FATIGUE CRACK GROWTH IN 316L UNDER UNIAXIAL AND TORSIONAL LOADING

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Abstract

A study of fatigue crack initiation and growth in 316L austenitic stainless steel is reported. Fatigue experiments were performed at room temperature on full cylindrical specimens cycled axially (tension-compression) and on hollow cylindrical specimens tested in reversed torsion. Microstructure and damage evolution (crack initiation and growth) on the surface of mechanically and electrolytically polished specimens were observed using light and electron microscopy. An analysis of the orientation of microcracks and macrocracks which led to failure was made. Axially loaded specimens exhibited presence of several microcracks which resulted in macrocrack propagating perpendicularly to specimen axis. In the case of torsional loading, orientation of macrocrack propagation was dependent on applied load and presence of notches. High amount of short cracks initiated parallel to specimen axis. Long cracks exhibited a tendency to bifurcate with crack branches oriented at approximately 45° to the specimen axis.

Keywords: 316L austenitic steel, surface relief, fatigue, crack orientation, axial and torsional loading

1. INTRODUCTION

The 316L steel is corrosion resistant austenitic steel with low carbon content. It is used in the chemical and oil industry, in food processing as well as medicine due to its high toughness at low temperatures and good tensile strength and high creep in hot conditions.

Multiaxial tension-compression-torsion fatigue tests made in [1] and [2] reported that the crack initiation occurred along the slip bands of the material. The stress concentration in the persistent slip bands was the main initiation factor for the cracks. The crack growth in the tension-compression setup as performed in [2] was found to be oriented perpendicularly to the specimen axis. However, in the multiaxial cycling cracks nucleate and grow in preferred planes, which depend on material and state of loading [2].

The crack growth rates of hollow tubular aluminium samples with notched surface in [3], resulting from torsional loading were reported to be higher than for the axial loading with the same equivalent stress intensity. This leads to the lower fatigue life of torsionaly tested samples. Reduction of the fatigue life due to torsional loading with the same effective stress was reported in [4] as well. The cracks were reported to initiate at the principal slip planes in the artificial notches and material defects. The cracks present in various planes coalesced once the crack ends approached enough created zig-zag steps in the cracks.

The aim of this work is to study fatigue life of the mentioned stainless steel and the fatigue crack initiation and propagation under various stress modes in axial and torsional loading. In certain specimens different stress concentrating features were created to enhance the crack initiation in the desired site of the specimen surface. The fatigue life in the tension-compression loading and the torsional loading is compared. In addition we follow and analyse the crack growth rate in the tension-compression loading regime.

2. EXPERIMENTAL PROCEDURE

The 316L steel was fabricated by Acerinox Europa (Spain) in form of 20 mm thick hot-rolled sheets. This treatment resulted in rather equiaxed grains with average diameter of 40 μm. Chemical composition is given in **Table 1**. Tensile material properties as declared by the producer are: Rp0.2 = 336 MPa, Rm = 586 MPa, fracture elongation 57 %.

Table 1 Chemical composition of 316 L steel (wt. %)

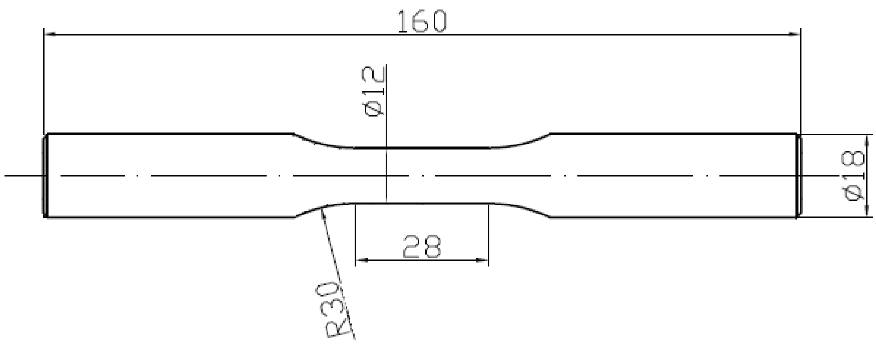
C	Cr	Mn	Mo	N	Ni	P	S	Si	Fe
0.018	16.631	1.261	2.044	0.042	10.000	0.032	0.001	0.380	bal.

Three different types of specimens were used during this study. Full cylindrical specimen (**Figure 1a**) was used for symmetrical cyclic axial tension-compression loading, hollow cylindrical specimen (**Figure 1b**) for cyclic fully reversed torsion and full cylindrical specimens with the shallow notch (**Figure 1c**) for fatigue crack growth study in axial tension-compression mode.

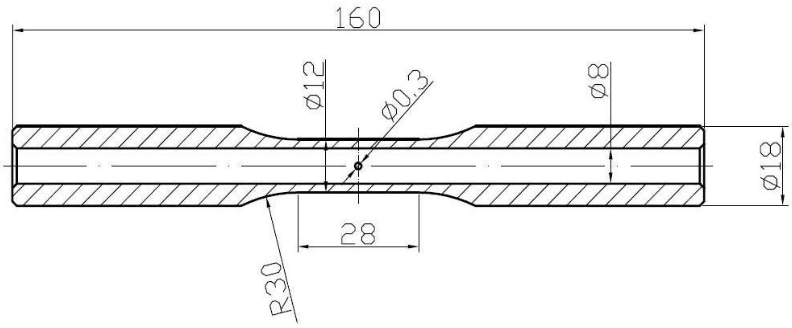
The tests were performed using computer controlled MTS 810 and MTS 809 servohydraulic machines at room temperature. A symmetrical strain controlled cycling was used and the total strain amplitude was kept constant during cycling (R_ε = -1). Strain was measured by an extensometer attached to the specimen gauge length. Plastic strain amplitude was determined in the middle of fatigue life as a half-width of the stress-strain hysteresis loop.

The tests for measurements of crack growth rate were interrupted regularly and micrographs of the notch area were taken using a light microscope Navitar with long focal distance attached to the machine frame. Micrographs were analysed, fatigue crack nucleation mechanisms were determined and the dependence of crack length on the number of cycles was obtained. The crack length was defined as half of the surface crack length projected into the direction perpendicular to the specimen axis. The crack growth was followed in the length interval between 20 to ~ 1000 μm. The resolution of the light microscope is better that 1 μm. The specimens were also dismounted and observed in SEM Tescan Lyra once the cracks exceeded the observed area on the gauge length.

a) Full specimen



b) hollow specimen



c) Full specimen with notch **d) Specimen microstructure**

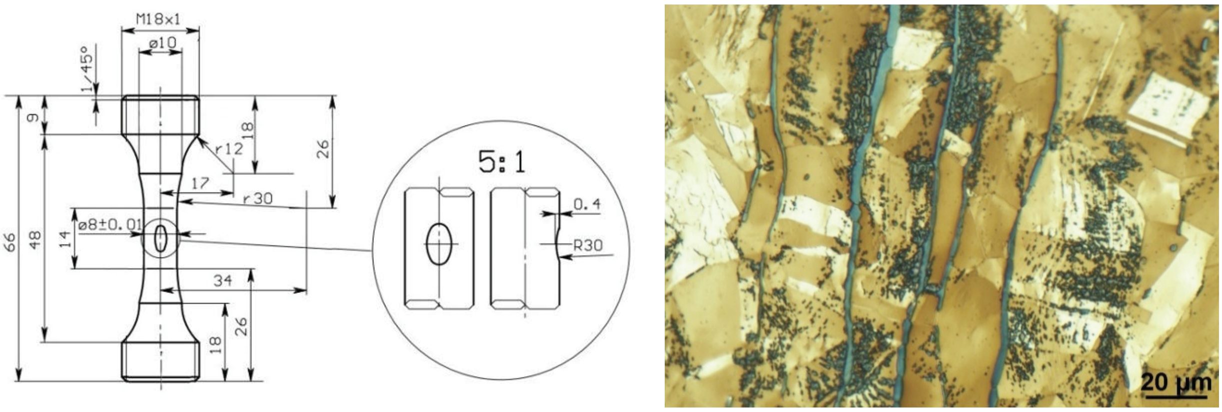


Figure 1 Schematics of specimens (a, b, c) used in this study with their dimensions in mm. Microstructure of the material (d). Notice chains of δ ferrite in grey colour.

3. RESULTS AND DISCUSION

The microstructure of the studied specimens was analysed and it is shown in **Figure 1d**. Equiaxed austenitic grains as well as chains of delta ferrites were found. The average size of the austenitic grains was measured as 40 µm. The presence of δ ferrite is a consequence of the manufacturing process when the material was hot-rolled into large thick plates and minimum content of Ni allowed by the standard for 316L.

3.1. Tension-compression loading

The orientation and density of the surface cracks was observed and analysed in order to determine the initiation mechanism. It was found that the cracks initiated along the slip bands in individual grains (**Figure 2**). Later, the observed microcracks grew perpendicular to the specimen axis. The crack growth rate was analysed using notched specimens where the crack length was measured regularly. The surface crack length as a function of number of loading cycles was evaluated (**Figure 3**).

The crack growth rate changed significantly during the cycling. The rate of growth was obviously dependent on the imposed strain amplitudes. In addition, it was observed that the crack growth rate of smaller cracks decreased if a bigger one appeared in the vicinity. This means that once a macrocrack was formed, its stress shielding effect inevitably slows down the growth of smaller cracks.

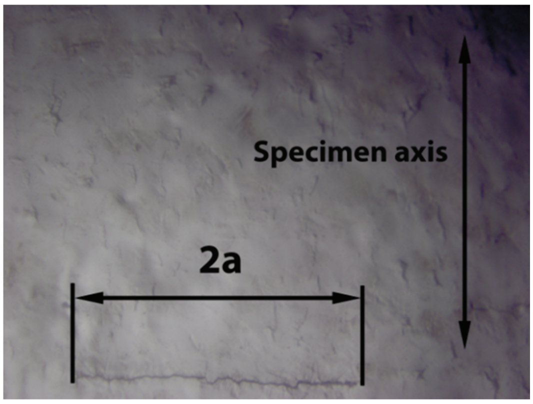


Figure 2 Crack initiation along the slip bands in axial tension-compression loading

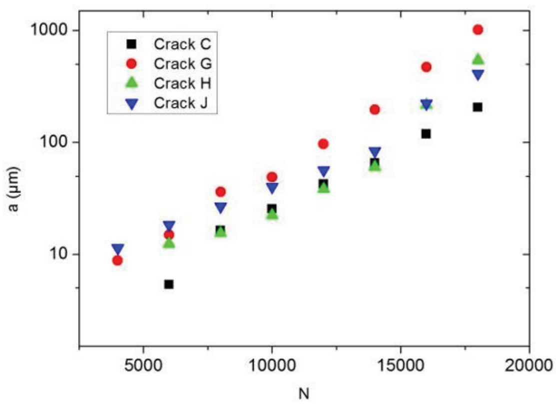


Figure 3 An example of crack length as a function of the number of cycles. Axial tension-compression loading with strain amplitude $\varepsilon_a = 0.32$ %.

3.2. Torsional loading

In the case of samples loaded cyclically in fully reversed torsion, many microcracks initiated along persistent slip bands but further propagation was observed only in those planes which were oriented parallel to specimen axis as reported in [1, 2]. The crack initiation, propagation and also the crack shape was strongly dependent on the loading strain amplitude applied. At higher levels of strains the initial crack propagation and growth along the specimen axis was observed, later bifurcation of the crack ends occurred leading to final fracture of the specimen. These crack branches propagated in directions approx. 45° to the specimen axis. An example of this behaviour is shown in **Figure 4**. Zhang and Akid [5] studied difference of crack initiation and propagation in 316L steel and high strength Si-Mn spring steel. In 316L steel they observed similar crack propagation path as in **Figure 4**. However, fatigue cracks propagated perpendicularly to the specimen axis in the Si-Mn spring steel and bifurcated on the ends of long cracks at the final stages of the fatigue life.

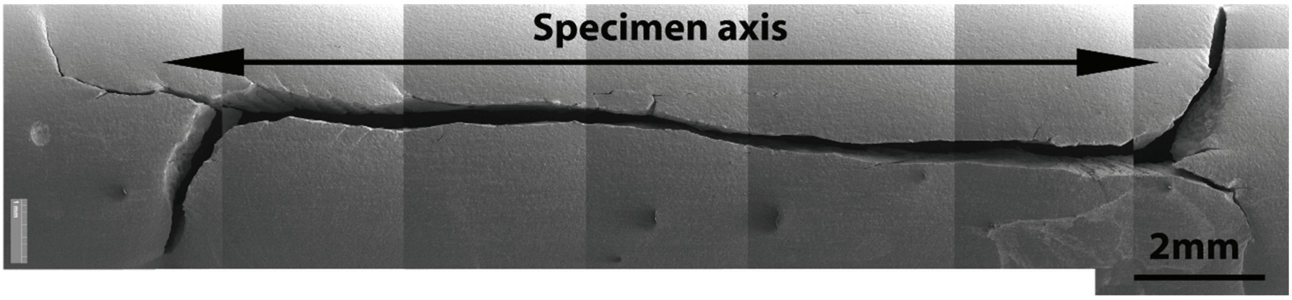


Figure 4 SEM micrograph of specimen after fracture, loaded in torsion with shear strain amplitude γ_a = 1.732 %. Major crack propagating along the specimen axis direction bifurcates at the crack ends in the final stage of fatigue life.

For low levels of strain amplitude slightly different crack path was observed. Cracks nucleated at approx. 45° to the specimen axis. This behaviour on the same steel was also reported in [2]. The authors [2] report that cycling with high loading levels results in formation of long cracks parallel to the specimen axis while X shaped cracks appeared for low strain amplitudes. An image of such crack taken on a torsionaly loaded sample cycled with low strain amplitude is shown in **Figure 5**.

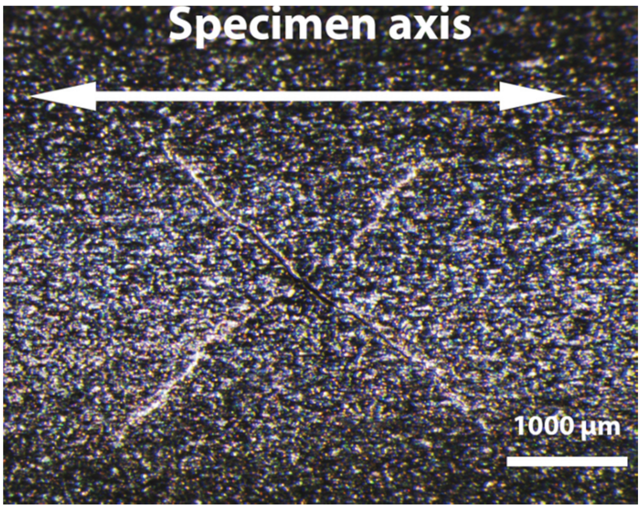


Figure 5 Secondary crack imaged by light microscope taken after fracture in torsionaly loaded sample with shear strain amplitude γ_a = 0.41 %

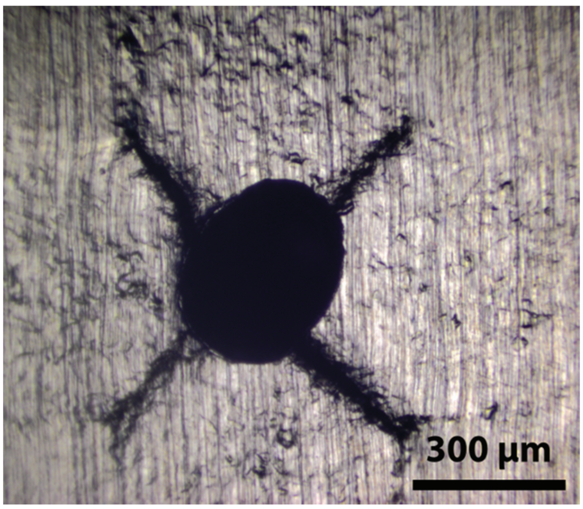


Figure 6 Fatigue crack growth from a drilled hole after 250 fully reversed torsional cycles with a shear strain amplitude of γ_a = 0.71 %

When a small hole was drilled into gauge length of the sample through the specimen wall, the crack growth along the specimen axis was not present even at high strains. The hole acted as a strong stress concentrator and the cracks grew directly outwards from the hole under the angle of about 45° to the specimen axis (**Figure 6**). The main role of the drilled hole is that the initiation phase is not present hence the cracks grow from high stress region to the holes edges. The consequence is significant shortening of the fatigue life since the crack initiation phase, which takes an important portion of the fatigue life, was skipped.

Throughout the torsional loading, it was also observed that the surface relief changed significantly. The torsion has produced lots of extrusions and intrusions on the observed gauge length surface. These surface imperfections act like stress concentrators and hence help to initiate the cracks. This was also reported in [1]. On three different stages of loading the changes of surface relief are shown in **Figure 7**.

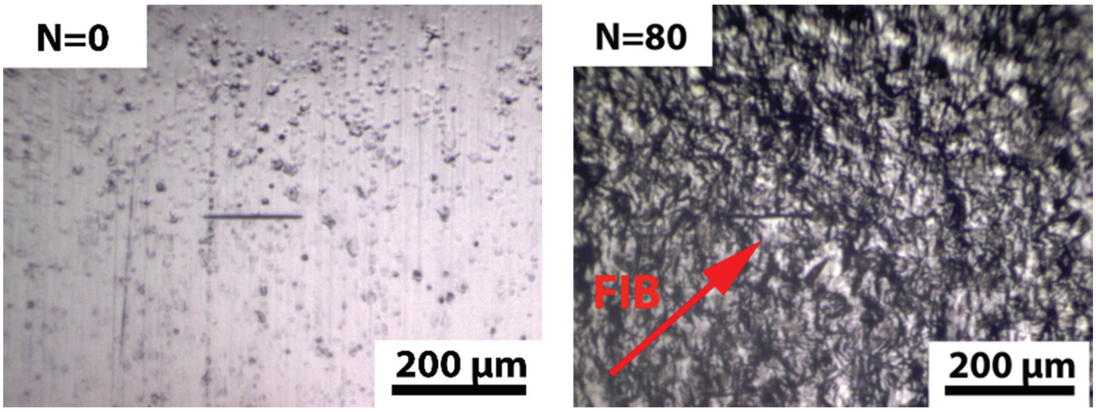


Figure 7 Surface relief at different stages of torsional cycling. Large amount of extrusions and surface warping can be seen.

3.3. Tension-Compression vs. Torsion

The comparison of the fatigue life of axially and torsionally cycled samples was made using a conversion of measured shear strain into an equivalent strain defined by (eq. 1):

$$\varepsilon_{a,eqv} = \varepsilon_a \ and \ \varepsilon_{a,eqv} = \gamma_a / \sqrt{3} \tag{1}$$

The recalculated values were then plotted as a function of number of cycles to failure in **Figure 8**. The fatigue life is clearly longer in the case of axially loaded samples.

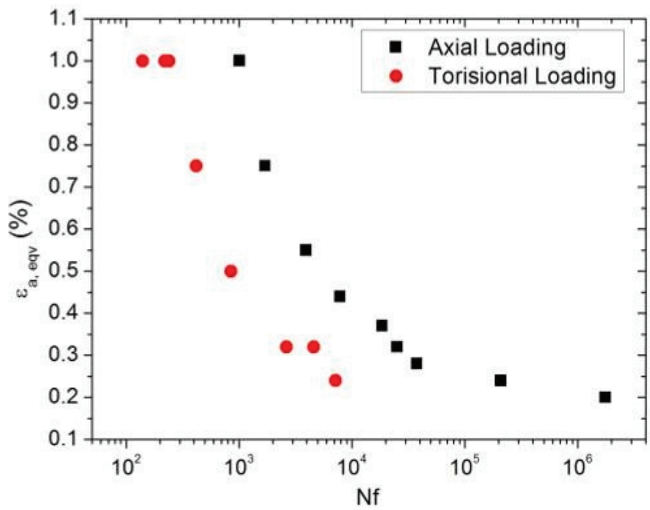


Figure 8 Fatigue life comparison for torsional fully reversed and tension-compression fully reversed loading

It can be concluded that the cyclic torsion is more damaging for the material than tension-compression loading with the same equivalent applied strain amplitude.

4. CONCLUSION

Fatigue crack nucleation, crack path, crack growth rate and fatigue life of 316L stainless steel in torsional and tension-compression loading were studied and following was concluded:

- In tension-compression cycling, fatigue cracks initiate in slip bands and propagate perpendicularly to the specimen axis.
- In torsional cycling with low shear strain amplitudes fatigue cracks grow in X shape with branches inclined approximately 45° to the specimen axis.
- High shear strain amplitudes result in propagation of long fatigue cracks along specimen axis which bifurcate at the final stage of fatigue life.
- Significantly shorter fatigue life is observed in torsion compared to tension-compression for the same equivalent strain amplitude.

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