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Influence of mechanical (ball burnishing) surface treatment on fatigue behaviour of AISI 1045 steel

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Abstract

Ball burnishing is a surface treatment process in which plastic deformation of surface irregularities occurs by exerting pressure through a very hard ball on a surface to generate a uniform and work-hardened surface. In this work, the effect of ball burnishing with different pressures (100, 200 and 300 bar) on the fatigue behaviour of AISI 1045 steel was investigated. Ball burnished specimens were cyclically deformed at room temperature using rotating bending tests and compared to the non-surface treated specimens as a reference state. As the results of fatigue tests, ball burnishing can significantly enhance both fatigue limit and fatigue life as compared to non-surface treated specimens for each pressure value of the ball burnishing while fatigue limits of specimens treated by different pressures were almost equal to each other. This improvement of fatigue behaviour may be due to near surface compressive residual stresses as well as cold hardening and increased hardness induced by mechanical surface treatment (ball burnishing).

Key words: fatigue, cold working, surface properties

1. Introduction

It is well established that fatigue properties of components are seriously affected by the surface finish and surface treatment. Almost all fatigue failures that occurred in industries start on the surface [1]. Shot peening, laser shock and ball burnishing are the most effective mechanical surface treatments for the enhancement of the fatigue performance of structural materials such as steels and titanium alloys [2, 3]. This improvement results from process-induced plastic deformation within surface layer which increases the resistance to fatigue crack nucleation [4]. Such condition of surface layer improves many usable properties in addition to fatigue properties [5, 6]. Shot peening is routinely applied to many automotive and aerospace components and alloys. High velocity impact of each particle of shot stretches the surface initially in tension, and leaves a dimple with a region of compression in the centre upon rebounding. Because shot impacts the surface randomly, peening to achieve uniform coverage results in many areas of multiple impacts and a highly cold worked surface layer [7]. Laser shock produces a layer of compression of comparable magnitude to shot peening, but much deeper with less cold work. Single shock can produce high compression with less than 1 % cold work [8]. Ball burnishing method is relatively inexpensive and easy implement compared to other treatments such as peening, and does not require any complicated devices.

The present investigation was performed to evaluate the influence of ball burnishing treatment under various pressures on the fatigue performance of AISI 1045 steel.

2. Experimental details

The material used in this study is a commercial medium carbon steel (AISI 1045), which is widely used for gears and shaft manufacturing. Chemical composition of the material is (in wt.%) 0.4220 C, 0.2440 Si, 0.6070 Mn, 0.0190 P, 0.0330 S, 0.1970 Cr, 0.0332 Mo and 0.1220 Ni. The fatigue samples with a gauge diameter of 6.3 mm and a gauge length of 40 mm were used.

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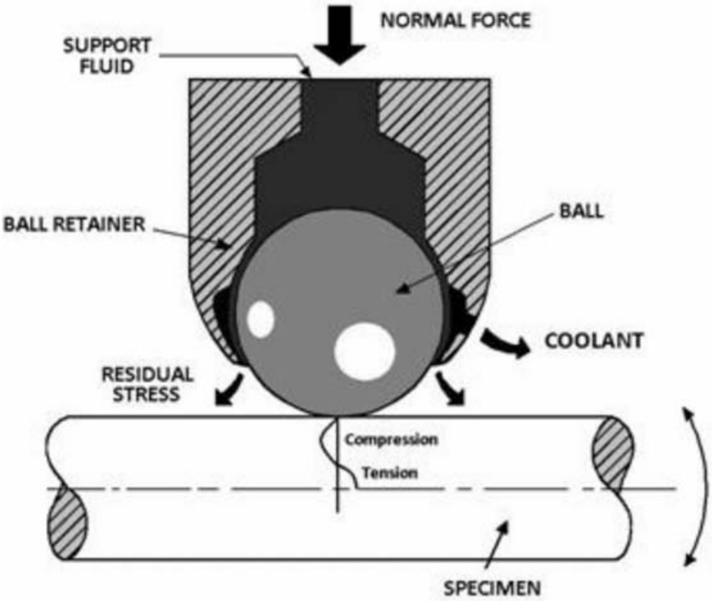

Fig. 1. Hydrostatic principle of the ball burnishing tool.

The gauge parts of the fatigue specimens were polished with silicon carbide papers grit 800–1200 and then degreased with acetone. Ball burnishing was performed using a conventional lathe and a hydrostatically supported burnishing tool from ECOROLL Company, as shown in Fig. 1. A hard metal ball of ø 6 mm (HG6) was utilized as the burnishing element. The burnishing pressure was varied from 100 to 300 bar. The samples were deep rolled at a rotational speed of 1000 min^{-1}.

The burnishing element is operated by the coolant of machine which is supplied via the tool shank. The required pressure is built up by an external hydraulic unit to the tool. This setup has several advantages, as follows:

– The self-regulating following system enables the ball to follow the specimen contour with a stroke, while the rolling force remains constant.

– The hydrostatic bearing of the ball allows it to run nearly without friction and to rotate in any direction.

– The tool can be installed on a conventional or CNC lathe.

Fatigue tests were carried out at room temperature in a four-point loading rotating bending machine under constant stress amplitude at rotational speed of 4000 rpm. The fatigue limit was defined by stress at which the samples survived up to 3×10^6 cycles for all samples considered. Fatigue limits were determined based on the standard JSME S002 with staircase method. According to standard's recommendation, fatigue limit can be calculated with 6 samples for 50 % probability of failure. After mechanical surface treatments, the representative samples were examined by a series of material characterization techniques, including metallographic examination (SEM) and microhardness tests.

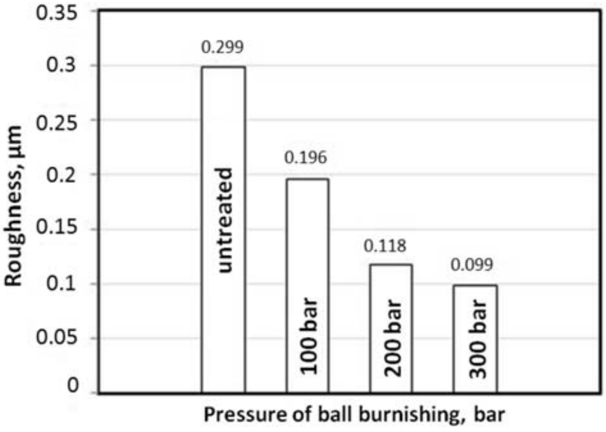

Fig. 2. Surface properties after ball burnishing.

3. Results and discussion

Figure 2 shows a visible improvement of surface finish after ball burnishing. The average of surface roughness decreases with increasing balling pressure after ball burnishing. This development is particularly more pronounced for pressure of 300 bar. Evaluated from the average values of roughness, the roughness of the 300 bar is about 0.099 µm, and that of untreated samples is about 0.299 µm. The value of average surface roughness caused by pressure of 300 bar is almost reduced to one third of this value for untreated samples. However, comparing the average val-

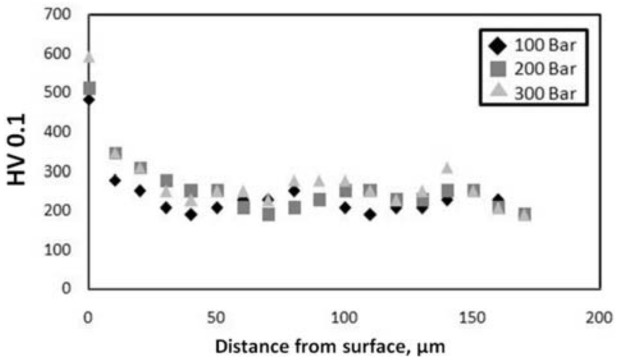

Fig. 3. Micro hardness-depth profiles at various ball burnishing.

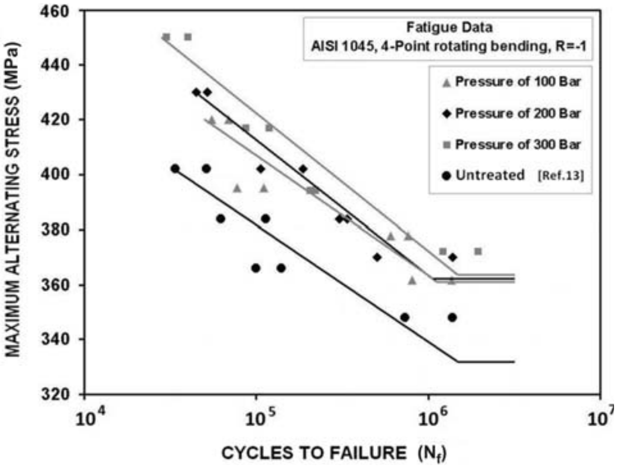

Fig. 4. *S-N* curves obtained from untreated and ball burnished samples of AISI 1045 steel.

ues of surface roughness obtained for different burnishing pressures, it is seen increasing ball pressure reduces the surface roughness. That is, there are differences among them although it is not too much.

Surface roughness is assumed as detrimental to fatigue crack nucleation due to stress concentration factor, so that reduction in surface roughness is one of the important steps in the production of fatigue resistant parts [9].

In this study, no attempt was made to measure the residual stresses. However, there are sufficient evidences from other study that pronounced compressive residual stresses directly at and beneath the surface were formed [10]. It is also reported that, with increasing the pressure, the residual stress both increases and shifts to a greater depth [11].

The effects of various ball burnishing pressures on the microhardness-depth profile are shown in Fig. 3. By considering the surface hardness of untreated sample (220 HV), it is obvious there is a significant increase in the microhardness value at the surface and in the depth due to the existence of a work hardened layer. Maximum hardness values after ball burnishing with pressures of 300 and 200 bar were measured at the surface. Evaluated from the average values of hardness, the surface hardness of the 300 bar revealed more than 100 % increase compared with untreated samples.

The *S-N* curves are shown in Fig. 4 comparing untreated samples (as reference) with different ball pressure conditions of ball burnishing.

The untreated reference samples had a fatigue limit of 332 MPa. It can be seen in Fig. 4 that ball burnishing results in a significant improvement in fatigue limit compared to that of untreated samples. After ball burnishing under pressure of 300 bar, a marked enhancement of about 10 % in the fatigue limit from 332 to 362 MPa was found.

However, fatigue limits of specimens treated by pressures of 100 and 200 bar were almost equal to each other and that of specimens with pressure of 300 bar. It is obvious that there are differences at finite regions of *S-N* curves for different pressures.

Maximum increase in fatigue life was observed in higher stress amplitude (400 MPa). The increase for the mentioned condition was almost 20 %. Similar to fatigue limits, ball burnishing caused serious increases in fatigue lives compared to reference untreated samples as shown in Fig. 5.

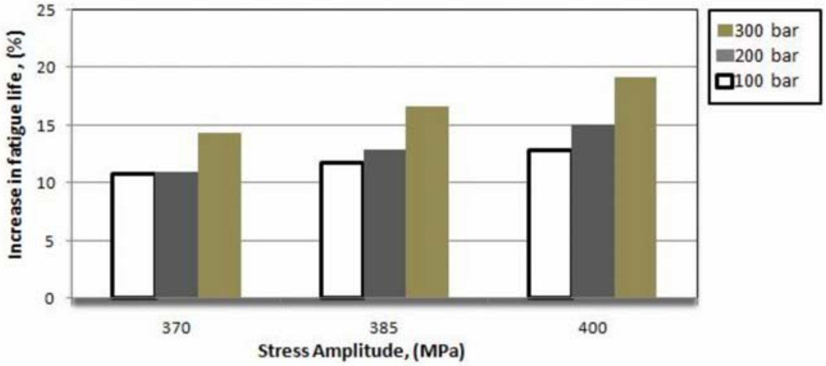

Fig. 5. Percentage increase fatigue lives vs. stress.

The outstanding fatigue properties of ball burnished samples are attributed to surface smoothening and the formation of strain hardened layers, exhibiting compressive residual stresses. Surface roughness is assumed as detrimental to fatigue crack nucleation due to stress concentration factor. The crack initiation in fatigue accounts for a large portion of the fatigue life and occurs through the movement of dislocation in the surface region by cyclic shear stress. Increasing hardness of the surface region makes dislocation motion more difficult, thus crack initiation delays and fatigue behaviour improves. It is also expected that the residual compressive stresses shift the fatigue crack nucleation site from surface to subsurface regions as compared to untreated condition. Thus, the superposition of residual stresses and applied stresses in bending leads to lower combined stresses in these deeper subsurface regions than nominal applied alternating stress.

However, when considering different pressures, there were differences only at finite regions of *S-N* curves while having the same fatigue limits. Possible reasons for this may include that fatigue limit is typically associated with surface compression governing the initiation of fatigue cracks while fatigue life in the finite regime is dominated by crack growth through the compressive layer left by surface enhancement [12].

Figure 6 presents the SEM micrographs of the fatigue fracture for untreated and ball burnished samples. Figure 6a shows multiple crack initiation sites in the surface region of the specimen. In contrast to the untreated samples, it seems that the ball burnished samples show crack initiation sites in the subsurface region of the specimens, as shown in Fig. 6b,c due to the introduction of compressive residual stress and intense strain hardened layers. Moreover, the fatigue limits for different burnishing pressures had remained at almost the same level even after using the highest pressure (300 bar). This may be also explained by the microscopic results that no noticeable changes in surface topography were observed by increasing the burnishing pressures (Fig. 6b,c).

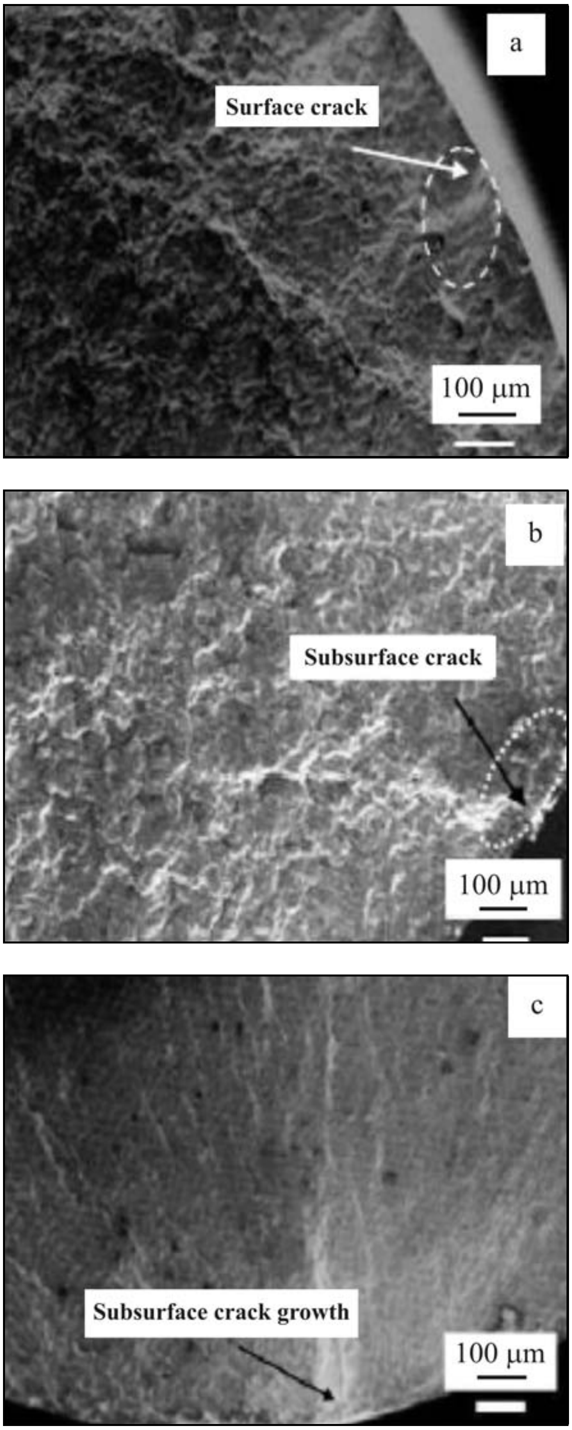

Fig. 6. SEM micrographs of the fatigue fracture: (a) untreated AISI 1045 steel sample at 1×10^5 cycles for 370 MPa; (b) ball burnished AISI 1045 steel sample at pressure of 300 bar at 30×10^3 cycles for 450 MPa; (c) ball burnished AISI 1045 steel sample at pressure of 200 bar at 540×10^3 cycles for 370 MPa.

4. Conclusions

Samples of an AISI 1045 steel were ball burnished at different pressures and the following conclusions were drawn:

The beneficial effect on fatigue behaviour from ball burnishing process can be ascribed to the creation of significant near-surface compressive residual stresses and a near-surface work hardened layer. The greater impressiveness of the ball burnishing is attributed to a higher magnitude of induced compressive stresses, a higher degree of work hardening, and the fact that process results in a significant decrease in the surface roughness.

Acknowledgements

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