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FATIGUE CRACK INITIATION AND GROWTH IN 316L STEEL IN TORSIONAL CYCLIC LOADING

M. Karoľ[*]**, A. Chlupová**[**]**, V. Mazánová**[***]**, T. Kruml**[****]

Abstract: *Fatigue crack initiation and growth study in 316L austenitic stainless steel was made in cyclic torsion. The experiments on hollow cylindrical specimens were performed at room temperature using fully reversed shear strain controlled cycles. The specimens used were polished mechanically and electrolytically to enable surface damage and crack propagation observation using optical light microscope, SEM. It was found that high density of extrusions and intrusions are formed on the specimen surface due to cyclic loading. TEM observations revealed that dislocation arrangement in well-known ladder-like structure is responsible for the localization of cyclic plastic deformation and for the origin of surface roughness in which the fatigue crack nucleate. The path of fatigue cracks leading to failure was observed, too. The crack path was found to be dependent upon the applied shear strain amplitude.*

Keywords: 316L austenitic steel, Fatigue crack initiation, Crack growth, Torsional loading, Crack path.

1. Introduction

The 316L austenitic stainless steel is a material widely used in the chemical and oil industries, medicine as well as food industry. In many industrial applications, the construction parts inherently contain stress concentrators as functional design features, Fatemi et al. (2014). Hence it is important to know its response to cyclic deformation including quantitative data of fatigue crack growth kinetics. The understanding of fatigue crack nucleation and propagation leads to better prediction of the fatigue lifetime of the material as well as adjustment of maintenance intervals, Suresh (1998).

Most of the studies until now have been made in strain controlled tension-compression setup. It is therefore important to study the crack initiation and growth in cyclic torsion, too. Mazánová et al. (2016) studied the fatigue crack initiation and the early stages of crack growth in cyclic torsion and multiaxial loading. Studies of Zhang et al. (1997) and Fatemi et al. (2011) had shown an evolution of crack path with the amplitude of the cyclic shear strain in cyclic torsion. They report propagation of a longitudinal crack along the specimen axis in the case of high shear strains and cracks in the form of letter X for low shear strains. In this work we have found a very similar crack path with addition of bifurcation of the ends of the longitudinal crack. Moreover, it was found that fatigue cracks growing from artificial transverse circular hole grow at 45 ° to the direction of the sample axis, which was also reported by Gladskyi (2013) on low carbon steel and by Fatemi et al. (2014) on aluminium.

2. Materials and Methods

The stainless steel 316L was manufactured by Acerinox Europa in form of 20 mm hot rolled plates. This treatment caused the internal structure to be equiaxed with an average grain diameter of 40 μm. The chemical composition is as given in the table pod**.** The manufacturer claims the following tensile properties of the material: $R_{p0.2}$ = 336 MPa, R_m = 586 MPa, fracture elongation 57 %.

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[*] BSc. Michal Karoľ: Institute of Physics of Materials; Žižkova 22; 616 62, Brno; CZ, michal.karol.91@gmail.com

[**] Ing. Alice Chlupová PhD.: Institute of Physics of Materials; Žižkova 22; 616 62, Brno; CZ, chlupova@ipm.cz

[***] Ing. Veronika Mazánová: Institute of Physics of Materials; Žižkova 22; 616 62, Brno; CZ, mazanova@ipm.cz

[****] prof. Mgr. Tomáš Kruml, CSc.: Institute of Physics of Materials; Žižkova 22; 616 62, Brno; CZ, kruml@ipm.cz

Tab. 1: Chemical composition of 316 L steel in 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.

Hollow cylindrical specimen (Fig. 1) for cyclic fully reversed torsion were used. Some of the specimens had a transverse circular hole through one of its walls. Those were used for fatigue crack growth measurement.

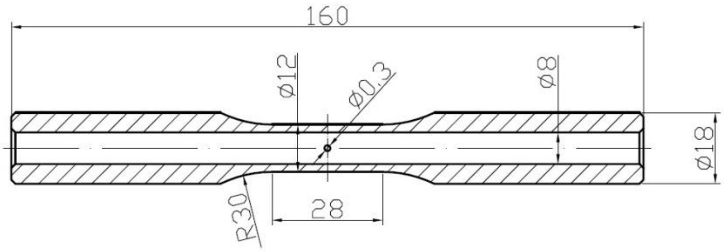

Fig. 1: Hollow specimen with a small hole drilled into the gauge length wall.

The tests were performed using computer controlled MTS servohydraulic machines at room temperature. A symmetrical strain controlled cycling was used and the total strain amplitude was kept constant during cycling ($R_\varepsilon = -1$) with the help of 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 growing fatigue cracks were taken using a light microscope Navitar. Micrographs were analyzed, fatigue crack nucleation mechanisms were determined and the crack growth rate was measured. The crack length was defined as half of the surface crack length. The crack growth was followed up to approx. 2 cm of surface length. The specimens were also dismounted and observed in SEM Tescan Lyra regularly. The initiation mechanism was investigated at the end of fatigue life, using nanofabricated craters perpendicular to the specimen surface, made by focused ion beam (FIB) technique.

Dislocation microstructure of the specimens after fracture was investigated by transmission electron microscopy (TEM). The foils were prepared by means of the traditional technique consisting of mechanical grinding and electrolytic polishing. They were observed on TEM Philips CM12 at 120 kV.

3. Results and Discussion

Cyclic torsional loading is known to induce surface roughness significantly, creating intrusions and extrusions on the strained sample. These act as stress concentrators for nucleation of fatigue cracks on the surface of the sample.

The internal structure of the specimens cycled to fracture was analyzed using TEM imaging. The α' martensite islands, ladder-like persistent slip bands (PSBs) as well as thin deformation induced twins were found (Fig. 2). These microscopic features are formed due to the cyclic deformation of the material. Ladder-like dislocation arrangement was frequently observed. It is known to form bands in which cyclic plastic deformation localizes and surface persistent slip markings (PSM) made of intrusions and extrusions are formed, Mughrabi (1983). Fig. 2 was taken on specimen cycled in combined axial/torsional mode, however, the microstructural features are the same as observed in pure torsional cycling.

The orientation of small surface cracks and crack density were analyzed in order to understand the initiation mechanism. It was found that high concentration of PSMs is induced on the specimen surface (Fig. 3). These are the initiation sites for the fatigue cracks. This can be seen in the Fig. 4 showing a surface PSM with a small fatigue crack growing from it.

The direction of the normal tensile stress in a cyclic shear loading changes each half cycle and the fatigue cracks grow typically perpendicularly to this stress. This results in a zig-zag shape of the fatigue cracks on the microscopic level. This was reported in the work of Branco et al. (2014) as well.

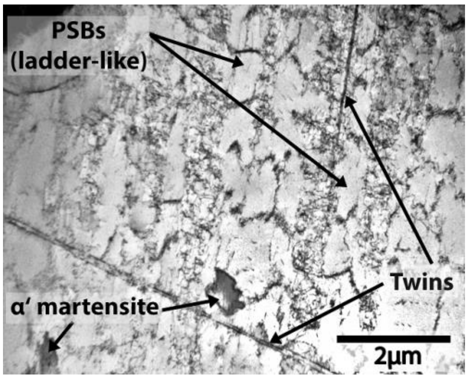

Fig. 2: TEM image of internal structure of the specimen after multiaxial in-phase cyclic loading.

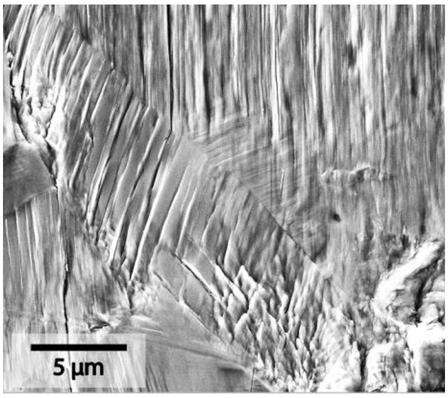

Fig. 3: Fatigue crack initiation at persistent slip markings of the surface.

It was found that the macroscopic crack path is strongly dependent on the imposed cyclic shear strain amplitude γ_a. We have found that in case of low γ_a the magistral cracks grow in a shapes resembling a letter X with the crack branches at 45 ° to the axis of the specimen (Fig. 5). On the other hand, high γ_a leads to a very long fatigue crack which grows paralel to the specimen axis and bifurcates at the last stages of the specimen fatigue life (Fig. 6). The observed crack paths are in agreement with observations of Zhang et al. (1997) and Fatemi et al. (2011) which show influence of the used cyclic torsional amplitude on the final crack path.

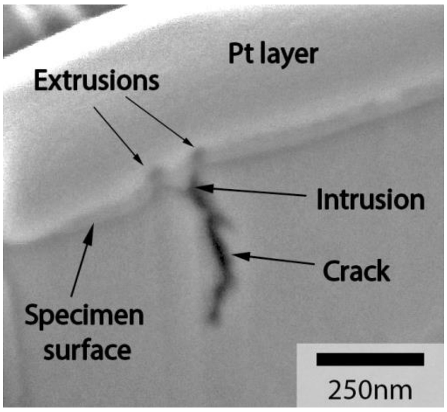

Fig. 4: Surface PSM with an initiated fatigue crack, FIB cross- section cut.

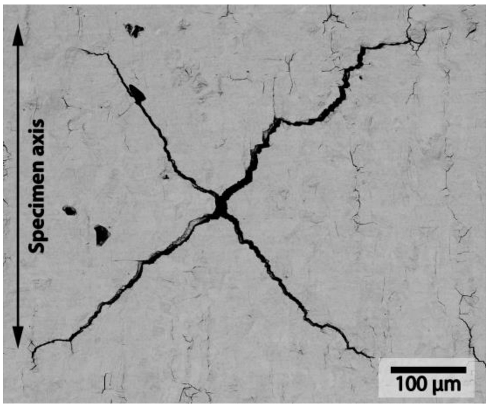

Fig. 5: SEM-BSE image of a fatigue crack, torsional cyclic loading, γ_a = 0.41 %.

Finally it was found that if an artificial crack starter is used, in our case transverse circular hole, the fatigue cracks grow outwards of the drilled hole under 45 ° to the specimen axis, Fig. 7. This was reported in works of Gladskyi (2013) and Fatemi et al. (2014) on different materials, too.

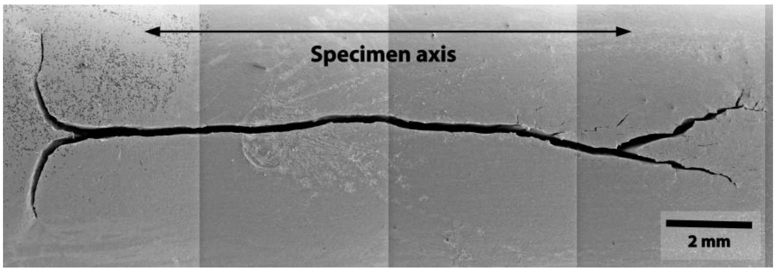

Fig. 6:Long fatigue crack along the specimen axis bifurcated on the ends γ_a = 1.73 %.

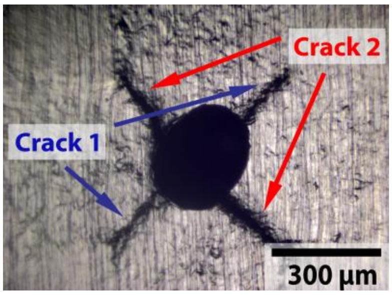

Fig. 7:Fatigue cracks growing from an artificial transverse circular hole γ_a = 0.45 %.

4. Conclusions

The fatigue crack initiation and crack path was studied in cyclic torsional loading on 316L austenitic stainless steel and the following was concluded:

- The cyclic torsion changes the surface relief of the sample creating PSMs made of intrusions and extrusions.
- The fatigue cracks nucleate at the sites of stress concentration within the PSMs.
- The fatigue cracks in shapes of letter X are results of low shear strain amplitudes. The longitudinal cracks along the specimen axis with bifurcation on the ends are found on samples cycled at high shear strains.
- In the case of a transverse circular hole acting as an artificial crack starter, the cracks grew out of the hole in direction of 45 ° to the specimen axis irrespective of the loading amplitude.

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