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A study of wear resistance of Fe-Cr-B alloy

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In this article, the wear resistance of Fe-Cr-B alloy containing different boron concentration after heat treatment at different temperature was studied. ML-10 type abrasive-wear test machine was used for processing Fe-Cr-B specimens, and its wear resistance was measured based on weight loss. Comprehensive analysis was carried out combined with Rockwell hardness, impact toughness, microstructure in section and other factors. The results showed that wear resistance of Fe-Cr-B alloy changed in the similar way with its variation of hardness, but different from its toughness totally. Under experimental conditions, the specimen whose boron content is 2.0% and quenching temperature is 1000 ^{o}C showed minimum weight loss of 3.4 mg, and it has excellent wear resistance.

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Keywords: Fe-Cr-B alloy, Boron concentration, Heat treatment, Wear resistance

1. Introduction

Abrasive-wear is the phenomenon or process causing material loss in the process of interaction between rough surface or the prominence and surface of the material. Abrasive-wear is mainly seen in the following two cases, one is fiction pair composed of rough hard and soft surface casus wear and tear. The other is hard and free particles in the friction interface causes wear and tear by sliding. Evaluation of wear resistance is mainly by two criteria, wear amount and wear rate. Wear amount is divided into wear length W_L, wear volume W_V and wear weight W_W, which is used as an criterion in this experiment.

Many studies [1] have shown that wear resistance of steel is concern with its hardness, heat treatment, carbon content and other factors. For brittle materials, hardness is not the only reliable standard for judging its wear resistant, and toughness may be another important parameter. The abrasive wear mechanism of Fe-Cr-B alloy is mainly micro-cutting: when an abrasive particle had an interaction with material interface, the force P on the wear surface could be divided into normal force N and tangential force T. N made abrasive particles into the surface of the material, and the depth was connected with hardness of the material. When sliding happened in the interface of specimen and abrasive particles, the force P mainly cut the surface of the specimen, and then, furrow generated.

Comprehensive analysis in terms of elements, microstructure, hardness and toughness of Fe-Cr-B alloy is needed to study its wear resistance. Trace amount of boron could increase the harden-ability of steel significantly [2], improve its strength and creep resistance [3]. Boride is up to the requirement of wear-resistant phase for its high micro-hardness and thermal stability [4-5]. However, if the boron content exceeds 0.01%, brittle borides will form at the grain boundary, which reduces toughness of the material significantly [6-7]. In this paper, boron content is set to 0%, 0.4%, 0.8%, 1.4% and 2.0% finally in the experiment with carbon content of less than 0.35%. We comprehensively study the effect of boron content, heat treatment, hardness and toughness of the material on wear resistance of Fe-Cr-B alloy.

2. Experimental procedures

The studied Fe-Cr-B alloys were prepared in a 40 kg vacuum induction melting furnace. Initial charge materials were clean steel scrap and carburant. Ferro-alloys such as Fe-63% Cr and Fe-19% B and Fe-75% Si and Fe-78% Mn were added to a slag-free molten steel so as to minimize the oxidation loss and the slag formation. Fe-Cr-B alloys were cast from 1550 ^{o}C as φ80 mm × 200 mm bars in cast iron moulds, followed by air cooling to room temperature. The main chemical compositions of test materials are shown in Table 1.

Table 1. Chemical composition of Fe-Cr-B alloy (wt %).

Sample	C	B	Cr	Mn	Si	Fe
1#	0.35	0	10.03	0.76	0.65	Bal.
2#	0.35	0.4	10.09	0.77	0.63	Bal.
3#	0.35	0.8	10.02	0.75	0.66	Bal.
4#	0.35	1.4	10.01	0.79	0.66	Bal.
5#	0.35	2.0	10.06	0.74	0.68	Bal.

To determine the appropriate quenching temperature, thermal stability analysis (DSC) was carried out and the result was shown in Fig. 1. As to seen in Fig. 1, the initial phase changing temperature of Fe-Cr-B alloy is 1150.3 ^{o}C and the end point is 1157.8 oC, so the phase transition temperature range ΔT=7.5 ^{o}C. According to Fe-B phase diagram [8], quenching temperature was decided not less than 900 ^{o}C. Long heat preservation time of quenching process will cause decarburization, boron taken off and other off phenomenon, so quenching temperature was eventually set as 900 ^{o}C, 950 ^{o}C, 1000 ^{o}C, 1050 ^{o}C and 1100 ^{o}C, oil cooling, and preservation time is 1h. Tempering temperature is 200 ^{o}C with furnace cooling, and heat preservation time is 4 hours.

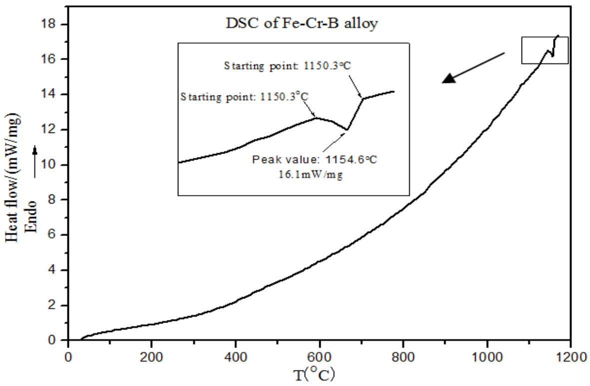


Fig. 1. DSC graph of Fe-Cr-B alloy.

After heat treatment, Fe-Cr-B alloy was processed into φ 6 mm × 20mm pin-shaped specimens. ML-10 wear testing machine was used for processing the specimens, the parameters are as follows: disc speed of 60 rpm, 280# SiC waterproof paper as abrasive, specimen radial feed of 4 mm/s, initial radius of 13 mm, terminal radius of 103 mm, wear travel of 16.4 mm, load of 0.5 Kg, specimen with no-groove, impact load energy of 150 J and the result was directly read out from the dial plate. S-3400N scanning electron microscope was used for observation of wear interface and fracture-interface microstructure. HR-150A type Rockwell hardness tester was used to measure its Rockwell hardness, with load of 150 Kg. The micro-hardness of phase in Fe-Cr-B specimen was measured by MICRO MET-5103 type tester, with load of 100 g and loading time of 15 s.

3. Results and discussion

Fig. 2 shows the results of hardness of Fe-Cr-B specimen of different boron concentration after quenching at different temperature. As to seen in Fig. 2, 1# specimen maintained high hardness due to the high micro-hardness of the phase composed of martensite and (Cr, Fe)7C3 phase. After boron addition, hardness of specimen rise with boron concentration increasing, that's because the main factor of hardness changed into the increasing amount of eutectic phase. Hardness of 1# to 5# specimens range of variation were: 51.5 HRC- 60.8 HRC, 50.7 HRC-59.2 HRC, 55.7 HRC- 62.2 HRC, 59.0 HRC- 64.8 HRC, 61.5 HRC-66.7 HRC. As shown in Figure 16, the highest hardness in experimental conditions was up to 66.7 HRC, when boron content was 2.0 % and quenching temperature was 1050 ^{o}C.

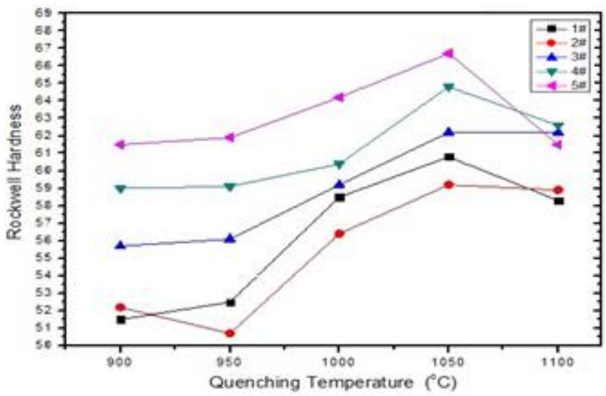


Fig. 2. Rockwell hardness of Fe-Cr-B steel after heat-treatment at different temperature.

Fig. 3 shows the relationship between quenching temperature and impact toughness of Fe-Cr-B alloy. When abrasive particles impacted the specimen, local deformation appeared on the surface of the specimen, and then, dislocation concentrated which caused stress concentration. After boron was added to the specimens, phase of high hardness and high brittleness composed of Fe2B and (Cr, Fe) 7(C, B) 3 phase formed and it extended along the grain boundary. Formation of the eutectic phase caused segregation of the element of B, C and Cr at grain boundary, stress concentration caused by dislocations, and then, crack happened. After quenching, the fracture of network structure of the eutectic phase blocked the extending of the crack; nevertheless, it reduced the bond strength between the grains. Crack formed between eutectic phase and the matrix easily and extended when the specimen was impacted, that's because different ability of deformation of the two phase. With increasing of boron content, the amount of eutectic phase rise and contact area increased which leading to the increasing of the number of crack source and extension channel. According to literature [9], Fe2B showed sheet structure and (Cr, Fe) 7(C, B) 3 phase showed short rod-like, which was a reason for low toughness of Fe-Cr-B alloy. As to seen in Fig. 3, after quenching at different temperature, 1# specimen showed optimal toughness in the experimental condition. Compared with 1# specimen, the toughness of other specimens containing different boron decreased. In condition of the same quenching temperature, the impact toughness of Fe-Cr-B alloy decreased with the increasing of boron concentration.

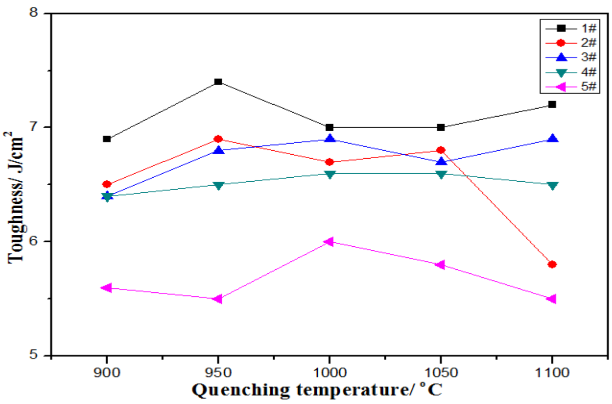
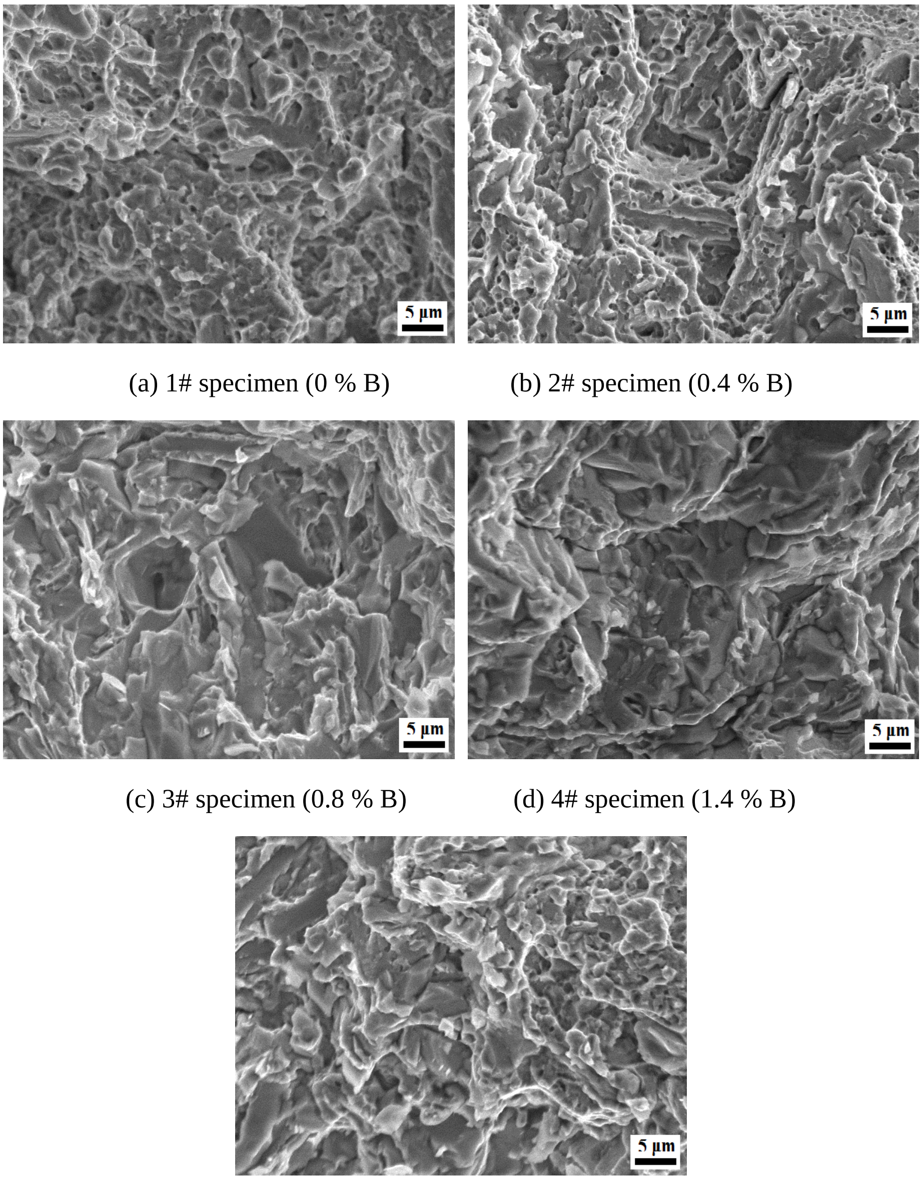


Fig. 3. Toughness of Fe-Cr-B steel after heat-treatment at different temperature.

Morphology of Fe-Cr-B alloy fracture interface after quenching at 1000 °C is shown in Fig. 4. As to seen, its mode was cleavage fracture, which fracture surface separated along a certain crystal boundary. Many grain-like reflective facets appeared on fracture surface and each of the cleavage fracture surface had a small stage and the macro-morphology showed wave-like. As there were no obvious dimples on the fracture interface, Fe-Cr-B alloy fractured in a brittle way. Fracture interface of 1# specimen is relatively flat, which was due to uniform and homogenous element distribution. Fig. 4 (b) to Fig. 4 (e) showed that on the crack interface, there were many tear ridge, which was caused by plastic tear when crack assembled at some point. After boron added, the eutectic phase played the role of skeleton and large hole generated in the crack interface because eutectic phase was get rid of by the adhesion between two phases when crack occurred.



(a) 1# specimen (0 % B) (b) 2# specimen (0.4 % B)

(c) 3# specimen (0.8 % B) (d) 4# specimen (1.4 % B)

(e) 5# specimen (2.0 % B)

Fig. 4. SEM fracture morphology of specimen containing different boron content quenching at 1000 °C.

Wear resistance of Fe-Cr-B alloy was studied by weighing the specimen weight before and after abrasive-wear test and calculated wear weight loss as a standard for evaluating the property of wear-resistant of the alloy. The results were showed in Table 2- Table 6 and Fig. 5 showed the relationship between quenching temperature and Ww loss of Fe-Cr-B specimen containing different boron content. It could be seen from Fig. 5 and Table 1 - Table 6 that quenching temperature had little influence on wear-resistant of the specimen in the experimental conditions, but boron concentration. Ww of 1# specimen is largest for 19.7 mg to 22.9 mg. WW of 2# specimen was lower than that of 1# specimen for 10.9 mg to 20 mg. As the boron content increased, WW of other specimens continued decreasing; Ww of 3# specimen to 5# specimen was 6.6 mg to 11.3 mg, 7.3 mg to 8.1 mg, 3.4 mg to 6.3 mg separately. The decreasing of Ww showed improving of wear resistant. When boron concentration was 2.0 % and quenching temperature was 1000 ^{o}C, the specimen showed minimum Ww for 3.4 mg. The reason for that was high hardness of 5# specimen and the eutectic phase had a great proportion in its microstructure, and both of them were tare when the groove wearied the material. With quenching temperature rising, the amount of secondary carbide particles decreased to totally dissolve in the matrix finally, and secondary carbide had obviously influence on wear-resistant of the material [12-13]. Property of wear-resistant of Fe-Cr-B alloy changed in the similar way with its hardness's variation, but totally different with the changing of its impact toughness, indicating that the wear-resistance of the material is not only evaluated by its hardness and impact toughness, but also the factors composed of microstructure, precipitation, diffusion material, hardness of groove, maximum hardness after abrasive wear etc.

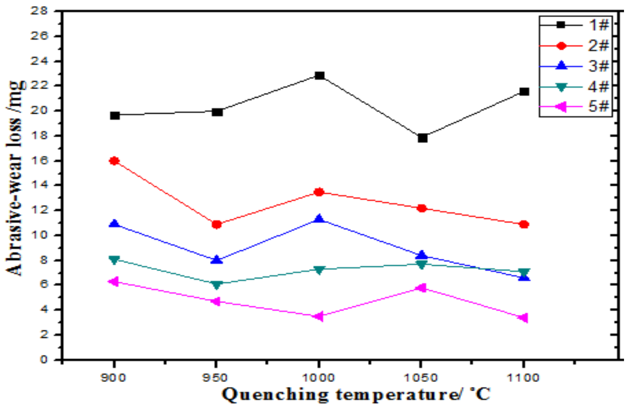


Fig. 5. Abrasive-wear weight loss of Fe-Cr-B alloy after heat-treatment at different temperature.

Table 2. Weight loss and relative wear resistance of 1# specimen after quenching at different temperature.

Temperature (℃)	Weight before wear (g)	Weight after wear (g)	Weight loss (mg)
900	5.3654	5.3457	19.7
950	5.3417	5.3217	20.0
1000	5.3561	5.3332	22.9
1050	5.3684	5.3505	17.9
1100	5.3269	5.3053	21.6

Table 3. Weight loss and relative wear resistance of 2# specimen after quenching at different temperature.

Temperature (℃)	Weight before wear (g)	Weight after wear (g)	Weight loss (mg)
900	5.3431	5.3217	20.0
950	5.3345	5.3236	10.9
1000	5.3328	5.3193	13.5
1050	5.3204	5.3082	12.2
1100	5.3570	5.3461	10.9

Table 4. Weight loss and relative wear resistance of 3# specimen after quenching at different temperature.

Temperature (℃)	Weight before wear (g)	Weight after wear (g)	Weight loss (mg)
900	5.3116	5.3007	10.9
950	5.3276	5.3196	8.0
1000	5.3012	5.2899	11.3
1050	5.2834	5.2750	8.4
1100	5.2835	5.2769	6.6

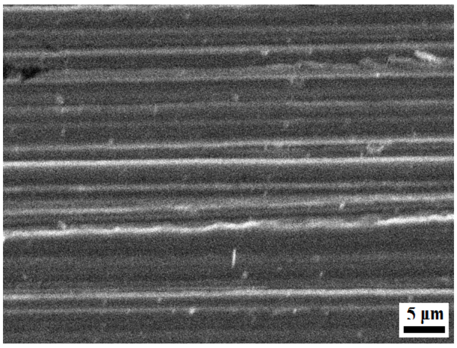
Table 5. Weight loss and relative wear resistance of 4# specimen after quenching at different temperature.

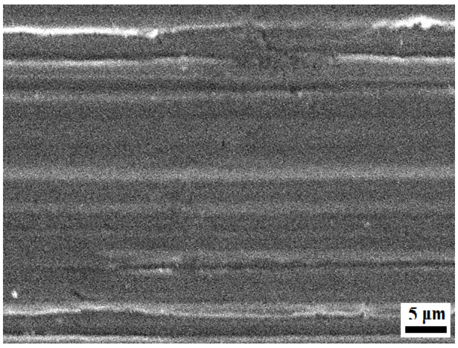
Temperature (℃)	Weight before wear (g)	Weight after wear (g)	Weight loss (mg)
900	5.1074	5.0993	8.1
950	5.2935	5.2874	6.1
1000	5.2621	5.2548	7.3
1050	5.2567	5.2490	7.7
1100	5.1748	5.1677	7.1

Table 6. Weight loss and relative wear resistance of 5# specimen after quenching at different temperature.

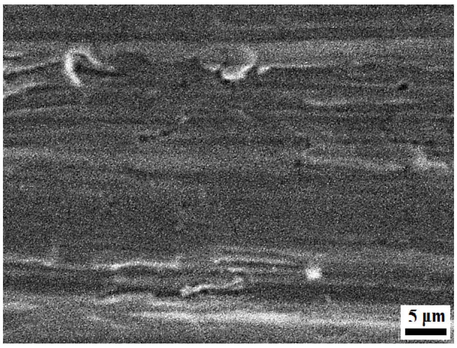
Temperature (℃)	Weight before wear (g)	Weight after wear (g)	Weight loss (mg)
900	5.2356	5.2293	6.3
950	5.2647	5.2600	4.7
1000	5.2603	5.2568	3.4
1050	5.2341	5.2283	5.8
1100	5.2651	5.2617	3.5

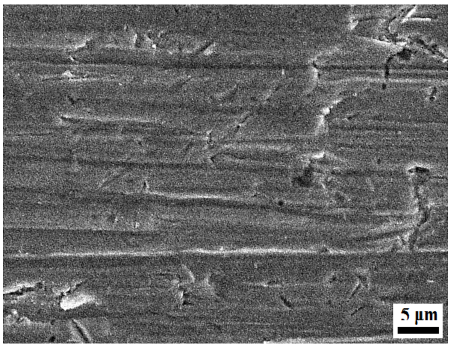
Furrow is a direct result of the friction effect and the formation of resistance from mechanical interaction. During abrasive wear of Fe-Cr-B alloy, sliding happened between hard particles in 240# waterproof abrasive paper and surface of the material, which made density of dislocation on the interface of the alloy rise and stress assemble, then the surface material spelling in brittle fracture mode and furrows formed.



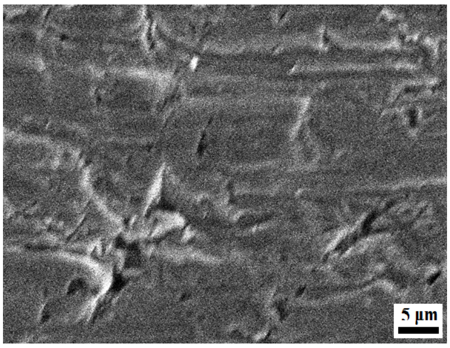


(a) 1# specimen (0 % B) (b) 2# specimen (0.4 % B)





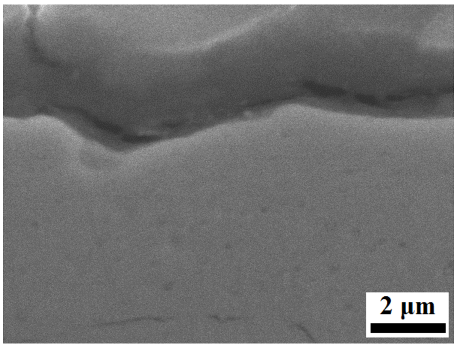
(c) 3# specimen (0.8 % B) (d) 4# specimen (1.4 % B)

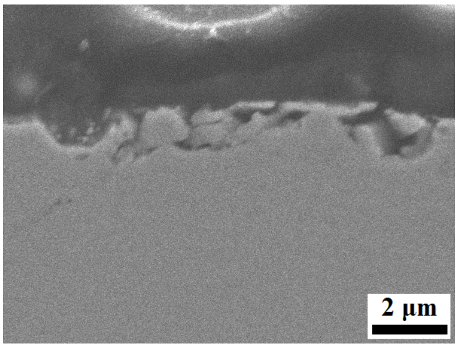


(e) 5# specimen (2.0 % B)

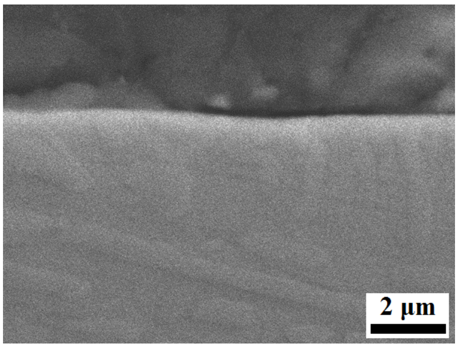
Fig. 6. Worn surface SEM morphology of Fe-Cr-B alloy containing different boron concentration quenching at 1000°C.

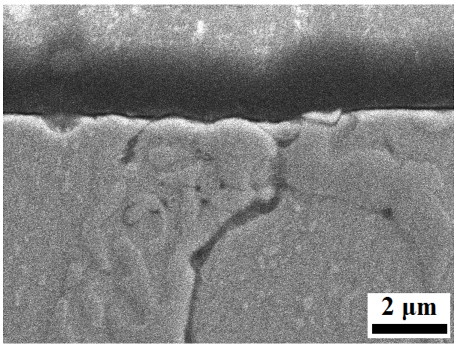
Worn surface SEM morphology of Fe-Cr-B specimen after quenching at 1000oC is showed in Fig. 6. As to seen in Fig. 6 (a), the amount of furrow on 1# specimen interface was large and in wide and deep sharp. The reason for that was hardness of 1# specimen was low, so N could go deep into the surface and P could cut it effectively, and no eutectic phase no blocking effect. So wear resistance of 1# specimen was bad, indicating that hardness of the material plays an important role of its wear-resistance. Fig. 6 (b) to Fig. 6 (e) showed that, with boron concentration increased, wear-resistance improved with number of furrow decreased and its shape shallow and narrow. From 3# specimen, the furrows cannot fully form and obvious blocking effect appeared which was more and more apparent with boron concentration increased. To 5# specimen, the furrow could not form. This is because as the boron content increased, the proportion of the eutectic phase increased and hardness of the specimen rise, normal force N could not go deep into the surface and tangential force T could not cut the surface effectively for blocking from eutectic phase of high hardness.



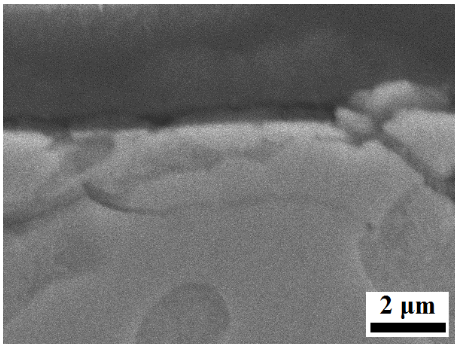


(a) 1# specimen (0 % B) (b) 2# specimen (0.4 % B)





(c) 3# specimen (0.8 % B) (d) 4# specimen (1.4 % B)



(e) 5# specimen (2.0 % B)

Fig. 7. Subsurface cross-sections SEM morphology of Fe-Cr-B alloy containing different boron concentration quenching at 1000°C.

In order to study the effect of microstructure on the wear resistance of Fe-Cr-B alloy of different boron content, micro-structure of subsurface cross-sections was analyzed out after quenching at 1000 °C and tempering at 200 °C, the result was shown in Fig. 7. Fig. 7(a) showed that there was no protrusion or deformation accumulation on the wear interface of 1# specimen. Adding boron element into the specimens improved hardenability of matrix generated the eutectic phase. As shown in Fig. 7 (b), brittle fracture occurred when abrasive cut material surface, part of eutectic phase was divided from mother-material and crack assembled in the interface. Microstructure of 2# specimen was similar with 1# specimen's because low amount of the eutectic phase and weak influence on wear-resistance. In Fig. 7 (c), wear interface of 3# specimen was plat and the amount of eutectic phase increased. The eutectic hard phase directly fractured without plastic deformation in the process of cutting, but no crack appeared in its microstructure because the strength of eutectic and matrix matched well, so Ww of 3# specimen was lower. As boron content increased, the eutectic phase of which amount increased had powerful support for wear interface. However, abrasive cutting in the material surface made dislocation accumulated and stress assembled. And formation of the eutectic phase made the elements of B, C and Cr segregated at grain boundary, which made the strength of matrix and eutectic phase mismatched, so in the wear interface crack formed and extended along grain boundary to interior of the material, as shown in Fig. 7 (d) to Fig. 7 (e).

4. Conclusions

(1) The hardness of Fe-Cr-B alloy increases with the increase of boron content. With the increase of quenching temperature, the hardness of Fe-Cr-B alloy increases. When the quenching temperature excels 1050 ^{o}C, the hardness has no apparent change.

(2) Quenching temperature has little effect on the impact toughness of Fe-Cr-B alloy. After boron addition, the impact toughness of Fe-Cr-B alloy reduces obviously with the increase of boron content.

(3) The wear resistance of Fe-Cr-B alloy improves with the increase of boron content, and the weight loss of specimen whose boron content is 2.0% and quenching temperature is 1000 ^{o}C is only 3.4 mg, showing excellent wear resistance.

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