The influence of microstructure on the mechanical properties of metallurgical rolls made of G200CrMoNi4-3-3 cast steel

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Abstract

The subject of the study is the high-carbon tool cast steel G200CrMoNi4-3-3 used for metallurgical rolls, especially in section rolling mills. The test material was derived from a roll damaged in production; therefore, the authors had the material in a raw state at their disposal, on which they were able to carry out additional heat treatment operations. The pearlitic matrix of casting steel G200CrMoNi4-3-3 allows machining to be done to modify the pass or to remove any defects, and the primary and secondary precipitates of carbides enhance the tribological properties. The authors have been for years involved in the optimization of the structure of this material by slight correction to its chemical composition and/or the modification of heat treatment. The presented principles of heat treatment modifications will lead to considerable economic and ecologic profits. It has also been demonstrated that raising slightly the contents of carbide-forming elements, which markedly increases the quantity of transformed ledeburite, results in an enhancement of tribological properties. The analysis of a dozen or so rolls exploited down to the dead roll diameter has shown that roll of cast steel with increased contents of carbon and carbide-forming elements exhibit better service properties, as characterized by the amount of feedstock rolled. Such a method of enhancing the service properties required the assessment of fracture toughness, which was verified using the linear-elastic methods of fracture mechanics.

Keywords: Heat treatment, Hypereutectoid cast steel, Tribology, Ledeburite, Stress intensity factors

1. Introduction

Among the tools used in the metallurgical industry, metallurgical rolls make up a special group, often being very bulky, with the weight ranging from several to several dozen tons. Owing to their price, which is competitive to that of forged or assembled rolls, cast steel rolls are irreplaceable tools in many types of rolling mills, especially section rolling mills. In addition to the considerably lower price, they are also distinguished by a number of operational and technological advantages. The moderate hardness, usually not exceeding 350HB, allows the roll face to be repeatedly redressed to remove any defects or to change the pass. The pearlitic matrix assures also abrasion resistance and uniform wear, as well as little tendency to developing fatigue cracks [1-4]. Because of this first requirement, the pearlitic-carbide structure of hypereutectoid steels, often containing also transformed ledeburite, is most often used. Due to the considerable overall dimensions and the necessity to make passes, it is normalizing, and not hardening and tempering, that is the predominant heat treatment operation. A typical material that is most often used for cast metallurgical rolls is the low-alloy hypereutectoid cast steel G200CrMoNi4-3-3 in which, due to the presence of chromium and molybdenum, an eutectic reaction occurs with an interdendritic arrangement of microstructure.
constituents characteristic of transformed ledeburite. Such a structure considerably reduces fracture resistance, and heat treatment operations applied, chiefly in the form of normalizing, little prevent this phenomenon [5–8].

The presented investigation concerned the possibility of structure optimization by correcting the chemical composition and modifying the heat treatment. In the latter case, the aim is to substitute the long-lasting and costly high-temperature heat treatment of rolls with the stress relieving operation carried out in a considerably lower temperature range [9].

2. Material and methodology of tests

The high-carbon tool cast steel G200CrMoNi4-3-3 under study, with chemical composition as shown in Table 1, derived from an industrial heat of carbon and molybdenum contents slightly increased compared to the standard requirements.

Table 1. Chemical composition of G200CrMoNi4-3-3 cast steel, %wt.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN-90/H-83161</td>
<td>1.90</td>
<td>0.50</td>
<td>0.50</td>
<td>max</td>
<td>max</td>
<td>0.90</td>
<td>0.50</td>
<td>0.20</td>
</tr>
<tr>
<td>Heat</td>
<td>2.20</td>
<td>0.69</td>
<td>0.57</td>
<td>0.024</td>
<td>0.017</td>
<td>1.15</td>
<td>0.69</td>
<td>0.42</td>
</tr>
</tbody>
</table>

The investigation scope encompassed the analysis of microstructure and the determination of fracture toughness with the value of $K_{IC}$. The evaluation of the quantities of carbide (Fe$_3$C) structures and ledeburite was made using the Termo-Calc program. The microscopic analysis of cast steel was made on a Zeiss Axiovert 25 optical microscope and a Jeol JSM-5400 scanning microscope. The metallographic specimens used in microstructure examination were etched with Mi1F (4%HNO$_3$ in C$_2$H$_5$OH). In fracture mechanics tests, 80x10x20 mm SEMB type specimens with an approx. 10 mm long electric-spark machined notch, and an MTS 810 testing machine with a loading increment rate of 0.08 mm/s were used.

3. Results and discussion

Figures 1a and 1b show the results of the microstructural examination of a roll, respectively, in a raw condition and after heat treatment carried out according to the industrial variant. Cast steel G200CrMoNi4-3-3 as supplied (directly after casting) is characterized by the occurrence of pro-eutectoid cementite and transformed ledeburite in the form of a continuous network along the primary boundaries of austenite grains and precipitates of pro-eutectoid cementite in Widmannstätten structure.
Table 2.
The results of ledeburite and cementite quantity analysis

<table>
<thead>
<tr>
<th>TermoCalc’s analysis</th>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>E’</th>
<th>C’</th>
<th>E90°C</th>
<th>Vv</th>
<th>Percentage of carbonate phase</th>
<th>HB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyzed chemical composition</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Points of Fe-Fe3C system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>1.90</td>
<td>1.15</td>
<td>0.37</td>
<td>2.021</td>
<td>4.3745</td>
<td>1.38</td>
<td>0.0</td>
<td></td>
<td>293</td>
</tr>
<tr>
<td>2.</td>
<td>2.10</td>
<td>1.43</td>
<td>0.52</td>
<td>2.006</td>
<td>4.3725</td>
<td>1.34</td>
<td>4.1</td>
<td></td>
<td>281</td>
</tr>
<tr>
<td>3.</td>
<td>2.20</td>
<td>1.15</td>
<td>0.42</td>
<td>2.0162</td>
<td>4.375</td>
<td>1.34</td>
<td>8.5</td>
<td></td>
<td>329</td>
</tr>
</tbody>
</table>

Increasing the carbon content above the upper level as defined by the standard results in a more than twofold increase of the quantity of transformed ledeburite, as shown by the results of analysis by the TermoCalc method, summarized in Table 2.

As the result of the heat treatment operation applicable so far, a partial reduction of the quantity of cementite in Widmannstätten structure, being characteristic of the coarse-grained cast steel structure, occurs, as shown in Figure 1b. This positive heat treatment effect seems to be partially offset by the appearance of a film of pro-eutectoid cementite along the boundaries of the pearlite subgrain structure (the detail in Figure 1b) [10]. In this connection, the authors propose to substitute the presently applicable heat treatment with a stress relief annealing operation carried out at a temperature of about 700°C, which, although not influencing the morphology of cementite, does remove casting and structural stresses and does not introduce any additional weakening of grain boundaries with the above-mentioned cementite film (Fig. 1c).

It should be underlined that increasing the contents of carbides, in line with the Zum Gahr relationship of \( W = \frac{\lambda^2}{V/\lambda} \), is an obvious method of increasing abrasion resistance [11]. The values of the stress intensity factor, \( K_{IC} \), as determined following the recommendations of PN-87/H-04335 and ASTM E399, are summarized in Table 3.

Table 3.
Values of stress intensity factors

<table>
<thead>
<tr>
<th>Mark</th>
<th>( K_{IC} ) MPa( \sqrt{m} )</th>
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<th>( K_{IC} ) MPa( \sqrt{m} )</th>
<th>( K_{IC} ) MPa( \sqrt{m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>cast steel</td>
<td>25.70</td>
<td>26.30</td>
<td>29.30</td>
<td>30.20</td>
</tr>
<tr>
<td>industrial heat treatment</td>
<td>27.90</td>
<td>30.60</td>
<td>29.30</td>
<td>29.25</td>
</tr>
<tr>
<td>new heat treatment</td>
<td>31.10</td>
<td>28.40</td>
<td>31.10</td>
<td>30.20</td>
</tr>
</tbody>
</table>

In relation to the raw condition with the \( K_{IC} \) value of 26.00 MPa\( \sqrt{m} \), both heat treatment operations cause a fracture toughness increase to 29.25 MPa\( \sqrt{m} \) and 30.20 MPa\( \sqrt{m} \), respectively, for the material subjected to industrial heat treatment and stress relief annealing. Based on literature data, which estimate the limiting value of \( K_{IC} \) for tool steel at a level of approx. 25 MPa\( \sqrt{m} \), both heat treatment operations cause an increase in \( K_{IC} \) by about 20% [13].

According to data from pilot trials carried out by the user on a dozen or so rolls with chemical composition modified as per the authors’ proposal, much better service properties, as characterized by the amount of feedstock rolled, were achieved. In the carbon content range from 1.96% to 2.1%, the amount of steel rolled is around the average level of 32000±1500 tons. Above the carbon content of 2.1%, a significant enhancement of service properties is observed up to a level of above 60000 tons until the full exploitation of the roll.

![Fig. 2. The effect of carbon content on the number of tons of steel rolled out](image-url)
 operation of the tool, required the application of fracture mechanics methods. The safe level of $K_{IC}$ values was achieved not only for the increased carbon content, but also for the material subjected to stress relief annealing in lieu of traditional normalizing. Very interesting results were also obtained for cast steel with the contents of Mo and Cr increased compared to the standard requirements. This data is important insomuch as it is derived from tools exploited down to the dead diameter.

**References**


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**Fig. 3.** The effect of carbon content on the hardness of rolls of cast steel G200CrMoNi4-3-3

**Fig. 4.** The effect of carbide-forming elements on the amount of steel rolled out with a carbon content of 2.1% C

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**4. Summary**

The investigations carried out show that even for materials that have been perfectly understood and applied for decades there is still a potential for improving their service properties. It has been demonstrated that, in respect of cast steel G200CrMoNi4-3-3 being the subject of the present study, a slight adjustment of the contents of carbide-forming elements results in a significant enhancement of tribological properties, as measured by the amount of steel rolled out. The authors performed also the analysis of over a hundred of successive heats of this cast steel and found that 68% of cast rolls had a carbon content below the average level (2.0%), and only 10% of rolls fell within the range of 2.06-2.1%. This is shows that, in fear of the cracking of rolls, there is a tendency to reducing, and no to increasing the content of this element in production. The demonstration that a slight adjustment to chemical composition does not necessarily result in an increased tendency to cracking and assures a continued safe