Experimental Investigation of the Effect of Burnishing Force on Service Properties of AISI 1010 Steel Plates

F. Gharbi, S. Sghaier, F. Morel, and T. Benameur

This paper presents the results obtained with a new ball burnishing tool developed for the mechanical treatment of large flat surfaces. Several parameters can affect the mechanical behavior and fatigue of workpiece. Our study focused on the effect of the burnishing force on the surface quality and on the service properties (mechanical behavior, fatigue) of AISI 1010 steel hot-rolled plates. Experimental results assert that burnishing force not exceeding 300 N causes an increase in the ductility. In addition, results indicated that the effect of the burnishing force on the residual surface stress was greater in the direction of advance than in the cross-feed direction. Furthermore, the flat burnishing surfaces did not improve the fatigue strength of AISI 1010 steel flat specimens.

Keywords ball burnishing, fatigue, residual stress, tensile properties

1. Introduction

Surface quality is of great importance in the performance of mechanical components. The change in properties of the surface layer by superficial plastic deformation is due to the application of surface mechanical treatments. Burnishing is one of the mechanical treatments.

It is a cold treatment that involves the passing of a deforming tool onto the workpiece surface, under a generated pressure. This can be done by ball (ball burnishing) or by rolling (roller burnishing). During burnishing, the generated pressure exerted by the tool exceeds the yield point of part surface at the point of contact, causing a small plastic deformation. This plastic deformation created by ball or roll burnishing is a displacement of the material from the peaks that flows under pressure into the valleys, resulting in a mirror-like finish with a strain-hardened, wear-, and corrosion-resistant surface (Ref 1). Burnishing offers a performance improvement of materials by a combined action of surface hardening, microgeometric modification, and introduction of compressive residual stresses through a heterogeneous plastic deformation on the surface of the mechanical components (Ref 2). In addition, this process transforms tensile residual stress induced in the near surface by machining into compressive residual stresses, giving several improvements to mechanical properties (Ref 3).

Several authors have investigated the effect of burnishing on mechanical properties improvement such as hardness and surface quality (Ref 4, 5), state of residual stress (Ref 6-9), fatigue strength, corrosion of the workpiece (Ref 10), and tensile strength (Ref 6, 11).

There are several controlling parameters that can have an influence on the workpiece surface properties (Ref 12). In general, the two most frequently cited parameters affecting surface finish are the burnishing force and the feed rate. In a previous study by Gharbi et al. (Ref 4), three optimal burnishing parameters were investigated for AISI 1010 steel plates, namely burnishing force, speed, and feed rate. A force of 400 N, a speed of 235 rpm, and a feed rate of 0.18 mm/rev were found to yield the best surface quality. The authors found that the surface quality of AISI 1010 steel plates is most influenced by the burnishing force, followed by the burnishing speed, and least by the burnishing feed. The purpose of the current study was to investigate the effect of burnishing force on the surface quality (mean roughness and surface hardness) and on the service properties (residual stress, tensile properties, and fatigue) of rolled sheets of AISI 1010 steel. In order to deepen our understanding of the effect of the burnishing force on the surface quality and on the service properties, the optimum values for the speed and feed rate were kept constant during experiments. Experiments were performed by means of a newly developed burnishing tool device especially designed to treat large flat surfaces. The burnished specimens were then tested to find the burnishing condition under which tensile properties were improved.

2. Material and Methodology

We use in this work a material that is made of AISI 1010 steel. It was received in a form of hot-rolled plates with a thickness of 3 mm. This material was selected because of its importance in the manufacturing industries. The chemical

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composition and the mechanical properties of the studied material are shown in Table 1 of Ref 4. The hardness and the roughness of the unburnished surfaces were measured to be 59 ± 1 HRB and 2.48 ± 0.4 µm, respectively. The mean roughness, as well as the hardness, is calculated by averaging several measurements (total of nine measurements were made) at different locations of the workpiece surface. The steel plates were cut into tensile and fatigue specimens so that they can be burnished and then used for investigation of their mechanical behavior and fatigue strength. Figure 1 indicates the dimensions of the two types of specimen used in this study. The specimens were cut along the rolling direction of the original plates by laser cutting to guarantee the smoothest surfaces with best possible dimensional precision. The burnishing tool device and the test specimens were assembled onto a C-tek machining center (CNT 830) as shown in Fig. 2 (Ref 4). All experiments of burnishing were performed using a ball diameter of 10 mm, a number of burnishing passes of 2, and a penetration depth of 0.2 mm. ESSOLUBE HD 15 W-40 is used as lubricant oil between the tool and the workpiece. The oil has a kinematic viscosity of 113 and 15.4 mm^2/s at 40 and 100 °C, respectively.

The tensile tests were performed using an Instron Servohydraulic UTS 8502 machine with a maximum capacity of 250 kN. All the tests were conducted with a speed of 5 mm/min. The fatigue tests with corrugated tensile were carried under imposed loading using a frequency $f = 25$ Hz at a room temperature. The stress ratio for the fatigue experiment is $R = 0.1$. In addition, analysis of the fracture surfaces of the burnished samples was examined using a JSM-6300 Scanning Electron Microscope SEM.

The residual surface stresses were determined using a Proto XRD unit. The latter is fitted with a chromium Kα radiation tube (wavelength, $\lambda = 2.291$ Å) at 20 kV, 4 mA to acquire the $(hkl) = (211)$ diffraction peak at Bragg's angle $2\theta = 156.41°$. A collimator of diameter 2 mm was used. $\mathrm{Sin}^2\psi$ method measurements were performed at seven β angles from 25° to −25° using 3° oscillations at each β angle (with Proto XRD unit $\psi = \beta \pm \frac{(\pi - 2\theta)}{2}$) (Ref 6).

3. Results and Discussion

3.1 Effect of Burnishing Force on the Mean Roughness R_a

An empirical model of ball burnishing process on AISI 1010 steel plates was developed to study the mean roughness variation as a function of the burnishing speed (x_1), force (x_2), and feed (x_3). The equation developed in the previous paper is as follows (Ref 4):

$$R_a = 1.747 + 0.052x_1 + 0.239x_2 + 0.03x_3 + 0.166x_1^2 - 0.145x_2^2 + 0.002x_3^3 + 0.067x_1x_2 - 0.081x_1x_3 \quad \text{(Eq 1)}$$

By using Eq 1, the effect of burnishing force on the mean roughness for the optimum values of the burnishing speed and the feed rate is shown in Fig. 3. As observed from Fig. 3, an increase of the burnishing force causes a decrease in mean roughness down to a minimum value of 300 N. Beyond this minimum value, the mean roughness starts to increase with the increase of the burnishing force. We recall that in a previous study by Gharbi et al. (Ref 4), a force of 400 N was found to yield the best surface quality. This burnishing force should not exceed 400 N or otherwise flaking of the metal would occur. In this paper, the optimum conditions of 0.18 mm/rev and 235 rpm were used in the equations, and a value of 300 N was obtained under which ductility was also improved ("Effect of Burnishing Force on the Tensile Properties" section). Therefore, the optimum burnishing conditions for AISI 1010 steel plates are 235 rpm for the burnishing speed, 0.18 mm/rev for the feed rate, and 300 N for the burnishing force.

3.2 Effect of Burnishing Force on the Surface Hardness HRB

An empirical model of ball burnishing process on AISI 1010 steel plates was developed in terms of the burnishing speed (x_1), force (x_2), and feed (x_3). The equation developed in the previous paper for the surface hardness variation is as follows (Ref 4):

$$\mathrm{HRB} = 65.2 - 0.49x_1 + 0.86x_2 - 0.73x_3 + 0.117x_1^2 + 0.2x_2^2 - 0.318x_3^2 - 0.44x_1x_2 + 0.41x_1x_3 \quad \text{(Eq 2)}$$

The effect of burnishing force on the surface hardness for optimal burnishing speed and feed rate is shown in Fig. 4. This figure is produced based on the developed empirical model in Eq 2 (Ref 4) by taking the optimal values of the speed and feed rate. As observed from Fig. 4, an increase of the burnishing force increases the surface hardness. When high burnishing force is applied, the depth and amount of plastic deformation are expected to increase at the surface of the workpiece. This in turn causes an increase in the work hardening of the surface layers. It should be noted that the empirical equations developed in this study are valid within the range of the experimental values. Since the optimum values were found to be within the experimental data range, no extrapolation was needed to find the performance of the models for values outside this data range used.

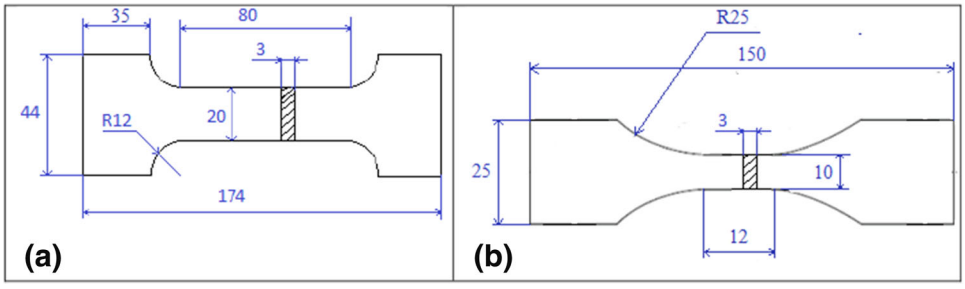

Fig. 1 Dimensions of the two types of specimen; (a) tensile specimen, (b) fatigue specimen

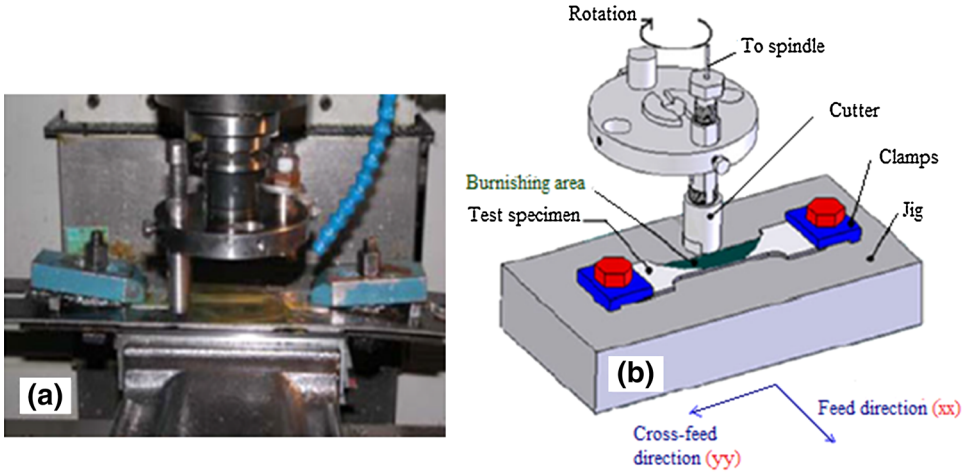

Fig. 2 (a) Burnishing tool device mounted on the machining center. (b) Machining setup (Ref 4)

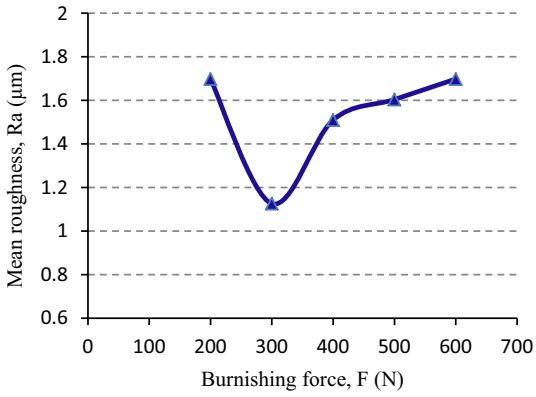

Fig. 3 Effect of burnishing force on mean roughness under the optimum conditions: n = 235 rpm and f = 0.18 mm/rev

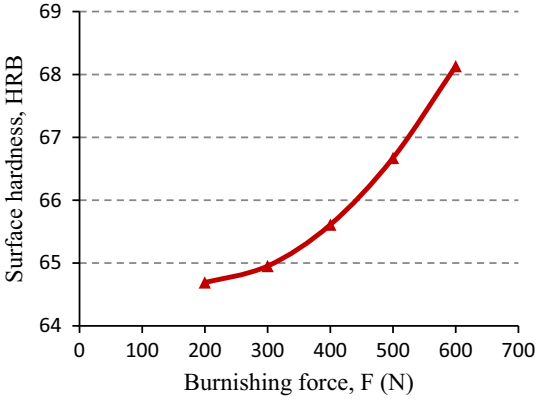

Fig. 4 Effect of burnishing force on mean surface hardness under the optimum conditions: n = 235 rpm and f = 0.18 mm/rev

3.3 Effect of Burnishing Force on the Tensile Properties

The tensile test curves of hot-rolled AISI 1010 steel for different burnishing conditions are illustrated in Fig. 5. During burnishing process, the applied force is variable but the other processing parameters such as speed and feed are set to be 235 rpm and 0.18 mm/rev, respectively (Ref 4). As shown in Fig. 5, the burnishing of the AISI 1010 steel plate can have a significant effect on the stress-strain behavior. According to the applied force, the ultimate tensile strength may decrease or increase compared to the unburnished condition. For burnishing forces 200, 300, 400, 500, and 600 N, the yield stresses are 240, 260, 247, 248, and 270 MPa, respectively.

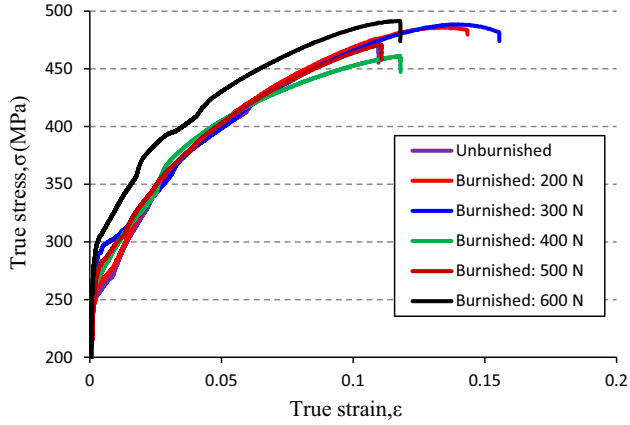

Fig. 5 True stress-strain curves of burnished and unburnished specimens for different burnishing forces (n = 235 rpm and f = 0.18 mm/rev)

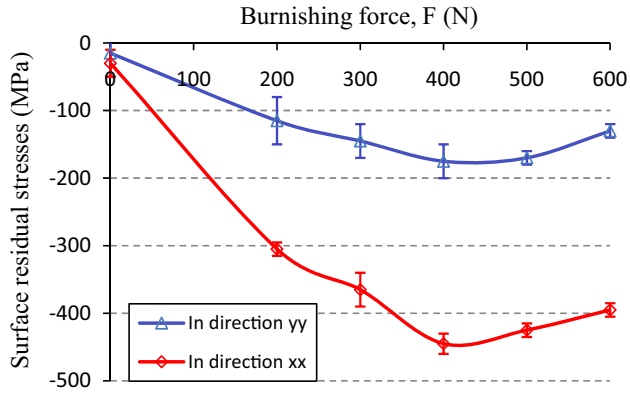

Fig. 6 Profile of the measured surface residual stress in the optimum conditions: n = 235 rpm and f = 0.18 mm/rev

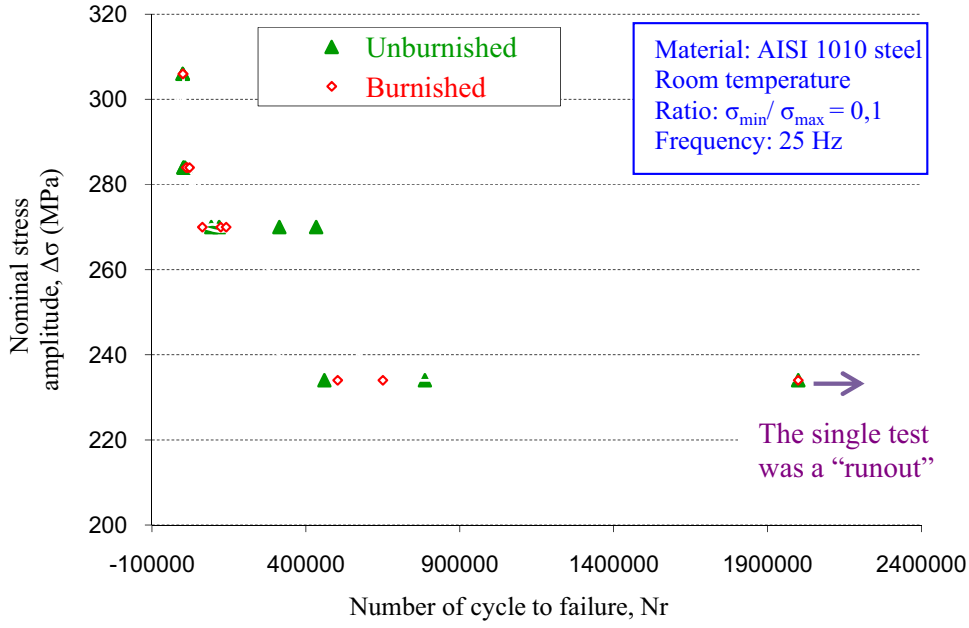

Fig. 7 Comparison of Wohler curves of AISI 1010 steel for unburnished and burnished conditions: n = 235 rpm, F = 400 N, and f = 0.18 mm/rev

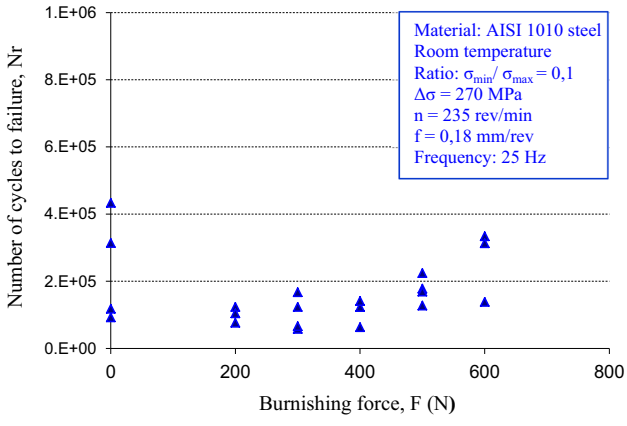

Fig. 8 Behavior of the life at fracture of AISI 1010 steel for different burnishing forces

In comparison with the unburnished specimen, the improvement in elongation is up to 49% when the specimen is burnished with burnishing conditions of 300 N, 235 rpm, and 0.18 mm/rev. In this optimum case, the yield strength, ultimate tensile strength, and percent elongation at fracture for AISI 1010 steel were 260 MPa, 371 MPa, and 43.05%, respectively.

In this case, the burnished specimen under the optimal conditions resists tensile well and its plasticity increases. This increase may be caused by the improvement in the surface finish that significantly reduces the surface flaws from where cracks can initiate. Alternatively, it may be due to the removal of the microcracks on the edges of the specimen during tool rotation.

3.4 Effect of Burnishing Force on the Surface Residual Stresses

Another further study was performed to investigate the effect of burnishing forces on the distribution of surface residual stress in the hot-rolled AISI 1010 steel plate. The mechanical stresses exerted by the ball burnishing on the surface of the sample lead to a stable modification of the state of residual stress. Figure 6 shows the levels of residual stress on the surface measured in the feed direction (xx) and in the cross-feed direction (yy) (Fig. 2). As shown in Fig. 6, for the case of unburnished specimen, there is the presence of compressive residual stresses on the surface due to the hot rolling of the sheet during its preparation. The increase in burnishing force leads to an increase of surface residual stresses in the two directions.

More specifically, in the feed direction (xx), these stresses are more important. They reach a maximum value of −450 MPa for a burnishing force of 400 N. Beyond this value, these stresses will decrease due to decohesion (flaking) of the metal that will cover the hardened layer (Ref 4). In the cross-feed direction (yy), these compressive surface residual stresses reach a value of −175 MPa for the same applied force representing a reduction of more than 150% at a burnishing force of 400 N. They were lower than those in the feed direction. This is probably due to the material flow around the burnishing ball when rolling on the surface, where the lateral flow takes a greater place than the frontal one.

3.5 Effect of Burnishing Force on the Fatigue

The effects of burnishing force on the fatigue strength of AISI 1010 steel specimens are shown in Fig. 7 and 8. Figure 7 shows the Wohler curves that calculate the endurance limit σ_D of the studied material. This endurance limit, of the order of 233 MPa, was not altered by this mechanical treatment due to the creation of defects (sawtooth) on the edge of the specimen which is the sources of initiation of microcracks (Fig. 9). Moreover, Fig. 7 shows that in the region of low cycle fatigue, under high stress amplitudes, the number of cycles to failure (Nr) of the unburnished specimens is greater than those treated in the condition: F = 400 N, n = 235 rpm, and f = 0.18 mm/rev. The evolution of the number of cycles to failure (Nr) as function of the applied force is shown in Fig. 8. As indicated in Fig. 8 and for reliability of the experimental data, four data points of the fatigue tests are collected for every burnishing force. This figure shows that for an imposed load

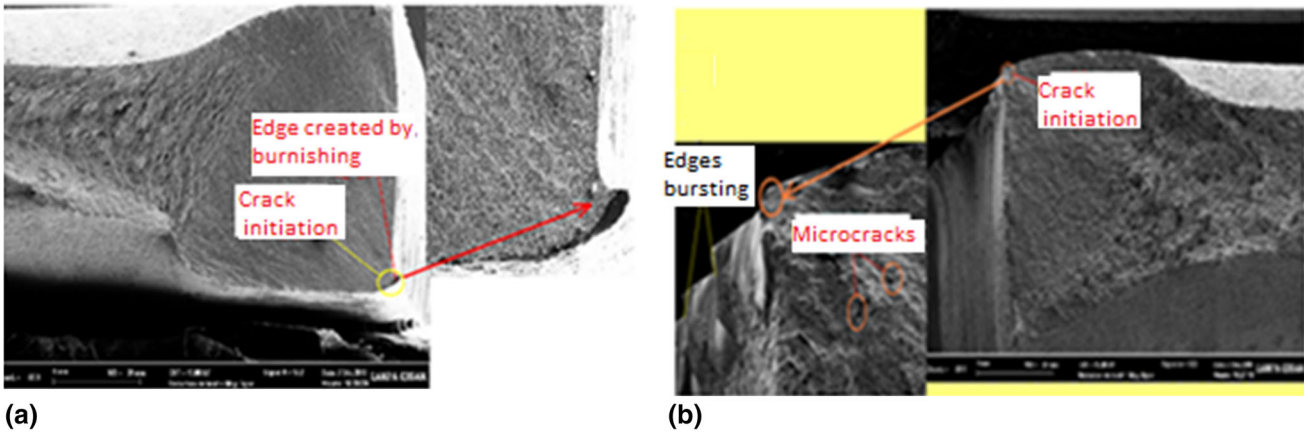

Fig. 9 Analysis of the fracture surfaces of burnished AISI 1010 steel specimens using SEM under the conditions: $n = 235$ rpm and $f = 0.18$ mm/rev

($\Delta\sigma = 270$ MPa), the ball burnishing of AISI 1010 steel plates does not have a beneficial effect on the fatigue strength. The variation of number of cycles to failure decreases with burnishing force below 400 N and then increases above 400 N. Therefore, the unburnished case has better fatigue properties than the burnished cases with different applied forces.

4. Conclusion

The effects of the burnishing force on the surface quality and on the service properties of the hot-rolled AISI 1010 steel plate were determined. Based on this study, the following conclusions may be drawn:

(1) The optimal burnishing parameters of rolled sheets of AISI 1010 steel have been determined to be 300 N, 235 rpm, and 0.18 mm/rev.
(2) At the optimal condition of burnishing force, the ductility of AISI 1010 steel was improved by 49%.
(3) The burnishing forces have a significant influence on residual stresses in the surface in the feed direction, but not in the cross-feed direction. A reduction of 420 MPa was achieved in the feed direction compared to 155 MPa in the cross-feed direction.
(4) The burnishing flat surfaces did not improve the fatigue strength of AISI 1010 steel flat specimens.

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