Abstract

Surface hardness plays an important role in lifetime of a mechanical piece subjected to friction and wear. Indeed, the hardness can be improved by superficial plastic deformation processes (SDP), such as mechanical surface treatment “MST”, in particular the ball burnishing. However, the treatment result of is conditioned by mastery of operation thus ensuring treated piece good mechanical and geometric properties. Experimental work was carried out by applying the ball burnishing process on steel tensile specimens S355JR, in order to observe the influence of treatment parameters regime on surface hardness 'Hv' and the effect of latter on tensile behavior of this steel. Two parameters of regime were considered namely: burnishing force "Py" and number of passes "i". The relationship between these parameters and microhardness measured at "Hv" surface has been highlighting using factorial plans 2^2. Moreover a mathematical model has been obtained allowing prediction of response (Hv) as well as optimization of parameters of treatment regime. The experimental results showed that for surface hardness Hv it is possible to reach a 45% improvement rate for a burnishing force py = 20 Kgf and a number of passages i = 3 for this material. Regarding behavior of material during tensile test, for a low burnishing force (py = 10N) and a number of passes (i = 5), the section further weakening (S = 4.14), proof than ductility of material has decreased.

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Keywords: Surface hardness, factorial designs, ball burnishing, mathematical model, tensile behaviour

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1. Introduction

In service, the pieces surfaces are most exposed to different external stresses which often lead to altering service life of structural elements [1, 2]. Thus, a careful physico-geometrical state of superficial layers is more and more valued to guarantee the high-characteristic pieces [3, 4] and consequently a proper functioning of mechanisms in which they are mounted. To improve service life and performance of mechanical structures, the implementation methods more and more modern are used, which modify basic properties of material such as mechanical surface treatments (MST). The ball-burnishing process which is part of this treatment family finds wide applications in various pieces manufacturing ranges even to point of sometimes provide alternatives to conventional processes by chip removal. Following a surface plastic deformation of pieces mechanical, the process allows it possible, by same action, to combine a superficial hardening [5-7], a structural modification [8], the introduction of residual compression stresses, and a geometric surface condition that is often close to or better than that resulting from some finishing processes by chip removal [9-10]. These simultaneous effects often result in greater resistance to wear, corrosion and fatigue [11-13]. This work allows quantifying the work hardening of steel S355 JR having undergone treatment by burnishing. The effect of treatment is estimated through measurement of surface hardness (Hv) and tensile behavior at rupture time of this steel. The influence of two main burnishing parameters, in this case number of tools passes (i) and burnishing force (Py), was demonstrated by means of response surface methodology (RSM) carried out with a complete plan multifactorial experiences type 2^2. A mathematical model has been established for this purpose to predict surface hardness (Hv) as a function of treatment parameters (Py and i).

2. Materials and methods

2.1 Material

The material used is S355 JR steel supplied in form of cylindrical bars. This steel, like all medium carbon steels, is used in general construction. The sample intended for determination of chemical composition is prepared according to ISO 14284 (FIG. 1). The results of chemical analysis are shown in Table 1.

Table 1. Chemical composition of S355 JR

<table>
<thead>
<tr>
<th>% elements</th>
<th>C</th>
<th>S</th>
<th>Al</th>
<th>Si</th>
<th>P</th>
<th>V</th>
<th>Cr</th>
<th>Mn</th>
<th>Ni</th>
<th>Cu</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.188</td>
<td>0.003</td>
<td>0.0273</td>
<td>0.2314</td>
<td>0.0051</td>
<td>0.00327</td>
<td>0.1571</td>
<td>1.053</td>
<td>0.0548</td>
<td>0.0575</td>
<td>0.0297</td>
</tr>
</tbody>
</table>

Mechanical characteristics Hv=237.3, Rm =523.6 N/mm2, Re=365.6 N/mm2, A=30.0%.

2.2 Experimental methodology

The experimental stage was based on a 2^2 factorial design and the Response Surface Methodology. Two parameters (Py and i) at two levels each (high and low) have been selected within limits of their variation domains [14]. To do this, in the study field they form (Fig. 1); these parameters were coded and combined with each other according to following experimental design (Table 2).
Table 2. Experience matrix

<table>
<thead>
<tr>
<th>TEST NO.</th>
<th>Py (kgf)</th>
<th>X1</th>
<th>X2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>+1</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>+1</td>
<td>+1</td>
<td></td>
</tr>
</tbody>
</table>

Livel - 10  3
Livel + 20  5

![Field of study](image)

Fig. 1. Definition of study field by experimental points

The output response (y) which expresses superficial hardness (Hv) is predicted from a first-degree polynomial mathematical model with interactions (Eq.1).

\[
Y = a_0 + a_1X_1 + a_2X_2 + a_{12}X_1X_2 \tag{1}
\]

- \(a_0\): constant coefficient of the model;
- \(a_1\): coefficient of factor 1;
- \(a_2\): coefficient of factor 2;
- \(a_{12}\): coefficient of term x1x2;
- \(Y\): response

2.3 Experimental procedure

Given the experiments design \(2^2\), four test pieces (Figure 2) were taken from cylindrical bars of length \(L = 130\) mm and diameter \(D = 12\) mm have been prepared according to ISO 6892-1 standard on universal turn ALMO Type SN.

The tensile tests were performed at URAM / CRTI laboratory on a ZKNICK 1476 test machine with 10KN capacities (Figure 3).
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Beforehand, specimens underwent burnishing treatment on a universal lathe (Fig. 4) by means of a diamond point under a work piece rotation frequency \( n = 560 \) rpm" [15] and a burnishing feed \( f = 0.054 \) mm rev\(^{-1}\) and under an abundant lubrication by means of a SAE20 oil emulsion [16]. The burnishing force (Py) and number of burnishing tool passes (i) being variable as mentioned above (Table 2).

The surface hardness Hv was measured with a micro durometer type Matsuzawa MXT70 (Fig. 5) under a load 200 grams force.
Measurements were taken before and after burnishing and the results are shown in Table 3.

Table 3. Conduct of tests and experimental results

<table>
<thead>
<tr>
<th>TEST N°</th>
<th>Burnishing force Py (kgf)</th>
<th>Number of burnishing tool passes (1)</th>
<th>Hardness Hv</th>
<th>Machined</th>
<th>Burnished</th>
<th>Improvement Rate %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>3</td>
<td>226.6</td>
<td>317.2</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>3</td>
<td>211.9</td>
<td>307.5</td>
<td>45%</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>5</td>
<td>239.7</td>
<td>318.0</td>
<td>33%</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>5</td>
<td>229.4</td>
<td>291.8</td>
<td>27%</td>
<td></td>
</tr>
</tbody>
</table>

3. Mathematical model

The "Hv" measurement results obtained after burnishing were used to deduce a mathematical model (Eq.2) allowing output response prediction (Y) as a function of input factors (Xi) their interaction (Xij).

\[ Y_i = a_0 + \sum a_i X_i + \sum a_j X_j + \sum a_{ij} X_i X_j \]  

The matrix notation of this equation is given in Table 4.

<table>
<thead>
<tr>
<th>TEST N°</th>
<th>Constant a0</th>
<th>Factor X1</th>
<th>Factor X2</th>
<th>Interaction X1 X2</th>
<th>Response Yi</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>Y1</td>
</tr>
<tr>
<td>2</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>Y2</td>
</tr>
<tr>
<td>3</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>Y3</td>
</tr>
<tr>
<td>4</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>Y4</td>
</tr>
</tbody>
</table>

The influence degree of each parameter can be estimated from the constants a0, ai, aj and aij which can be calculated by following equation system (Eq.3).

\[
\begin{align*}
    a_0 &= \frac{1}{4} \left[ Y_1 + Y_2 + Y_3 + Y_4 \right] \\
    a_i &= \frac{1}{4} \left[ -Y_1 + Y_2 - Y_3 + Y_4 \right] \\
    a_j &= \frac{1}{4} \left[ -Y_1 - Y_2 + Y_3 + Y_4 \right] \\
    a_{ij} &= \frac{1}{4} \left[ Y_1 - Y_2 - Y_3 + Y_4 \right]
\end{align*}
\]  

In this case, this system resolution enable it possible to response predict Y (for Hv) at any point in study field covered by factors X1 (for Py) and X2, (for i). The result in reduced centered values is given by (Eq.4).

\[ Hv = 308.625 - 8.975 X_1 - 3.725 X_2 - 4.125 X_1 X_2 \]
4. Results and interpretation

4.1 Effect of burnishing on micro-hardness "Hv"

Burnishing confer at surface a improvement hardness superficial. This result concord well that of works [11] [12] [17]. The resulting superficial layers of turning were characterized by a micro-hardness between 211.9 HV and 239.7. After superficial treatment, an improvement rate between 27% and 45% was observed (Fig. 6). This increase in surface hardness is due to fact that burnishing created by plastic deformation of new superficial layers hardened with fine texture and elongated.

4.2 Effect of treatment regime on surface hardness "Hv"

Surface mechanical treatments (SMT) give the surfaces a high hardness, allowing them better resistance to fatigue, corrosion and wear according to [18]. The effect of treatment parameters on surface hardness Hv can be evaluated by iso-response curve shown in Figure 7a. It is observed that number of burnishing tool passes does not affect the hardness Hv when burnishing force is taken at its low level. In this case the hardness values oscillate between 317.2 ÷ 318 Hv (Fig. 7b). This can be explained by fact that passage of ball under a low charge with several passes (i = 3 ÷ 5) [17] generates by plastic deformation of superficial layers more reinforced, which results in an increase the surface hardness. On other hand, if burnishing force (Py) is at its maximum level, the interaction of number of burnishing tool passes is remarkable (Fig. 7c). Thus, considering low level of this factor (i = 3) superficial hardness Hv decreases to a value of 307.5, and up to a value of 291.8 if it is taken at high level (i = 5). Under high load burnishing, the material appears to be over-hardening, the ball ironing seems to even alter superficial layers and to soften them, hence Hv reduced [19].

NB: in the iso-reponses curves, the value of "X" corresponds to factor X1 (Py stress) "Y" is factor X2 (number of passes i) and "Z" is Response (Hv).
The way in which the material was hardened in burnishing process was characterized by an observation of relative decrease of initial and final sections. Thus, it appears from morphological analysis of break during its tensile test that material develops a necking phenomenon before breaking under all treatment conditions. The fracture surface is often inclined or mixed, presenting a nerve rupture character even if cup is large and incomplete in machining case. This testifies to ductile nature of a soft material of very good quality capable of undergoing the plastic superficial deformation induced by burnishing (Fig. 8).

Under all conditions of treatment, the state of plane stresses is predominant in surfaces from where shear of ductile lips leading to a mechanism of fracture by sliding, however, at heart of material, the state of plane deformation is predominant one which leads to a cleavage failure (mode I) marked by a nearly plane fracture surface. The area of section broken by cleavage (Ac) is variable with burnishing parameters (Fig. 9). In machining state it represents 59.6% of final section after necking (As). After burnishing, it is estimated between 57.6% and 61.7%. A low number of passes, the increase of Py causes a reduction of final section (necking), which is not the case if the number of passes increases to 5, since in this case, when Py converges from 10 to 20 the occupation rate of cleaved section increases from 57.6 to 60.8%. This is probably due to hardening phenomenon of which intensifies with increase of these two parameters (i and Py). Otherwise, the combination of lower burnishing force (Py = 10 kgf) to greatest number of passes (i = 5) contributes to further shorten the material at its weakest section to mark more necking. This suggests that in these conditions burnishing, the metal flow is easier and the material becomes even more ductile compared to its machining state.

Fig. 7. Effect of burnishing parameters on superficial hardness "Hv"
4.3 Effect of hardening on fracture facies

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4. Conclusion

In light of experimental results, the burnishing process, which by acting by plastic deformation of surface layers of steel S355 JR allowed to further consolidate and improve superficial hardness Hv. the methodology of factorial plans $2^5$ contributes quantitatively to effects of burnishing on superficial hardness Hv. The following conclusions can be drawn.

- Mathematical model developed allowed to predict the surface hardness "$Hv" according to parameters of treatment (Py and i) in field of study.
- Burnishing force "Py" has a significant effect on micro hardness "$Hv". Indeed, for Py =10kgf and whatever number of passes "i", "$Hv" is improved for achieve a value of 318 for i = 5;
- High loads, Py = 20kgf combined with a high number of passes i = 5 tend to decrease "$Hv";
- Iso-response curve derived from numerical simulation contributed more clearly to analysis of the effects of treatment parameters (input factors) on response studied (Hv);
- Failure facies Analysis confirmed the material ductile appearance and allowed to judge its ductility according burnishing parameters.

References

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