Effect of Fe₂B boride orientation on abrasion wear resistance of Fe-B cast alloy

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Abstract: The microstructures and abrasion wear resistance of directional solidification Fe-B alloy have been investigated using optical microscopy, X-ray diffraction, scanning electron microscopy and laser scanning microscopy. The results show that the microstructure of as-cast Fe-B alloy consists of ferrite, pearlite and eutectic boride. After heat treatment, the microstructure is composed of boride and martensite. The plane which is perpendicular to the boride growth direction possesses the highest hardness. In two-body abrasive wear tests, the silicon carbide abrasive can cut the boride and martensite matrix synchronously, and the wear mechanism is micro cutting mechanism. The worn surface roughness and the wear weight loss both increase with the increasing contact load. Moreover, when the boride growth direction is perpendicular to the worn surface, the highest hardness plane of the boride can effectively oppose abrasion, and the martensite matrix can surround and support borides perfectly.

Key words: directional solidification; microstructure; wear weight loss; wear mechanism

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Wear is one of the most important cost factors during mineral processing, rolling steel, cement production and material handling [1-3]. High chromium cast irons and Ni hard cast irons contain many eutectic carbides which have high hardness and excellent wear resistance. They are widely used in the above wear domain [4-6]. Because high chromium cast irons contain many alloy elements, such as chromium, nickel and molybdenum, etc., they have higher production cost. Moreover, they also have high brittleness and low toughness. Therefore, the development of a high property and low cost wear-resistant material has an important meaning. The proper boron concentration in a low alloy cast steel can produce high hardness boride and improve the wear resistance [7-10], which also reduces the addition

of scarce molybdenum and chromium elements, and therefore decreases the production cost.

Previous studies [11,12] showed that the hardness of Fe₂B and FeB type borides is up to 1,500 and 2,400 HV, respectively, while the hardness of (Cr,Fe)₇C₃ type carbide is only 1,300–1,500 HV. The investigations [13,14] on abrasion wear resistance of high chromium cast irons discovered that M₇C₃ carbides have higher microindentation hardness in the transverse direction than in the longitudinal direction, and high chromium cast irons present higher abrasion resistance in the transverse section than in the longitudinal section of the M₇C₃ carbides. Similarly, it has been reported that the borides (Fe₂B) in Fe-B alloys also have higher microindentation hardness in the transverse than in the longitudinal direction [15]. However, scores of studies have been performed on the effect of boride orientation on abrasion wear resistance. Therefore, focus of this study is on the microstructures and the effect of boride orientation on wear behaviors of the Fe-B cast alloys under directional solidification conditions.

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1 Experimental procedures

1.1 Melting, casting and heat treatment of Fe-B cast alloy

Figure 1(a) shows a schematic representation of the equipment used to perform the directional solidification of Fe-B alloy with a longitudinal thermal gradient. The equipment of directional solidification consists of a copper permanent mold (namely chill) cooled with water, and a wrapper of sodium silicate-CO₂ bonded sand with exothermal materials.

The test alloy was melted in a 8-kg capacity medium frequency induction furnace with a quartzite lining. Initial charge materials were clean pig iron and steel scrap. Ferroalloys such as Fe-16.1wt.%B, Fe-61.5wt.%Cr, Fe-66.5wt.%Mn and Fe-75.3wt.%Si were added to a slag-free molten steel. After being deoxidized with aluminium at 1,630 °C, the molten alloy was transferred into the ladle. When the temperature was at about 1,480 °C, the molten alloy was poured into the sand mold to solidify and obtain Y-block ingots of directional Fe-B alloy.

The main chemical compositions of the ingots, determined by optical emission spectroscopy, are shown in Table 1.

The solidification rate of the directional region near the chill was about 19 °C·s⁻¹ measured by a thermocouple, as shown in Fig. 1(a). Randomly oriented grains of small size next to the chill wall (i.e. equiaxed grain zone) were removed 3 mm from the undersurface of the Y-block in the lower part, and only the large columnar grains oriented from the chill toward the centre of the casting were used in the wear test. The specimens A, B, C, D, E used in the wear test and microstructure examination were cut in the directional and ordinary regions, as shown in Fig. 1(b). The specimens were austenized at 1,050 °C for 1 h, followed by water quenching. All the quenched specimens were tempered at 180 °C for 4 h.

Table 1: Chemical compositions of Fe-B alloy (wt.%)

C	B	Cr	Mn	Si	Fe
0.32	1.12	1.08	0.71	0.63	Bal.

Fig. 1: Schematic diagram of directional solidification equipment (a) and sampling positions of specimens A, B, C, D, E (b)

1.2 Microstructure examination

Specimens of approximate dimension 20 mm×20 mm×20 mm (Specimens D and E, as shown in Fig.1b) were cut from the directional and ordinary regions, respectively. The microstructure examination of Specimen D in the directional region were made on the cross and vertical sections (Fig. 1b), their metallographic observations were performed on the polished plane of the specimen that was etched in 5% nital. Microindentation hardness tests were also performed at this polished plane.

The material characterizations were investigated using optical microscopy, X-ray diffraction, scanning electron microscopy and laser scanning microscopy. The optical microscope used was Neophot 21. The scanning electron microscope was a JEOL JSM-6360LV. The laser scanning microscope was KEYENCE VK-9700. X-ray diffraction was performed on a D/MAX-2400 diffractometer with cuprum K α radiation at 40 kV and 200 mA as an X-ray source. The specimen was scanned in the 2 θ range of 20–90° in a step scan mode (0.02° per step).

1.3 Hardness tests

HRS-150 Rockwell-hardness tester was used to measure the

room temperature hardness, and the test load was 1,470 N. The hardness value was the average of ten measured values. Microindentation hardness tests were completed on a HXD-1000TMC tester according to ASTM standard E384-08^[16], and the test loads were 0.98 N and 0.49 N for borides and matrix, respectively. The full test force was applied for 10 s. Twenty values were measured on each specimen to check the reproducibility of the hardness data.

1.4 Two-body abrasion wear test

Abrasion wear property of directionally solidified Fe-B alloy was determined using a ML-100 type pin-on-disk abrasion tester. The data reproducibility of the machine is very good with a data scatter of 3%^[17]. This abrasion tester was widely used for investigating the wear behaviors of pure metals, steels and cast irons^[18]. A schematic diagram of the abrasion wear equipment is shown in Fig. 2. Wear tests were performed under contact loads of 20 N, 50 N and 80 N, respectively. Moreover, the roughness of the worn surface was measured by laser scanning microscope, and the result was average of three measured areas.

The test was completed (in the dry condition) in one pass

Fig. 2: Schematic diagram of abrasion wear equipment

through a spiral orbit (9.639 m) by the specimen on a rotating disk (the disk was revolved continuously at $60 \text{ rev} \cdot \text{min}^{-1}$) covered with 240 mesh ($61 \mu\text{m}$) silicon carbide abrasive paper. The dimension of the specimen was $\Phi 5.5 \text{ mm} \times 25 \text{ mm}$ (specimens A, B and C in Fig. 1b). The electronic balance with an accuracy of 0.1 mg was used to measure the wear weight loss. The test results were average of three specimens. Before testing, the specimens were worn down under the same contact load (10 N), and the running in way was 9.639 meters.

In the wear test, the relation between boride growth direction and wear direction is shown in Fig. 3. For specimen A, the boride growth direction was perpendicular to the worn surface, while the wear direction was parallel to the worn surface. Specimen B₁ showed that the boride growth direction was parallel to the worn surface, but the wear direction was

Fig. 3: Relation between boride growth direction and wear direction

perpendicular to the boride growth direction. For specimen B₂, the boride growth direction was parallel to the worn surface, and the wear direction was parallel to the boride growth direction. Specimen C was cut in ordinary regions (as shown in Fig. 1b).

2 Results and discussion

2.1 Microstructures of as-cast and heat treated Fe-B alloys

The microstructures of as-cast and heat treated Fe-B alloys are shown in Fig. 4. From Specimen E shown in Fig. 4(a), it can be seen that as-cast microstructures are composed of the eutectic boride and matrix. The existence of Fe_2B network morphology, seen in area 3 of Fig. 4(a), and pearlite were proved by X-ray diffraction spectrum (Fig. 5) of specimen E. The microindentation hardnesses of ferrite and pearlite were $215 \pm 11 \text{ HV}$ and $312 \pm 13 \text{ HV}$, respectively^[19]. Areas 1 and 2 of Fig. 4(a) and (b) display their morphologies.

Fig. 4: Microstructures of Fe-B alloy: (a) Specimen E as-cast structures labeled 1-ferrite, 2-pearlite, 3- Fe_2B ; (b) Specimen E heat treated structures labeled 1- Fe_2B , 2-martensite; (c) and (d) heat treated Specimen D structures of the cross and vertical sections, respectively

After heat treatment, the microstructures of Fe-B alloy (Specimen E) are composed of eutectic boride [Fig. 4(b), Area 1] and martensite matrix [Fig. 4(b), Area 2]. The microindentation hardness is 548 ± 10 HV. The morphology and microindentation hardness of boride in the directional region are different from those of the ordinary region. In the present study, the microstructures of the cross and vertical sections of heat treated Specimen D are shown in Figs. 4(c) and (d), respectively. In the vertical section, the borides reveal long rod morphology. The microindentation hardness analysis (Fig. 6) indicates that the boride hardness in the cross section is the highest, and the vertical section has the lowest boride hardness. In Rockwell-

Fig. 5: X-ray diffraction spectrum of as-cast Specimen E

Fig. 6: Microindentation hardness of borides in Specimens D and E

Fig. 7: Rockwell-hardness of Specimens D and E

hardness testing (Fig. 7), the cross section also displays the highest hardness, and this result should be caused by the highest boride microindentation hardness in the cross section.

2.2 Two-body abrasive wear behavior

Table 2 shows microindentation hardness of borides in Fe-B alloys. Figure 8 shows the wear weight loss data of Fe-B alloy specimens in the directional and ordinary regions at different test loads. It can be seen that the amount of the wear weight loss keeps increasing with the applied load. Meanwhile, Specimen A with the highest boride microindentation hardness ($HV1503 \pm 11$) has the lowest wear weight loss and best abrasion resistance than those of Specimens B₁, B₂ and C.

The eutectic Fe₂B boride is a brittle constituent in Fe-B alloy, and it seems to have little or no plastic deformation during abrasive wear^[20]. In terms of Richardson's theory^[21], the wear weight loss of the tested material would be great when the hardness of the material (H_m) is lower than 0.6–0.8 times the hardness of the abrasive particles (H_a). In this study, SiC ($H_a \sim 2,600$ HV)^[22] is used as abrasive, and the hardness of Fe₂B boride is between 1,410 and 1,520 HV; so, the ratio of H_m/H_a (0.54–0.58) is lower than 0.6–0.8, which signifies the hard abrasive particles can "indent" into the boride, and induce the mainly wear weight loss. Meanwhile, for the martensite matrix in the directional and ordinary regions of Fe-B alloy, the SiC abrasive can easily plough the matrix.

The scanning electron microscopy graphs of the worn surfaces (under 80 N load) of Specimens A, B₁, B₂ and C are shown in Fig. 9. The parallel ploughings on the worn surface of Specimen A are shown in Fig. 9(a). The ploughing morphology indicates the wear mechanism in the two-body wear process of Fe-B alloy is micro cutting mechanism.

Table 2: Boride microindentation hardness (HV)

Specimen A	Specimen B ₁	Specimen B ₂	Specimen C
1503±11	1428±13	1421±11	1455±10

Fig. 8: Wear weight loss data of specimen A, B₁, B₂ and C

Fig. 9: Scanning electron microscopy graphs of worn surfaces of Specimens A, B₁, B₂ and C under 80 N load: (a) worn surface morphology of Specimen A at low magnification; (b) and (c) worn surface of specimen A; (d) and (e) worn surface of Specimen B₁; (f) and (g): worn surface of Specimen B₂; (h) and (i): worn surface of Specimen C

The wear weight loss is generally determined by the hardness ratio of eutectic boride and abrasive, but the martensite matrix also plays an important role during microploughing^[23]. For Specimen A, the boride growth direction is perpendicular to the worn surface (as shown in Fig. 3 Specimen A), the highest hardness plane of the boride can effectively oppose the abrasion, and the martensite matrix can surround and support borides perfectly. In this situation, a few cracks in borides appear (Fig. 9c), the borides are broken slightly, and Specimen A shows the best wear resistance property.

Compared to Specimen C, the boride growth direction in Specimens B₁ and B₂ is parallel to the worn surface, the lower hardness plane of the boride will oppose abrasive, and the martensite matrix cannot surround and support borides perfectly. So, the wear resistance properties of Specimens B₁ and B₂ are both lower than that of Specimen C. Because the B-B bond which is parallel to the boride growth direction possesses the lowest bond energy^[15], when the abrasives plough on the

Specimen B₁ surface (the ploughing direction is perpendicular to the boride growth direction), the ploughing force (force F in Fig. 10)^[13] can “bend boride” and produce the tangential stresses (the stresses are parallel to the boride growth direction, Fig. 10b). The appearance of many cracks (Fig. 9e) in boride should be induced by tangential stresses. Compared with Specimen B₁, the wear direction and ploughing force in Specimen B₂ is parallel to the boride growth direction, and the ploughing force can easily produce the tangential stresses (with no need for bending boride, as shown in Fig. 10d) to pull cut the borides. So, there are more broken borides (more cracks appear in Fig. 9g) in Specimen B₂ than that in Specimen B₁.

For all the wear specimens, the ploughing depth and roughness (as shown in Fig. 11b) will increase with the increasing load^[22]. The borides in Specimen B₂ are severely broken, the martensite matrix cannot be perfectly protected. So, the ploughing depth, worn surface roughness and wear weight loss of Specimen B₂ are the highest of all the specimens.

Fig. 10: Wear mechanism of Specimens B₁ and B₂ (F represents the ploughing force)

Fig. 11: (a) 3-D profile image of worn surface of Specimens A under 80 N load and (b) worn surface roughnesses of Specimens A, B₁, B₂ and C

Compared with B₂ specimen, there are fewer broken borides in Specimen A (Figs. 9b and c), and the borides in Specimen A can cooperate with martensite matrix to oppose the abrasive perfectly. So Specimen A possesses the lowest worn surface roughness and wear weight loss.

3 Conclusions

(1) The microstructures of as-cast Fe-B alloy are composed of eutectic boride, pearlite and ferrite. The phases in the heat treated Fe-B alloy consist of boride and martensite. The plane which is perpendicular to the boride growth direction has the highest Rockwell-hardness.

(2) The worn surface roughness and wear weight loss increase with the increasing of contact load. When the boride growth direction is perpendicular to the worn surface, the highest hardness plane of the boride can oppose the abrasion effectively, and the martensite matrix can surround and support borides perfectly. The Fe-B alloy meeting the above-mentioned conditions will possess the highest wear resistance property. This result extends a new approach to achieve a high wear-resistance material.

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