A study on microstructure and erosion-corrosion performance of Fe–Cr–Ni–B alloy

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Abstract

The microstructure and erosion-corrosion performance of Fe–Cr–Ni–B alloy were studied. The experimental results were analyzed by hardness tester, energy spectrum analyzer, scanning electron microscope, X-ray diffraction analyzer. The results show that the Fe–Cr–Ni–B alloy consists of martensite and borocarbides \( \text{M}_2(\text{B}, \text{C}) \) and \( \text{M}_7(\text{B}, \text{C})_3 \), \( \text{M}_2(\text{B}, \text{C}) \) and \( \text{M}_7(\text{B}, \text{C})_3 \) borocarbides both have more chromium and less nickel than the matrix. After heat treatment, the hardness of the alloy reaches 52.3 HRC. For the test alloys, the higher rotating speed test condition results in higher erosion-corrosion weight loss, and the erosion-corrosion weight loss increases first and then decreases with the increase of the impingement angle. Compared with Cr28 high chromium cast iron, the erosion-corrosion surface of Fe–Cr–Ni–B alloy, the borocarbides are slightly broken, so, the Fe–Cr–Ni–B alloy exhibits excellent erosion-corrosion resistance under the borocarbide protection.

1. Introduction

High chromium cast iron is widely used in machinery, mining and metallurgy as a wear performance material due to its high hardness, better corrosion performance and excellent oxidation resistance [1–3]. Some scholars have studied the microstructure of high chromium cast iron and its wear performance, getting conclusion that the structure after air-cooled quenching was martensite and \( \text{M}_7\text{C}_3 \) carbide, and its hardness and wear performance were higher than that of as-cast structure [4]. Simultaneously, Pokusova et al [5] studied the wear behavior of high chromium cast iron, which turned out to be that as-cast high chromium cast iron with austenite as the main matrix (about 40 HRC) would work hardening in the wear strain zone, and its wear resistance was better than that of X210Cr12 steel (about 61 HRC). However, Ozdemir et al [6] studied boronizing on pure iron matrix, and found two hard phases of \( \text{Fe}_2\text{B} \) and \( \text{FeB} \) in the boride layer with higher hardness than carbide. Thus, it can be used as a breakthrough in the research of new wear-resistant materials. Besides, Durmuş et al [7] studied the wear resistance of Fe–Cr–B–C coatings. It was revealed that the wear performance was increased due to the formation of massive carbide/boride phases and a tough matrix protected by the high amount of secondary carbides. Wang et al [8] studied the wear resistance of Fe–Cr–B–C hardfacing alloy, and found that its wear resistance increased first and then decreased with the increase of boron content. When B content was 4 wt%, the wear resistance of Fe–Cr–B–C hardfacing alloy increased five times. The wear resistance of the alloy depends not only on the alloy elements, but also on the cooling conditions. Meanwhile, Hornung et al [9] studied the wear resistance of hypereutectic Fe–Cr–C coatings by cooling rate, and found that rapid cooling under impact and wear conditions could improve the wear resistance of the coatings, but the wear resistance of the coatings under erosion-corrosion conditions could not be improved by changing the cooling rate. Recent research results show that the Fe-B alloys have good toughness and excellent wear resistance [10], the service life of Fe-B alloy roll is 8 times that of nodular cast iron roll [11], and the service life of Fe-B alloy slurry pump impeller is 1.5 times that of Cr27Mo2Cu impeller [12].
Based on the excellent wear resistance of Fe–B alloy, a new erosion-corrosion resistant material Fe–Cr–Ni–B alloy was developed by adding nickel and chromium elements. The microstructure and erosion-corrosion resistance of Fe–Cr–Ni–B alloy were studied.

2. Experimental steps

2.1. Casting and heat treatment of samples

The alloy was melted in a 10 kg medium frequency induction furnace in air atmosphere. Pure iron and scrap steel were added to the furnace. After melting, ferrochrome, ferrosilicon, ferromanganese and pure nickel were added in turn. Then, the half of the molten alloy was poured into the ladle, the ferroboron was added to the furnace, and the molten alloy in the ladle was poured into the furnace. When the temperature reached 1630 °C, the pure aluminum was inserted into the ladle for deoxidation. Finally, the molten alloy was poured into the sand box to solidify and form the Y test block (figure 1(a)) when the molten alloy temperature dropped to 1490 °C. The test samples were austenized at 1050 °C for 2 h, followed by quenching in Oil. Subsequently, the test samples were tempered at 280 °C for 4 h. The chemical compositions of the Fe–Cr–Ni–B alloy determined by optical emission spectroscopy are shown in table 1.

2.2. Microstructure examination

The metallographic sample (sample A in figure 1(a)) whose size was 20 × 20 × 10 mm was cut form the Y test block. The etching solution consisting of 45 ml 4% picral, 5 ml hydrochloric acid and 50 ml 5% nital was used to corrode the metallographic samples. The x-ray diffraction (XRD), scanning electron microscopy (SEM) and energy dispersive x-ray spectrometry (EDS) were used to analyze the microstructure and erosion-corrosion morphology. The XRD analysis was carried on a D/Max-2400 diffractometer with copper Kα radiation at 40 kV and 30 mA as an x-ray source. The test samples were scanned in a 2θ range from 10 to 90° with an increment of 0.02° per step. The scanning electron microscopy was a TESCAN VEGAIIXMU model equipped with an energy dispersive x-ray spectrometry (Oxford 7718).

2.3. Hardness tests

The hardness of the sample A in figure 1(a) was measured by HRS-150 Rockwell hardness tester at room temperature. The applied load was 1470 N and the continued time was 10 s. The average value of ten hardness tests was the measurement result. According to ASTM standard E384-08 [13], the microhardnesses of the matrix and borocarbide in sample A (figure 1(a)) were measured by microhardness tester (HXD-1000TM). The applied loads were 0.49 N (the load for matrix) and 0.98 N (the load for borocarbide), and the continued time was 10 s. The average of twelve microhardness values was the test result.

![Figure 1. Schematics of casting Y test block (a) and erosion-corrosion sample B (b) (unit: mm).](image-url)
2.4. Erosion-corrosion tests

The erosion-corrosion performance of Fe–Cr–Ni–B alloy was studied by using erosion-corrosion tester (the structure was shown in figure 2). Cr28 white cast iron (2.51C-28.13Cr-2.21Mo, wt%, the hardness is 62 ± 0.8 HRC) was used as a comparison material. The geometric size of the erosion-corrosion sample B (figure 1) was shown in figure 1(a). The erosion-corrosion face (figure 1(b)) of the sample B was polished before the test. The erosion-corrosion slurry was composed of 8000 ml 2.4% sulfuric acid solution and 3 kg quartz sand (900–1100 HV [14]), and the size of the quartz sand was 0.63 ± 0.11 mm. The distance between the erosion-corrosion sample B and the mixing wheel center (L in figure 2) was 80 mm. The rotating speed of the mixing wheel was 1200 rev min⁻¹ and 1700 rev min⁻¹, respectively. The impingement angles were set to 0°, 30°, 45° and 60° (figure 2), respectively. Each erosion-corrosion test time was 3 h. During the test, the slurry temperature was kept at 20 ± 1°C by cooling water. The weight loss of the sample B was measured by an electronic balance, and the accuracy was 0.1 mg. The average value of three weight losses from three samples was regarded as the test result.

3. Results and discussion

3.1. As-cast microstructure and hardness

The as-cast microstructures of Fe–Cr–Ni–B alloy are shown in figure 3. The x-ray diffraction spectrum of as-cast Fe–Cr–Ni–B alloy is shown in figure 4. It can be seen from figures 3(a) and 4 that the as-cast microstructures of Fe–Cr–Ni–B alloy are composed of matrix and borocarbides [15].

According to the microhardness test values in table 2, it is determined that the matrix of Fe–Cr–Ni–B alloy is martensite. The borocarbides are distributed in the grain boundary and intragranular. The borocarbide at the grain boundary is M2(B, C) [16, 17] (as show in figure 3(b), table 2 shows the microhardness of M2(B, C), which is in the form of the network. The morphology (figure 3(e)) of M7(B, C)3 borocarbide (the microhardness is between 1300 HV and 1800 HV [18]) inside the grain is tiny rod-shaped and granular, and this morphology is different to that of M2(B, C) borocarbide. (For all the borocarbides, M stands for Fe and Cr).

The distributions of the Cr and Ni elements in M2(B, C) (figures 3(b)–(d)), M7(B, C)3 (figures 3(e)–(g)) and matrix are shown in figure 3. According to figures 3(b)–(g), for M2(B, C) and M7(B, C)3 borocarbides, the content of chromium in the two types borocarbides is higher than that in the matrix, and the content of nickel in the two types borocarbides is lower than that in the matrix.

3.2. Heat treatment microstructure and hardness

The heat-treated microstructures of Fe–Cr–Ni–B alloy are shown in figure 5. The microhardness and Rockwell hardness of Fe–Cr–Ni–B alloy are shown in table 2. According to figure 5 and table 2, the microstructures of heat-treated Fe–Cr–Ni–B alloy are composed of the martensite matrix and two types borocarbides [M2(B,C) and
Figure 3. The as-cast microstructures and EDS analyses of Fe–Cr–Ni–B alloy: (a) microstructures of as-cast Fe–Cr–Ni–B alloy; (b) showing the morphology of A area: D-matrix, E-borocarbide $[\text{M}_4(\text{B},\text{C})]$; (c) and (d) showing the distributions of chromium and nickel elements along red arrow in figure (b), respectively; (e) showing the morphology of B area: D-matrix, F-borocarbide $[\text{M}_7(\text{B},\text{C})_3]$; (f) and (g) showing the distributions of chromium and nickel elements along red arrow in figure (e), respectively.
After heat treatment, the morphologies of M2(B,C) and M7(B,C)3 borocarbides do not change significantly, which indicates that two types borocarbides have strong thermostability.

3.3. Erosion-corrosion performance of Fe–Cr–Ni–B alloy

The erosion-corrosion weight loss data of the Fe–Cr–Ni–B alloy and Cr28 white cast iron (Cr28) at different test conditions are shown in figure 6. The erosion-corrosion mechanism diagram is shown in figure 7. The morphologies of the erosion-corrosion surfaces of Fe–Cr–Ni–B alloy and Cr28 samples are shown in figures 8–10. According to figure 6, the erosion-corrosion weight loss of Fe–Cr–Ni–B alloy is lower than that of Cr28 at the same erosion-corrosion test conditions.

The hardness of the quartz sand abrasive is regarded as the Ha (Ha = 900–1100 HV [14]). In the initial stage of erosion-corrosion test (figure 7(a)), for the matrix of the Fe–Cr–Ni–B alloy (Hu1 = 536 ± 7 HV), the ratio of Hu1/Ha is under 0.8, and the quartz sand is hard abrasive compared to the matrix. So, the abrasive grain can scratch the matrix (figure 7(a)). However, for the M2(B,C) and M7(B,C)3 borocarbides in Fe–Cr–Ni–B alloy (Hu2 = 1561 ± 15 HV and Hu2* = 1300–1800 HV [18]), the ratios of Hu2/Ha and Hu2*/Ha are above 1.2, the quartz sand is soft abrasive compared to the two types borocarbides [19]. When the matrix is scratched and eroded (figure 7(b)), the abrasive grains with high speed can impact exposed borocarbides and break the borocarbides (figure 7(c)). Corresponding to the above, the hardneses of the matrix and carbide in Cr28 are 692 ± 11 HV and 1505 ± 15 HV, respectively. So, the abrasive grain can scratch the matrix, and it can make carbide broken by impact.

It can be evidenced from figure 8 that the borocarbide pits (red arrows in figure 8(b) and black arrows in figure 8(c)) and scratch marks (blue arrows in figure 8(c)) are left on the erosion-corrosion surface of Fe–Cr–Ni–B alloy. Corresponding to the analysis in figure 7 above, the matrix of Fe–Cr–Ni–B alloy is scratched and corroded by the slurry, which results in the expose of borocarbides. The exposed borocarbides are broken by the impact of abrasive grains, so the borocarbide pits appear on the erosion-corrosion surface.

The erosion–corrosion weight losses of the Fe–Cr–Ni–B alloy and Cr28 in the high rotating speed (the rotating speed of the mixing wheel is 1700 rev min−1) test condition are higher than in the low rotating speed
For Fe–Cr–Ni–B alloy, compared to the low rotating speed test condition (red arrows in figure 8(a)), it can be evidenced that the deeper and bigger borocarbide pits (red arrows in figure 9(b)) are left on the erosion-corrosion surface under the high rotating speed test condition. The mixing wheel with high rotating speed can raise the slurry flow speed, which can aggravate the matrix damage and the borocarbides breakage. Thereby, the higher erosion-corrosion weight loss of Fe–Cr–Ni–B alloy appears.
The erosion-corrosion weight losses of the Fe–Cr–Ni–B alloy and Cr28 first increase and then decrease with the increasing of the impingement angle (0°, 30°, 45° and 60°), and they reach maximum at impingement angle of 45°. For Fe–Cr–Ni–B alloy, compared with impingement angle of 0° and 60° (red arrows in figures 9(a) and (d)), it is evident that a larger amount of borocarbides are broken, and more pits are left on the erosion-corrosion surface (red arrows in figure 9(b) and black arrows in figure 9(c)) under impingement angle of 45°. It

Figure 7. The erosion-corrosion mechanism diagram: A-impingement angle, B-abrasive grains, C-matrix, D-borocarbides, E-borocarbide pits.

Figure 8. The SEM graphs of erosion-corrosion surface of Fe–Cr–Ni–B alloy: (a) The morphology of erosion-corrosion surface; (b) showing the morphology of area A in figure (a); (c) showing the morphology of area B in figure (a); for erosion-corrosion test conditions, the impingement angle is 45°, and the rotating speed of the mixing wheel is 1200 rev min⁻¹.
can be concluded that the solid particles have the most serious damage ability to the erosion-corrosion surface under the impingement angle of 45°.

It can be seen from figure 6 that the erosion-corrosion weight losses of Cr28 are higher than those of Fe–Cr–Ni–B alloy in the same erosion-corrosion test conditions. Corresponding to the above results, compared with the Fe–Cr–Ni–B alloy (figure 9(b)), the deeper and bigger carbide pits (red arrows in figures 10(a) and (b)) appear on the erosion-corrosion surface of the Cr28 sample. Compared with the Fe–Cr–Ni–B alloy, the matrix of Cr28 is corroded more seriously by slurry, and a large number of the carbides are broken. To sum up, the Fe–Cr–Ni–B alloy exhibits better erosion-corrosion resistance than Cr28.
4. Conclusions

(1) The Fe–Cr–Ni–B alloy is composed of martensite and borocarbides. The borocarbides are distributed in the grain boundary [network $M_2(B,C)$ borocarbide] and intragranular [tiny rod and granular $M_2(B,C)_3$ borocarbide]. The contents of chromium and nickel in the borocarbides are different from these in the matrix.

(2) The erosion-corrosion weight losses of Fe–Cr–Ni–B alloy and Cr28 first increase and then decrease with the increasing of the impingement angle $(0^\circ, 30^\circ, 45^\circ$ and $60^\circ$), and they reach the maximum value at $45^\circ$ impingement angle. For Fe–Cr–Ni–B alloy, the Cr28 is eroded and corroded more seriously at the same test condition, so Fe–Cr–Ni–B alloy exhibits better erosion-corrosion resistance.

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