Heat treatment of long term serviced Cr – Mo cast steel

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Abstract

The paper presents results of research on the influence of heat treatment on the structure and properties of L20HM cast steel after long term operation at elevated temperature. Investigated cast steel was taken out from an outer frame of a steam turbine serviced for 167 424 hours at the temp. of 535 °C and pressure 12.75 MPa. In post-operating condition the investigated cast steel was characterized by mechanical properties below the required minimum and by high brittleness. Performed research on the influence of austenitizing parameters has revealed that the range of austenitizing temperatures for the examined cast steel: $A_{c3} + 30\div60$ °C ensures obtaining of a fine austenite grain, homogeneous in size. It has been proved that tempering of bainitic – ferritic structure above $680\div690$ °C causes an increase of impact energy along with a decrease of mechanical properties below the required minimum. Moreover, it has been noticed that applying of under-annealing instead of tempering, after full-annealing, guarantees the required impact energy of $KV > 27J$, with the mechanical properties similar to those after service.

Keywords: Heat Treatment, Mechanical Properties, Cr – Mo Cast Steel

1. Introduction

Heat treatment of steel casts after their long-term service is the fundamental process whose purpose is to extend the time of safe operation, especially that a wide individual research has not revealed any creep changes in the cast steels after service. The purpose of regenerative heat treatment, which is included in the process of revitalization of the steel casts, is to achieve improvement of plastic properties – increase of hardness and decrease of the NDT temperature through obtaining of a “new” regenerated structure [1÷3].

In order to improve mechanical properties, and most of all plastic properties, of the steel casts after long term operation, the following changes in the degraded structure are necessary [4÷6]:

- removal of the reversible brittleness caused by segregation of phosphorus on grain boundaries;
- dissolution of carbides in austenite, in particular the carbides which are precipitated on grain boundaries, in order to obtain required mechanical properties (hardness and tensile strength) in the regenerated structure.

Regenerative heat treatment, at costs not exceeding 40% of the new frame’s price, allows to obtain mechanical properties similar to the properties of new casts, and the regenerated cast is fit for further service for at least another 100 000 hours [1, 2].

2. Investigated material

The material under research was low alloy chromium – molybdenum L20HM casts steel after long-term operation at elevated temperature. Samples for tests were taken out (in the form of a section) from an outer frame of steam turbine serviced...
for 167 424 hours at the temperature of 535 °C and pressure 12.75 MPa.

Chemical composition of the examined cast steel is presented in Table 1.

Table 1.
Chemical composition of the examined cast steel, %wt.

<table>
<thead>
<tr>
<th>Investigated material</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>L20HM</td>
<td>0.21</td>
<td>0.60</td>
<td>0.23</td>
<td>0.014</td>
<td>0.009</td>
<td>0.54</td>
<td>0.49</td>
</tr>
<tr>
<td>According to Polish Standard [7]</td>
<td>0.15</td>
<td>0.50</td>
<td>0.20</td>
<td>max</td>
<td>max</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>0.80</td>
<td>0.50</td>
<td>0.030</td>
<td>0.030</td>
<td>0.70</td>
<td>0.60</td>
</tr>
</tbody>
</table>

After long-term service at the temperature of 535 °C the investigated cast steel was characterized by degraded ferritic – pearlitic structure. Inside pearlite colonies an advanced process of spheroidization and coagulation of carbides could be observed. On ferrite grain boundaries, numerous carbide precipitates were noticed. In some areas they formed a „continuous grid“ of precipitations. (Fig. 1).

Identification of the extracted precipitates revealed presence of the following carbides: $\text{M}_2\text{C}$, $\text{M}_6\text{C}_3$ and $\text{M}_{23}\text{C}_6$ inside ferrite grains, $\text{M}_{23}\text{C}_6$ on ferrite grain boundaries and $\text{M}_3\text{C}$ inside pearlite grains. Example of a structure with revealed carbides is illustrated in Fig. 2.

After service the L20HM cast steel was characterized by tensile strength, yield point and impact energy lower than the minimum standard requirements - only the elongation reached the required level (Table 2).

Table 2.
Requirements for chemical composition and mechanical properties according to Polish Standard

<table>
<thead>
<tr>
<th></th>
<th>TS MPa</th>
<th>YS MPa</th>
<th>El. %</th>
<th>KV J</th>
<th>HB</th>
</tr>
</thead>
<tbody>
<tr>
<td>L20HM after service</td>
<td>492</td>
<td>279</td>
<td>22</td>
<td>13</td>
<td>139*</td>
</tr>
<tr>
<td>According to Polish Standard [7]</td>
<td>min. 600</td>
<td>min. 245</td>
<td>min. 15</td>
<td>27</td>
<td>max. 190</td>
</tr>
</tbody>
</table>

*hardness HV30

The NDT temperature determined for Cr – Mo cast steel amounted to ca. 50°C (Fig. 3).

3. Methodology of research

Research on the influence of austenitization parameters on mean diameter and mean surface area of austenite grain was carried out in the temperature range of 895 ÷ 985 °C applying holding time of 3 and 5 hours. Images necessary for measurement
of grain sizes were recorded by means of an optical microscope - Axiovert 25. Computer aided analysis of image was done by means of ImagePro Plus program, assuming the number of grains necessary for calculations – ranging between 900 ÷ 1000. Dilatometric tests in order to determine the influence of cooling rate on the structure of L20HM cast steel were done by means of LS – 4 optical dilatometer. The calculated critical temperatures $A_{c1}$ and $A_{c3}$ for investigated cast steel amounted to 757 and 884 °C, respectively. Heat treatment of the examined cast steel consisted in austenitizing of samples for 3 hours at the temperature of 910 °C and subsequent four-hour tempering in the temp. range of 680 ÷ 700 °C. For samples fully annealed an additional ($\alpha$ + $\gamma$) treatment was applied (under – annealing) at the temperatures of: 770, 790 and 810 °C. Observation and record of the microstructures obtained as a result of heat treatment, were made using the optical microscope Axiovert 25. Measurements of mechanical properties were taken according to current standard norms.

4. Research results and their analysis

For the investigated Cr – Mo cast steel there was the influence of austenitizing parameters (temperature and time) on the mean diameter and mean surface area of austenite grain determined. Achieved results are shown in Fig 4. Grain size diversity for particular austenitizing parameters is expressed by the $\nu$ coefficient, which describes the heterogeneity of grain size [8] and is illustrated in Fig. 5.

![Fig. 4](image-url)  
**Fig. 4.** Influence of austenitizing temperature and time on the mean diameter (a) and mean surface area of austenite grain (b)

Performed research has proved that for the austenitizing temperature range of 895 ÷ 955 °C, the values of grains’ mean diameters are contained in the range of 21.42 ÷ 23.12 $\mu$m for holding time of 3 hours, and – 20.20 ÷ 23.07 $\mu$m for holding time of 5 hours. Similarly for mean surface areas of grains: 536.18 ÷ 677.19 $\mu$m$^2$ and 447.82 ÷ 647.46 $\mu$m$^2$, for holding times of 3 and 5 hours.

For austenitizing temperatures higher than 955 °C, i.e. for temperatures, such as: 970 and 985 °C it has been observed that there is over twofold increase of grain’s mean diameter and around 5 – 10 - fold increase of grain’s mean surface area in comparison with the grain size defined for the temperature range of: 895 ÷ 955 °C (Fig. 4).

The tests have proved that holding time (3 and 5 hours) in the examined range of austenitizing temperatures did not have any significant influence on the difference in sizes of mean diameters and mean surface areas of grains.

![Fig. 5](image-url)  
**Fig. 5.** Dependence of the $\nu$ coefficient of the former austenite grain size heterogeneity in the L20HM cast steel on the austenitizing parameters for: a) mean diameter; b) mean surface area

The value of $\nu$ coefficient, being the measure of grain size dispersion, ranged between 0.60 ÷ 0.65 for the austenitizing temperatures of: 895 ÷ 955 °C and holding time: 3 and 5 hours, while for 970 and 985 °C it increased to 0.73 ÷ 0.82. In the case of
mean surface areas the $\nu$ coefficient amounted to: 1.47 ÷ 1.78 respectively for the temperature range of 895 ÷ 955 °C, and – 2.1 ÷ 2.7 for the temperatures of: 970 and 985 °C (Fig. 5). The higher the values of $\nu$ coefficient, the more heterogeneous the grains are in terms of their size. Detailed description of the influence of austenitizing parameters on the size of austenite grain in L20HM cast steel has been presented in paper [9].

In order to determine the influence of cooling rate in the structure and properties (hardness), the TTT curve has been constructed for the examined cast steel – Fig. 6.

Analysis of the dilatometric curves has revealed that austenite cooled at the rate $v_{8.5} \geq 0.027$ K/s gets transformed into ferrite and pearlite. Cooling rate within the range: 0.091 $\geq v_{8.5} \leq 0.042$ K/s enables to obtain ferritic – pearlitic – bainitic structures. Whereas after cooling at the rate of $v_{8.5} \geq 0.208$ K/s, the bainitic – ferritic structures were obtained, with an increasing bainite content as the cooling rate increased. Applying the cooling rate of $v_{8.5} \geq 13.043$ allows to get the bainitic structure with around 5% of ferrite content (Fig. 6).

The applied heat treatment consisted in cooling of the investigated cast steel at the rates corresponding to the processes, such as: bainitic hardening, normalizing and full annealing. Structures obtained as a result of cooling from the austenitizing temperature were then subject to tempering or under annealing. Examples of microstructures received as a result of the performed heat treatment are illustrated in Fig. 7.

After bainitic hardening and high-temperature tempering the Cr – Mo cast steel was characterized by tempered bainitic – ferritic structure with numerous carbides precipitated mostly on grain boundaries of former austenite grain and on bainite laths. Amount of ferrite in the structure was around 25% (Fig. 7a). Tempered bainitic – ferritic structure of the Cr – Mo cast steel allowed to obtain high impact energy and required mechanical properties (Table 3, Fig. 8). However, low content of chromium and molybdenum in the cast steel as well as around 25 ÷ 30% amount of ferrite in the structure contributes to greater sensitivity of the examined cast steel to the tempering effect of temperature.

This results in faster falling of mechanical properties along with the tempering temperature.
Tempering at temperatures higher than $680 \div 690\,^\circ C$ contributes to a faster decrease of mechanical properties with the tempering temperature. Tempering at temperatures higher than $680 \div 690\,^\circ C$ contributes to a fall of mechanical properties below the required minimum. (Table 3, Fig. 8a).

![Fig. 8. Influence of heat treatment on properties of the L20HM cast steel: a) bainitic hardening and tempering; b) normalizing and tempering; c) full annealing and tempering/annealing](image)

After normalizing in the Cr - Mo cast steel the ferritic – pearlitic structure was obtained (Fig. 7b). Tempering of a cast steel with such a structure results in obtaining of high impact energy similar to that of cast steel with bainitic – ferritic structure, but with mechanical properties (except hardness) below the required minimum regardless of the tempering temperature. Mechanical properties were lower than the required ones by around 5 ÷ 13% (Table 3, Fig. 8b).

Table 3. Structure and properties of Cr – Mo cast steel after heat treatment

<table>
<thead>
<tr>
<th>Heat treatment parameters</th>
<th>TS MPa</th>
<th>YS MPa</th>
<th>El. %</th>
<th>KV J</th>
<th>HV30</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>after service</td>
<td>492</td>
<td>279</td>
<td>22</td>
<td>13</td>
<td>139</td>
<td>ferritic - pearlitic</td>
</tr>
<tr>
<td>Bainitic hardening + 680 °C/4h</td>
<td>614</td>
<td>444</td>
<td>21</td>
<td>106</td>
<td>182</td>
<td>bainitic-25%ferritic</td>
</tr>
<tr>
<td>Bainitic hardening + 700 °C/4h</td>
<td>577</td>
<td>419</td>
<td>23</td>
<td>168</td>
<td>172</td>
<td>bainitic-25%ferritic</td>
</tr>
<tr>
<td>normalizing + 680 °C/4h</td>
<td>534</td>
<td>374</td>
<td>24</td>
<td>110</td>
<td>173</td>
<td>ferritic - bainitic-pearlitic</td>
</tr>
<tr>
<td>normalizing + 700 °C/4h</td>
<td>524</td>
<td>372</td>
<td>24</td>
<td>135</td>
<td>166</td>
<td>ferritic-pearlitic</td>
</tr>
<tr>
<td>full annealing + 700 °C/4h</td>
<td>479</td>
<td>295</td>
<td>27</td>
<td>28</td>
<td>150</td>
<td>ferritic-20%pearlitic</td>
</tr>
<tr>
<td>full annealing + 780 °C/4h</td>
<td>496</td>
<td>293</td>
<td>24</td>
<td>38</td>
<td>152</td>
<td>ferritic-20%pearlitic</td>
</tr>
<tr>
<td>full annealing + 820 °C/4h</td>
<td>493</td>
<td>304</td>
<td>25</td>
<td>54</td>
<td>155</td>
<td>ferritic-20%pearlitic</td>
</tr>
<tr>
<td>Standard requirements*</td>
<td>min.</td>
<td>min.</td>
<td>min.</td>
<td>max</td>
<td>max</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>400</td>
<td>15</td>
<td>27</td>
<td>190**</td>
<td>—</td>
</tr>
</tbody>
</table>

*: Polish Standard - 89/ H - 83157 ; ** - hardness according to Brinell

Slow cooling of the investigated cast steel results in obtaining of the ferritic – pearlitic structure (Fig. 7c) with pearlite located mostly on ferrite grain boundaries. After full annealing, similarly as in the case of regenerative heat treatment of the L21HMF cast steel [10, 11], it is recommended to apply under annealing instead of tempering. Tempering of ferritic – pearlitic structure contributes to further privileged precipitation of carbides on grain boundaries and segregation of phosphorus to the boundaries. Ferritic – pearlitic structure and properties of the examined cast steel, obtained after such a heat treatment, are very similar to the structure and properties of cast steel after long-term operation.

Applying ($\alpha + \gamma$) annealing instead of tempering to the ferritic – pearlitic structure, contributes to obtaining of the required impact energy (however, with the mechanical properties on the level of those after service) through dissolution of carbides precipitated on grain boundaries and the process of desegregation.
of phosphorus (Table 3, Fig. 8). Wider description of the influence of heat treatment on the structure of L20HM cast steel is presented in paper [12].

Conclusions

1. Due to the processes of structure degradation, long-term service of the steel cast contributes to a decrease of mechanical properties (larger in the case of yield strength than tensile strength) and an increase of brittleness.

2. Austenitizing in the temperature range $A_{c3} + 30 \div 60^\circ C$ ensures obtaining of a fine austenite grain, homogeneous in terms of size.

3. Tempering temperature of the investigated cast steel after bainitic hardening should not be higher than $680 \div 690^\circ C$ with regard to lowering of the mechanical properties below the minimum.

4. After full annealing it is recommended to apply under annealing instead of tempering, which guarantees obtaining of the required impact energy with mechanical properties similar to those after service.

References


