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Fatigue behaviour of SLM maraging steel under variable-amplitude loading

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Abstract

One of the most challenging issues for additive manufactured materials is fatigue endurance. Engineering components often operate under complex, variable amplitude loadings, in which existing technological imperfections promote fatigue cracks growth and damage of elements eventually. In this study the effects of different variable-amplitude strain levels on fatigue life, 18Ni300 steel was tested. The work presents various behaviours of the material depending on the load level.

Keywords: Fatigue of material, SLM maraging steel, variable-amplitud loading

1. Introduction

Maraging steel is a special class of advanced high-strength steels, widely used in the aircraft, aerospace, military, offshore, tooling and mould making industries, due to the combination of unusual properties, namely high-strength,

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Nomenclature

ε_a	strain amplitude
σ_y	yield strength
σ_u	tensile strength
σ	stress
t	time
E	Young's modulus
N_f	number of cycles to failure
LCF	low cycle fatigue
HCF	high cycle fatigue

toughness, ductility, and weldability along with dimensional stability (Kempen K at al. 2011). Because of their martensitic matrix, these materials require a rapid quench from the austenitic region to temperatures below the martensite start temperature, which makes them particularly suited for the selective laser melting (SLM) technology. Although this alloy produced by SLM has been relatively studied in terms of microstructure features (Macek W. et al. 2022) and monotonic response for different manufacturing conditions (Branco, R. et al. 2012, Garcias J.F. at al. 2022), its behaviour under fatigue loading is not clear. Fatigue tests of SLM 18Ni300 steel have been mainly focused on determining the basic fatigue characteristics (Branco et al., 2018) but the deep understanding of fatigue behaviour under more complex loading is missing. Scientists are looking for the best fatigue parameters to effectively define the relationship between load and durability.

In the above-mentioned areas of application, most components experience variable-amplitude loading which makes them prone to fatigue failure. Under these service conditions, engineering design against fatigue requires not only a detailed knowledge on the loading history but also a deep understating of the cyclic deformation response (Marciniak Z. at al. 2008). Nevertheless, so far, very few studies have addressed the loading sequence effect and the damage accumulation mechanisms in fatigue life of maraging steel produced by selective laser melting. Thus, this paper studies the uniaxial fatigue behaviour of 18Ni300 maraging steel produced by selective laser melting under variable-amplitude loading.

2. Material and methods

The material selected for all experiments performed in this study was the 18Ni300 maraging steel produced by selective laser melting. The specimen geometries were fabricated with a vertical orientation, on the base plate, using a Concept Laser M3 linear printing system equipped with a Nd:YAG fibre laser (see Figure 1). The building strategy comprised the deposition of 40 μm thick layers, with a hatch spacing of 100 μm, at a scan speed of 200 mm/s. The nominal chemical composition of tested steel is presented in Table 1, and the mechanical properties are presented in Table 2.

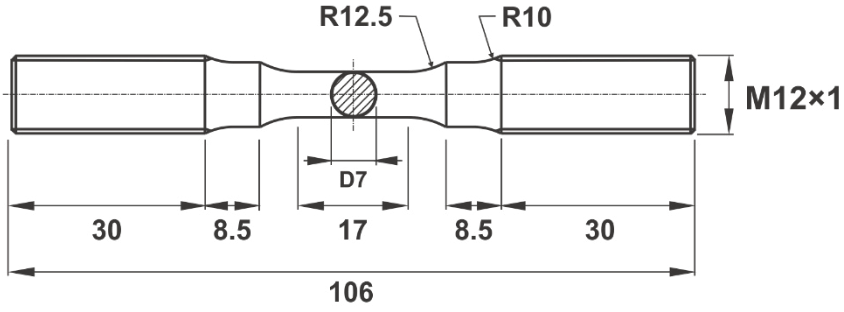

Fig. 1. Specimen geometries used in the low-cycle fatigue tests (unit: mm).

Table 1. Chemical composition (wt.%) of 18Ni300 steel manufactured by SLM.

C	*Ni*	*Co*	Mo	Ti	Al	Cr	P	Si	Fe
0.01	18.2	9.0	5.0	0.6	0.05	0.3	0.01	0.1	balance

Table 2. Mechanical properties of 18Ni300 steel manufactured by SLM.

Porosity (%)	Density (g/cm^3)	Hardness (HV1)	E (GPa)	σ_u (MPa)	σ_y (MPa)	Strain at Failure (%)
0.74±0.09	7.42	354±5	168±29	1147±13	910±11	5.12±0.001

The microstructure of the tested material is formed by grains elongated, with about 150 μm long and 35 μm width, see Fig. 2. It can also be seen martensitic needles dispersed throughout the entire surface. As expected, the laser passes are visible in the surface. Micrography shows small porosities (0.74%). Tests were performed in low-cycle fatigue (LCF) and high-cycle fatigue (HCF) regimes under fully-reversed strain-controlled conditions using cyclic sinusoidal waves on a 100 kN closed-loop servo-hydraulic testing machine (Instron).

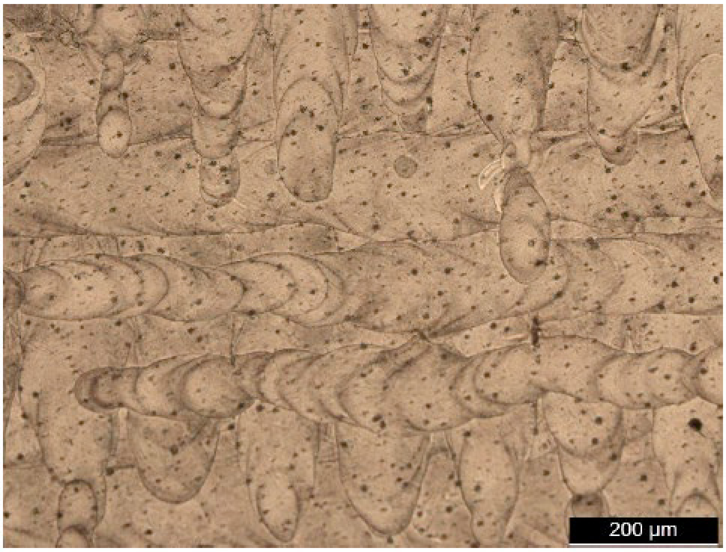

Fig. 2. Microstructure of the tested SLM 18Ni300 maraging steel. Reprinted from reference Branco et al., 2018. Low-cycle fatigue behaviour of AISI 18Ni300 maraging steel produced by selective laser melting, Metals 8(1), 32.

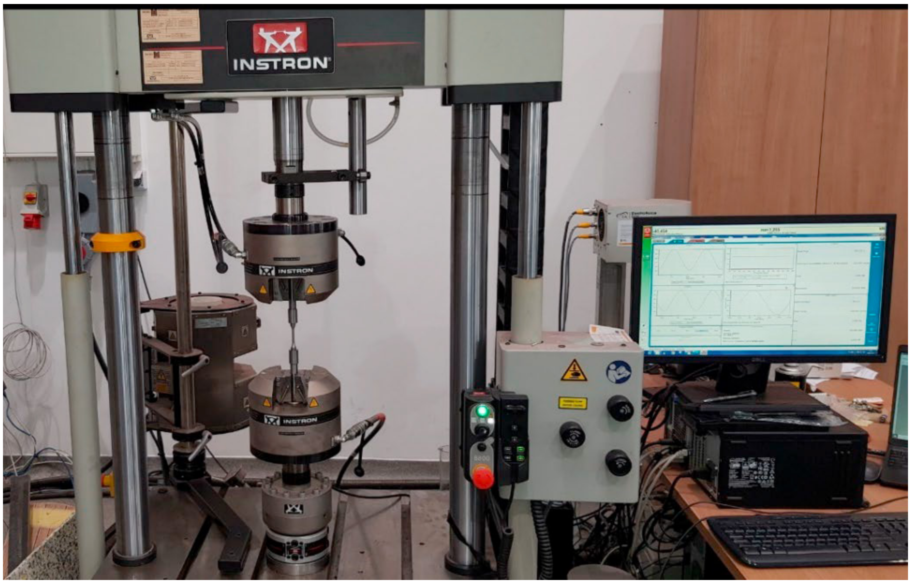

Fig. 3. Universal testing system Instron 8802.

The loading history consisted of two blocks of three cycles each (Fig. 4), repeated until failure. In the first block, the amplitude increased, and in the second they decreased. The amplitudes of the individual cycles were 50%, 75% and 100% of the maximum strain amplitude. The tests were carried out at four load levels at the maximum value of the strain amplitude: 1.00%, 0.75%, 0.50% and 0.35%. Twelve specimens were tested, three on each level.

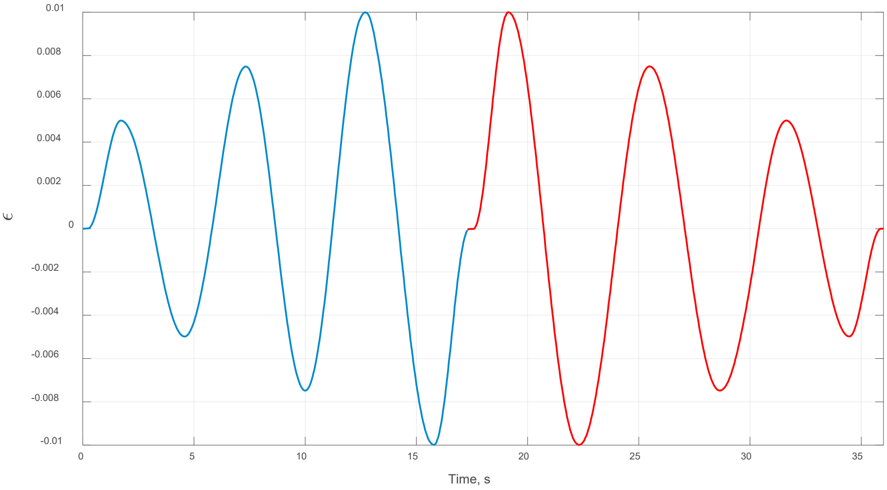

Fig. 4. The shape of the strain course carried out during the tests.

3. Results and discussion

During the tests, the deformation and stress courses were recorded continuously, as exhibited in Fig. 5, thanks to which the analysis of the behaviour of the tested samples was possible. The tests showed different transient responses of the material depending on the strain level. At the two highest load levels, the samples showed a cyclic softening behaviour (Fig. 5a), which was evident by the decrease in stress amplitude and the degeneration of the hysteresis loops throughout the test (Fig. 6). On the other hand, for the two lowest strain levels, where the value of plastic deformation was small, a stable behaviour was observed (Fig. 5b), and the stress level was constant until the crack appeared, as can be inferred from the hysteresis loops shown in Fig. 7.

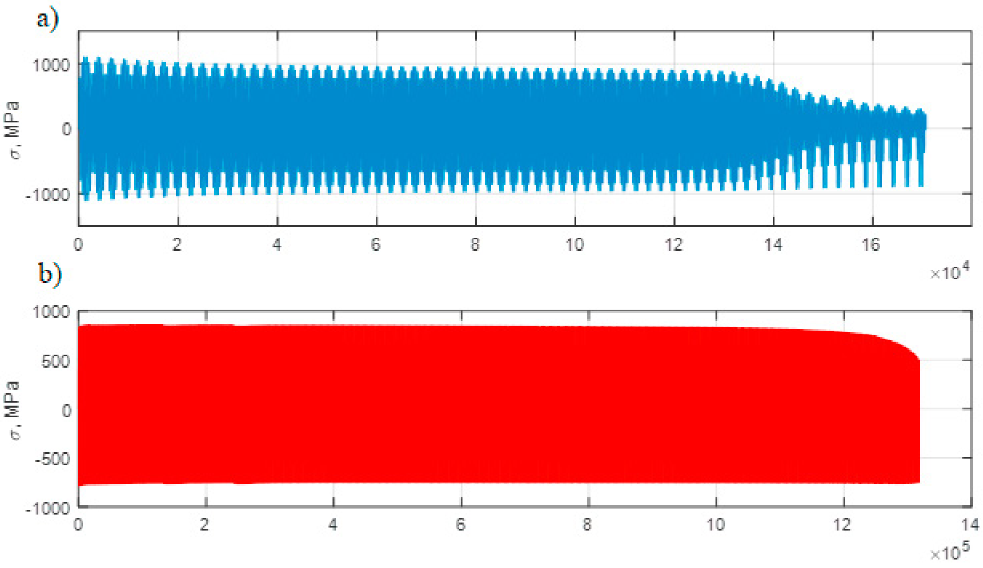

Fig. 5. Stress changes during the tests for the maximum strain amplitude: a) 1%, b) 0.5%.

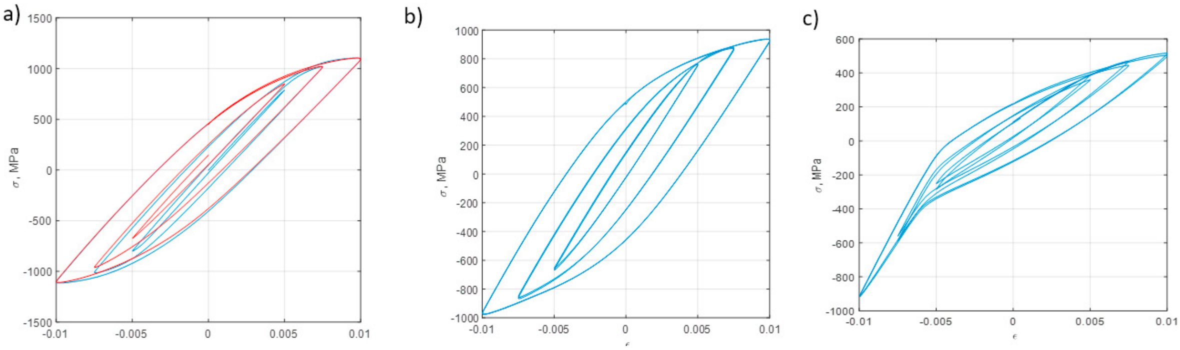

Fig. 6. Examples of the hysteresis loops collected in the tests at a maximum strain amplitude of 1% for different stages of fatigue life: a) at the beginning, b) in the middle, c) before failure.

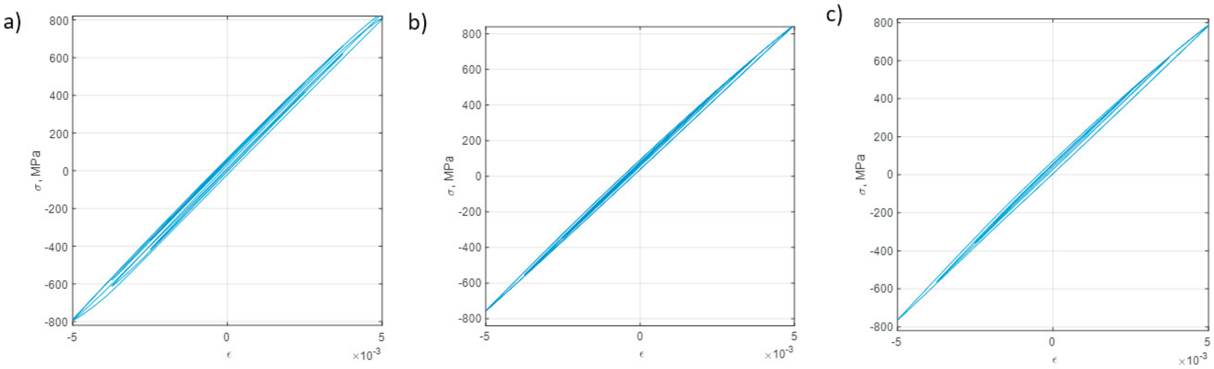

Fig. 7. Examples of the hysteresis loops collected in the tests a maximum strain amplitude of 0.5% for different stages of fatigue life: a) at the beginning, b) in the middle, c) before failure.

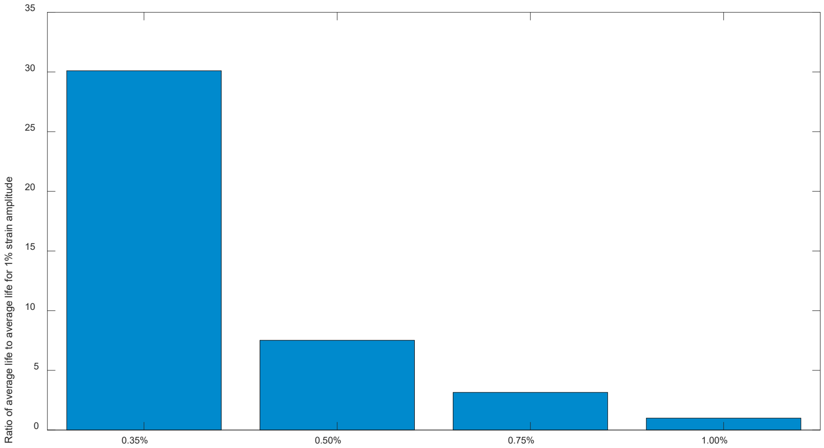

Fig. 8. Ratio of average fatigue life to average fatigue life for 1% strain amplitude.

The analysis of the obtained results showed a significant increase in durability with a decrease in the maximum strain amplitude. This behaviour can be seen in Fig. 8, which shows the ratio of the average fatigue life to the average fatigue life for a strain amplitude of 1%. Research has shown that a decrease in load amplitude by 25% resulted in an increase in durability about three times, and a 50% decrease in amplitude resulted in an increase in durability about eight times. On the other hand, reducing the amplitude value by 65% extended the durability 30 times (see Fig. 8).

4. Conclusions

Based on the obtained test results, it was noticed that for the two highest loading levels, where the maximum strain amplitude was 1.00% and 0.75%, the material cyclically softened, which was evident by about a 20% decrease in the stress amplitude, while for the other two loading scenarios, it behaved stably, i.e. the transient response was negligible. The average fatigue life increased, concerning the average fatigue life at the maximum strain amplitude of 1.00%, three times (at a strain amplitude of 0.75%), eight times (at a strain amplitude of 0.50%) and over thirty times (at a strain amplitude of 0.35%).

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