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Evolution of the surface roughness of a low carbon steel subjected to fatigue

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ABSTRACT

This work aims to analyze the evolution of the surface roughness of a low carbon steel (SAE 1020) subjected to different loads and fatigue life. The fatigue tests were performed by rotary bending. Images of the specimen surfaces were obtained by scanning electron microscopy (SEM) and analyzed by specific image processing software (SPIP™ - 3D Image Processing). The average roughness, extrusions (peaks), and intrusions (valleys) produced by persistent slip bands (PSBs) on the surfaces of the specimens were observed and quantified for different loadings and fatigue life. From the values of the peaks and valleys, as a function of the load and fatigue cycles, it was possible to determine the relationship between the evolution behavior of these parameters.

1. Introduction

The evolution of persistent slip bands (PSBs) on the surface of materials under cyclic loading is one of the main causes of fatigue initiation in many materials [1,2]. The formation of such PSBs occurs with the sliding of a first plane causing extrusion of material on the surface. The extrudate material oxidizes when it comes in contact with the air and deforms plastically, making it difficult to return to the initial position with the reversal of loading. With this reversal there is intrusion near the extruded material [1]. As shown, the immediate consequence of PSBs is the increase in the surface roughness of the material due to the presence of extrusions and intrusions. As the crack nucleation process is greatly influenced by the surface conditions of the material, the PSBs have great importance in the development of fatigue [2,3].

Currently, there has been great interest in the knowledge of technologies that allow the early detection of damage evolution in metallic materials subjected to cyclic loading that can cause them to fail due to fatigue [3]. The evolution of PSBs and the initiation of surface cracks are observed in polycrystalline materials deformed by cyclic loading [4]. The formation of PSBs favors the appearance of peaks and valleys on the surface of the material. These peaks and valleys act as stress concentrators (micro notches) favoring fatigue cracking nucleation [5].

Recent studies have reported several observations regarding the beginning of fatigue cracks, as presented below. According to the literature [6], in high purity polycrystalline copper, fatigue cracks systematically nucleate in grain boundaries that present different levels of surface elevation with fatigue loading. The difference between the stress levels generated by the fatigue loading between the two grains is considered the driving force for intergranular cracking nucleation. Studies on fatigue behavior of magnesium alloys have revealed that cracks have started on the surface of the specimens [7,8]. In 316 stainless steel alloys, surface cracks with a radial pattern revealed by markings on the surface of the fracture have been observed [9]. Superficial cracks in superalloys based on nickel are attributed to surface roughness and the large difference in hardness between the matrix and precipitates present [10]. Fatigue cracks occur due to a process of plastic deformation competition and to the initiation of microcracks formed due to the appearance of extrusion and intrusion on the surface of the material [11]. Initiation of fatigue cracks in different steel alloys are attributed to the surface roughness of specimens [12,13]. Studies on the process of the beginning of fatigue cracks have shown that the nucleation of fatigue cracks is a predominantly superficial phenomenon but can, however, begin in sub-surface defects [14]. In this case, the existence of inclusions or other types of subsurface defects can make it difficult to correlate the evolution of surface roughness with the fatigue life of the material.

According to Polák et al. [15], in their study on the evolution of surface roughness by fatigue of a 316L stainless steel, the intrusions (valleys) were considered the main cause of fatigue cracking nucleation. The intrusions occurred on one or both sides of extrusions (peaks) representing a rudiment of a stage I crack. Fatigue cracks started more frequently from intrusions located parallel to extrusions.

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As previously reported, intrusions (valleys) produced by PSBs usually present as numerous crack-like sharp defects on the initially smooth surface of the material in areas with high amplitude of local deformation. The number of PSBs producing such intrusions increases with the amplitude of the applied plastic deformation. The depth of the intrusions increases linearly with the number of cycles. During this process the amplitude of the local deformation of the PSBs is concentrated at the crack tip. The crack propagation occurs due to the cyclical sliding of surfaces at the crack tip. From the tip of the crack, in each cycle, a new surface is formed due to the irreversibility of sliding and the impossibility to rewelding, usually due to the effect of the environment [3,16,17]. According to the literature [3], in a high alloy austenitic stainless steel it was observed that, generally as extrusions grow, intrusions deepen and fatigue cracks initiate from the tip of the deepest intrusions.

Considering the process of formation of PSBs and the consequent nucleation of fatigue cracks in metallic materials, it is proposed to correlate the evolution of the surface roughness of an SAE 1020 steel under fatigue with its structural integrity when subjected to cyclic loads. The study of this correlation may be useful for the development of predictive technologies for failure of machines subjected to fatigue.

2. Experimental procedures

The SAE 1020 steel used in the research was obtained in the form of a cold rolled circular bar with a diameter of 5/16 in. and its typical chemical composition is presented in Table 1.

The tensile strength properties of the steel were obtained from specimens prepared according to ASTM E-8 Standard [18]. The tensile tests were performed on 3 specimens at a rate of 5 mm/min in a universal test machine, EMIC, model WDW-100E. The fatigue tests with load control were performed on a rotary flex fatigue test machine EDIBON, model EEFC, with rotation of 1500 RPM (25 Hz). The specimens for the fatigue tests were machined with 50 mm continuous radius, as shown in Fig. 1. The radius region of the specimens was machined and had the following sanding: 180, 320, 400, 600, 1200, and 2400. For each sandpaper a sanding time of 5 min was adopted with the specimen at 1300 rpm. After the sanding, the polishing with 1 μm diamond paste was done, also for 5 min for each specimen.As shown in Fig. 1, the variation of fatigue tensions was produced by different values of "L", since a single loading value (30 N) was used during the tests. The maximum stress (σ) acting on the critical region of fatigue (continuous radius) was determined by the balance loading equation (Eq. (1)).

$$\sigma = \frac{P.L}{0,1.d^3} \tag{1}$$

(P - applied load; L - distance from the critical region of fatigue; d - critical diameter of fatigue).

Table 1
Typical chemical composition of SAE 1020 steel (wt%) [14].

C	Si	Mn	S_{max}	P_{max}
0.2	0.3	0.5	0.05	0.04

The fatigue tests were performed with three values of maximum tension: 320 MPa, 280 Mpa, and 240 MPa. These stress values are associated, respectively, with the low cycle, high cycle and infinite fatigue life of the steel, according to its S-N curve (Wöhler curve) [19]. At the three loading levels, samples were taken from the specimens submitted to different values of fatigue cycles for the analysis of surface roughness. Images of MEV, model VEGA 3 - TESCAN, were processed by SPIP™ software to obtain 3D images, average roughness values, and measures of peaks and valleys formed in the analyzed surfaces.

3. Results and discussion

Table 2 shows the mechanical strength tensions of SAE 1020 steel obtained by tensile tests.

Figs. 2-4 show images of the surfaces of SAE 1020 steel subjected to fatigue, respectively, at three stress levels: 320 MPa, 280 MPa and 240 MPa. Figs. 2(a), 3(a), and 4(a) were obtained by scanning electron microscopy and Figs. 2(b,c), 3(b,c), and 4 (b,c) present 3-dimensional images of specific regions of occurrences of extrusions and intrusions on the steel surface (regions highlighted by circles in SEM images).

In Fig. 2(b) a number of extrusions and intrusions can be seen concentrated in a small region. Fig. 2(c) shows an intrusion with a linear form, limited on both sides by two extrusions, giving a micro valley suitable for the nucleation of a crack by fatigue.

In Fig. 3(a) it can be observed that there was a lower incidence of higher stress concentrations due to intrusions, compared to Fig. 2(a). As the number of fatigue cycles of the two specimens were not very different, the lower applied stress (280 MPa) may have been the cause of the lower damage to the steel surface at this loading level.

In Fig. 3(b,c) it can be observed that at the loading level of 280 MPa, unlike the previous one (320 MPa), there was only a

Table 2
Tensile mechanical properties of the SAE 1020 carbon steel.

σ_{UTS} (MPa)	σ_{YS} (MPa)
355 ± 12	240 ± 8

(σ_{UTS} - ultimate tensile stress; σ_{YS} - yield stress).

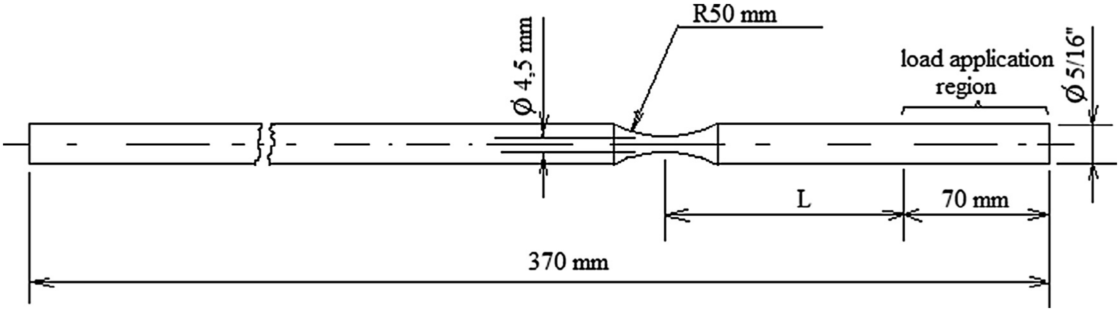

Fig. 1. Specimen for fatigue test.