Uniaxial LCF Properties of Additively Manufactured In718

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Abstract: The paper focusses on the stress-strain behaviour of Inconel 718 prepared by the selective laser melting technology. Uniaxial cyclic plastic properties are reported together with lifetimes of particular specimens. The transient behaviour of the material is a challenge for advanced constitutive modelling. The cyclic plasticity model considering a virtual backstress for memory surface evolution is used in the description of the strain-range-dependent transient behaviour. Strain-controlled cases considered in the study are predicted very well for strain amplitudes higher than 0.9%.

Keywords: Low cycle fatigue; Cyclic plasticity; Inconel 718; Additive manufacturing

1 Introduction

Recently, additive manufacturing has played an important role in technical practice not only in prototyping but also in the production of functional parts. This article focusses on the investigation of low-cycle fatigue (LCF) properties of the Ni-based superalloy Inconel 718. It is well known that the material is designed to maintain high strength and fatigue performance at high operating temperatures (650°C). There are many studies available in the literature that focus on the heat treatment of the additively prepared variant of Inconel 718 [1-3]. However, cyclic plastic properties and low cycle fatigue data are reported in the literature very rarely. This contribution brings new results of the stress-strain behaviour of Inconel 718 manufactured by selective laser melting (SLM), as well as further numerical modelling of its complexity under uniaxial loading.

2 Experiments

2.1 Specimens manufacturing

All specimens prepared for low-cycle fatigue testing were printed from a virgin powder with selective laser melting (SLM) technology using Renishaw AM500E. Specimens were printed in the Z direction (vertical orientation of the specimen axis) and were tested in as-built state. The main printing parameters used during the AM process are listed in Table 1. The chamber was filled with argon with purity 5.0 during fabrication to prevent oxidation. The building platform was preheated to 170 °C to reduce residual stresses during the AM process.

Table 1. Printing parameters used in AM process.

Specimens orientation	3D printing strategy	Laser power (W)	Laser rate (mm · s^{-1})	Layer thickness (µm)	Preheating of building platform (°C)
90°	"meander"	400	1150	60	170

2.2 Fatigue testing

Uniaxial fatigue tests were performed in tension-compression on the LabControl 100kN/120Nm biaxial electro-servohydraulic test machine. Strain-controlled tests were performed on a solid specimen with 6.3 mm diameter (up to 1% of the strain amplitude) and on a thin-walled tubular specimen with 11.3 mm inner diameter and 13.9 mm outer diameter.

2.3 Results

Cyclic stress-strain behaviour and lifetimes have been evaluated in constant strain amplitude tests using own Python scripts. The most important results are: lifetimes N_f, stress amplitude σ_a, plastic strain amplitude ε_{ap}, dynamic modulus E and cyclic yield stress Y (see Fig. 1). In general, dynamic modulus has different values in the tensile and compressive branches of the hysteresis loop (an aluminium alloy is considered in the scheme shown in Fig.1).

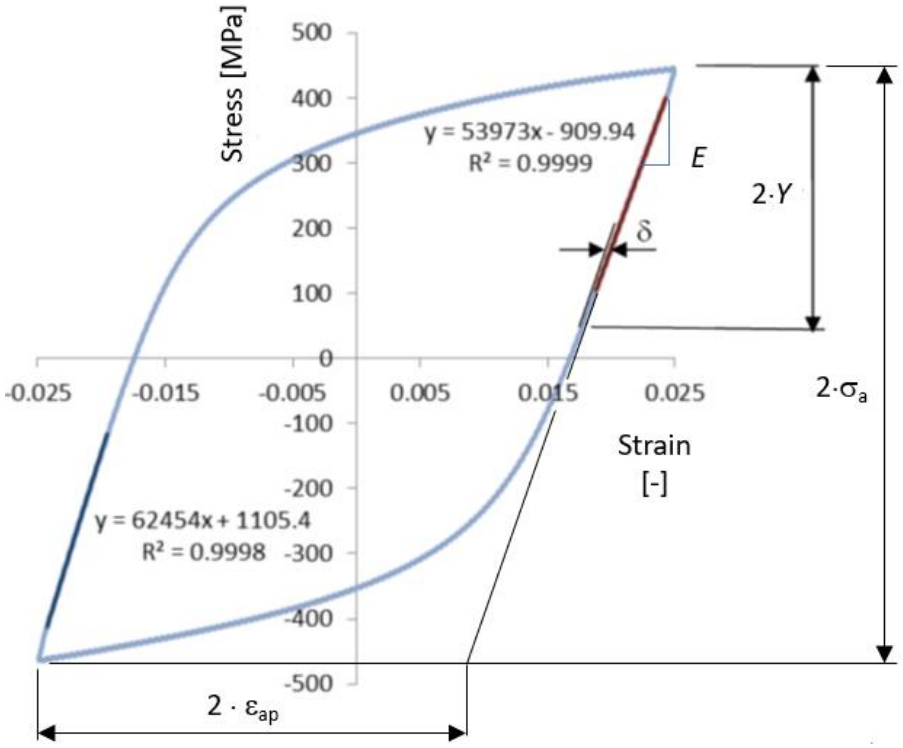

Fig. 1 Scheme of a hysteresis loop.

The results show a significant cyclic hardening in the initial cycles followed by a cyclic softening under strain amplitudes greater than 0.4% (Fig. 2). Saturated hysteresis loops at half-life are shown in Fig.3. The material also shows a non-Masing behaviour (Fig.4).

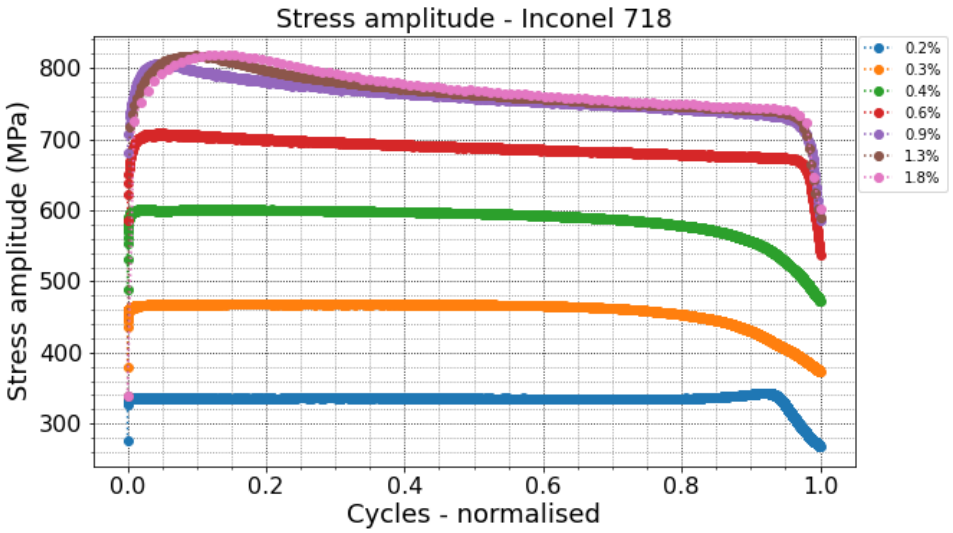

Fig. 2 Stress amplitude evolution of Inconel 718 manufactured by SLM technology.

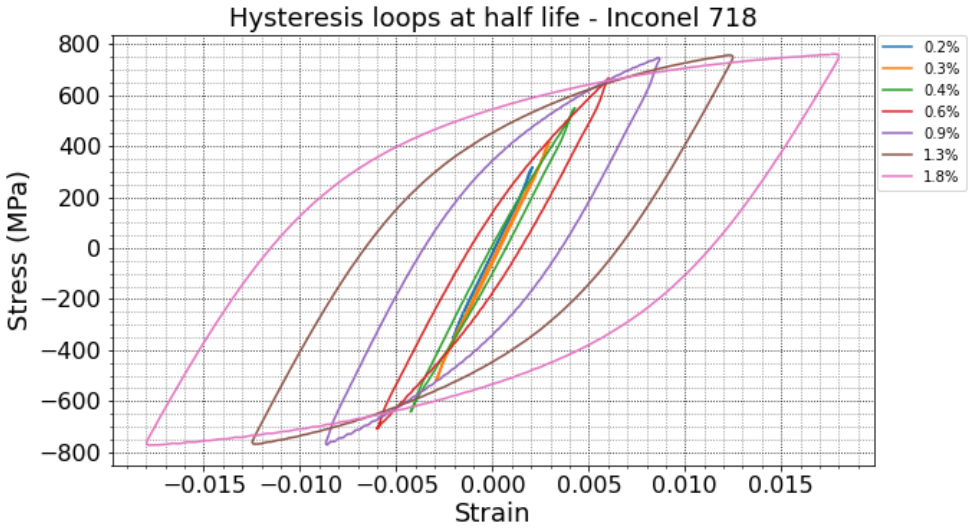

Fig. 3 Uniaxial hysteresis loops of Inconel 718 manufactured by SLM technology.

The most important results of the low cycle fatigue tests are reported in Table 2. The stress amplitudes correspond to the half-life. The number of cycles to failure was evaluated with a criterion of 25% decrease from the asymptotic line created in the diagram stress amplitude vs number of cycles.

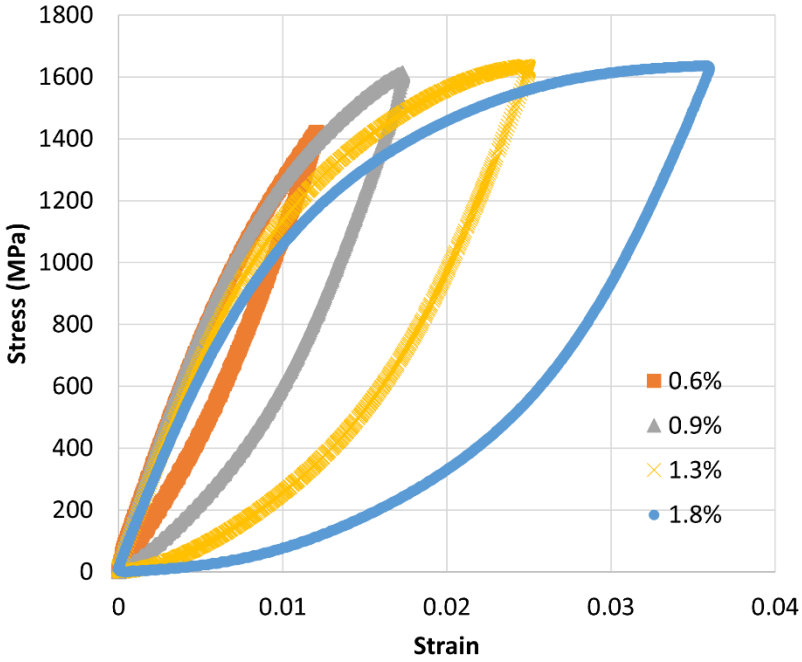

Fig. 4 Non-Masing behaviour of Inconel 718 manufactured by SLM technology.

Table 2. Main results of LCF tests performed on Inconel 718.

Strain amplitude [%]	Stress amplitude [MPa]	Number of cycles to failure [-]
0.2	335.6	50082
0.3	467.1	21839
0.4	594.9	8407
0.6	689.9	1935
0.9	758.9	1063
1.3	762.7	302
1.8	767.2	103

3 Constitutive modelling

3.1 Cyclic plasticity model description

For simplicity, the constitutive model is described for the uniaxial loading case. The main equations of the incremental theory of plasticity follow. The yield condition is defined as

$$f = |\sigma - \alpha| - \sigma_Y - R = 0 \tag{1}$$

where σ is the axial stress, α is the backstress (kinematic variable), R is the isotropic variable and σ_Y is the yield stress. The superposition of six backstress parts ($M = 6$) is considered as in the original Chaboche model, i.e.

$$\alpha = \sum_{i=1}^{M} \alpha^{(i)} \tag{2}$$

whereas the evolution equation of kinematic hardening is considered as

$$d\alpha^{(i)} = C_i d\varepsilon_p - \gamma_i \varphi(p) \alpha^{(i)} dp, \tag{3}$$

where C_i, γ_i are material parameters, $d\varepsilon_p$ is the increment of plastic strain and dp is the accumulated plastic strain increment. The Marquis parameter is dependent on the current value of the accumulated plastic strain

$$\varphi(p) = \varphi_{\infty 1} - (\varphi_{\infty 1} - \varphi_{01})e^{-\omega_1 \cdot p} + \varphi_{\infty 2} - (\varphi_{\infty 2} - \varphi_{02})\, e^{-\omega_2 \cdot p}, \quad (4)$$

Two Marquis terms are used to describe the cyclic hardening/softening behaviour. The parameters φ_{01} and $\varphi_{\infty 2}$ are dependent on the size of the memory surface R_M:

$$\varphi_{01} = A_{01} e^{B_{01} \mathrm{R}_M}, \quad (5)$$

$$\varphi_{\infty 2} = A_{\infty 2} e^{B_{\infty 2} \mathrm{R}_M}, \quad (6)$$

In this work, the memory surface is introduced in the stress space with isotropic behaviour and is calculated from the virtual backstress [5]. Its size corresponds to the maximal absolute value of the virtual backstress for uniaxial loading. This property is in accordance with the Jiang-Sehitoglu memory surface [6]. The isotropic hardening is considered a linear one

$$dR = R_0 dp, \quad (7)$$

but the value of material parameter R_0 is dependent on the memory surface size as follows

$$R_0 = -\langle A_1 \cdot \mathrm{R}_M + A_2 \rangle, \text{ for } \mathrm{R}_M < \mathrm{R}_{ML}, \quad (8)$$

$$R_0 = -(A_3 \cdot \mathrm{R}_M + A_4), \text{ otherwise}, \quad (9)$$

where A_1, A_2, A_3, A_4 are material parameters, $\langle x \rangle = (x + |x|)/2$, and the transition memory size is calculated by

$$\mathrm{R}_{ML} = (A_4 - A_2)/(A_1 - A_3). \quad (10)$$

All material parameters are stated in Table 3. The implementation of the proposed cyclic plasticity model was done in Python for the strain-controlled uniaxial case based on the algorithm presented elsewhere [4].

Table 3. Parameters of the proposed cyclic plasticity model.

Parameter	Value
C_{1-6} [MPa]	426190, 99567, 41526, 25502, 18386, 5494
γ_{1-6}	3333, 1212, 519, 253, 137, 54
σ_Y [MPa]	220
ω_1, ω_2	4.3, 2.2
$\varphi_{\infty 1}, \varphi_{02}$	-0.15, 0.8
A_{01}, B_{01}	0.003056, 0.008469
$A_{\infty 2}, B_{\infty 2}$	0.3216763, 0.0021203
A_1, A_3	0.007763, 0.1351
A_2, A_4 [MPa]	-1.455174, -61.295

3.2 Results of simulations

The first example of stress-strain prediction corresponds to the fatigue test with a constant strain amplitude of 1.8%. Uniaxial hysteresis loops from the whole history of loading are presented in Fig. 5. The prediction of the hysteresis loop shape is good as can be seen from Fig. 6.

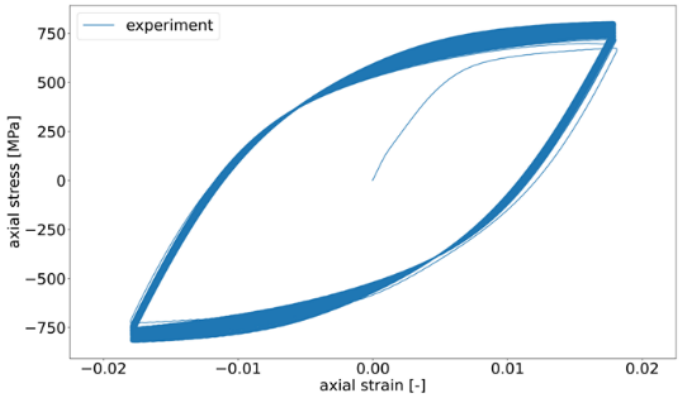

Fig. 5 Uniaxial hysteresis loop for 1.8% of strain amplitude - experiment.

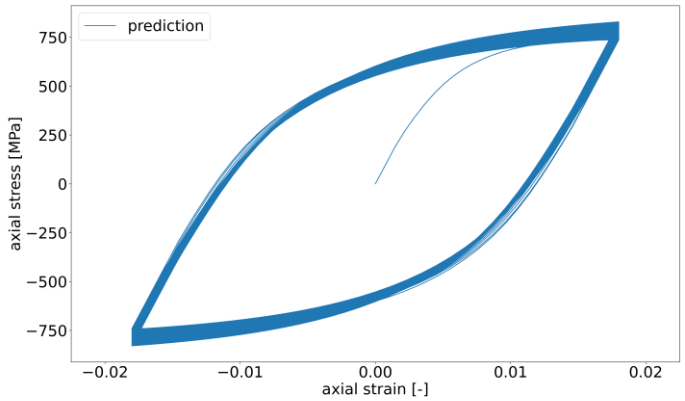

Fig. 6 Uniaxial hysteresis loop for 1.8% of strain amplitude - prediction.

The cyclic hardening/softening behaviour is accurately described for the case of 1.8% strain amplitude (Fig. 7).

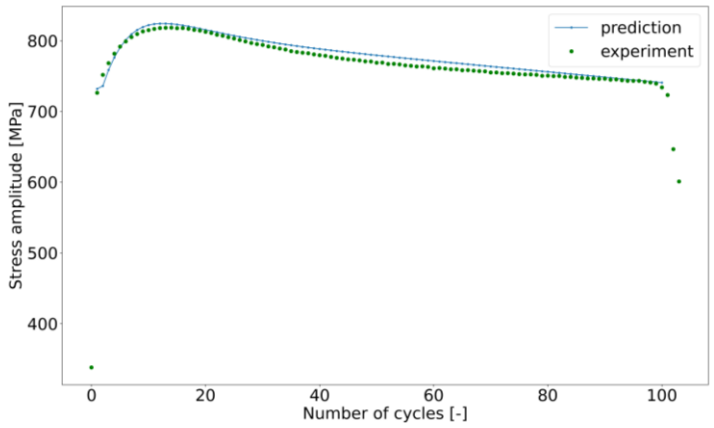

Fig. 7 Results of evolution of stress amplitude with cycling - 1.8% of strain amplitude.

The incremental test performed under strain amplitudes 0.22%, 0.31%, 0.44%, 0.66%, 0.88% and 1.1% serves us as a verification case. From Fig. 8, it is obvious that the highest error occurs for small amplitudes, where the dynamic modulus was higher than E=130000MPa.

Therefore, a possible improvement of the robustness of the material model is in the consideration of the variation of the elastic modulus.

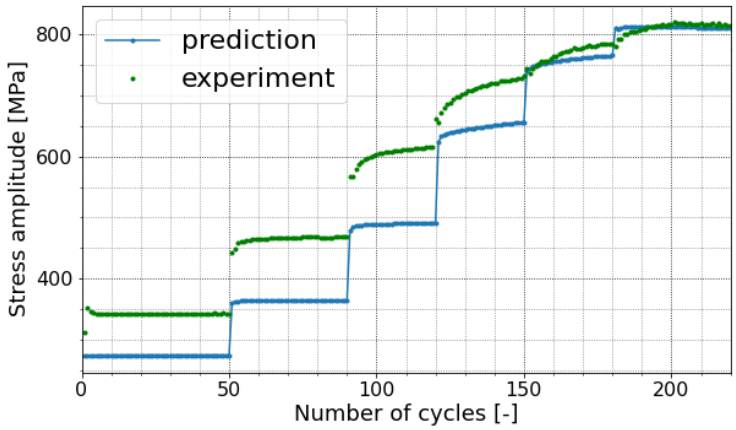

Fig. 8 Results of evolution of stress amplitude with cycling – the incremental test.

Uniaxial hysteresis loops from the incremental test are shown in the Fig. 9. The prediction by proposed material model is very good, see Fig. 10.

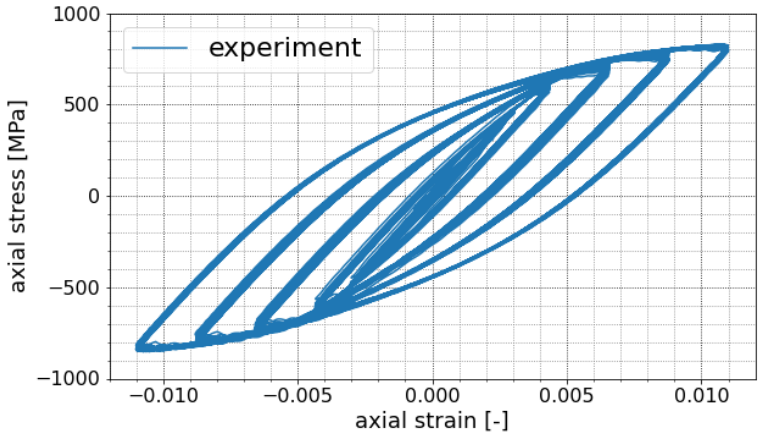

Fig. 9 Uniaxial hysteresis loops from the incremental fatigue test.

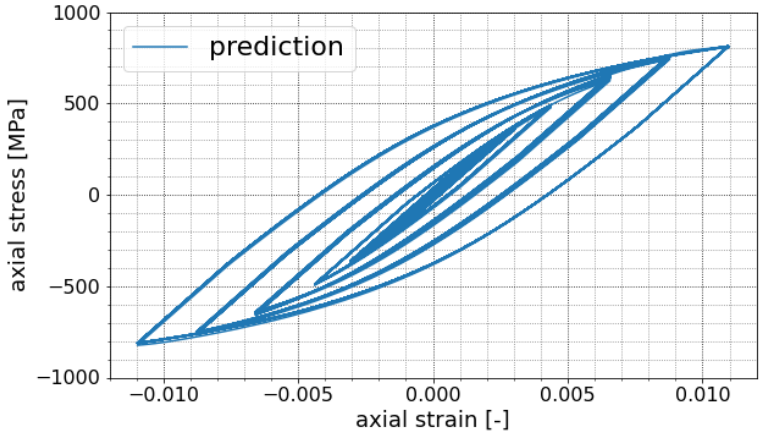

Fig. 10 Prediction of uniaxial hysteresis loops from the incremental fatigue test.

Conclusion/Summary

The article describes selected results of low-cycle fatigue tests performed on as built specimens made of Inconel 718. The material printed with SLM technology shows a complex cyclic hardening/softening and non-Masing behaviour. Dynamic moduli are strain dependent, but for the numerical predictions an average value was considered. A new cyclic plasticity model with a memory surface is applied to describe the complex stress-strain behaviour of the material under constant amplitude loading, as well as in an incremental fatigue test. Very good correlation of predictions with experiments was achieved in the case of hysteresis loop shape and in the evolution of the stress amplitude with cycling.

Acknowledgements

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References

[1] Marchese, G., Atzeni, E., Salmi, A. and Biamino, S. "Microstructure and residual stress evolution of laser powder bed fused Inconel 718 under heat treatments," *J Mater Eng Perform*, **30**, pp. 565–574 (2021).

[2] Trosch, T, Strößner, J, Völkl, R and Glatzel, U. "Microstructure and mechanical properties of selective laser melted Inconel 718 compared to forging and casting," *Mater Lett*, **164**, pp. 428-431 (2016).

[3] Zhang, Q, Ren, P, Tu, X, Dai, Y., Wang, X. and Li, W. "Effect of heat treatment on microstructure evolution and mechanical properties of selective laser melted inconel 718 alloy," *J Mater Eng Perform*, **28**, pp. 5376–5386 (2019).

[4] Halama, R, Markopoulos, A, Jančo, R and Bartecký, M. "Implementation of MAKOC Cyclic Plasticity Model with Memory," *Adv Eng Softw*, **113**, pp. 34-46 (2017).

[5] Halama, R., Fumfera, J., Gál, P., Kumar, T. and Markopoulos, A. "Modeling the Strain-Range Dependent Cyclic Hardening of SS304 and 08Ch18N10T Stainless Steel with a Memory Surface," *Metals*, **9**, 832 (2019).

[6] Jiang, Y. and Sehitoglu, H. "Modeling of cyclic ratchetting plasticity, part I: Development of constitutive relations," *J Appl Mech*, **63**(3), pp. 720-725 (1996).