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EFFECT OF SHOT PEENING WITH GLASS MICROSPHERES ON THE FATIGUE BEHAVIOR OF A LOW CARBON STEEL

The present work has the objective of studying the effect of shot peening with glass microspheres on SAE 1020 steel in its resistance to fatigue. Fatigue tests were carried out by rotary bending with load control and loading on balance in specimens with and without shot peening. A rotation speed of approximately 750 rpm (12.5 Hz) was employed in the fatigue tests. Vickers microhardness tests were performed in order to verify the surface hardening produced by shot peening with glass microspheres. Analysis of the steel surface and fatigue fractures was performed using scanning electron microscopy (SEM). Fatigue tests were performed in order to obtain S-N curves (Wöhler curves). It was observed that shot peening with glass microspheres improved the fatigue strength of the steel at high cycle.

Keywords: Fatigue; shot peening; Wöhler curve; low carbon steel, glass microspheres.

1. Introduction

With the increasing technological development, mainly in the automobile and aeronautical industries, more and more structural parts and components are submitted to high dynamic loads favoring the occurrence of fatigue failure. According to T. Klotz et al. [1], shot peening is commonly used in the aerospace industry to increase the fatigue life of mechanical components. Its use introduces compressive residual stresses and cold work on the surface which tend to close short cracks of fatigue as well as delay their propagation. However, shot peening also alters surface roughness, which may be detrimental to fatigue strength due to the possibility of increased stress concentration. Depending on the blasting procedure, the fatigue life in high cycle can be increased from 2 to 20 times [1]. The effect of the roughness from shot peening is more pronounced in the low cycle while the effect of the residual compressive stresses have more influence in the high cycle. According to Lili Hu et al. [2], fatigue failure is one of the most serious types of failure for steel structures and can result in considerable casualties and economic loss. Materials with higher yield limits are more sensitive to fatigue susceptibility with the existence of stress concentration and surface roughness, although the fatigue strength of the material increases with its yield limit [3]. Fatigue fracture occurs because parts and / or sets of machines are subjected to the application of cyclic loads causing repetitive stresses in the material. These stresses applied after a certain number of cycles, although their values are lower than the limits of static resistance of the respective materials, can cause them to rupture [4]. Fatigue is a process of degradation of the mechanical properties of a material characterized by the slow growth of one or more cracks under the action of dynamic loading, eventually leading to fracture [5]. Fatigue failures have the undesirable characteristic of catastrophic material rupture.

Fatigue failures usually start at the surface of the material, due to two reasons: the occurrence of maximum stresses in these regions in most types of loads (e.g. torsion and bending) and the concentration of surface tension due to surface finishing conditions or the existence of extrusions and intrusions produced by persistent slip bands (PSBs) [6]. PSBs are fine plastic tension bands formed during a cyclic loading that extend through a single crystal or a grain into a polycrystalline material [7]. 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 failures due to fatigue. The evolution of PSBs and the initiation of surface cracks are observed in polycrystalline materials deformed by cyclic loading. 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 that favor the nucleation of cracks by fatigue [8]. The surface finish has a strong influence on the fatigue resistance of the materials, since there are more points of concentration of surface tension with the increase of roughness [9]. Thus, the surface quality of the material plays an important role in the fatigue behavior of a component, as pol-

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ishing the surface can result in considerable gain in the fatigue resistance. Another important aspect to be observed in relation to parts subjected to fatigue is the introduction of compression stress on the surface. The introduction of surface compression stress hinders the appearance of the intrusions and extrusions caused by PSBs [5]. According to H.Y. Li et al. [9], shot peening is intentionally applied to introduce compressive residual stresses on the surface layers of mechanical components to improve their fatigue resistance. The beneficial shot peening effects aimed at prolonging fatigue life have long been recognized [10]. Due to the high compressive residual stresses produced by the shot peening on the surface layer, the initiation of cracks from the surface of the component is difficult. In this case, it is possible that cracks start internally where the material exhibits less resistance to the surface. Another possibility is that small crack nuclei grow on the surface due to the increased roughness induced by shot peening. Cracked nuclei in this region have reduced growth rates within the compressive layer. Shot peening is a type of cold work where small granules (balls) are hurled against the surface of the material like tiny hammers, producing a local plastic deformation. The region below the surface is plastically deformed, and its increase in mechanical strength is due to the hardening caused by the increase in the density of discordances [9].

Many factors need to be evaluated before the shot peening is performed, including chemical composition, hardness and thickness of the material submitted to the process, desired roughness, expected thickness of the generated compressive layer, ball type and size, shot peening intensity, surface coverage, time of exposure to the process, and speed of application [10]. These parameters are important because, although shot peening normally increases the fatigue limit, in some cases it is possible that deformation caused by a process such as increased roughness or other surface defects, has the inverse effect, reducing this limit [11].

There has been great interest in the application of shot peening with the aim to improve metal alloy fatigue resistance. The compressive residual stresses induced by shot peening on a carbon steel after being chromium electroplated, delayed or arrested the fatigue process [12]. According to Yu-kui Gao et al. [13], shot peening induced high compressive residual stress field on the surface layer of a 40CrNi2Si2MoVA steel. In that case, he transferred the crack source into the material and then increased the fatigue limit by about 36%. In addition to shot peening, other metal surface modification processes, such as: ultrasonic impact treatment combined with the electric discharge [14-15] and laser peening [16] have been studied with the aim to improve metal alloy fatigue resistance.

According to E. Maleki et al. [17], most metals are produced through thermo-mechanical processing, and grain sizes typically range between 5-10 μm. It is known that the strength of metals and alloys is strongly influenced by their grain size. Shot peening has been shown to be very efficient in the process of surface grain refinement [18]. Shot peening is a cold working process on the surface of the material that consequently increases the density of dislocations by the plastic deformation [19-20]. In the shot peening process, plastic deformation is directly proportional to the amount of total kinetic energy of the shot stream transferred to the component.

SAE 1020 steel, which will be studied in this work, is a low cost steel that presents excellent plasticity and weldability, but its mechanical resistance is low due to its high ductility. This steel has applications in mechanical components such as gears, shafts, guiding pins, columns, ratchets, screws, wheel discs, and parts generally for machines and equipment that have moderate mechanical demands. With the introduction of compressive stresses on the surface of SAE 1020 steel by shot peening with glass microspheres, a desirable balance is expected between a high strength surface layer and a soft and ductile core [1,2]. Thus, considering the above, proposed in this work is a study of the effect of shot peening with glass microspheres on the fatigue behavior of SAE 1020 steel. Therefore, fatigue tests were performed on steel specimens with and without shot peening with the subsequent construction of their respective S-N curves (Wöhler Curves). The results obtained from the present study may contribute to a better understanding of the fatigue lifetime gain of the SAE 1020 steel with the shot peening process with glass microspheres.

2. Experimental procedures

The SAE 1020 steel used in this research was obtained in the form of a 5/16 inch cold rolled bar, and its typical chemical composition and mechanical strength tensions obtained by tensile tests is shown in Table 1 and Table 2.

TABLE 1

Chemical composition of SAE 1020 steel (wt%)

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

TABLE 2

Tensile mechanical properties of the SAE 1020 carbon steel

σ_{UTS} (MPa)	σ_{YS} (MPa)	ε %	ψ %
355±12	240±8	33.4±2	59.6±3

(σ_{UTS} – ultimate tensile stress; σ_{YS} – yield stress; ε – elongation; ψ – area reduction).

The tensile strength properties of SAE 1020 steel used in this work were obtained from specimens prepared according to ASTM Standard E-8 [21]. The tensile tests were performed at a rate of 5 mm / min in a universal test machine, brand EMIC, model WDW-100E. The tensile tests were performed at a rate of 5 mm / min on an EMIC universal test machine, model WDW-100E. The fatigue tests with load control were performed on a rotary flex fatigue testing machine EDIBON, model EEFC, with rotation of 750 rpm (12.5 Hz). In this machine the specimen has loading in balance. The specimens for the fatigue tests were machined with 50 mm continuous radius, as shown in Figure 1.

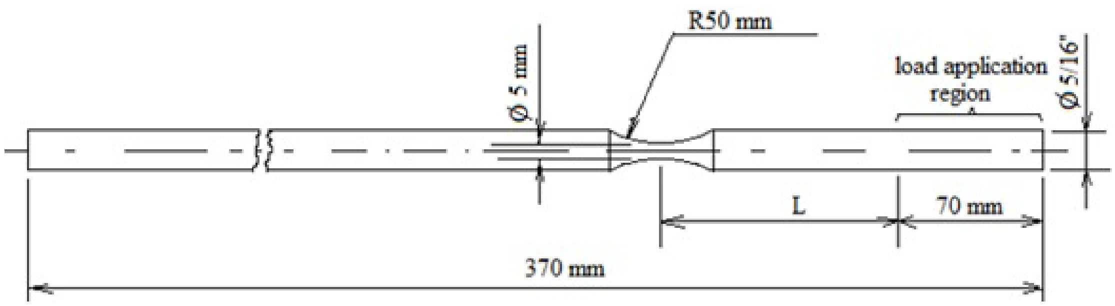


Fig. 1. Specimen for fatigue test

As shown in Figure 1, the fatigue stresses applied during the tests were produced from variations in the "*L*" dimension in the specimens. In all tests the applied load (*P*) was 30 N. Thus, the maximum stress (σ) in the critical region of the specimen was determined by Equation 1.

$$\sigma = \frac{PL}{0.1\,d^3} \quad (1)$$

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

The fatigue tests on specimens subjected to shot peening with glass microspheres were performed at the following stress: 320 MPa (*L* = 203.3 mm); 300 MPa (*L* = 195.0 mm); 280 MPa (*L* = 186.67 mm); 260 MPa (*L* = 178.33 mm), and 240 MPa (*L* = 170.0 mm).

The shot peening of the fatigue specimens was performed with glass microspheres measuring 53-105 µm, for 5 minutes for each specimen, specifically in the machined region of the critical fatigue diameter. The shot peening was performed using nozzle diameter of 6.35 mm (1/4 in) air gun, compressed air pressure of 600 kPa, 90° jet angle and the nozzle-specimen distance of 10 cm.

Vickers microhardness measurements were performed on a Wilson Instruments 402MVD micro-durometer. The microfracture images were obtained from a Bruker scanning electron microscope (SEM), model XFlash detector 410-M. The roughness tests were performed on a Mitutoyo rugosimeter SJ-210.

3. Results and discussion

Shot peening with glass microspheres applied on the specimen resulted in the increase of its surface hardness compared to steel without shot peening. The roughnesses obtained on the surfaces of the specimens were: without shot peening (*Ra* = 0.067 ± 0.012 µm; *Rt* = 1.382 ± 22 µm) and with shot peening (*Ra* = 2.842 ± 0.032 µm; *Rt* = 34.775 ± 1.34 µm). The steel in the condition without shot peening showed medium Vickers hardness of 1407.3 ± 97.1 MPa (load of 100g) and with shot peening 1903.5 ± 133.4 MPa (load of 100g). In this case there was an increase of approximately 35% in the surface hardness of the specimen. According to the literature [9], shot peening induces residual compression stresses on the surface of the material. According to the literature, shot peening similar to that applied in this work can induce surface compressive stress around from –150 MPa to –250 MPa [22]. Surface tensions of compression as well as increase in hardness induce an increase in the resistance to the fatigue. Increased hardness and surface stresses make it difficult to form persistent slip bands (PSBs). PSBs induce stress concentrations that favor the nucleation and propagation of cracks by fatigue [23]. The shot peening of the glass microspheres on the steel surface produced micro superficial plastic deformation, as shown in Figure 2(a).

In the two images of Figure 2, the inclusion of a particle from the shot peening on the steel surface is highlighted by circles. According to the chemical composition of the inclusion,

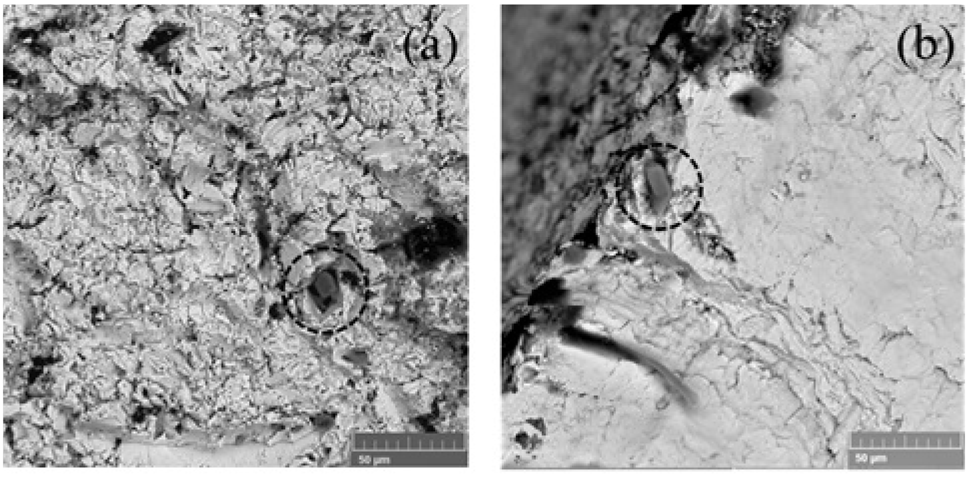
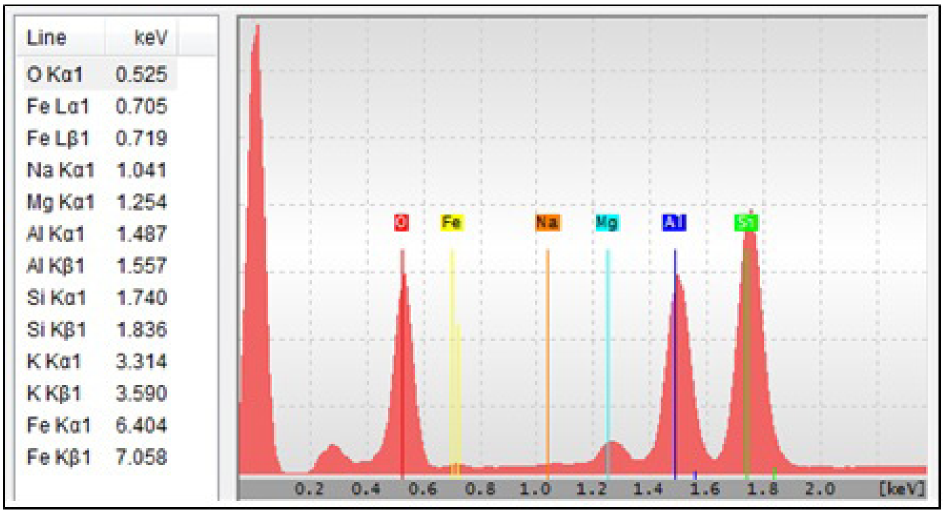


Fig. 2. Surface of the specimen: (a) top view; (b) cross-section. (SEM)



Line	keV
O Kα1	0.525
Fe Lα1	0.705
Fe Lβ1	0.719
Na Kα1	1.041
Mg Kα1	1.254
Al Kα1	1.487
Al Kβ1	1.557
Si Kα1	1.740
Si Kβ1	1.836
K Kα1	3.314
K Kβ1	3.590
Fe Kα1	6.404
Fe Kβ1	7.058

Fig. 3. Chemical composition of the inclusion (EDX-SEM)

identified by EDX analysis in the SEM (Fig. 3), it is a glass particle (high presence of silicon and oxygen).

According to the literature [4], shot peening increases the resistance to fatigue, but eventually damage to the surface of the material can act as a stress concentrator and in this case produce an opposite effect.

Figure 4(a) shows the Wöhler Curves of the SAE 1020 steel under both conditions: with shot peening with glass microspheres and without shot peening. Figure 4(b) shows the linear fatigue behavior of the steel, with and without shot peeening, through Linearized stress-life curves related to low and high fatigue cycles.

As can be observed, in the high cycle the steel with shot peening presented significant improvement of fatigue resistance compared to the steel without shot peening. In the low cycle and in infinite life the difference in resistance to the fatigue of the steel in the two conditions (with and without shot peening) was gradually less significant. The behavior of better fatigue resistance in the high steel cycle with shot peening is justified by the increase in surface hardness and the existence of residual compression stresses produced in this region. The lower influence of shot peening on fatigue in the low cycle is justified because in this condition the behavior resembles the condition of static solicitation where the surface resistance is not so important. In the condition of static solicitation, the mechanism of the fracture is based on the nucleation and growth of micro voids inside the material [24-25].

Figure 5 shows fatigue fracture images of a specimen without shot peening (machined and polished with SiC paper with 200 to 600 grid) and a specimen with glass shot peening. Highlighted by arrows in both images is the region of appearance of the cracks of fatigue as well as the direction of propagation.

The fatigue fracture on the specimen without shot peening (Fig. 5a) began on one side of the specimen (highlighted by arrows) and then propagated in the opposite direction until the specimen was completely ruptured. The sample with shot peening (Fig. 5b) showed a fatigue crack on the entire perimeter of the piece (highlighted by arrows), which then propagated to the interior of the piece with the total rupture of the specimen by traction.

Figure 6 presents images of the fatigue fracture of the sample with shot peening. In Figure 6(a), relative to the edge of

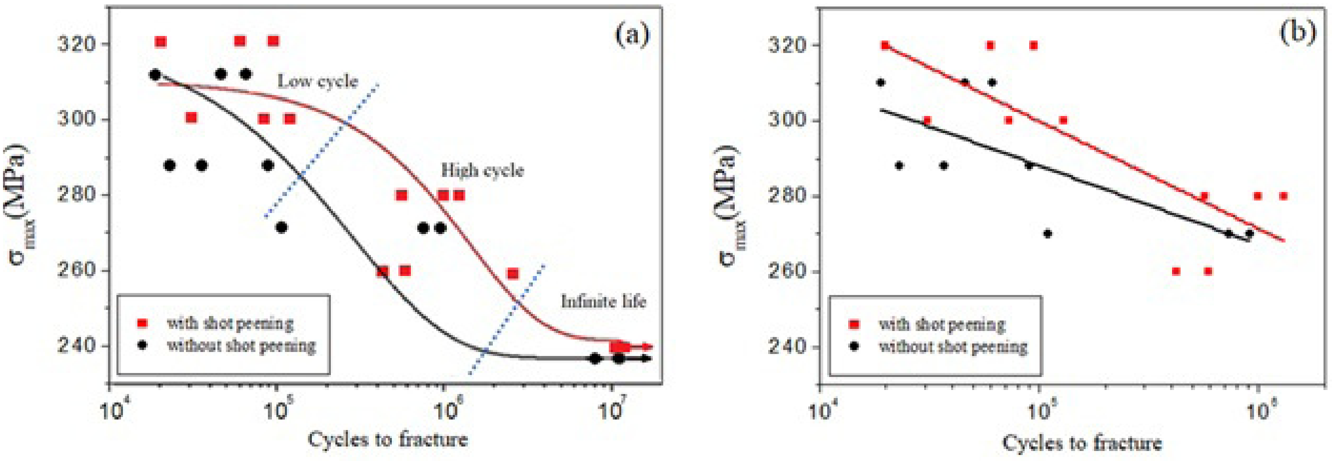


Fig. 4. Fatigue behavior of SAE 1020 steel: (a) Wöhler curves; (b) Linearized stress-life curves

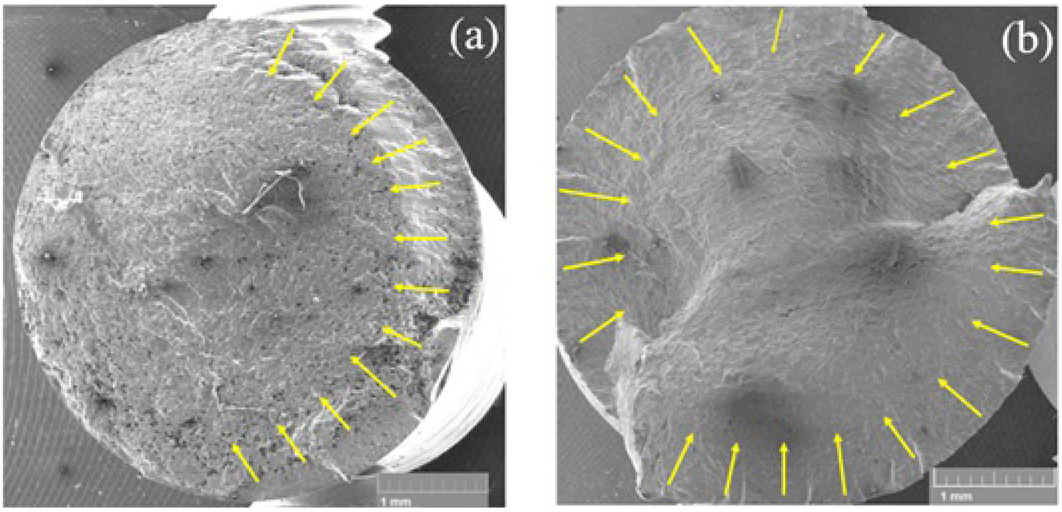


Fig. 5. Fatigue fractures: (a) sample without shot peening; (b) sample with shot peening. (SEM)

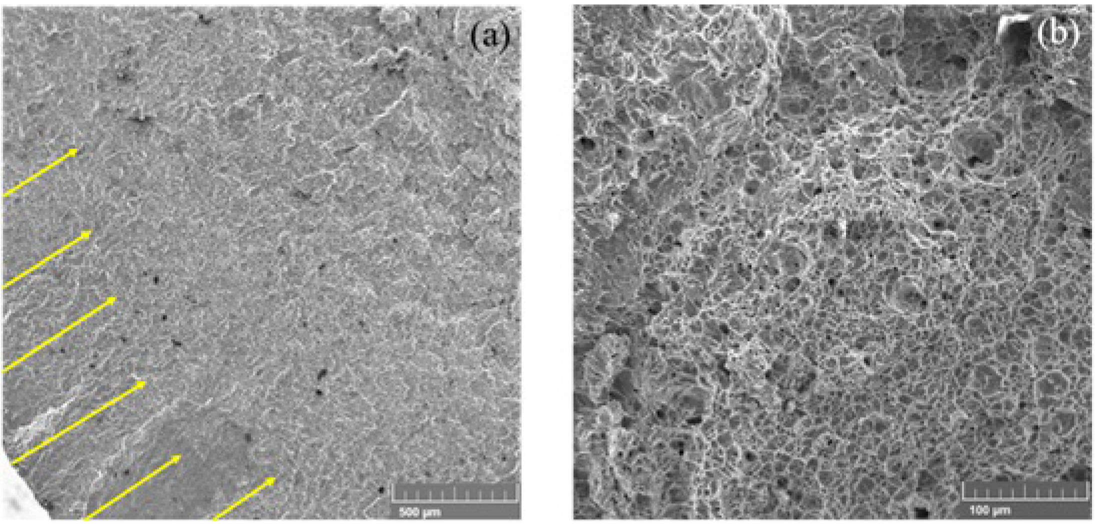


Fig. 6. Microfractography of the sample with shot peening: (a) border region; (b) central region. (SEM)

the fracture, a faceted surface is presented with the occurrence of cleavage planes indicating the fragile fracture behavior. The direction of fracture propagation is indicated by arrows. Figure 6(b) is relative to the image of the central region of the fracture. In this image the ductile characteristic of the fracture can be observed with the presence of several dimples.

3. Conclusions

- The micro-plastic deformations, resulting from the impact of the glass microspheres, produced approximately 35% increase in the surface hardness of the specimen;
- The shot peening with glass microspheres caused a significant increase in the resistance of the steel in the high cycle of fatigue. In the low fatigue cycle and in infinite fatigue life, no significant change was observed in the resistance of the steel in the conditions of with and without shot peening;
- The nucleation of the fatigue cracks in the steel with shot peening with glass microspheres occurred throughout the perimeter of the fracture and its propagation to its interior where there was a final rupture by traction;
- In the steel without shot peening the fatigue cracks nucleated on one side of the fracture and from there it propagated to the other end of the fracture where the final collapse occurred by traction;
- The shot peening with glass microspheres was presented as an efficient alternative for improving the resistance of low carbon steel in high cycles of fatigue.

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