Cyclic Plasticity and LCF Properties of Additive and Conventional SS316L

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This paper shows differences in stress-strain behavior of conventional and additively manufactured SS316L. Low-cycle fatigue tests were performed on specimens from both used production technologies. Uniaxial fatigue tests were evaluated to study cyclic stress-strain curve. An interesting result of the study is the possibility of Digital Image Correlation to get cyclic stress-strain curve for maximal peaks in history from a single low-cycle fatigue test performed in strain controlled mode.

Keywords

SS316L, LPBF, cyclic plasticity, low-cycle fatigue, digital image correlation

Introduction

Low-cycle fatigue [2] refers to the deterioration of materials under repeated loading conditions that exceed the yield strength, causing permanent plastic deformation. Unlike high-cycle fatigue (HCF), which primarily remains within the elastic range and can last for millions of cycles, low-cycle fatigue (LCF) involves substantial accumulation of plastic strain, leading to failure after a few hundred to several thousand cycles. This type of fatigue is especially relevant in industries where components are exposed to extreme stress fluctuations and thermal cycles, such as aerospace, automotive, and power generation sectors.

In LCF, three basic equations are used. The first describes the cyclic stress-strain (CSS) curve, thus the relationship between the stress amplitude and the plastic strain amplitude

$$\sigma_a = K' \cdot \epsilon_{ap}^{n'} , \quad (1)$$

where σ_a is the amplitude of stress, K' is the strain hardening coefficient, ϵ_{ap} = amplitude of plastic strain and n' is the strain hardening exponent.

Also, it is possible to use the Coffin-Manson equation to estimate fatigue life by analyzing the relationship between the plastic strain amplitude and the number of cycles to failure

$$\epsilon_{ap} = \epsilon_f' \cdot \left(2N_f\right)^c , \quad (2)$$

where $\epsilon_f{}'$ is the fatigue ductility coefficient, N_f is the number of cycles to failure, and c is the fatigue ductility exponent.

Finally, the Basquin equation can also be used, which, unlike the Coffin-Manson equation, describes the relationship between the stress amplitude and the number of cycles to failure

$$\epsilon_{ae} = \frac{\sigma_a}{E} = \sigma_f{}' \cdot \left(2N_f\right)^b , \tag{3}$$

where ϵ_{ae} is the elastic strain amplitude, σ_a is the elastic stress amplitude, E is Young modulus, $\sigma_f{}'$ is the fatigue strength coefficient, and b is the fatigue strength exponent. The amplitudes of particular quantities are considered in the midlife.

In this contribution, the CSS curves obtained on additively and conventionally produced specimens are studied. First, the influence of orientation is shown followed by the comparison with conventionally manufactured specimens including fatigue life discussions. Finally, the results of accelerated technique based on optical measurement on curved part of the specimen are discussed.

Stainless steel 316L

Austenitic steel 316L [1] is a low-carbon nickel-chromium-molybdenum steel alloy that combines high strength, corrosion resistance, and weldability. These properties make it widely used across various industries. Due to additional properties such as low thermal conductivity, high melting point, and others, this alloy is also well suited for additive manufacturing (AM).

Influence of orientation on cyclic strain curve

Samples in [1] were manufactured using the laser powder bed fusion (LPBF) method, with printing carried out in three different orientations (XY, ZX, Z). After printing, they were subjected to stress relief heat treatment at 470 ° C for 6 hours, cut from the build plate, and machined to ensure geometric accuracy. The uniaxial fatigue of the specimens in three different orientations was investigated using force-controlled fatigue tests, with stress amplitudes ranging from ±300 MPa to ±500 MPa.

The data from the research [1] were evaluated and graphs based on the above equations were generated using scripts written in Python language. These graphs were obtained through linear regression on the logarithmic scale for different orientations.

Based on Figure 1, it is evident that the ZX45 orientation has the smallest slope, indicating a lower amplitude of plastic strain for a given stress amplitude compared to the other orientations up to 450 MPa. In this range, the XY orientation exhibits an even lower plastic strain amplitude. The orientation of the specimen axis during printing significantly affects its CSS curve. Lifetime curves for all three orientations are presented in [1].

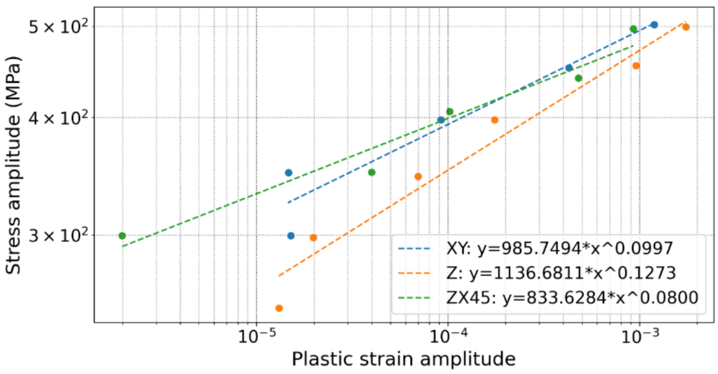


Fig. 1 Cyclic stress – strain curves for three orientations of specimen's axis in AM

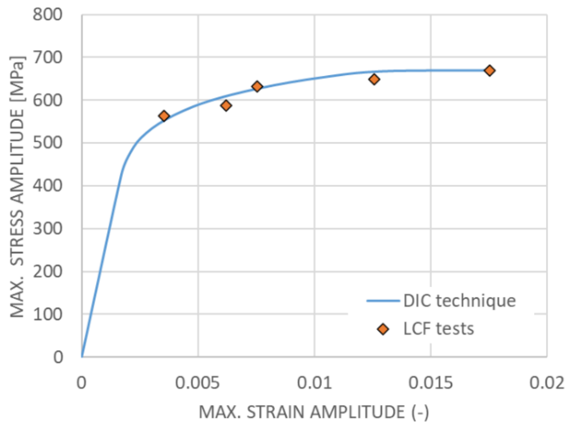
Comparison of low-cycle fatigue for both manufacturing methods

The LCF data in [3] reveal key differences in LCF behaviour between conventionally (wrought) and additively manufactured SS316L. It should be noted that the AM specimens were built with the horizontal orientation of the axis. No heat treatment was applied, just fine machining this time. A comparison of the parameters of the CSS curve and the fatigue parameters of the e-N curves for both variants of SS316L can be seen in Table 1.

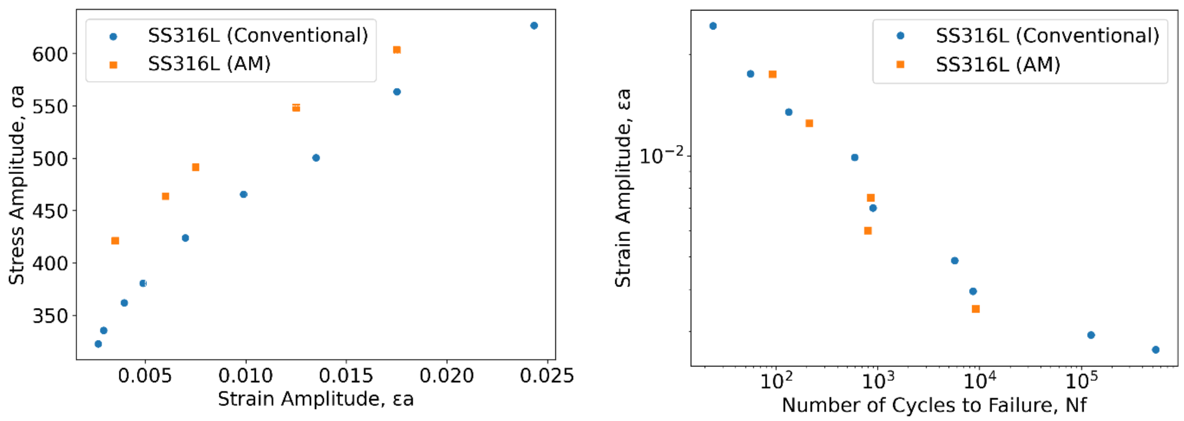
The K' and n' values show that specimens produced by the conventional method provide higher toughness; i.e., for the same stress, they exhibit the largest amplitude of plastic strain compared to specimens fabricated by AM (Fig. 2a). The fatigue curves are compared visually in Fig. 2b.

Tab. 1 Differences between fatigue parameters of conventionally and additively manufactured SS316L

Parameters	AM	Conven.
$n'\ [-]$	0.1490	0.1919
$c\ [-]$	-0.5249	-0.3442
$b\ [-]$	-0.0782	-0.0661
$K'\ [MPa]$	1102	1238
$\epsilon_f{}'[-]$	0.2201	0.0702
$\sigma_f{}'[MPa]$	879	743



c)



a) b)

Fig. 2 LCF results of SS316L: a) CSS curves, b) e-N curves, c) DIC technique applied on specimen manufactured by AM

Digital image correlation based accelerated technique

The CSS curve is often estimated with an incremental load application. Every loading sequence maintains the same cycle parameters, which can be set to a predetermined number of cycles or interactively set by an experimenter during test realization, often after achieving a stable material response. The cyclic stress-strain curve can be obtained using an alternative method based on Digital Image Correlation (DIC) or another appropriate optical method full field measurement of strain on the curved portion of the sample ([4] and [5]). Nevertheless, some materials, particularly stainless steels, exhibit transient behaviour over time; a steady state is not present. Then, the accelerated technique brings, for instance, the cyclic stress-strain curve corresponding to maximal peaks of stress, which can be used to prevent buckling of specimens by appropriate planning of strain amplitudes.

Figure 2c shows the relationship between the maximum stress amplitude and the maximum strain amplitude obtained in the tubular specimen with ±1.75% axial strain. The results confirm that the DIC method almost perfectly replicates classical LCF tests, proving its reliability [4].

Conclusion

The study shows the highest cyclic yield stress for horizontally built specimens and provides a comprehensive comparison of the LCF behaviour and the cyclic plastic properties of conventionally and additively manufactured SS316L (considering the horizontal orientation). In the latter part, the results reveal that additively manufactured specimens exhibit lower plastic strain amplitudes under the same loading compared to conventionally manufactured specimens, while offering similar lifetimes. Furthermore, the digital image correlation (DIC) method has proven to be a reliable tool for estimating the cyclic stress-strain curve. These findings emphasize the importance of selecting an appropriate manufacturing method based on the desired mechanical properties and fatigue performance. Future research should focus on the optimizing the heat treatment of additively manufactured parts to reduce residual stresses of SS316L components.

Acknowledgment

This work was supported by the project Computational modelling of ductile fracture of identical wrought and printed metallic materials under ultra-low-cycle fatigue created with financial support from the Czech Science Foundation under the registration no. 23-04724S and by the Specific Research project named „Computational and experimental modeling in applied mechanics and biomechanics"(SP2025/048).

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