, calculated sensitivity factor is much higher than in experimental data.

5. CONCLUSION

The fatigue tests of additive manufactured samples of 316L stainless steel presented in this paper shows that hysteresis loops exhibit an approximately linear relationship between load and displacement. It is also observed that as the number of cycles increases, the curves shift toward higher displacement values for similar load levels. Uniaxial tension-compression tests were performed under different values of cycle asymmetry ratio, which shows that lower values of mean stress amplitude (R=-0,5) do not have a significant effect on fatigue life in comparison with results at R=-1. For higher mean stress (R=0), the fatigue life at similar stress amplitude in significantly lower. Obtained equations for each cycle asymmetry ratio shows high correlation with experimental data. Applied the material sensitivity factor to cycle asymmetry approach to the calculated points for given number of cycles shows more conservative predictions compared to SWT parameter.

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