Study on wear resistant cast B-containing 1Cr18Ni9Ti stainless steel

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**Abstract:** The developed 1Cr18Ni9Ti austenitic stainless steel containing 1.63 wt.%B have been characterized by X-ray diffraction (XRD), electron probe microanalyzer (EPMA), optical microscopy (OM), scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS) and Vickers microhardness measurement. The microstructural evolution and property of high boron stainless steel after solution treatment at the temperature of 1050°C are also investigated. The results show that the main compositions of borides are Fe, Cr and B, and with small amount of Ni, Mn and C elements. Silicon is insoluble in the borides. The hardness of borides is over 1,500 HV. It has been found that borides do not decompose during solution treatment, but part of borides dissolves into the matrix. The effect of increasing the solubility of boron element in the austenitic matrix favours the hardness enhancement by 8.54%. High boron stainless steel has excellent wear resistance in corrosive environment. Lifetime of transfer pipe made of high boron-containing stainless steel is 1.5–1.8 times longer than that of boron-free 1Cr18Ni9Ti stainless steel.

**Key words:** 1Cr18Ni9Ti austenitic stainless steel; boron; boride; corrosive wear

In the present study, we attempted to elucidate some properties (e.g. hardness) and microstructure features of 1Cr18Ni9Ti austenitic stainless steel containing 1.63 wt.% B. We also tested the corrosion and wear resistance of developed stainless steel as the carrier pipe of molten zinc; and excellent result was achieved.

**1 Experimental procedure**

Austenitic stainless steel pipes with boron and rare earth (RE) additions were centrifugally cast to the final dimensions: Ø150 mm outer diameter, Ø120 mm inner diameter and 800 mm length. Titanium was added to the melt in the transfer ladle from the induction furnace before pouring. A ternary alloy, Fe-RE-Si, was used for the RE addition due to its high reactivity with oxygen. This alloy was placed at the bottom of the transfer ladle in order to minimize its contacting time with the molten steel, and enable its complete dissolution. The elapsed time between pouring of the metal and solidification of the pipes was less than 5.0 minutes. The final chemical composition of the alloy is given in Table 1. Examination of the alloy was done under the as-cast and solution-treated (1,050°C for 1.5 h) conditions. The investigation techniques used for material characterization included X-ray diffraction (XRD), OM, SEM, EDS, EPMA and Vickers microhardness. Metallographic observations were made on samples etched with a mixture of 5 ml HCl, 45 ml 4% Picral and 50 ml 5% nital. The optical microscopy used was a Neophot 32. The scanning electron microscopy was done with a JEOL JSM-6100 and a Philips XL-30 microscope equipped with an...
energy-dispersive X-ray spectrometer (Link IS-IS). EPMA was carried on a JXA-8800R electron probe micro-analyzer. XRD was carried on a MXP21VAHF diffractometer with Copper K\(_\alpha\) radiation at 40 kV and 200 mA.

<table>
<thead>
<tr>
<th>Table 1 Chemical composition of the pipe (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
</tr>
<tr>
<td>---</td>
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<tr>
<td>0.06</td>
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</table>

2 Results and discussion

2.1 Microstructure and properties of as-cast high boron stainless steel

Both macro- and micro-structures of as-cast high boron stainless steel are shown in Fig.1. It can be seen that its microstructure consists of the metallic matrix and eutectic structure. It should be pointed out that only austenite is consisted in the solidification structure of nominal 1Cr18Ni9Ti stainless steel with trace boron or boron-free \([11, 12]\). Referring to the quaternary phase diagram of Fe-25Cr-C-B alloy in literature \([13]\), the solidification process of high boron stainless steel is different from that of the conventional 1Cr18Ni9Ti austenitic stainless steel. Because of the high boron concentration, eutectic point of alloy shifts to the left and a number of eutectic structures can be produced.

The XRD in Fig. 2 shows that the eutectic structures of as-cast high boron stainless steel consist of eutectic austenite and boride. The boride of (Fe, Cr)\(_2\)B type in as-cast structure is uniformly distributed, and the eutectic austenite still keep to be the austenite during the subsequent cooling. Figure 1 also indicates that there are many primary austenites besides the eutectic structures. The EDS (Fig. 3) identifies that the main compositions of boride are Fe, Cr and B, and with a small amount of Ni, Mn and C. Silicon element does not dissolve in the boride. There is Ni element in the matrix, which benefits to obtain the austenitic matrix in the high boron stainless steel and to improve its corrosion resistance. Moreover, the boron concentration in the matrix is quantified to be 0.73 wt.% exceeding the solubility value of 0.02 wt.% in the \(\gamma\)-Fe \([14]\).
It has been reported that there are many Ni and Cr elements in the high boron austenitic stainless steel and the atomic diameter of Ni and Cr is larger than that of Fe, which enlarges the Fe atomic crystal lattice and therefore increases the solution amount of boron in the $\gamma$-Fe \[^{[15]}\].

The EPMA analytical results (as shown in Fig.4) illustrates that the distributions of B, C, Ni and Cr elements are non-homogeneous in the as-cast high boron stainless steel. Boron is mainly distributed at the grain boundaries with small amount inside the matrix. The enrichment region of boron is corresponding to the distribution of (Fe, Cr)$_2$B at the grain boundary. Carbon element is mainly distributed over the matrix. Chromium element is mainly distributed over the (Fe, Cr)$_2$B, and there are also some chromium elements in the matrix. Nickel element is mainly distributed inside the matrix. The hardness of high boron stainless steel is listed in Table 2. Since boron elements were dissolved into the austenite during casting and cooling periods, the hardness of austenitic matrix was improved obviously (i.e. solution hardening mechanism). Moreover, there are some high hardness (Fe, Cr)$_2$B borides whose values exceed 1,500 HV over the austenitic matrix, so, the hardness of high boron stainless steel is higher than that of the boron-free austenitic stainless steel.

### 2.2 Microstructure and properties of high boron stainless steel after solution treatment

Figure 5 shows the microstructure of high boron stainless steel after solution treatment at the temperature of 1,050°C for 1.5 h. The boride is still continuously distributed over the metallic matrix, with some broken points in networks (arrowed in Fig.5(b)). The XRD of sample after solution treatment shows that the microstructures of high boron stainless steel consist still of the austenitic matrix and (Fe, Cr)$_2$B boride, as shown in Fig. 6.

<table>
<thead>
<tr>
<th>State</th>
<th>Location</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Average</th>
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<tbody>
<tr>
<td>As-cast</td>
<td>Boride</td>
<td>1,588</td>
<td>1,603</td>
<td>1,572</td>
<td>1,617</td>
<td>1,625</td>
<td>1,601.0</td>
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<tr>
<td></td>
<td>Matrix</td>
<td>188</td>
<td>174</td>
<td>193</td>
<td>176</td>
<td>195</td>
<td>185.2</td>
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<tr>
<td></td>
<td>Integer</td>
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<td>253</td>
<td>238</td>
<td>242</td>
<td>249</td>
<td>245.8</td>
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<tr>
<td>Solution treatment</td>
<td>Boride</td>
<td>1,578</td>
<td>1,611</td>
<td>1,604</td>
<td>1,585</td>
<td>1,628</td>
<td>1,589.2</td>
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<tr>
<td></td>
<td>Matrix</td>
<td>223</td>
<td>240</td>
<td>244</td>
<td>237</td>
<td>228</td>
<td>234.4</td>
</tr>
<tr>
<td></td>
<td>Integer</td>
<td>261</td>
<td>275</td>
<td>258</td>
<td>268</td>
<td>272</td>
<td>266.8</td>
</tr>
</tbody>
</table>

Note: The hardness of free-boron 1Cr18Ni9Ti austenitic stainless steel after solution treatment is 160–190 HV.
After solution treatment, the borides do not decompose, but part of borides dissolves into the matrix, which increases the solubility of boron element in the austenitic matrix and promotes the increase of hardness of stainless steel by 8.54%, as presented in Table 2. The EDS in Fig. 7 shows that the solution of part boride leads to the increase of the chromium concentration in the matrix, which will conclusively increase the corrosion resistance of high boron stainless steel. The existence of high hardness boride \((\text{Fe, Cr})_2\text{B}\) will improve the wear resistance. The co-action between austenitic matrix and \((\text{Fe, Cr})_2\text{B}\) boride will improve the corrosive-wear resistance of high boron stainless steel.

### 2.3 Application of high boron stainless steel

The granulated zinc is the main consumables in the production of electro-galvanizing coated sheet. The major operational procedure is that the zinc ingot is smelt in the electrical resistance furnace at first; after the temperature of molten zinc is up to 435–455 °C, the molten zinc is delivered to the maintaining furnace by a carrier pipe with outer diameter, inner diameter and length are \(\Omega150\text{ mm}, \Omega120\text{ mm and 800 mm, respectively; and then the molten zinc is dripped to the graphite cooling roller through the batcher and drip nozzle, and thus the granulated zinc is obtained. The carrier pipe of molten zinc was initially made of 1Cr18Ni9Ti austenitic stainless steel. The carrier pipe endures the complex challenges of high temperature, corrosion and abrasion of molten zinc. Practice of employing conventional 1Cr18Ni9Ti as carrier pipe has exposed shortcomings, such as low hardness and poor abrasive resistance. As a result, the carrier pipes are needed to be replaced frequently. The service time of 1Cr18Ni9Ti carrier pipe is in the range of 150–180 hours. The carrier pipe of molten zinc making from the ceramics has excellent wear and corrosion resistance, but it has high brittleness and is easy to fracture during the application.
The wear resistant 1Cr18Ni9Ti stainless steel containing 1.63 wt.%B has been successfully applied to the carrier pipe of molten zinc. It overcomes both poor abrasive resistance of conventional 1Cr18Ni9Ti pipe and large brittleness of ceramics pipe, and improves the performance of molten zinc carrier pipe. It was verified that the lifetime for this particular application is 420–450 hours around 1.5–1.8 times longer than the previously used material. Further, the production process of high boron austenitic stainless steel is simple and the cost is also low. It can be expected that the developed high boron austenitic stainless steel can be extended into other corrosive-wear environment, which would bring good economic and social benefits.

3 Conclusions

(1) When 1.63 wt.%B is added into the 1Cr18Ni9Ti austenitic stainless steel, the as-cast microstructure of steel is a mixture of austenite and (Fe, Cr),B boride, the micro-hardness of (Fe, Cr),B exceeds 1,500 HV and the average hardness of stainless steel reaches 245.8 HV.

(2) The distributions of B, C, Ni and Cr etc. elements are non-homogeneous in the as-cast high boron stainless steel. Boron element is mainly distributed at the grain boundaries, carbon element is mainly distributed over the matrix, chromium element is mainly distributed over the (Fe, Cr),B, and there are some chromium elements in the matrix also, nickel element is mainly distributed in the austenitic matrix.

(3) The microstructure of high boron stainless steel after solution treatment at the temperature of 1,050°C still consists of the austenite and (Fe, Cr),B boride. Moreover, part of borides dissolves into the matrix, which increases the solubility of boron element in the austenitic matrix and promotes the increase of hardness of stainless steel by 8.54% and reaches 266.8 HV.

(4) The wear resistant boron-containing 1Cr18Ni9Ti stainless steel has been successfully applied as carrier pipe of molten zinc. Its servicing time is 1.5–1.8 times longer than that of the conventional boron-free 1Cr18Ni9Ti stainless steel pipe.

References