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A Study on the Wear Behavior of Cast Boron Steel

Han-guang Fu, Jian-dong Xing, Yong-ping Lei, and Li-ming Huang

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In this study, a wear-resistant Cast Boron Steel (CBS) of nominal composition 0.25% C, 1.18% B, 1.27% Cr, 0.85% Mn, and 0.69% Si was oil-quenched at different temperatures. The effect of quenching temperature on the microstructure and wear resistance of CBS was investigated. Moreover, the wear resistance between CBS and high chromium cast iron was compared. The results show that a martensite matrix can be obtained by quenching from 900 to 1050 °C, and the wear resistance of quenched CBS is excellent, which reaches the level of high chromium cast iron. The reason behind the fact that CBS has excellent wear resistance is discussed.

Keywords borocarbide, cast boron steel, quenching temperature, wear resistance

1. Introduction

High chromium white cast irons have superior wear resistance and are widely used in mineral processing, cement production, the paper and pulp industry, thermal electric power plants, and others (Ref 1-3). Their exceptional wear resistance is the result of their high carbon and chromium concentrations, which form $(Cr,Fe)_7C_3$ carbides along with austenite during solidification. However, high chromium white cast irons suffer from shortcomings such as high concentration of alloying elements, exorbitant production cost, and propensity to deformation and fracture after heat treatment (Ref 4). The development of new type wear-resistant material is very important.

The boron present in cast steels, in combination with carbon, may form borocarbides that can be only partially dissolved at high temperatures (Ref 5, 6). The borocarbides existing in cast steels can improve the wear resistance of Cast Boron Steel (CBS) (Ref 7, 8). The aim of this study is to investigate the effect of quenching on the microstructure and wear resistance of CBS and compare the differences between the wear resistances in CBS and high chromium white cast iron, which can provide the information for the application of CBS.

2. Experimental Procedure

2.1 The Melting and Heat Treatment of Sample

The alloy used in this study was made in a laboratory induction furnace by using high-purity raw materials. 10 kg of the alloy was melted and poured at 1450 °C into a sand mold. The cavity in the sand mold was rounded bar-like, and the dimension of sample was ∅ 50 mm × 150 mm. The chemical composition of CBS is 0.25% C, 1.18% B, 1.27% Cr, 0.85% Mn, and 0.69% Si. The samples were heat treated at 900, 950, 1000, and 1050 °C, for 2 h and followed by oil cooling to the room temperature. The tempering process of samples was heating at 200 °C for 3 h, followed by cooling to the room temperature in still air.

Han-guang Fu and **Yong-ping Lei**, School of Materials Science and Engineering, Beijing University of Technology, No. 100 of Pingle Garden, Chaoyang District, Beijing 100124, People's Republic of China; and **Jian-dong Xing** and **Li-ming Huang**, School of Materials Science and Engineering, Xi'an Jiaotong University, Xi'an 710049, Shaanxi Province, People's Republic of China. Contact e-mail: fhg64@263.net.

2.2 Wear Tests

Wear test was done on a three-body abrasion machine based on the study of Boyes (Ref 9). The wear test is conducted by sliding a specimen against a circular track of mild steel buried in loose abrasives. Figure 1(a) is a sketch of a specimen being tested, and Fig. 1(b) is the specimen dimension. The load is 28.5 N. The abrasive is quartzite (about 1160 Hv) and its size is 195-355 μm, namely 45-75 mesh. One test cycle of each specimen is 150 min. The weight loss was measured every 30 min. The quartzite abrasive begins to crush, and its size begins to decrease during wear, which will influence the weight loss of specimen. The quartzite abrasive needs to be replenished every 30 min. The first 30 min was taken as "running in," and this weight loss was not accounted into the test results. The relative wear resistance of the material is referred to as β in this article, and it is taken as the ratio of the weight loss of a commercial high chromium white cast iron (its composition is 3.04% C, 15.26% Cr, 2.10% Mo, and 0.97% Cu, and its hardness is 61HRC after normalizing at 980 °C for 2 h and tempering at 350 °C for 3 h) to the weight loss of CBS. The results of the wear tests were the average values of the three samples. The weight loss was measured on a scale with a sensitivity of 0.1 mg.

The investigation techniques used for CBS microstructure characterization included optical microscopy (OM) and scanning electron microscopy (SEM). The samples were etched with 5% nital for optical microscopy examination, while a mixture of 5 cm^3 HCl, 45 cm^3 4% picral, and 50 cm^3 5% nital was used as an etchant for SEM evaluation. In order to investigate the failure of the worn surface of CBS, the taper-section method was conducted by preparing a polished metallographic surface oriented about 15° from the plane of wear (Fig. 2). In this way, it is possible to effect a magnified

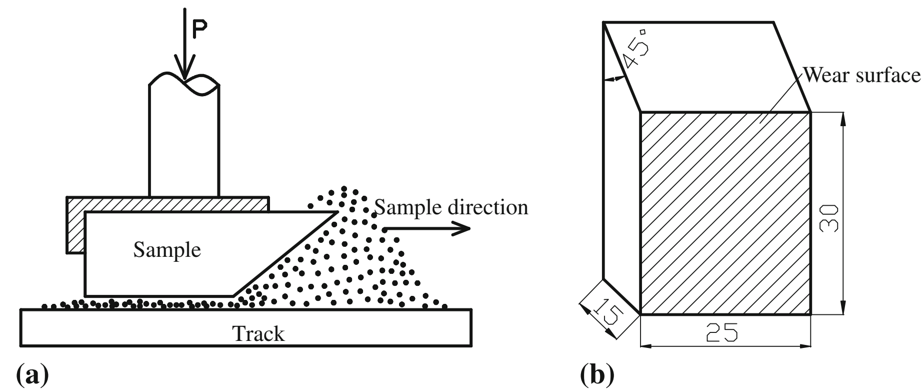

Fig. 1 Sketch of three-body abrasion machine principle and sample: (a) Sketch of sample and track in three-body test; (b) Sample used in three-body test

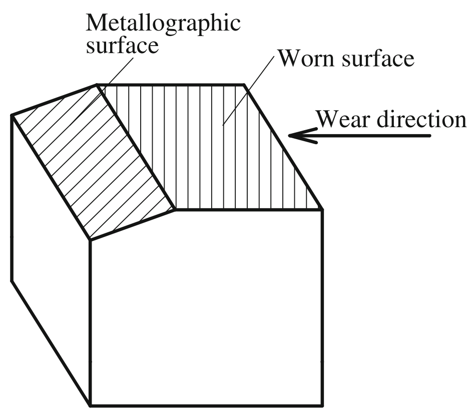

Fig. 2 Sample prepared by taper-section method

observation of the variation in subsurface structure. In the SEM, this method makes it possible to observe the worn surface and the subsurface structure simultaneously, which aids in connecting types of wear with behavior of the substrate constituents.

3. Results

3.1 Microstructure and Hardness of CBS

The as-cast structures of CBS consist of pearlite, ferrite, and $Fe_2(B,C)$ type borocarbide according to reference (Ref 8). The microhardness of $Fe_2(B,C)$ type borocarbides is 1430-1480 Hv. The macrohardness of as-cast CBS sample is 38-41 HRC (Ref 8). Oil-quenching structures and hardness of CBS in different temperatures are shown in Fig. 3-5. At the end of oil-quenching each at 900, 950, 1000, and 1050 °C, the entire metallic matrix transforms into the martensite, and the hardness of CBS exceeds 55 HRC. Because of low carbon concentration of CBS, the metallic matrix after oil-quenching is lath martensite which has high strength and toughness.

The effects of tempering temperature on structure of CBS are as follows. Retained austenite in the quenched structure begins to transform into the martensite with the increase of tempering temperature. When the temper temperature reaches 350 °C, the retained austenite in the quenched structure transforms into the martensite completely. Moreover, when the tempering temperature exceeds 200 °C, the martensite begins to decompose and the hardness of CBS begins to decrease, which maybe influence the wear resistance of CBS. So the tempering temperature of CBS is 200 °C.

3.2 Wear Resistance

Table 1 shows the wear loss and relative wear resistance β of CBS in different quenching temperature. The change of quenching temperature has no obvious effect on the wear loss and relative wear resistance β of CBS. In the three-body wear condition, CBS has excellent wear resistance and reaches the level of normalized high chromium white cast iron.

4. Discussion

4.1 SEM of Worn Surface

All of the tested samples show similar wear resistance values although they undergo quenching at different temperatures. The main reason is that the CBS at different quenching temperatures (such as 900, 950, 1000, and 1050 °C) has the same lath martensitic martix and boride, and its hardness values are equal to 55.9, 56.5, 57.5, and 57.4 HRC at quenching temperatures of 900, 950, 1000, and 1050 °C, respectively. Therefore, the wear resistances of CBS at different quenching temperatures are nearly the same.

Figure 6 is the SEM of worn surface of samples. There are many traces of surface deformation and extrusion, and the cutting trace is lesser on the worn surface of CBS, as shown in Fig. 6(a) and (b). When the abrasive pushes the CBS, CBS begins to deform and the abrasive dust of CBS is squeezed around. However, the abrasive dust of CBS does not fracture. In order to break the abrasive dust of CBS, the abrasive must act on the abrasive dust again and again, up to the work-hardening or fatigue fracture. Because CBS has high plasticity (its impact toughness reaches 16-18 J/cm^2, and the matrix is lath martensite) (Ref 8), the galling and fatigue wear are the main wear-out-failure mechanism. The cutting trace is obvious on the worn surface of high chromium cast iron, as shown in Fig. 6(c). The pitting due to the deformation and pushing shown in Fig. 6(c) is more shallow than that shown in Fig. 6(a)

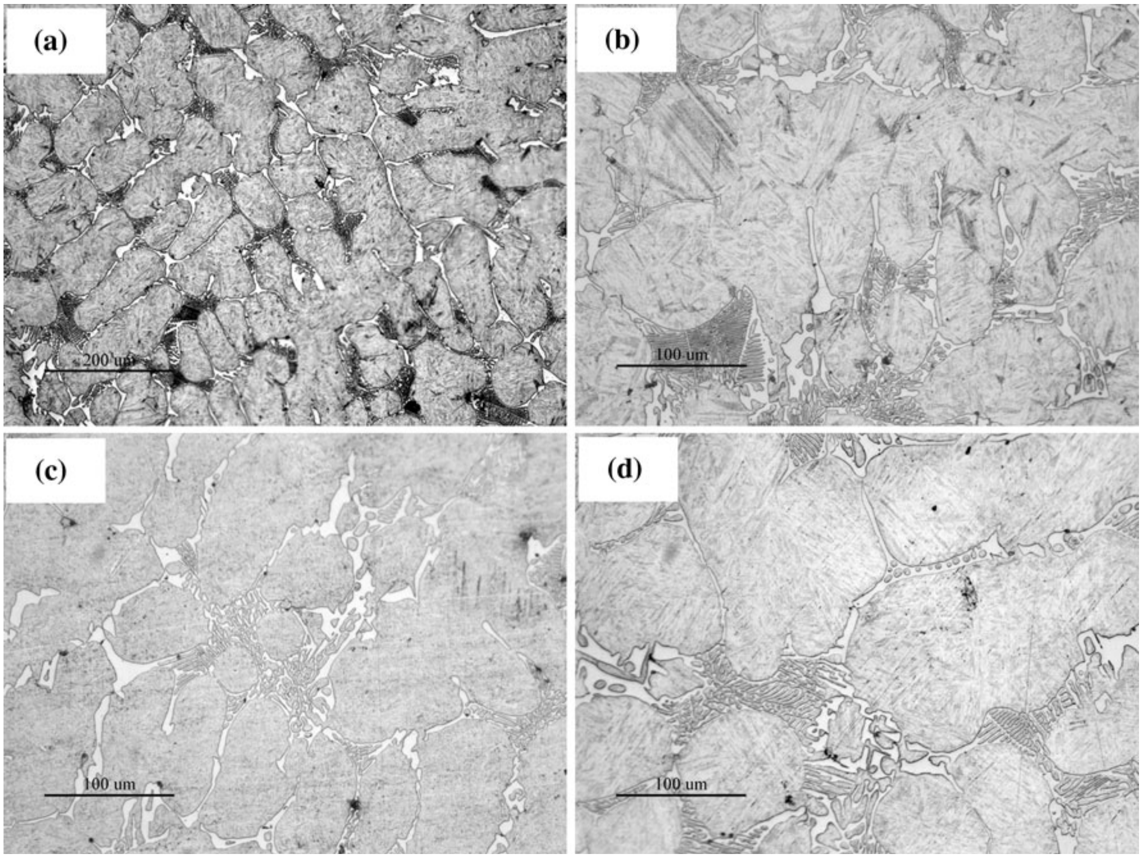

Fig. 3 Microstructures of CBS quenched from (a) 900 °C, (b) 950 °C, (c) 1000 °C, and (d) 1050 °C

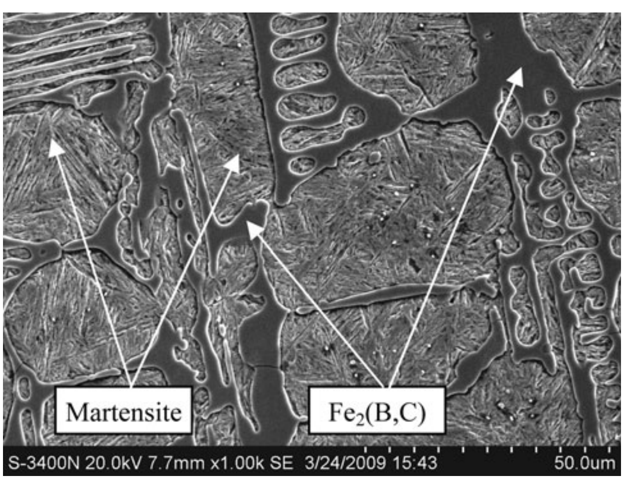

Fig. 4 SEM image of CBS quenched from 1000 °C

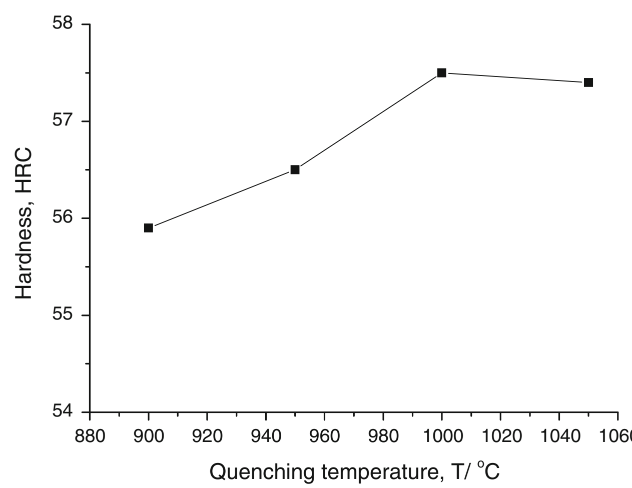

Fig. 5 Effect of quenching temperature on the hardness of CBS

and (b). Because of low plasticity (the impact toughness of high chromium cast iron is 7-10 J/cm^2 only) (Ref 8), the microcutting is the main wear-out-failure mechanism of high chromium cast iron. The galling and fatigue wear also affects the wear of high chromium cast iron.

4.2 The Microstructure Analyses of Worn Subsurface

Figure 7 is the microstructure of worn subsurface of CBS. When the abrasives extrude and cut the metallic matrix of CBS, the crack appears in the $Fe_2(B,C)$ of worn subsurface because of high brittleness and network distribution of $Fe_2(B,C)$-type borocarbide, as shown in Fig. 7(a). $Fe_2(B,C)$ type borocarbide begins to crush, scale off, and fracture in the subsequent wear, as shown in the arrowhead of Fig. 7(b), which will weaken the wear resistance of CBS.

Figure 8 is the microstructure of worn subsurface of high chromium cast iron. Because the hardness of carbide (about 1500-1600 Hv) is higher than that of abrasive (1160 Hv), it is

Table 1 The test results of three-body wear

Sample	CBS quenched from 900 °C	CBS quenched from 950 °C	CBS quenched from 1000 °C	CBS quenched from 1050 °C	High Cr cast iron
Wear loss, mg					
First	195.7	194.8	202.3	195.7	204.1
Second	191.6	197.0	200.8	191.4	200.4
Three	192.6	195.8	201.4	192.6	199.8
Average	193.3	195.9	201.5	193.2	201.4
Relative wear resistance, β	1.04	1.03	1.00	1.04	1.00

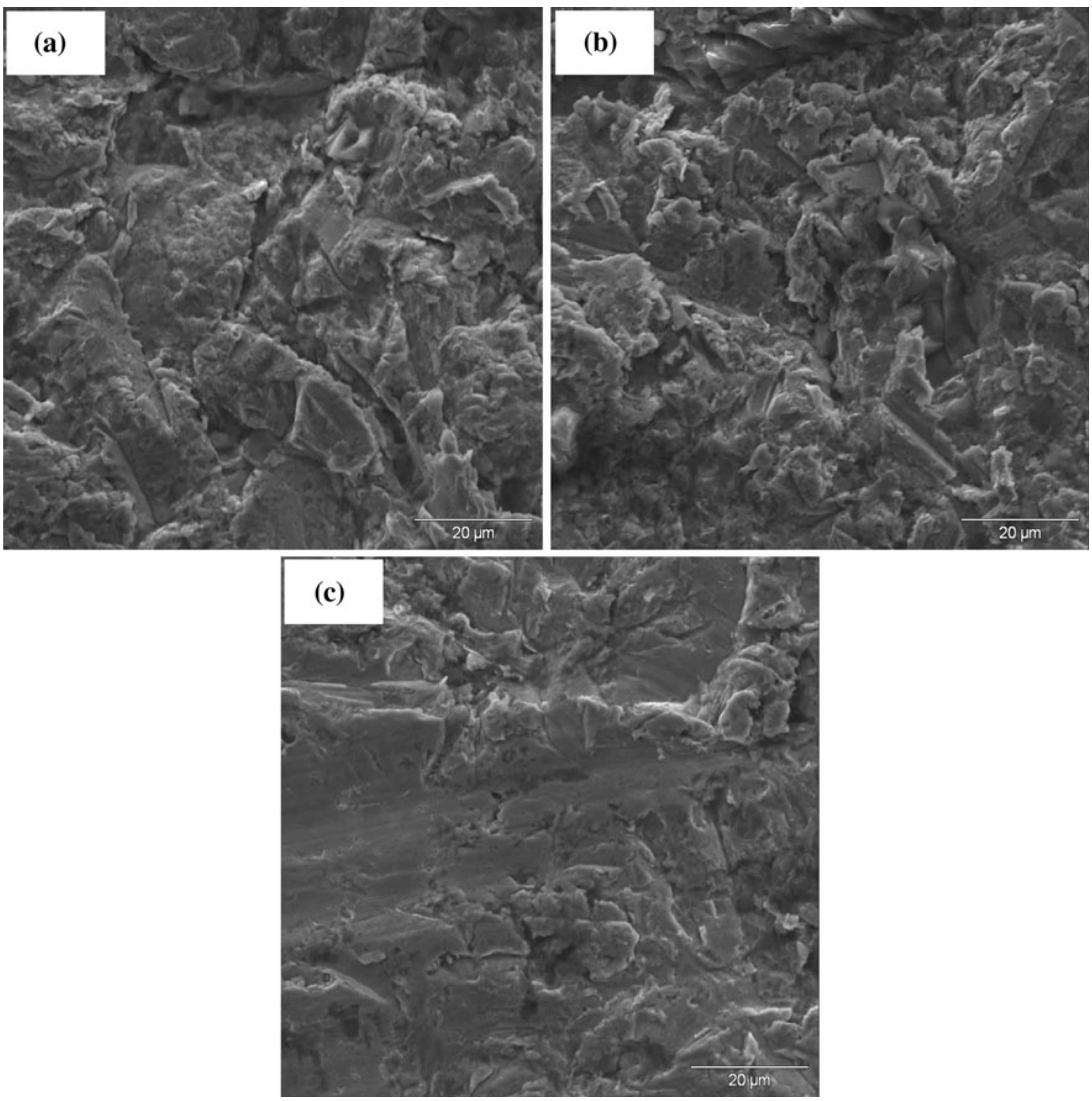

Fig. 6 SEM images of worn surface in CBS quenched from (a) 950 °C and (b) 1050 °C, and in (c) high Cr cast iron

not that easy for the abrasive to chisel off the carbides in high chromium cast iron. The carbides in the worn subsurface of high chromium cast iron have no obvious yielding tendency to crushing phenomena, as shown in Fig. 8(a). Therefore, most carbides have the ability to resist the cutting by abrasive. Some carbides begin to fracture in the wear, as shown in Fig. 8(b). Because the size of abrasive is larger (about 45-75 mesh), the amplitude of microcutting and plastic deformation in the wear is also larger; smaller $(Cr,Fe)_7C_3$-type carbides are easy to be cut along with the matrix. Larger plastic deformation leads to the fracture and scaling of carbides, as shown in Fig. 8(c). Therefore, when the size of abrasive is larger (about 45-75

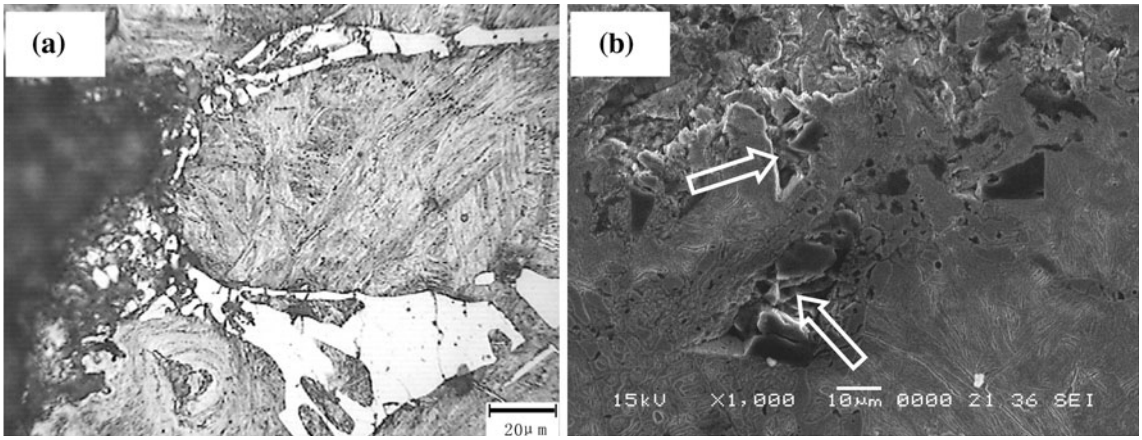

Fig. 7 Microstructure of worn subsurface in CBS quenched from 950 °C: (a) Metallurgical structure—the crack appears in the $Fe_2(B,C)$; (b) SEM image—borocarbide begins to crush, scale off, and fracture

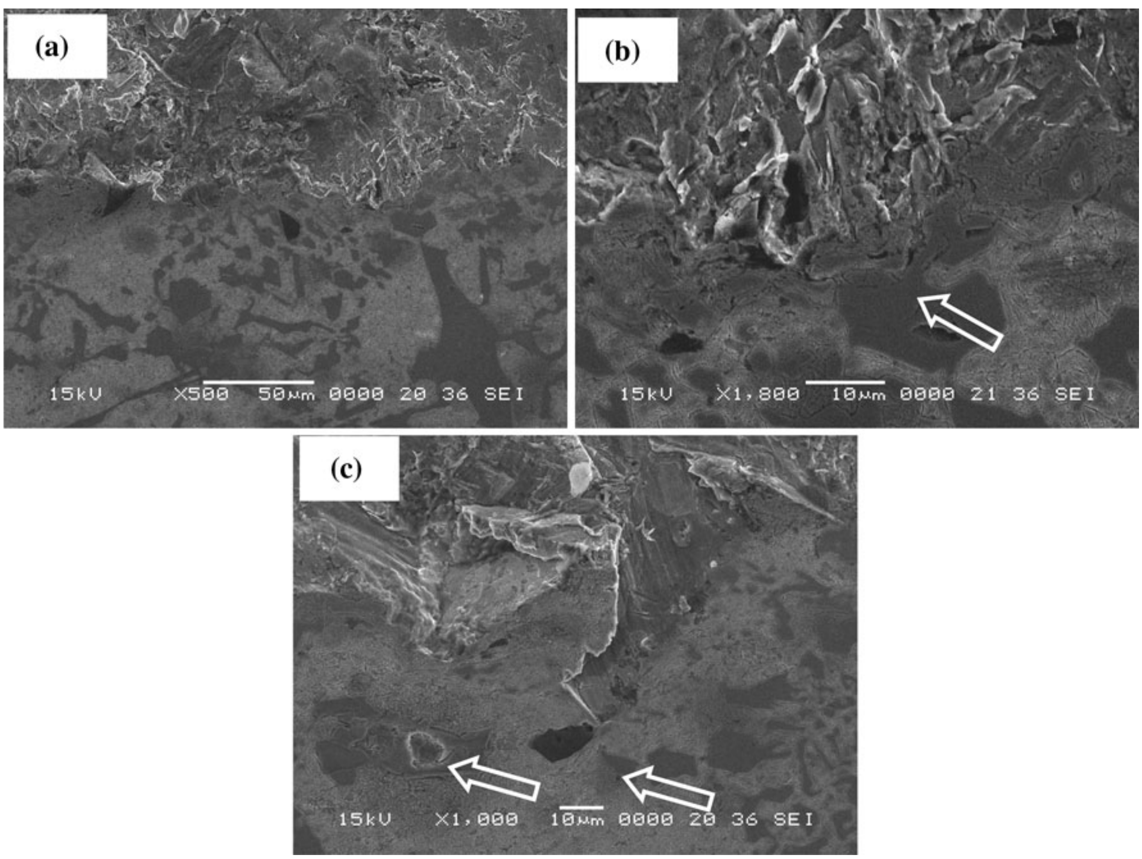

Fig. 8 Microstructure of worn subsurface in high chromium cast iron: (a) subsurface structure; (b) fracture of carbide; (c) abscission and extruding pit of carbide

mesh), the wear resistance of high chromium cast iron is slightly lower than that of CBS.

5. Conclusions

(1) The whole matrix of CBS sample transforms into the lath martensite after oil cooling at quenching temperatures in the range of 900-1050 °C.

(2) The change of quenching temperature has no obvious effect on the wear behavior of CBS.

(3) When the tempering temperature exceeds 200 °C, the martensite begins to decompose, and the hardness of CBS begins to decrease. The optimum tempering temperature of CBS is 200 °C.

(4) In the three-body wear condition, CBS has excellent wear resistance and has reached the level of high chromium white cast iron, but the cost ratio of CBS/cast iron is in the range of 0.65-0.68.

Acknowledgments

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