INFLUENCE OF BORON ON WEAR RESISTANCE AND TOUGHNESS OF HIGH-CHROMIUM WHITE IRONS

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Abstract

In this paper, the results of the examinations of the influence of boron on wear resistance and toughness of high-chromium white iron containing 13% of chromium, are given. Boron was added in the quantities of 0.26, 0.39 and 0.59%. The results of the examinations showed that the boron contents of 0.59% ensured approximately double value of wear resistance, but substantial drop of toughness at the same time.

Keywords: boron, wear resistance, toughness, chromium white iron.

1. Introduction

Wear resistance and toughness are two basic properties of high chromium white irons, that determine the possibilities of their applications under the particular exploitation conditions. Generally speaking, these alloys possess very good wear resistance, but very low fracture toughness at the same time [1-4]. Both properties directly depend on the structural properties of the alloy (volume fractions of the structural phases, size and morphology of eutectic carbides and matrix structure) which can be changed by the change of chemical composition or by the appropriate heat treatment.

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Generally, high chromium white irons with lower contents of chromium (10-15%) possess somewhat lower wearing characteristics compared to (the most often used) high chromium white irons containing 18-22% of chromium [5,6]. Such a conclusion is a consequence of the fact that at higher contents of carbon and chromium in the structure, the carbide phase fraction in the alloy is greater, that ensures better wear resistance of the alloy. On the other hand, reduction of chromium contents at constant carbon contents can cause the appearance of pearlite in the structure of the alloy, that significantly reduces its wear resistance. For this reason, these alloys are not often used for production of the parts exposed to strong wearing. However, this does not a priori mean that such alloys are not used for these applications. By additional alloying, it is possible to achieve significant improvement of their properties and make them applicable under the appropriate working conditions.

Many elements can be used for the alloying high chromium white irons [7,8]. Their role is that, influencing the stereological parameters, primarily the carbide phase, of the basic alloy, ensure the improvement of its properties - wear resistance and toughness - the properties relevant for this group of materials.

2. Experimental

Chemical composition of the examined alloys is given in the Table 1. Boron was added to the basic alloy in the quantity of 0.26, 0.39 and 0.59%. The influence of boron on the microstructure and the properties of the basic alloy was examined.

<table>
<thead>
<tr>
<th>Table 1 - Chemical composition of the examined alloys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contents of alloying elements, mass %</td>
</tr>
<tr>
<td>No</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>
The above mentioned alloys were produced by melting the material in a 50 kg medium frequency induction furnace. Of these alloys, the digging teeth were cast in the moulds prepared by means of the CO₂ technology. The examined samples were cut out of the castings at positions at which the tooth thickness was about 50 mm. The microstructure of the samples obtained in such a way was analyzed, both qualitatively and quantitatively. Qualitative analysis was performed by optical and scanning microscopoy. For that purpose the samples were grinded, polished to a 1/4μm diamond finish and than etched with picric acid solution (1g) in distilled water (100ml) with metil-alcohol (5ml). On the same samples, the examination of the volume fraction of the phases (Vv), the width of the dendritic arm space (DAS) and the size of the eutectic carbides (L) were performed on the automatic image analysis device Q500MC by Leica. These stereological measurements were performed on the cross sections of the samples, by means of the linear method of measuring. The relative standard error (RSE) of measuring was in the range 1.73005-4.94756 for all the measurements.

The microhardness of the matrix and the eutectic carbide in the examined alloys was measured under the loading of 0.49 N (0.05 kg) on the microscope Leitz. For the measuring of the micro hardness of the eutectic carbide in the alloy 4, the loading was 1.47 N (0.15 kg).

The abrasion wear resistance of the examined alloys in the as cast state was determined by the 'dry sand/rubber wheel' method, according to the standard ASTM G-65-94 - procedure B [9]. For these examinations, the rectangular samples were used, of dimensions 25×76×10 mm. The fracture toughness was determined by the Sharpie's method according to the standard ASTM E-399-90 [10].

According to the ASTM E-399-90 standard the value of $K_{1c}$ is obtained by the following formula:

$$K_{1c} = (P_{Q} \cdot S / B \cdot W^{3/2}) \times f(a/W)$$

where:
\[ f(a/W) = \frac{3(a/W)^{1/2} \left[ 1.99 - (a/W)(1 - a/W) \times (2.15 - 3.93a/W + 2.7a^2/W^2) \right]}{2(1 + 2a/W)(1 - a/W)^{3/2}} \]

- \( P_0 \) - test-bar crack load (it is determined from the diagram), kg
- \( S \) - distance between the supports of the test-bar, mm
- \( B \) - thickness of the test-bar, mm
- \( W \) - width of the test-bar, mm
- \( a \) - crack length, mm

Apart from the examinations of the mechanical properties of the alloys, that were performed on the standard samples by application of the standard methods, their behavior under the exploitation conditions was monitored as well. For this purpose, the digging teeth were cast - 10 pieces from the alloy 4, containing 0.59% of boron. The teeth were mounted on the caterpillar for mining application in the Kolubara mine, Yugoslavia. During the monitoring, material containing 50-90% of SiO₂ was dug. For the quality estimation of the examined teeth, their "life" was compared to the "life" of the teeth cast from high chromium white iron containing 2.7% C - 17% Cr - 0.5% Mo.

### 3. Results

The characteristic microstructures of the examined alloys are presented in the Fig. 1. It can be seen that the structure of the basic alloy (Fig. 1a and 1b) consists of the austenite matrix (primary dendrites of the austenite) and the eutecticum composed of the austenite and the carbides.

Due to the addition of boron to the basic alloy, the structural phases ratio is significantly changed in the sense that the volume fraction of the carbide phase increases, whereas the metal matrix volume fraction decreases (Fig. 1 c-h). That was confirmed by the results of the measurements of the volume fractions of the phases present in the structure of the examined alloys, versus the contents of boron Table 2.
Influence of boron on wear resistance...

Fig. 1 - Microstructure: a),b)-alloy No1; c),d)-alloy No2; e),f)-alloy No3; g),h)-alloy No4. (a,c,e,g-optical microphotographs; b,d,f,h-scanning electron microphotographs)
Table 2 - Volume fraction of the structural phases in the examined alloys, versus the contents of boron

<table>
<thead>
<tr>
<th>No</th>
<th>Metal matrix (Primary austenite or martensite)</th>
<th>Carbides</th>
<th>Eutectic austenite or martensite</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>69.43</td>
<td>13.25</td>
<td>17.32</td>
</tr>
<tr>
<td>2</td>
<td>61.88</td>
<td>19.96</td>
<td>18.16</td>
</tr>
<tr>
<td>3</td>
<td>56.22</td>
<td>24.77</td>
<td>19.01</td>
</tr>
<tr>
<td>4</td>
<td>29.56</td>
<td>51.27</td>
<td>19.17</td>
</tr>
</tbody>
</table>

The results of the measurements of dendritic arm space (DAS) and the eutectic carbides size (L) in the examined alloys, versus the contents of boron, are given in the Table 3.

Table 3 - DAS and the eutectic carbides size, versus the contents of boron

<table>
<thead>
<tr>
<th>No</th>
<th>DAS</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30.78</td>
<td>2.96</td>
</tr>
<tr>
<td>2</td>
<td>28.43</td>
<td>4.09</td>
</tr>
<tr>
<td>3</td>
<td>28.07</td>
<td>4.44</td>
</tr>
<tr>
<td>4</td>
<td>22.14</td>
<td>8.99</td>
</tr>
</tbody>
</table>

The results of the measurement of the micro hardness of the structural phases (matrix and the eutectic carbides) are given in the Table 4.

Table 4 - Microhardness of the structural phases

<table>
<thead>
<tr>
<th>No</th>
<th>Matrix</th>
<th>Eutectic carbides</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>428</td>
<td>992</td>
</tr>
<tr>
<td>2</td>
<td>434</td>
<td>1041</td>
</tr>
<tr>
<td>3</td>
<td>486</td>
<td>1076</td>
</tr>
<tr>
<td>4</td>
<td>640</td>
<td>1645</td>
</tr>
</tbody>
</table>

The results obtained during the determining of the abrasion wear resistance of the examined alloys are given in the Table 5.

Table 5 - Abrasion wear resistance

<table>
<thead>
<tr>
<th>No</th>
<th>Mass loss [g]</th>
<th>Volume loss [mm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1470</td>
<td>19.09</td>
</tr>
<tr>
<td>2</td>
<td>0.2016</td>
<td>26.18</td>
</tr>
<tr>
<td>3</td>
<td>0.1216</td>
<td>15.79</td>
</tr>
<tr>
<td>4</td>
<td>0.0730</td>
<td>9.48</td>
</tr>
</tbody>
</table>
Influence of the contents of boron on the fracture toughness of the examined alloys is presented in the Fig. 2.

![Fracture toughness of the examined alloys versus the boron contents](image)

**Fig. 2** - Fracture toughness of the examined alloys versus the boron contents

The digging teeth cast from the alloy 4, whose work was monitored in order to estimate abrasion wear resistance of the examined alloy under the real exploitation conditions, are shown in the Fig. 3. The results of this monitoring showed that the "life" of the examined teeth was 15% longer than the "life" of the teeth cast from the alloy, whose composition was: 2.7% C - 17% Cr - 0.5% Mo.
4. Discussion

4.1. Wear resistance

Wear resistance of the examined alloys is expressed through the mass or volume loss of the material. With the increase of the contents of boron in the alloy, the loss of the material due to wearing decreases, which means that the wear resistance increases (Table 5). The exception is the alloy 2. Such a behavior of the examined alloys is the consequence of their microstructure properties.

The structure of the basic alloy consists of the austenite matrix and the eutecticum, and the austenite is dominant (Fig. 1 a and 1b). The hardness of these phases is relatively low (Table 4), compared to the hardness of quartz (SiO$_2$) which is used as an abrasive material in the examinations, that were performed. This is important to stress, because the wearing of the alloy is not only influenced by its hardness, i.e. the hardness of its structural phases, but also by the properties of the abrasive material and the wearing mechanism [11]. Under such examination conditions, the wear resistance of this alloy was 19.09 mm$^3$. 

Fig. 3 - The examined digging teeth in the process of work
The addition of boron to the basic alloy causes certain structural changes. The structure becomes finer, in the sense that the width of the dendritic arm space decreases (Fig. 1 a, c, e, g and Table 3). Besides, the degree of transformation of austenite to martensite is high, (Fig. 1 b, d, f, h) and the quantity of precipitated secondary carbides is significant, which makes the matrix harder and more wear resistant [12].

On the other hand, the fraction and the size of the carbides increase (Fig. 1 and Tables 2 and 3). The hardness of the carbides increases at the same time (Table 4).

All these structural changes, together with the wearing mechanism, caused the increase of the wear resistance (Table 5). The harder matrix becomes tougher support to the carbide phase, which is the main 'receiver' of the wearing load. Such a 'reinforced' carbide phase, together with its increased hardness, size (primary carbides) and the characteristic shape of the continuous colonies of cells, resists the wearing action of the abrasive material more easily.

4.2. Fracture toughness

Fe-Cr-C-B alloys possess lower toughness compared to the basic alloy (Fig. 2). This is a consequence of the microstructural properties of those alloys. According to the references [1,13,14], the toughness of the alloy depends primarily on its volume fraction of the carbide phase, but also on the other characteristics of the structural phases - the carbides size, their morphology, the width of the dendritic arm spaces and the structure of the matrix.

In our case, the addition of boron to the basic alloy caused significant increase of the carbide phase fraction (Table 2). This caused drop of the toughness of the alloy (Fig. 2), especially because these carbides are extremely hard and brittle (Table 4). The fact that by the increase of the contents of boron in the alloy, the carbides become larger and that in the alloy 4, characterized by the lowest toughness, they build a continuous network, additionally contributes to the abovementioned drop of toughness. Such a form of carbides is inconvenient in general, because the eventual cracks in the structure of the material propagate through the continuous carbide network more easily. This propagation certainly leads to the fracture of the material.
The influence of the matrix structure is also very important. Its role is, primarily, to prevent or to slow as much as possible the propagation of the crack that appeared in the carbide phase or at the contact surface carbide/matrix. Generally speaking, the austenite matrix performs this task 'more successfully' compared to the martensite matrix, i.e. the alloys with the austenite matrix generally possess better toughness. This also appeared to be true in our case. Namely, the alloy 1, whose matrix is mainly composed of austenite, possesses the best toughness. By the increase of the boron contents in the alloy, the fraction of martensite increases. The increase of the fraction of martensite in the alloys 2 and 3 is accompanied by the slight drop of toughness. However, the sudden drop of toughness takes place in the alloy 4. This is a consequence of the large fraction of martensite in the structure of the alloy, together with the carbide phase with all its characteristics, that were commented above.

5. Conclusion

The results obtained by the examination of the wear resistance, where dry sand was used as the abrasive means, indicate that the higher contents of boron yields better wear resistance.

On the other hand, the toughness of the alloy decreases with the increase of the contents of boron.

Good wear resistance of the alloy 4, with 0.59% of boron, was also confirmed under the exploitation conditions. It was shown that the "life" of the digging teeth cast from this alloy, that were exposed to the abrasion wearing, but not to tearing, was approximately 15% longer than the "life" of the teeth cast from the high chromium white iron, whose chemical composition was: 2.7% C - 17% Cr - 0.5% Mo.

References


