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Propagation of notch fatigue cracks on maraging steel under biaxial conditions

A.S. Cruces[a], A. Exposito[a], R. Branco[b], L.P. Borrego[b], F.V. Antunes[b], P. Lopez-Crespo[a*].

[a]*Department of Civil and Materials Engineering, University of Mlaga, C/Dr Ortiz Ramos s/n, 29071 Málaga, Spain*
[b]*Department of Mechanical Engineering, University of Coimbra, 3030-788 Coimbra, Portugal*

Abstract

The current work aims at characterizing the fatigue behaviour of an additively manufactured maraging steel. This is a class of high-strength steels widely used in aircracft, aerospace, offshore and military industries thanks to its good performance in terms of strength, toughness, ductility, dimensional stability and weldability. Fabrication of such steel via laser-beam powder bed fusion (additive manufacturing) makes it an excellent candidate for producing prosthetic parts because of its properties, offering a reduction in manufacturing material consumption, labor and machining time. The study is focused on the multiaxial behaviour of the steel, given the wide range of loads often existing in biomedical components. To this end, different critical plane methods are used to predict the fatigue life and the cracking orientation under several biaxial loading scenarios. Thickness effects were also evaluated. Cylindrical specimens were used and these were fabricated in the vertical orientation on the base plate, using a linear printing system equipped with a Nd:YAG fibre laser. The building strategy comprised the deposition of 40 μm thick layers at a scan speed of 80 mm/s. The results are useful to understand the predominant failure mode and the type of critical plane method that is most convenient for such material.

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Keywords: Multiaxial fatigue, Maraging steel, Critical Plane Methods

* Corresponding author. Tel.: +34-951952308
E-mail address: plopezcrespo@uma.es

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1. Introduction

Nowadays new manufacturing methods allow to optimize designs with complex shapes. Selective Laser Melting (SLM) is an additive manufacturing process that allows the production of components directly from 3D models. Components are produced by the fusion of thin metal powder layers (Yadroitsev, Bertrand, and Smurov 2007). This production system generates defects such as voids and un-melted powder particles that contribute to reduce the fatigue resistance of the material. Monotonic properties of materials obtained with this process can be similar to the components manufactures with conventional process (Abe et al. 2001). On the other hand, the presence of this defects will be detrimental to the fatigue resistance (Branco et al. 2018).

In this work, it is assessed the 18Ni300 multiaxial fatigue behavior. The loading paths include the combination of axial and torsional loads with non-zero mean stress. For each loading path, it was obtained the fatigue life of the material with and without notch. The samples with notch were prepared to include in the study a damage tolerant analysis using the Digital Image Correlation technique. From this samples, it was obtained the crack opening load and the relation between the mode I and mode II stress intensity factors at the crack front.

Nomenclature

E	Young's modulus
G	shear modulus
σ'_f	fatigue strength coefficient
ε'_f	fatigue ductility coefficient
b	fatigue strength exponent
c	fatigue ductility exponent
τ'_f	shear fatigue strength coefficient
γ'_f	shear fatigue ductility coefficient
b_γ	shear fatigue strength exponent
c_γ	shear fatigue ductility exponent
$\Delta\varepsilon$	strain range
$\Delta\gamma$	shear strain range
σ_m	mean stress
φ^*	critical plane
k	normal stress weight parameter
N_f	fatigue life
K_I	mode I tress intensity factor
K_{II}	mode II stress intensity factor

2. Materials and methods

The material used in this study was an AISI 18Ni300 maraging steel. This is a high strength steel widely used in the industry because of its good strength, toughness, ductility, dimensional stability and weldability. The monotonic mechanical properties are shown in Table 1 (Branco et al. 2018).

Tests with load control mode were conducted by a MTS 809 fatigue machine. Strains were measured with a biaxial extensometer Epsilon 3550 coupled to the sample. To avoid the extensometer to slide, the frequency was of 2Hz. After the cycle stabilization the extensometer was unmounted, and frequency increased to 6Hz. The failure criterion was a 20% change of displacement after stabilization.

Table 1. Monotonic properties of 18Ni300.

Property	Value
Tensile strength, σ_u	1147MPa
Yield strength, σ_y	910MPa
Young's Modulus, E	168GPa

The geometrical values of the sample are presented in Fig. 1. These samples were built via laser-beam powder bed fusion, with a power of 400W, a scan speed of 850 mm/s and 40μm layer thickness.

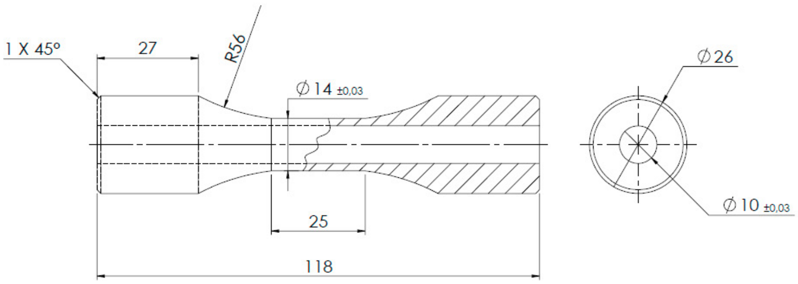

Fig. 1. Geometry of the hollow cylinder specimen. All dimensions are in mm.

Two different loading paths were carried out with two levels of stress, see Fig. 2, to obtain a lower fatigue life (A) and a higher fatigue life (B). The mean stress effect on the material is assessed in both cases. Biaxial test details are summarized in Table 2: specimen identification, loading path, the notch diameter, the axial stress range $\Delta\sigma$, the mean stress σ_m, the shear stress range $\Delta\tau$, the axial and shear strain ranges obtained at half-life fatigue $\Delta\varepsilon$ and $\Delta\gamma$, and the fatigue life N_f.

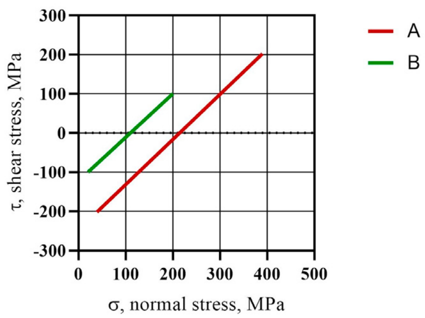

Fig. 2. Loading path (a) A and (b) B.

Table 2. Biaxial tests details for loading path A and B.

Id.	Path	Notch Ø (mm)	$\Delta\sigma$ (MPa)	σ_m (MPa)	$\Delta\tau$ (MPa)	$\Delta\varepsilon$ (%)	$\Delta\gamma$ (rad)	N_f (cycles)
1	A	-	350	215	350	0.2834	0.00722	18690
2	A	0.44	350	215	350	0.2984	0.00759	16420
3	B	-	175	107	175	0.068	0.00342	334478
4	B	0.42	175	107	175	0.14	0.00393	235733
5	A	0.45	350	215	350	0.29	0.0075	19256

A crack is induced to start from a notch to track it during the fatigue process with a CCD camera. A hole is drilled in the middle of the sample with a drill bit of 0.3mm diameter, a total of 10 steps was required with a drill working at low speed. The hole diameter produced is approximately 0.1mm larger than the bit diameter.

The crack appears with 8K cycles for sample 2, but finally failed far from the notch, close to the sample change of section. Values obtained with DIC were discarded for this test and it was repeated with the same conditions in a new sample. In sample 5, the crack appears around the notch at 7.5K cycles approximately and growth during the test until fail. The nucleation of the crack from the notch in sample 5 probes that the stress concentrator works. Tests with and without notch returned a similar fatigue life. Although the number of tests is reduced is not possible to obtain a clear conclusion, but these values show that for this strain level, the notch effect is low for this material. At higher fatigue life values (samples 3 and 4), the notch effect can be seen clearly, in this case the notch specimen fatigue life is approximately 30% lower than the one without notch.

2.1. Image acquisition

Crack tip displacement fields were captured during cyclic loading with a 5 MP CCD camera coupled with a macro Navitar lens which returned a field of view of $3.55\times2.97mm^2$. The pattern required to apply the Digital Image Correlation (DIC) technique was applied by finely abrading the surface. Because of the original rough surface in this type of materials, it was necessary to apply a previous grind step with a #400 sandpaper. The final pattern was obtained with sandpapers of #800 and #1200.

Images were taken each 500 and 5K cycles for loading path A and B, respectively. Frequency was reduced to 0.05Hz to take 60 pictures for 4 cycles. Images were processed with VIC 2D V6 software to obtained displacement fields (Vic-2D V6 Reference Manual, Correlated Solutions Incorporated (C.S.Inc) n.d.).

3. Critical Plane Models

3.1. Fatemi Socie Model

Fatemi-Socie (FS) critical plane model is used here to estimate the fatigue life and the failure plane for the two samples (Fatemi and Socie 1988). Fatemi-Socie model was chosen because it has proven to generate good predictions on S355 steel under few different loading conditions (Lopez-Crespo et al. 2015). Fatemi-Socie model is an equivalent strain type of model and is based on mode II/III failure. The critical plane is defined from the plane where the shear strain is maximum. In addition, it includes the mean stress effect through the maximum value of the normal stress on the critical plane. The model is summarised according to Eq. (1):

$$\frac{\Delta\gamma_{max}}{2}\left(1+k\frac{\sigma_{n,max}}{\sigma_y}\right)=\frac{\tau'_f}{G}(2N_f)^{b_\gamma}+\gamma'_f(2N_f)^{c_\gamma} \quad (1)$$

where k parameter is a correction factor that relates the shear strains that appear in a pure torsion test and the maximum shear strains that appear in a tension-compression test.

3.2. Smith-Watson-Topper Model

The Smith, Watson and Topper model (Smith, Topper, and Watson 1970) defines a strain energy density type DP, see Eq. (2). The DP considers the normal strain and stress acting on the critical plane φ^*. The DP is defined on the plane φ^* that maximises the normal strain range, $\Delta\varepsilon$.

$$\frac{\Delta\varepsilon}{2}\sigma_{n,max}=\frac{{\sigma'}_f^2}{E}\left(2N_f\right)^{2b}+\sigma'_f\varepsilon'_f\left(2N_f\right)^{b+c} \quad (2)$$

The strain hardening effect is considered in the SWT model through the $\Delta\varepsilon/2$ and $\sigma_{n,max}$ product. The mean normal stress effect is also taken into account via $\sigma_{n,max}$.

4. Results

4.1. Fatigue life and crack angle

The fatigue life estimates for FS and SWT are shown in Fig. 3 (A) for loading path A and (B) for loading path B. FS results are shown with blue squares and SWT with green triangles. A scatter band of two is included in the figure with black dashed lines and a coincident fatigue life estimation with a red line. Fatigue life estimations returned by SWT are more conservative than FS. For the low-cycle fatigue life tests (A) estimations are on the conservative side, and for the tests with higher fatigue life (B), model estimations are on the non-conservative side. Energy and strain CPM are oriented to work better in low cycle fatigue regime (Socie and Marquis 2000), but in this case the poor result of these models can be explained with the insufficient characterization of the material fatigue properties.

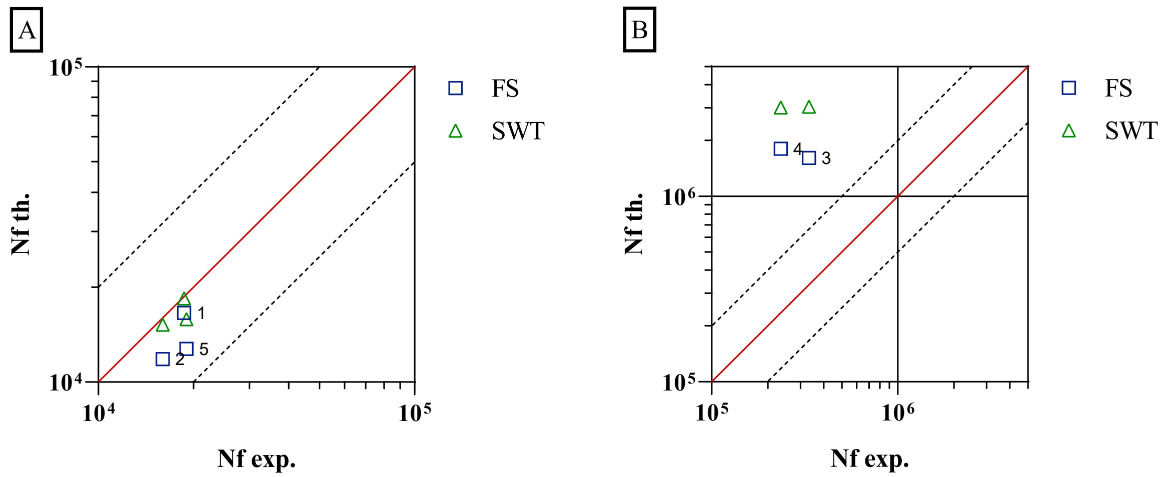

Fig. 3. Critical plane model fatigue life predictions for loading path A (a) and B (b) in 18Ni300.

It is also possible to determine the crack angle in the next step after the crack nucleation with the CPM. In this case, it only can be evaluated the specimens with the notch, as it can be measured when the crack appears. In all cases, the angle between the axial direction of the sample and the crack is of 65º approximately. FS returns to critical planes at 10 and 80º, and SWT gives a better angle value of 60º.

4.2. Experimental evaluation of SIF

The displacement field around the crack tip was extracted with DIC. With this information is possible to obtain the stress intensity factor in mode I and mode II. The process fits the experimental displacement data to William's power series using a multipoint over-deterministic method (Sanford and Dally 1979). An area of size 0.8×0.8mm^2 was defined, so two terms in the Williams' solution were used (Mokhtarishirazabad et al. 2016).

Results are shown in Fig. 4 for sample 5 at different cycles during the test. K_I values are shown with circles and K_{II} values are shown with squares. For this loading path, the K_{II} is approximately 50% of K_I.

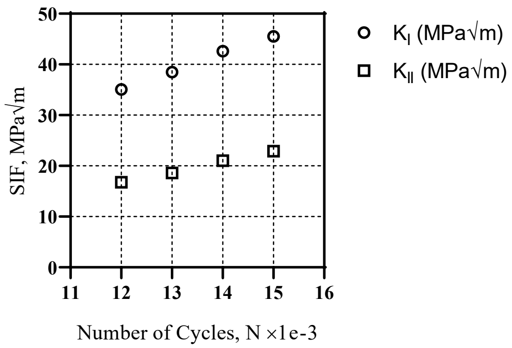

Fig. 4. Evolution of mode I and II stress intensity factor, estimated by hybrid DIC based tool on sample 5.

5. Conclusions

A preliminary study of a notched additive manufactured maraging steel has been done based on critical plane models. Smith Watson and Topper model appears to give good results both in terms of life and cracking direction, probably due to the material failure mode being tensile. The predictions given by critical plane model are very accurate in the LCF regime. For longer lives the critical plane approach overestimates the fatigue life. The SIF was computed, based on a hybrid methodology that combines the experimental displacement data with Williams analytical model. The approach allowed us to quantify the proportion of opening model SIF and the proportion of shear model SIF.

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