On microstructure and performance of tempered high-boron high-speed steel roll

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Abstract: Influences of the tempering temperature on the microstructure, mechanical property and wear resistance of High-Boron High Speed Steel (HBHSS) roll materials were investigated by means of optical microscopy, scanning electron microscopy (SEM), X-ray diffraction, hardness measurement, impact tester, tensile tester and pin abrasion tester. The results show that the as-cast structure of HBHSS consists of a great amount of martensite and M23(B,C) and a few retained austenites and M23(B,C)6. After solution treated at 1,050 °C and followed by oil cooling, the amount of M23(B,C)6 carbo-borides in quenched HBHSS increases obviously and the macrohardness of the quenched HBHSS is 66 HRC, which is very close to the 65.8 HRC of as-cast HBHSS. On the whole, the hardness of HBHSS alloy shows a trend of slight decrease with increasing tempering temperature when tempered below 500 °C. While when above 500 °C, the hardness increases slightly as the tempering temperature increases and reaches a peak at 525 °C and then decreases obviously. The impact toughness of HBHSS has a tendency to increase as the tempering temperature increases. Tempering can improve the tensile strength and elongation of HBHSS, but a higher tempering temperature causes a slight decrease in both tensile strength and elongation. Excellent wear resistance can be obtained by tempering at 500 to 550 °C.

Key words: high boron high speed steel; tempering temperature; carbo-boride; metallic matrix; mechanical property; wear resistance

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In order to adapt to severe hot rolling conditions of a hot strip mill, a rolling mill roll should have a high resistance to wear and surface roughening. Accordingly, high speed steel rolls that have an excellent wear resistance, fire crack resistance and resistance to roll surface roughening have replaced conventional high-chromium cast iron rolls or Ni-hard cast iron rolls in many rolling mills [1-3].

High speed steels are ferrous-based alloys of the Fe-C-X multi-component system where X represents a group of alloying elements mainly including chromium, tungsten, molybdenum, vanadium, and cobalt. Previously, these steels were mainly used for cutting tools [4-5], since they are characterized by their capacity to retain a high level of hardness while cutting metals at high speed.

In the beginning of the 1990’s, a high speed steel roll containing more vanadium and carbon, which could form the eutectic MC type carbide with high hardness, was successfully developed in Japan and widely applied in many hot rolling mills [6-7]. However, the content of the valuable elements in high speed steel roll is high, which leads to a high production cost.

Boron is a low-cost alloying element for many materials. Some researchers have reported that the addition of boron to the high chromium cast steel can increase the hardness and improve the abrasion resistance of high chromium cast steel [8-9]. The proper boron concentration in the low alloy cast steel is of benefit by obtaining high hardness boride and improving the wear resistance of the cast steel [10-11]; the proper boron addition can also reduce the addition amounts of scarce nickel, molybdenum, chromium and tungsten, and therefore decrease the production cost of wear resistant cast steel. In this study, we developed a new roll material, High-Boron High-Speed Steel (HBHSS), by adding boron into the low alloy high speed steel. The as-cast and tempered microstructures, the mechanical properties and abrasion resistance of HBHSS were studied.
## 1 Experimental procedure

### 1.1 Specimen preparation

The initial charge materials of the HBHSS were clean pig iron and steel scrap. They were melted in a 20-kg capacity medium frequency induction furnace with a magnesia lining. Ferro-alloys such as Fe-20.6%B, Fe-60.8%Cr, Fe-68.5%V, Fe-59.0%Mo, Fe-79.6%W, Fe-78.4%Mn and Fe-32.8%Ti (by weight) were then added into the slag-free molten steel so as to minimize the oxidation loss and the slag formation. Table 1 shows the composition of the HBHSS. The melt was then super-heated to 1,620 to 1,650 °C. After being deoxidized by aluminum, the alloy melt was poured into the ‘‘Y’’ sample moulds. The test specimens were cut from its lower part of the sample, and all the specimens were machined with a linear cutting machine.

Some of the as-cast specimens were solution-treated at 1,050 °C for 1 h in vacuum, followed by oil cooling for the observation of quenched structure. Afterward, the quenched specimens were tempered at 200 °C, 300 °C, 400 °C, 500 °C, 525 °C, 550 °C and 600 °C for 3 h, respectively for the study of structure and properties.

### 1.2 Microstructure observation

The microstructures were observed by using of X-ray diffraction (XRD), XLG-04 optical microscopy (OM), and the CSM 950 scanning electron microscopy (SEM). The specimens were etched with 5% nital for optical microscopy examination; while a mixture of 5 mL HCl, 45 mL 4% Picral and 50 mL 5% nital was used as an etchant for SEM evaluation. XRD was carried out on a M21X diffractometer with the copper Kα radiation at 40 kV and 200 mA as the X-ray source. The specimen was scanned in the 2θ range of 10° to 90° in a step-scan mode (0.02° per step). The volume fraction of carbo-borides was measured by means of a Leica digital images analyzer on the deep etched specimens.

### 1.3 Mechanical properties tests

The tensile tests were performed on a universal material testing machine. The dimensions of specimens were Φ10 mm × 130 mm. Three identical specimens were tested, and the ultimate tensile strength was determined from the load-displacement diagrams. The value used was the average value for the three test specimens. Charpy un-notched impact tests were carried out on a JBN-300B type impact tester. The size of specimens was 20 mm × 20 mm × 110 mm. The toughness value was the average for the three specimens. The room temperature hardness was measured with an HR-150A type Rockwell-hardness tester. The microhardnesses of carbo-boride and matrix in HBHSS were measured on a HX-1000TM type Vickers-hardness tester with a load of 0.5 N. The size of specimens for hardness measurement was 20 mm × 20 mm × 15 mm. At least seven indentations were made on each specimen under each experimental condition to check the reproducibility of the hardness.

### 1.4 Wear test

The wear behavior of HBHSS was investigated using a pin abrasion tester. A schematic diagram of the main portion of the abrasion wear testing machine is shown in Fig. 1. Wear tests were performed under a contact loads of 9.8 N and 24.5 N, respectively. The disk, with a size of 30 mm in diameter and 5 mm in thickness, was covered with a 90 mesh carborundum abrasive paper. The dimensions of specimens were Φ 6 mm × 25 mm. The rotating speed of the disk was 90 rpm. The sliding velocity of specimen was 0.1 m s⁻¹, and its sliding distance was 10.5 m. The wear loss of the test piece was measured after each cycle using a balance with an accuracy of 0.1 mg. The results of the wear tests were the average for three specimens.

### Table 1: Composition of experimental HBHSS (wt.%)

<table>
<thead>
<tr>
<th>C</th>
<th>B</th>
<th>Cr</th>
<th>W</th>
<th>V</th>
<th>Mo</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>Ti</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1-1.3</td>
<td>1.3-1.5</td>
<td>4.8-5.0</td>
<td>0.8-1.0</td>
<td>0.5-0.8</td>
<td>1.2-1.5</td>
<td>0.3-0.6</td>
<td>0.5-0.7</td>
<td>&lt; 0.035</td>
<td>&lt; 0.035</td>
<td>&lt; 0.15</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Fig. 1: Schematic diagram of abrasion wear testing machine

## 2 Results and discussion

### 2.1 Solidification structure of HBHSS

The as-cast metallurgical structures of HBHSS are shown in Fig. 2. The matrix of HBHSS in the as-cast state consists of a great amount of martensite and a few retained austenites. There are many eutectic carbo-borides in the as-cast structure of the HBHSS, and their volume fraction is about 28vol.% to 30vol.%. The eutectic carbo-borides in HBHSS are M23(B,C)6 and M2(B,C) according to the XRD spectrum of Fig. 3, where M represents iron, chromium, tungsten, molybdenum, manganese and vanadium, etc.

Moreover the amount of M2(B,C) is the greatest, and that of M23(B,C) is the smallest. The M2(B,C) type carbo-boride is continuously distributed at the grain boundary and its microhardness is 1,440 to 1,510 HV. The microhardness of M23(B,C) type carbo-boride cannot be measured because its size is too small. The macrohardness of the as-cast HBHSS sample at room temperature is 65.8 HRC.
2.2 Microstructure of quenched HBHSS

The microstructures of quenched HBHSS, which was solution-treated at 1,050 °C for 1 h, followed by oil cooling, are shown in Fig. 4. The matrix of HBHSS all transforms into the martensite. While austenitizing at 1,050 °C, the solution amounts of boron, carbon, chromium, molybdenum, tungsten, and manganese etc. in the high temperature austenite increase and the stability of austenite also increases, so there is a little retained austenite in the quenched structures, as shown in Fig. 4(b).

During the quenching heat treatment, qualitative and quantitative changes in the carbo-boride constituent of HBHSS, caused by diffusion and mass transfer, take place. They are related to the diffusion redistribution of the alloying elements between the steel matrix and the carbo-boride phases that lead to the dissolution of existing phases and the formation of new ones. In particular, after solution-treatment at 1,050 °C, the amount of $\text{M}_2(\text{B,C})_6$ carbo-boride obviously increases. This is most likely to be caused by the $\text{M}_2(\text{B,C}) \rightarrow \text{M}_2(\text{B,C})_6$ transformation, which is known to occur in the interstitial phases in alloyed steels\textsuperscript{[12]}. After the quenched heat-treatment, the hardness is 66 HRC, which only changes a little when compared with the 65.8 HRC of as-cast HBHSS.

2.3 Microstructure and mechanical properties of tempered HBHSS

The microstructures of HBSSS after being tempered at different temperatures for 3 h are shown in Fig. 5. Figure 5(a) shows that when the tempering temperature is low (200 °C), the microstructure of HBSSS undergoes no obvious change compared with that of the quenched HBHSS. When the tempering temperature reaches 525 °C, the retained austenite all transforms into the martensite; the quenched martensite also transforms into the tempered martensite; and the amount of $\text{M}_2(\text{B,C})_6$ carbo-boride precipitated from the matrix has a slight increase, as shown in Fig. 5(b). The XRD spectrum of Fig. 6 shows that there is not any retained austenite in the tempered structure of HBSSS at 525 °C and the phase precipitated from the matrix is $\text{M}_2(\text{B,C})_6$ carbo-boride. When the tempering
temperature increases further, $M_{31}(B,C)_6$ carbo-boride precipitated from the matrix begins to grow up, as shown in Figs. 5(c) and 5(d).

The influences of the tempering temperature on hardness, impact toughness, tensile strength and elongation of HBHSS are shown in Figs. 7 and 8. When the tempering temperature is below 500 °C, the hardness shows a trend of decrease with increasing the tempering temperature; the hardness of the sample tempered at 500 °C is 60 HRC, reduces 6 HRC only compared with that of the as-quenched one. When above 500 °C, the hardness increases with the rise of tempering temperature at first and then reduces obviously when the tempering temperature is above 525 °C. HBHSS has excellent temper resistance and the hardness exceeds 60 HRC even when tempered at 550 °C. The impact toughness

Fig. 5: OM of HBHSS tempered at (a) 200 °C, (b) 525 °C, (c) 600 °C; and (d) SEM after tempering at 525 °C

Fig. 6: XRD spectrum of HBHSS tempered at 525 °C

Fig. 7: Effect of tempering temperature on hardness and impact toughness of HBHSS

Fig. 8: Effect of tempering temperature on tensile strength and elongation of HBHSS
of HBHSS increases in general as the tempering temperature rises. When the tempering temperature is below 525 °C, the impact toughness is relatively low, because the stress of transformation is not fully dispelled. Then, a large amount of M₂₃(B,C)₆ is separated out from the matrix, which decreases the boron and carbon content in the martensite and leads to the increase of toughness of the matrix. When the tempering temperature is above 525 °C, with the further increase in the amount of M₂₃(B,C)₆, the impact toughness of HBHSS begins to increase rapidly. It can be seen from Fig. 8 that tempering treatment can improve the tensile strength and elongation of HBHSS. However, a high tempering temperature causes a slight decrease in both tensile strength and elongation because of the precipitation of M₂₃(B,C)₆ and the decrease of boron and carbon content in the martensite. The elongation of HBHSS is very low because of the existence of large numbers of brittle M₂(B,C) carbo-borides; and its highest value is smaller than 1.5% after tempering below 600 °C.

### 2.4 Effect of tempering temperature on wear resistance of HBHSS

The effect of the tempering temperature on wear resistance is shown in Fig. 9. It can be seen that the HBHSS has lower weight loss and better wear resistance when tempering at 500 to 550 °C. When tempering temperature increases from 500 to 550 °C, the weight loss of HBHSS changes a little. While when the tempering temperature increases further, the weight loss of HBHSS begins to increase rapidly and its wear resistance clearly decreases. Under the same tempering condition, the weight loss of HBHSS with big wear load (24.5 N) is higher than that with small wear load (9.8 N). The special relationship between wear resistance and tempering temperature relates to the hardness and impact toughness of HBHSS. The wear of material is made up of two parts, namely

\[ W = W_c + W_f \]

where \( W_c \) is caused by cutting mechanism,

\[ W_c = K \frac{P}{H} \]

which shows that \( W_c \) is mainly decided by the hardness \((H)\). \( W_c \) is caused by fatigue mechanism;

\[ W_f = K \left( \frac{\varepsilon_f}{H} \right)^2 \]

where \( \varepsilon_f \) is fracture strain at single axis tensile, which reflects the toughness. \( W_f \) is mainly decided by the hardness and toughness. When tempering at 500 to 550 °C, the wear resistance is the best. With the further rising of temperature, though the toughness of HBHSS is obviously improved, the hardness drops by a large margin. Thus the wear resistance still drops.

The morphology of worn surface in Fig. 10 shows that the abrasion of samples tempered at 600 °C is more severe than that at lower temperature. So the tempering temperature of HBHSS roll should not exceed 550 °C.

### 3 Conclusions

1. As-cast structure of HBHSS consists of a great amount of martensite, a little retained austenite and 28vol.% to 30vol.% M₂₃(B,C)₆ and M₂(B,C) carbo-borides. The macrohardness of as-cast HBHSS is 65.8 HRC.

2. After solution-treatment at 1,050 °C and followed by oil cooling, the amount of M₂₃(B,C)₆ carbo-boride clearly increases, which is most likely to be caused by the M₂(B,C) → M₂₃(B,C)₆ transformation. The macrohardness of quenched HBHSS is 66 HRC.

3. When the tempering temperature is lower, the
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The microstructure of HBSSS has no obvious change. When the tempering temperature reaches 525 °C, the retained austenite all transforms into martensite; the quenched martensite also transforms into the tempered martensite; and the amount of $\text{M}_{23}(\text{B,C})_6$ carbo-boride precipitated from the matrix has a slight increase.

(4) When the tempering temperature is below 500 °C, the hardness exhibits a trend of decrease with increasing the tempering temperature. It increases slowly with the rise of tempering temperature when the tempering temperature is above 500 °C. While when the tempering temperature is above 550 °C, the hardness is clearly reduced. When the tempering temperature is below 525 °C, the impact toughness of HBHSS is relatively low; it begins to increase rapidly when the tempering temperature is above 525 °C. Tempering can improve the tensile strength and elongation of HBHSS, but too high a tempering temperature causes a slight decrease in tensile strength.

(5) HBHSS has lower weight loss and better wear resistance when tempered at 500 to 550 °C. When the tempering temperature increases further, the weight loss of HBHSS begins to increase and its wear resistance clearly decreases.

References


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