Abstract—The surface hardness plays an important role in the service life of a mechanical parts subjected to friction and wear. It can be improved by mechanical treatments or heat treatments. The latter occupy an important place in steel metallurgy, they aim to improve the performance of mechanical properties of materials such as resilience and hardness and consequently they contribute in a visible way to the good resistance to fatigue and wear treated pieces. This work aims to predict the surface hardness Hv as a function of heat treatment parameters in this case the treatment temperature and holding time. Therefore, thermal treatments have been envisaged following the methodology of factorial plans $2^2$ where two parameters have been considered, the temperature "T" and the holding time "t" where each parameter at two levels (min, max). These treatments were applied on forged XC38 steel samples, the obtained results have resulted in a mathematical model evaluating the surface hardness "Hv" as a function of treatment temperature and holding time. The experimental results indicate for this steel that holding time minimum and temperature minimum ($t = 2h$, $T = 850 ^\circ C$) have an apparent significant effect where "Hv" achieved the value of 750 (Hvi = 179).

Keywords—Heat treatment, superficial hardness, factorial designs, mathematical model.

I. EXPERIMENTAL TECHNIQUES

II-1 Characterization of material

a- Material

Samples were taken from a wrought ball (Figure 1). The chemical analysis of material was carried out at a central laboratory at IMETAL complex. The results of analyses are recorded in Table 1 according to which it is a carbon steel intended for forging.

Figure 1 Ball obtained by forging
b- Microstructure

The microstructural observation was performed on an optical microscope (Figure 2), the sample was cut from a forged ball and the surface intended for observation was polished. The microstructure observed in the non-forged zone (Figure 3-1) clearly shows two phases, the perlite (black zone) in a ferritic matrix (white zone). In forged zone (Figure 3-2), a hardening of zone subjected to effect of impact force during forging is observed, where it is noted a lengthening of grains with a structure composed of a ferritic matrix and presence of spheroid carbides at grain boundaries (Figure 3-3).

c- Resilience test

The resilience test was carried out on specimen indicated in figure 4b in URASM / CRTI laboratory on Charpy machine (figure 4a), the recorded result is: U = 24.6 j.

II-2- Experimental Methodology

The tests were conducted according to the factorial designs 2^2 (Figure 5), these latter are composed of two factors at two levels (-1, +1) Table 2. The postulated mathematical model is a polynomial model of first degree with interactions presented in equation (1) [12].

\[ Y = a_0 + a_1X_1 + a_2X_2 + a_{12}X_1X_2 \]  \hspace{1cm} (1)

\( a_0 \): constant coefficient of model; 
\( a_1 \): coefficient of factor 1; 
\( a_2 \): coefficient of factor 2; 
\( a_{12} \): coefficient of term \( X_1X_2 \).

\( Y \): Answer.

Table 2 Coded factors for heat treatment

<table>
<thead>
<tr>
<th>factors coded</th>
<th>Input parameters</th>
<th>levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>( X_1 )</td>
<td>( T (^\circ C) )</td>
<td>(-1)</td>
</tr>
<tr>
<td>( X_2 )</td>
<td>( t (h) )</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 2 optical microscope

Figure 3 Microstructures observed

Figure 4 a) the Charpy machine b) specimen after fracture

Figure 5 Experimentation principle
II-3 Sample preparation

The samples were taken from a forged ball of 60 mm diameter. In order to conform to factorial plans $2^2$, four samples were cut whose surfaces were polished (figure 6) for measurement of superficial hardness before heat treatment.

![Figure 6 | Prepared samples](image)

II-4 Measurement of surface hardness $H_v$

Measurements of surface hardness ($H_v$) were carried out with a micro-durometer of INNOVA TEST type presented in figure 7 under a load of 300 grams forces, the average values were recorded in Table 3.

Table 3 values of $H_v$ before heat treatment

<table>
<thead>
<tr>
<th>Measure</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_v$</td>
<td>179</td>
<td>177.3</td>
<td>220.4</td>
<td>225</td>
</tr>
</tbody>
</table>

![Figure 7 | Micro-duromètre INNOVA TEST](image)

II-5 Realization of heat treatments

The heat treatments were carried out at National School of Mines and Metallurgy, Annaba in a programmable muffle electric furnace with a holding bearing $T_{max}$ (1100 °C and 1200 °C) (Figure 7) and cooling was performed with water. These treatments were conducted according to factorial experiment planning model $2^2$ following the combinations shown in Table 4. Six measurements of micro-hardness $H_v$ were made average values are recorded on Table 4. Furthermore, after heat treatment, surface hardness measurements $H_v$ were made as well as observations under the microscope of surface hardness footprint.

![Figure 7 | Muffle electric furnace](image)

![Figure 8 | Evaluation of $H_v$ after heat treatment](image)

III MATHEMATICAL MODEL

The postulated mathematical model for the experiment allows predicting the surface hardness $H_v$ as a function of heat treatment parameters in this case the temperature ($T$) and holding time ($t$).

$$H_v= 604.98 - 90.63X_1 - 22.33X_2 + 32.06 X_1X_2$$ (2)

IV INTERPRETATION OF EXPERIMENTAL RESULTS

a- Effect of heat treatment on $H_v$

The effect of heat treatment parameters in this case the treatment temperature and holding time is remarkable with a rate of improvement of surface hardness $H_v$ of 76% (figure 8) for test No E1. The superficial layers were characterized by a micro-hardness which varies between 504.62 and 750 after heat treatment with a rate of improvement which varies between 59% to 76%. This increase in surface hardness is due to the grain refinement under effect of temperature which makes the structure harder and more resistant.

Table 4. Matrix of experiences and results

<table>
<thead>
<tr>
<th>Test N°</th>
<th>factors coded</th>
<th>Input parameters</th>
<th>Output parameters</th>
<th>Rate of improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X1</td>
<td>X2</td>
<td>$T(°c)$</td>
<td>$t$(h)</td>
</tr>
<tr>
<td>E1</td>
<td>-1</td>
<td>-1</td>
<td>850°C</td>
<td>2 h</td>
</tr>
<tr>
<td>E2</td>
<td>+1</td>
<td>-1</td>
<td>1000°C</td>
<td>2 h</td>
</tr>
<tr>
<td>E3</td>
<td>-1</td>
<td>+1</td>
<td>850°C</td>
<td>5 h</td>
</tr>
<tr>
<td>E4</td>
<td>+1</td>
<td>+1</td>
<td>1000°C</td>
<td>5 h</td>
</tr>
</tbody>
</table>

These results are used to deduce a mathematical model allowing the prediction of surface hardness $H_v$ as a function of heat treatment parameters in this case the temperature ($T$) and holding time ($t$).
b- Effect of heat treatment parameters on Hv

The improvement of surface hardness by heat treatment is one of most used means to fight against the various phenomena of wear and fatigue. The curve illustrating (figure 9) the evolution of surface hardness "Hv" as a function of heat treatment parameters (T, t) shows significant effect of holding time where it is found for this steel that if holding time is fixed (t = 2h) and varying the temperature we noted for a minimum temperature T= 850°C a significant increase of surface hardness Hv which reaches a value of 750 (Hvi = 179). As against for the same holding time if changing the temperature T = 1000°C, it noting a decrease of Hv which converges to a value of 504.62, which confirms by an increase in footprint diameter which changes from a value of 35.10² μm to 45.10² μm (figure 10 a-b). However, if the temperature decreases to a value of 850°C and t = 5h is recorded an increase in micro hardness Hv which reaches a value of 641.22. Moreover, when two influential factors (T, t) will be at their maximum level (T = 1000°C, t = 5h) Hv decreases to a value of 524.08 which is reflected by an increase in footprint diameter of surface hardness, which pass of 39 10² μm to 42 10² μm (Figure 10 c-d).

V CONCLUSION

Surface hardness is an essential parameter that characterizes surface of a material and contributes to improvement of service life of mechanical parts. Heat treatments are one of most sought after processes for improving surface hardness. The adoption of experimental plans for carrying out heat treatments has made it possible to predict surface hardness Hv as a function of treatment temperature and holding time. The results obtained in this work are based on experimental tests that were carried out on samples obtained from XC38 forged steel balls, applying a heat treatment with the water cooling. However, the effect of heat treatments depends on treatment temperature; holding time as well as cooling mode.

Moreover, the methodology of factorial 2 plans was followed during the tests, which made it possible to observe the influence of treatment parameters (T, t) on studied response (Hv). These plans constitute a major tool for the establishment of mathematical models, allowing the prediction of answers. In view of experimental results, it is obvious that heat treatment has made it possible to improve the microhardness "Hv", when the treatment parameters are suitably chosen. The numerical simulation presented by isoréponses curves has contributed to analysis of the effects of treatment parameters (input factors) on responses studied, where it can be concluded that for this steel when the two factors (T, t) are at their low level, surface hardness Hv increases with an improvement rate of 76%.
Acknowledgment

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References