RELATIONSHIP BETWEEN PARAMETERS OF TEMPERING AND EDDY CURRENT TESTING OF CARBURIZED PARTS

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Abstract: The process of low-temperature tempering has been studied by eddy current testing and measuring the hardness HRC at a constant temperature as well as at increasing temperature and duration. Technological factors of tempering were considered in their interdependence, according to the Hollomon-Jaffe equation. It has been argued that the factor levels, temperature and duration, are determined by the carburization and quenching results. Eddy current testing has been introduced as an indicator of quality with high sensitivity to changing technological factors; it has integral importance in terms of structural changes and electromagnetic properties of the parts. Hardness and electromagnetic characteristics, as indicators of quality after low-temperature tempering, were presented as a function of the tempering parameter \( P_a \).

Keywords: EDDY CURRENTS, LOW-TEMPERATURE TEMPERING, CARBURIZING, QUENCHING, HOLLOMON-JAFFE

1. Introduction

The tempering of carburized and quenched parts is the obligatory final stage of the technology of the thermochemical treatment. During this stage the purpose is to reduce the effects of quenching which reduce the potential for exploitation or subsequent treatment of parts, as well as to achieve different combinations of useful levels of the mechanical properties. After quenching, the properties achieved at room temperature change when the temperature rises and after various durations of heat treatment they try to achieve equilibrium. During this stage, called tempering, all changes which occur in the parts are related to diffusion processes. The latter are activated thermally and involve the dislocation of alloying elements, carbon, and impurities in the steel parts. The 150-250°C levels define the basic characteristic of low-temperature tempering. Having in mind the stronger effect of temperature on the results of tempering [7] the main classification of the process is based on limiting discrete values of that technological factor. The limits of the other technological factor, i.e. the duration of the process, are not so clearly defined. The usual technological solution is the application of isothermal and isochronal diagrams of tempering [12]. It is not difficult to predict that like every other search for equilibrium, with occurring diffusion processes [1], tempering would lead to different levels of mechanical properties depending on its duration. One should not underestimate the phase difference, grain size and the presence of defects, connected with carburising and quenching processes. That is the reason why this paper looks for arguments in favour of the statement that the technological factors, temperature and duration of tempering, should not be considered constant or fixed values, but they should change dynamically depending on the results of the previous processes of thermochemical treatment. On the other hand, the control of the tempering results control presents another challenge due to the nature of hardness measurements, the extent of this control, and the thickness of the layer, where changes are measured. Typically, when this zone is measured according to the Rockwell scale C, it does not exceed 0.1 mm, but it is there and also in depths up to 0.3 mm that carburized layers develop the main flaws.

2. Elements of the tempering theory

The process of low-temperature tempering causes the transformation of tetragonal martensite into cubic martensite [4, 5, 6, 7, 8] and the formation of hexagonal \(\varepsilon\)-carbides \(\text{Fe}_{2.4}\text{C} \) 10-20 mm in size [7]. Apart from carbides and martensite, the structure retains different quantities of residual (paramagnetic) austenite as the temperature of the end martensite transformation drops below 0°C [7]. With the quantity of carbon gradually diminishing, martensite reacts differently to temperature treatment by decreasing its tetragonality and tension. If the layer structure consists of martensite alone, it might be possible to register unequivocal changes after the tempering process. The layered structure with a gradual transition to the steel core, and the possible presence of characteristic sub-layers, such as:

- Surface oxidation layer;
- Carbides and troostite layer;
- Residual austenite layer;
- Martensite layer,
results in complications and uncertainty in the final grading of parts which have been gas carburized [2,10]. Steel improvement tempering seems a far better studied process; one of its characteristic features is the mutual relationship between the technological factors, temperature and time, a relationship called “tempering parameter” by Hollomon-Jaffe [1, 2, 3, 11]:

\[
(1) \quad P_a = T(a + \log \tau)
\]

Where:
- \( P_a \) is the tempering parameter;
- \( T \) is the temperature in Kelvin degrees;
- \( \tau \) is the tempering time in seconds [7] or hours [1,2,3];
- \( a \) is a constant which for most steels is equal to 20 [2,3].

There is too little information on the usage of this correlation in the control of low-temperature tempering of carburized and quenched parts [7]. The value of the constant \( a \) depends on the type of steel and the rate of heating and cooling of parts, i.e. it depends on their size and shape, too. That is why the value of the a constant has to be determined by a number of research teams. For steels meant for
carburization, the $a$ constant has been determined to be equal to 15-17 [7].

The $P_a$ parameter is in direct correlation with hardness. For example, for improvable steels, one hour is needed in order to achieve the same hardness at 400°C, while at 390°C, the time increases twice. For many steels the hardness-tempering parameter relation is presented graphically in the tempering diagrams [2]. The complete tempering diagram must contain data about the effect of the degree of hardening $R_h$ and the tempering parameter $P_a$, on hardness and toughness. $R_h$ is the correlation between the desired value of hardness and the maximum value of hardness [1, 2]. The tempering parameter allows for different combinations of factors $T$ and $\tau$, which will result in the same hardness, and according to many researchers, also in relative similarity of the rest of the mechanical properties [7, 8, 10]. Such tempering modes are called isosclerics [8]. This premise is at the basis of many cost-effective tempering processes. It is also desirable, in case embrittlement develops during tempering, that the desired hardness be achieved in a short time and maximum high temperatures [11].

Unlike improvable steels, carburized and hardened steels pose too many complications, connected both with quenching results, and their behavior during tempering. They experience the influence of quite a few of the major factors in carburizing, the process kinetics, carbon activity, and many others. Although the Hollomon-Jaffe correlation requires the availability of quite a lot of empirical information, it makes it possible to estimate the expected hardness quite accurately in a number of computer controlled gas carburizing units [7].

The other significant difference from improvable steels lies in the method of tempering results control, where if hardness penetration is sufficient, HRC, HV10, and HV30 hardness measurements offer good grade reliability. This, however, does not apply to hardness measurements of carburized and quenched parts [11]. A number of factors make the results for measured hardness uncertain. Among them are the presence of defective layers, sub-layers with increased contents of retained austenite, low-depth carburizing, the measured surface class or type, etc. These make it necessary to find an additional quality criterion. The metallographic control of low-temperature tempering is practically very hard to achieve [2, 4, 9]. In the search of a method which could register the changes in carburized layers of different thickness, eddy current testing offers a wide range of capabilities. According to the theory of eddy currents, the latter react to changes in the inside tensions, the change in electro-magnetic properties of separate phases and conglomerate structures, and depending on the excitation frequency, they derive information from layers of different depth, etc. [15, 16]. The high sensitivity of eddy current testing to tempering conditions has been studied many times and has been well proven by a great number of planned experiments [13, 14].

3. Object and methodology of the research

4 20CrMo5, BDS EN 10084 steel shafts have been studied. The parts were tested with eddy currents at different duration of tempering, at 225°C. Another 4 shafts of the same steel were tested at increasing duration and incremental temperature change. In the second group testing, apart from the electromagnetic property $Z$, [17], HRC hardness [18] was measured as well. The data was processed by means of statistical processing software [19].

4. Objectives of research

The objective of eddy current testing research is to find a criterion for the levels of tempering processes, “degree of tempering”, so that this criterion could become an indicator of the quality of the thermochemical treatment. The research also aims to collect data on the behavior of parts during tempering and present the data in relation to the tempering parameter $P_a$, so that this would become a prerequisite for optimizing and creating a cost-effective process of low-temperature tempering, and eddy current testing would be used as a quick and comfortable means of control.

5. Results of the experiment

5.1 Isothermal tempering: temperature 225°C and increasing duration of up to 6 hours

Table 1 and Figure 1 display the results of the eddy current testing of 4 threaded conical output shafts.

Table 1 contains the following designations:

$$\{Z_i = Z(i) = R(i) + X_L(i); i = 1,2,3,4\}$$

$\{R(i); i = 1, 2, 3, 4\}$ – active resistance

$\{X_L(i); i = 1, 2, 3, 4\}$ – inductive reactance

The values $\{R\}$ and $\{X_L\}$ are displayed by Eddy Current Tester MIZ 21B after the necessary calibration has been done.

Table 1 Variations in the electromagnetic property $\{Z_i; i = 1, 2, 3, 4\}$ for the i shaft in relation to the tempering duration $t$ at 225°C.

<table>
<thead>
<tr>
<th>$t$ - h</th>
<th>$Z_i$- shaft 1</th>
<th>$Z_i$- shaft 2</th>
<th>$Z_i$- shaft 3</th>
<th>$Z_i$- shaft 4</th>
<th>$Z_{\text{mean}}$</th>
<th>$Z_{i \text{ calculated}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,43</td>
<td>1,25</td>
<td>0,13</td>
<td>0,75</td>
<td>0,89</td>
<td>0,45</td>
</tr>
<tr>
<td>2</td>
<td>0,33</td>
<td>0,22</td>
<td>0,63</td>
<td>1,68</td>
<td>1,89</td>
<td>1,67</td>
</tr>
<tr>
<td>3</td>
<td>0,66</td>
<td>0,28</td>
<td>1,13</td>
<td>2,45</td>
<td>2,19</td>
<td>2,27</td>
</tr>
<tr>
<td>4</td>
<td>0,99</td>
<td>3,13</td>
<td>2</td>
<td>2,08</td>
<td>2,55</td>
<td>2,71</td>
</tr>
<tr>
<td>5</td>
<td>1,99</td>
<td>3,88</td>
<td>2,63</td>
<td>2,75</td>
<td>3,29</td>
<td>3,68</td>
</tr>
<tr>
<td>6</td>
<td>2,99</td>
<td>4,5</td>
<td>3,7</td>
<td>3,63</td>
<td>3,5</td>
<td>3,83</td>
</tr>
<tr>
<td>7</td>
<td>3,99</td>
<td>5,48</td>
<td>4,98</td>
<td>5,23</td>
<td>5,43</td>
<td>5,00</td>
</tr>
<tr>
<td>8</td>
<td>4,99</td>
<td>5,84</td>
<td>6,14</td>
<td>6,07</td>
<td>6,11</td>
<td>5,51</td>
</tr>
<tr>
<td>9</td>
<td>5,99</td>
<td>6,18</td>
<td>6,28</td>
<td>6,07</td>
<td>6,22</td>
<td>5,98</td>
</tr>
</tbody>
</table>

Fig. 1 Electromagnetic property variations $\{Z_i; i = 1, 2, 3, 4\}$ in relation to the tempering duration $t$ at 225°C.

Fig. 2 represents the interpolation between the mean electromagnetic property $Z$ and tempering time $t$, which is described by means of the following regression model with Correlation Coefficient - $R^2=0.95$:
(2) \( Y = 2.72 \times X^{0.4397} \)

where \( Y \leftrightarrow Z \) mean, \( X \leftrightarrow \) Time \( \tau \) [h].

Fig. 2 Variations in the mean electromagnetic property \( Z \) (for 4 shafts) in relation to the tempering duration \( \tau \) and the interpolation curve.

After taking the logarithm of (2), we obtain:

(3) \( \log Z = \log 2.72 + 0.4397 \times \log \tau \)

The relationship introduced by Hollomon-Jaffe for the tempering parameter at constant temperature (\( T = \text{constant} \)) would be:

(4) \( Pa = T + (a + \log \tau) = T + a + T \times \log \tau \)

or with \( T = \text{constant} \) =>

(5) \( Pa = \text{const} 1 + \text{const} 2 \times \log \tau \)

From (3) we get:

(6) \( \log Z = \text{const} 3 + \text{const} 4 \times \log \tau \)

The \( Pa \) values, calculated in (5) are given in Table 2 and Fig.3 with the constant \( a = 15 \).

Fig. 3 Variations in the tempering parameter \( Pa \) in relation to the duration of tempering \( \tau \).

The HRC hardness variations in the course of the experiment are represented by Fig. 4.

Fig. 4 Variations in HRC hardness during low-temperature tempering at increasing temperature and duration.

The interpolation of data on the mean hardness values for the four shafts during the different tempering stages is given by a third-degree polynomial:

(7) \[ HRC = 115 - 0.6296 \times T + 0.002413 \times T^2 - 3.096E - 6 \times T^3 \]

and Correlation Coefficient \( R^2 = 0.9858 \).

The variations in the electromagnetic property \( Z \) are given in Fig.5.

Fig. 5 Variations in the electromagnetic property \( Z \) during low-temperature tempering.

The experimental data on the electromagnetic property is also given in a third-degree polynomial:

(8) \[ Z(T - \tau) = 257.2 - 3.826 \times T + 0.01847 \times T^2 - 2.847E - 5 \times T^3 \]
The values calculated for the tempering parameter $P_a$ from equation (1) are given in Table 2.

**Table 2.** Experimental data on HRC and $Z$ for the studied temperatures and duration, given by means of the tempering parameter $P_a$.

<table>
<thead>
<tr>
<th>Time [sec]</th>
<th>Temperature [°K]</th>
<th>$P_a$</th>
<th>HRC</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3600</td>
<td>436,15</td>
<td>8093</td>
<td>63,78</td>
<td>0,83</td>
</tr>
<tr>
<td>7200</td>
<td>456,15</td>
<td>8602</td>
<td>62,58</td>
<td>1,61</td>
</tr>
<tr>
<td>10800</td>
<td>476,15</td>
<td>9063</td>
<td>61,25</td>
<td>3,09</td>
</tr>
<tr>
<td>14400</td>
<td>496,15</td>
<td>9505</td>
<td>61,05</td>
<td>6,49</td>
</tr>
<tr>
<td>18000</td>
<td>516,15</td>
<td>9939</td>
<td>60,88</td>
<td>10,01</td>
</tr>
<tr>
<td>21600</td>
<td>536,15</td>
<td>10366</td>
<td>60,7</td>
<td>10,40</td>
</tr>
</tbody>
</table>

**Fig.6** Variations in the hardness HRC and the electromagnetic property $Z$ in the course of the experiment

Fig.6 shows the variations in the hardness HRC and the electromagnetic property $Z$, and Fig. 7 represents part of the master diagram of the low tempering of 20CrMo5 steel after carburizing and quenching.

**Fig.7** Changes in the hardness at different tempering parameters

The representation of the variations in the two quality indicators HRC and $Z$ as a function of the tempering parameter reveals a range of capabilities of recalculating and achieving the necessary combinations of the two technological factors, so that the requirements would be met.

### 6. Discussion

The eddy current inspection of low-temperature tempering is sensitive to the changes in the structure and the inside tension of carburized and quenched parts. It is evident in Fig.1 and Fig.4 that the changes in the hardness and the electromagnetic property have the most significant deviation at the beginning of the process. It is only after 6 hours at constant temperature and after reaching 250°C that the quality indicators for the different specimens reach equivalent levels. Even this fact alone is enough to question the feasibility of low-temperature tempering processes and durations under 3 hours. The variations in the electromagnetic property and the tempering parameter in the first group of experiments, as a function of the duration of the process, are similar, and they show that with the increase in duration at a certain temperature, the changes in the parts are closer to stability and closer to termination/completion. This is a reason why all previous changes should be considered as degrees in the tempering process. On the other hand, with the increasing temperature and duration of tempering, in the second group of experiments, Fig.5, the electromagnetic property stops changing significantly at around 250°C. At the same time, significant changes in the hardness occur up to 200°C, Fig.4. The electromagnetic property starts changing significantly only after reaching the hardness of around 61-61.5 HRC, Fig. 6. The variations in hardness for the different tempering parameters, Fig.7, has two clear-cut linear periods: up to HRC 61.3, and after that value. After that hardness value, even if the tempering parameter increases significantly, the hardness will change very slowly. This fact makes it even more difficult to control the process at this stage by measuring the hardness by Rockwell C method. It is exactly here, in this period, that the electromagnetic property variations provide a favourable means of controlling the process.

### 7. Conclusions

Carburized and quenched parts pose a challenge in inspecting and grading after low-temperature tempering. Commercial production creates prerequisites for big deviations in quality indicators. In the last stage of thermochemical treatment, control by means of hardness measurements is unable to detect changes in parts, and the registered level of hardness cannot guarantee the quality of the process and give a correct forecast about the exploitation potential of parts. The measurement of hardness cannot provide the necessary information about the kinetics of the occurring processes. The combination of the two technological factors, temperature and duration, into one, the tempering parameter $P_a$, is useful and convenient, and allows for the technological determination of levels by means of two-dimensional diagrams and search for cost-effective modes of low tempering. It is necessary that observation is carried out for every steel grade used. The eddy current testing provides an opportunity for the simultaneous control of the two combined technological factors; it provides information on the speed of the ongoing processes; it registers and offers a quantity criterion for statistical data on deviation inherently occurring in the parts or externally conditioned by the furnace unit. The similarity in the changes in the electro-magnetic characteristic and the Hollomon-Jaffe tempering parameter in the experimental conditions of the study proves that the results of low-temperature tempering depend on the diffusion rate, and also on the fact that these two quantities are the two sides of the same technological process: its input and its output.
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