Effects of Heat Treatment on Wear Resistance and Fracture Toughness of Duo-Cast Materials Composed of High-Chromium White Cast Iron and Low-Chromium Steel

CHANG KYU KIM, SUNGHAK LEE, and JAE-YOUNG JUNG

The objective of this study is to investigate effects of heat treatment on wear resistance and fracture toughness in duo-cast materials composed of a high-chromium white cast iron and a low-chromium steel as a wear-resistant part and a ductile part, respectively. Different size, volume fraction, and distribution of M_7C_3 carbides were employed in the wear-resistant part by changing the amount of chromium, and the volume fraction of martensite in the austenitic matrix was varied by the heat treatment. In the alloys containing a small amount of chromium, an interdendritic structure of eutectic M_7C_3 carbides was formed, and led to the improvement of wear resistance and fracture toughness. After the heat treatment, the selective wear of the matrix and the cracking or spalled-off carbides were considerably reduced since the hardness difference between carbides and matrix decreased by the increase in the matrix hardness, thereby leading to the improvement of the wear resistance. However, the fracture toughness of the heat-treated alloys was lower than that of the as-cast alloys because the matrix containing a considerable amount of martensite did not effectively prevent the crack propagation.

I. INTRODUCTION

HYPER-EUTECTIC high-chromium white cast irons have excellent wear and corrosion resistance and are inexpensive, and thus have been used for impact coal crusher hammers, pulverizer rings, chute liner, and hardfacing alloys of rolls or molds.[1,2,3] Their excellent abrasive wear resistance is achieved from the high volume fraction of hard M_7C_3-type chromium carbides having Vickers hardness of 1200 to 1400.[4,5,6] However, these irons are not suitable for wear-resistant components, particularly those exposed to heavy impact. Thus, it is recommended for two parts, one for wear resistance and the other for toughness, to be combined to form one part.

Recently, duo-casting in which a high chromium steel having excellent wear resistance and a plain carbon steel (or a low chromium steel) having outstanding toughness are simultaneously cast has been developed.[7,8] In this method, the wear-resistant part is first cast, and then inserted into a mold to cast the ductile part, thereby making a mechanical bonding between the two cast parts. The recent study[8] on the wear-resistant alloys has focused on the improvement of microstructure and abrasive wear resistance. To ensure a wider application of duo-casting, it is required to extend the life of the wear-resistant part and to further improve its wear resistance.

Thus, in this study, the idea of heat treating duo-cast materials was suggested to further improve wear resistance because the austenitic matrix of the wear-resistant part can be hardened by forming martensite after the heat treatment. The duo-cast materials composed of a high-chromium white cast iron having excellent wear resistance and a low-chromium steel having sufficient toughness were fabricated using a duo-casting method, and effects of the size, volume fraction, and distribution of chromium carbides on hardness, wear resistance, and fracture toughness were investigated. By varying the chromium content, three wear-resistant alloys having different size, volume fraction, and distribution of chromium carbides were fabricated, and then heat treated to change the volume fraction of austenite and martensite in the matrix. From the correlation of microstructure with wear resistance and fracture toughness, optimum compositions of the wear-resistant part and heat-treatment conditions were achieved to improve the performance of the duo-cast materials.

II. EXPERIMENTAL

The wear-resistant alloys used in the current study were three hyper-eutectic high-chromium white cast irons containing primary and eutectic M_7C_3-type chromium carbides, and their chemical compositions are listed in Table I. The B alloy had the basic composition of 2.7C-27Cr-0.8Si-0.8Mn-2.0Mo-0.5Ni-Fe (wt pct), and the chromium content of the A and C alloys was varied from the basic composition to investigate the effect of the chromium addition. A low-chromium steel containing 2 wt pct chromium was used for the ductile part, with chemical composition of Fe-0.23C-1.92Cr-0.002P-0.003S (wt pct). The wear-resistant part was first cast, and then the molten metal of the ductile part was introduced into a mold and solidified to fabricate a columnar duo-cast material of 60 mm in diameter. In order to reduce the size and number of pores formed during casting, the mold was preheated to 200 °C to 300 °C, into which the molten metal of 1600 °C to 1700 °C was poured. The mold was heated throughout the entire casting process to improve

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Table I. Chemical Compositions of High-Chromium White Cast Iron Alloys Used for the Wear Resistant Part of Duo-Cast Materials (Weight Percent)

Alloy	C	Cr	Si	Mn	Mo	Ni	Fe
A	2.80	31.00	0.73	0.78	2.01	0.42	bal
B	2.73	26.90	0.73	0.78	1.86	0.51	bal
C	2.64	17.01	0.77	0.84	1.88	0.57	bal

the bonding strength of the duo-cast materials. These three duo-cast materials were austenitized at 1050 °C and then oil quenched or air cooled.

All the specimens were obtained from the wear-resistant part (10 to 20 mm apart from the bonded interface), etched in a Vilella solution (picric acid 1 g, HCl 5 mL, and ethyl alcohol 100 mL), and observed by optical microscope and scanning electron microscope (SEM). The size, volume fraction, and distribution of chromium carbides and the volume fraction of martensite formed in the matrix after the heat treatment were quantitatively analyzed by an image analyzer. Phases present in the wear-resistant alloys were analyzed by X-ray diffraction. The microstructure of the ductile part was observed by an optical microscope after etching in a 5 pct nital solution.

Bulk hardness of the wear-resistant alloys and microhardness of primary chromium carbides and matrix were measured by a Vickers hardness tester under 30 kg and 100 g loads, respectively. Microhardness of fine eutectic chromium carbides was measured under a 10 g load by an ultra microVickers hardness tester. Four-point bending tests were also conducted to evaluate the flexural bending strength of the duo-cast materials. Test specimens 5 × 5 × 50 mm in size were tested at a crosshead speed of 33.6 KN/min using a servo-hydraulic INSTRON* machine (model 8501) after the bonded interface was placed at the center of the specimen.

Abrasive wear tests were conducted on the wear-resistant alloys by a dry sand/rubber wheel abrasion wear test method in accordance with ASTM G65-85 specifications.[9] After grinding the surface of the wear-resistant alloys, wear test specimens of 25 × 75 × 18 mm in size were prepared. These specimens were worn in contact with sands (average diameter; 0.3 mm) between rubber-lined wheels under a testing load of 20 kg, and weight loss was measured to evaluate resistance to abrasive wear. The schematic illustration of the dry sand/rubber wheel abrasion wear test is shown in Figure 1. Wear testing was performed at room temperature for 25 minutes without using a lubricant, and total wear distance and rotation speed were 4500 m and 250 rpm, respectively. The worn surfaces were observed by an SEM after the wear test.

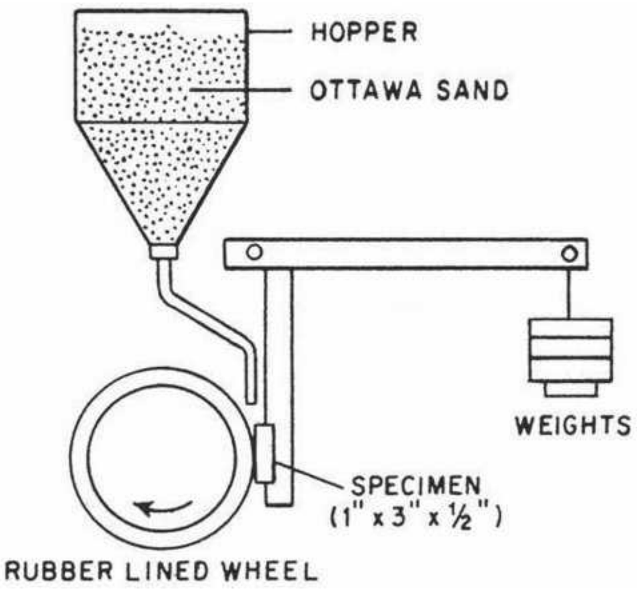

Fig. 1—Schematic illustration of the dry sand/rubber wheel abrasion wear test of the wear-resistant part.

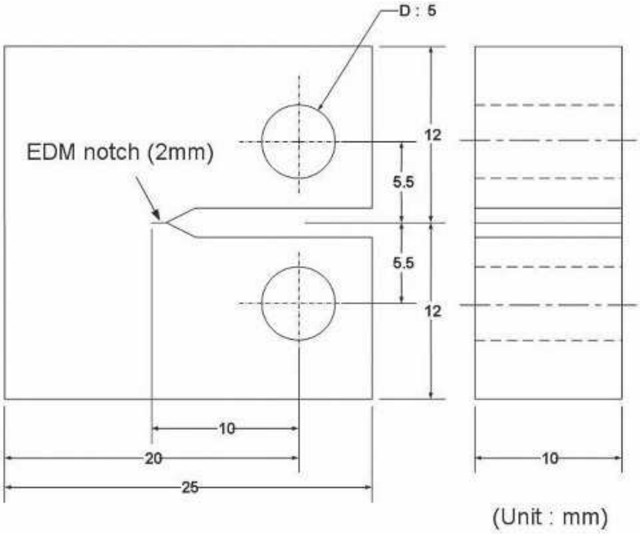

Fig. 2—Shape and dimensions of the CT type specimen with a sharp notch used for the apparent fracture toughness test (unit: mm).

Apparent fracture toughness of the wear-resistant alloys was measured using compact tension (CT)–type specimens with a sharp notch because the preparation of a fatigue precrack in these hard and brittle wear-resistant alloys was difficult. It has been reported that apparent fracture toughness measured from the sharp notched compact tension (CT) specimen (notch tip radius: 30 to 40 μm) is almost equivalent to plane strain fracture toughness, K_{IC}, in brittle materials such as ultra-high strength steels and metal matrix composites.[10–14] The CT specimen was obtained from the wear-resistant part, and a sharp notch of 35 to 40 μm in tip radius was introduced into this specimen by an electrodischarge machine. The shape and dimensions of the CT specimen are shown in Figure 2. Test and data interpretation procedures followed ASTM E399 specifications,[15] and all the test values satisfied the ASTM requirement for minimum specimen dimensions. Fracture surfaces of the fracture toughness specimens were examined by SEM.

III. RESULTS

A. *Microstructure of Duo-Cast Materials*

Figures 3(a) through (c) are optical micrographs of the wear-resistant part of the duo-cast materials. The A alloy

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*INSTRON is a trademark of Instron Corp., Norwood, MA.

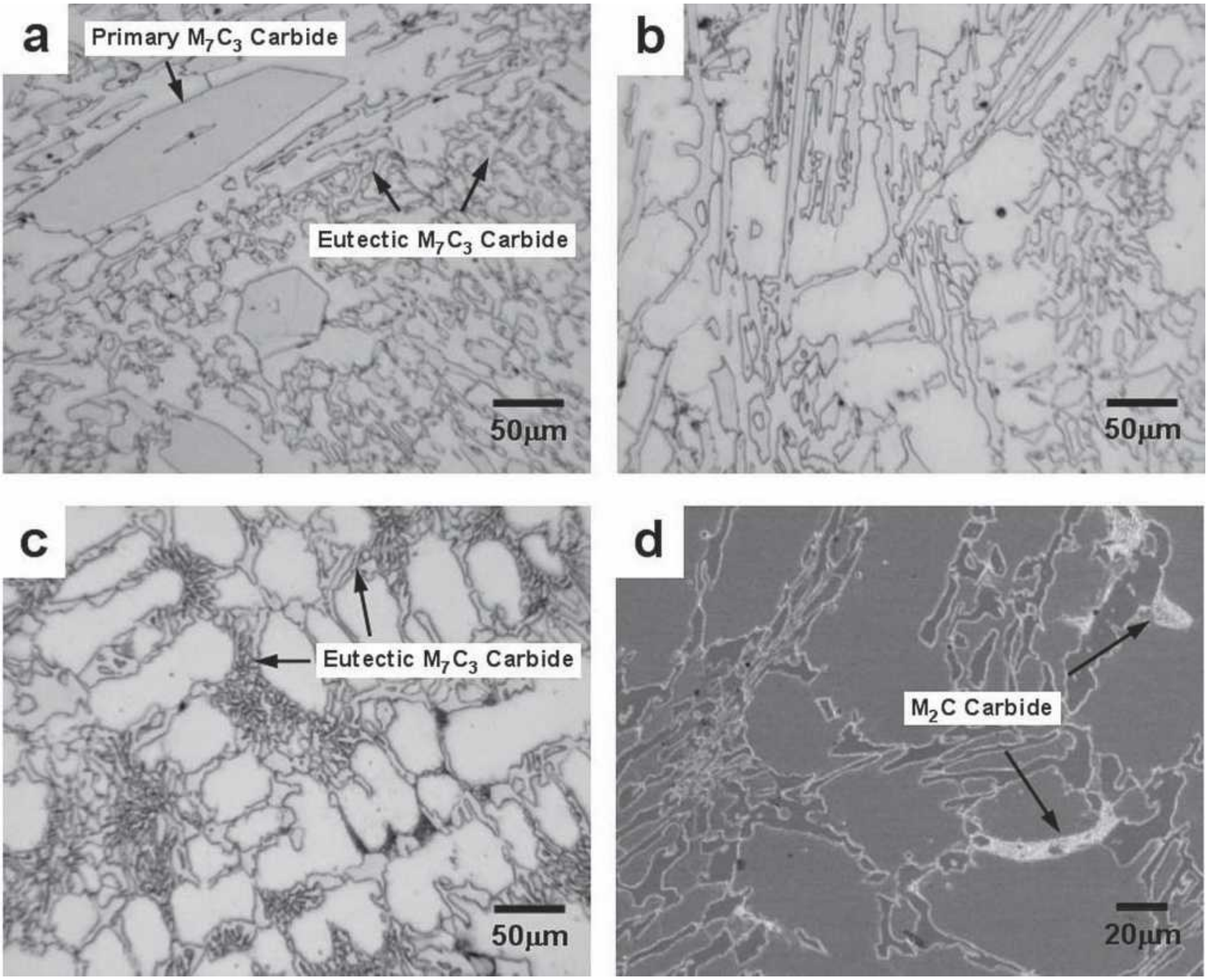


Fig. 3—Optical micrographs of the as-cast (*a*) A, (*b*) B, and (*c*) C alloys used for the wear-resistant part of the duo-cast materials. Arrows indicate large primary M_7C_3 carbides and fine eutectic M_7C_3 carbides. (*d*) An SEM micrograph of the C alloy, showing Mo-containing M_2C carbides.

has a number of large hexagonal-shaped primary M_7C_3-type chromium carbides of 50 to 100 μm in diameter and fine eutectic carbides of ~10 μm in diameter, as indicated by arrows in Figure 3(a). It was reported that large primary carbides are formed inside the molten metal after casting, and exhibit a columnar hexagonal growth.[3,16–21] The residual melt decomposes to fine eutectic carbides and austenite at the eutectic temperature (about 1250 °C), and then this austenite is retained down to room temperature as a metastable phase.

As the chromium content decreases, the volume fraction of primary carbides decreases, whereas that of eutectic carbides increases (Figures 3(b) and (c)). In the C alloy having the lowest chromium content, primary carbides are hardly observed, and eutectic carbides are interdendritically formed among dendritic arms (Figure 3(c)). In an SEM micrograph of the C alloy (Figure 3(d)), molybdenum-rich M_2C-type carbides are observed. The volume fraction of primary and eutectic carbides in the wear-resistant alloys was measured, and the results are shown in Table II. The A alloy contains 20 vol pct of primary M_7C_3 chromium carbides and 17 vol pct of eutectic M_7C_3 carbides, while the C alloy contains 28 vol pct of eutectic M_7C_3 carbides and 2 vol pct of eutectic M_2C carbides without primary M_7C_3 carbides. The B alloy is composed mainly of eutectic M_7C_3 carbides, together with a small amount (about 3 vol pct) of primary M_7C_3 carbides. Total volume fraction of carbides decreases in the order of the A, B, and C alloys, as it decreases with decreasing chromium content.

Figures 4(a) and (b) are optical micrographs of the air-cooled and oil-quenched C alloys after austenitization. The microstructure of the matrix of the heat-treated alloys is somewhat different from that of the as-cast alloy, while carbides remain unchanged. The SEM microstructures of the matrix of the air-cooled alloys are shown in Figures 5(a) through (c). A considerable amount of martensite is formed in the austenitic matrix, together with fine $M_{23}C_6$-type carbides, by the heat treatment. The volume fraction of martensite in the austenitic matrix varies with the chromium addition, as shown in Table II. The martensite volume fraction is higher in the oil-quenched alloys than in the air-cooled alloys. It

Table II. Volume Fractions of Primary and Eutectic Carbides and Martensite Formed in the Austenitic Matrix after Heat Treatment of High-Chromium White Cast Iron Alloys Used for the Wear-Resistant Part of Duo-Cast Materials

Alloy	Heat-Treatment Condition	Volume Fraction of Carbides (pct)			Volume Fraction of Martensite Formed in Austenitic Matrix (pct)
		Primary M_7C_3	Eutectic M_7C_3	Eutectic M_2C	
A	as cast	20	17	—	0
	air cooled				51
	oil quenched				58
B	as cast	3	33	—	0
	air cooled				53
	oil quenched				61
C	as cast	—	28	2	0
	air cooled				41
	oil quenched				45

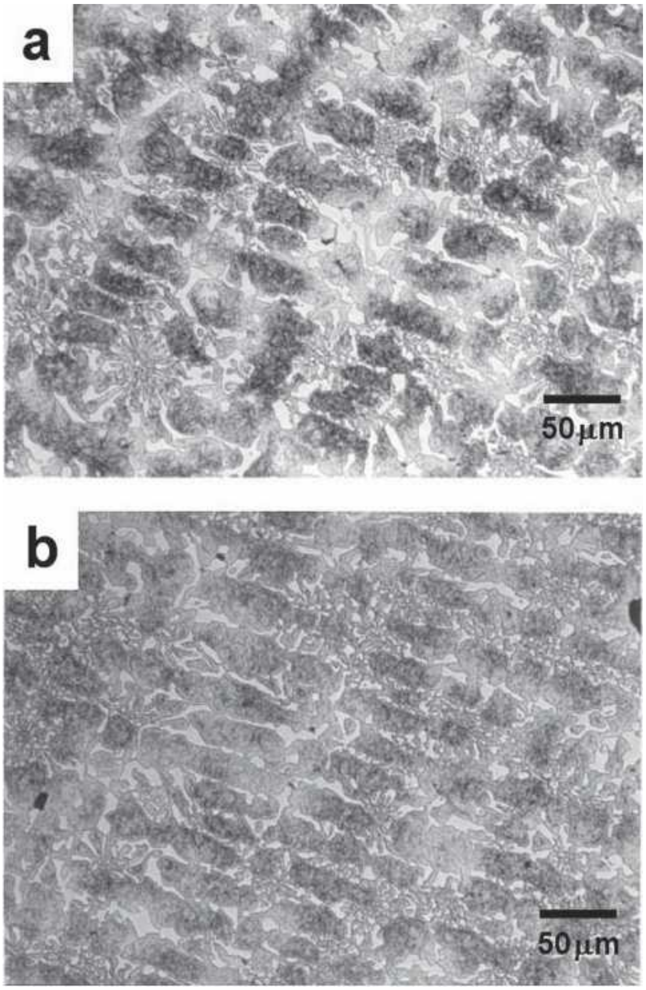


Fig. 4—Optical micrographs of the C alloy (*a*) air cooled and (*b*) oil quenched after austenitization.

is the highest in the B alloy, and decreases in the order of the A and C alloys.

An optical micrograph of the interfacial region between the wear-resistant part (C alloy) and ductile part (low-chromium steel) is shown in Figure 6. The bonded interface shows a good condition without any defects such as pores, cracks, or segregation. In the low-chromium steel, primary ferrite is formed along prior austenite grain boundaries, and pearlite is formed inside them.

B. *Hardness and Bending Strength*

Table III provides bulk hardness of the wear-resistant alloys and microhardness of M_7C_3 chromium carbides and matrix. Microhardness of primary M_7C_3 carbides in the A alloy is 1490 VHN, which is harder than that of eutectic M_7C_3 carbides in the B and C alloys. This is because the carbide hardness decreases with decreasing chromium content in M_7C_3 carbides, as shown in the energy-dispersive spectroscopy (EDS) analysis data of Table III. The bulk hardness increases in the order of the C, B, and A alloys, in proportion with the total carbide volume fraction. The hardness of the heat-treated alloys, oil-quenched alloys in particular, greatly increases as the matrix hardness increases because both the volume fraction and hardness of martensite are higher in the oil-quenched alloys than in the air-cooled alloys.

The bending test results of the as-cast duo-cast materials are shown in Table III. Their flexural bending strength ranges from 600 to 650 MPa, and shows a similar trend to that of bulk hardness. Figure 7 shows a fracture mode of the duo-cast material after the bending test. A crack initiates and propagates at the wear-resistant part, instead of the bonded interfacial region between the wear-resistant part and ductile part. This indicates that the bonded interface is quite good. Thus, in the current study, optimum compositions and heat-treatment conditions of the wear-resistant part are particularly focused because the wear-resistant part mainly determines the performance of the duo-cast materials.

C. *Abrasive Wear Resistance*

The abrasive wear test results of the wear-resistant alloys are shown in Table III. In the as-cast alloys, measured weight loss increases as the total carbide volume fraction increases. This is opposite to the general understanding that wear resistance improves with increasing hardness. In order to investigate the cause, worn surfaces of the as-cast A and C alloys were observed using an SEM as shown in Figures 8(a) and (b). The worn surface of the A alloy is very rough (Figure 8(a)), and the surface roughness tends to improve in the C alloy (Figure 8(b)). The dark areas indicated by arrows in Figure 8(a) were sectioned perpendicular to the worn surface, and were observed as shown in Figure 8(c). In the A alloy, the worn surface is considerably roughened because of the selective wear of the matrix, and some carbides near the worn surface are cracked (Figure 8(c)). This implies that the wear

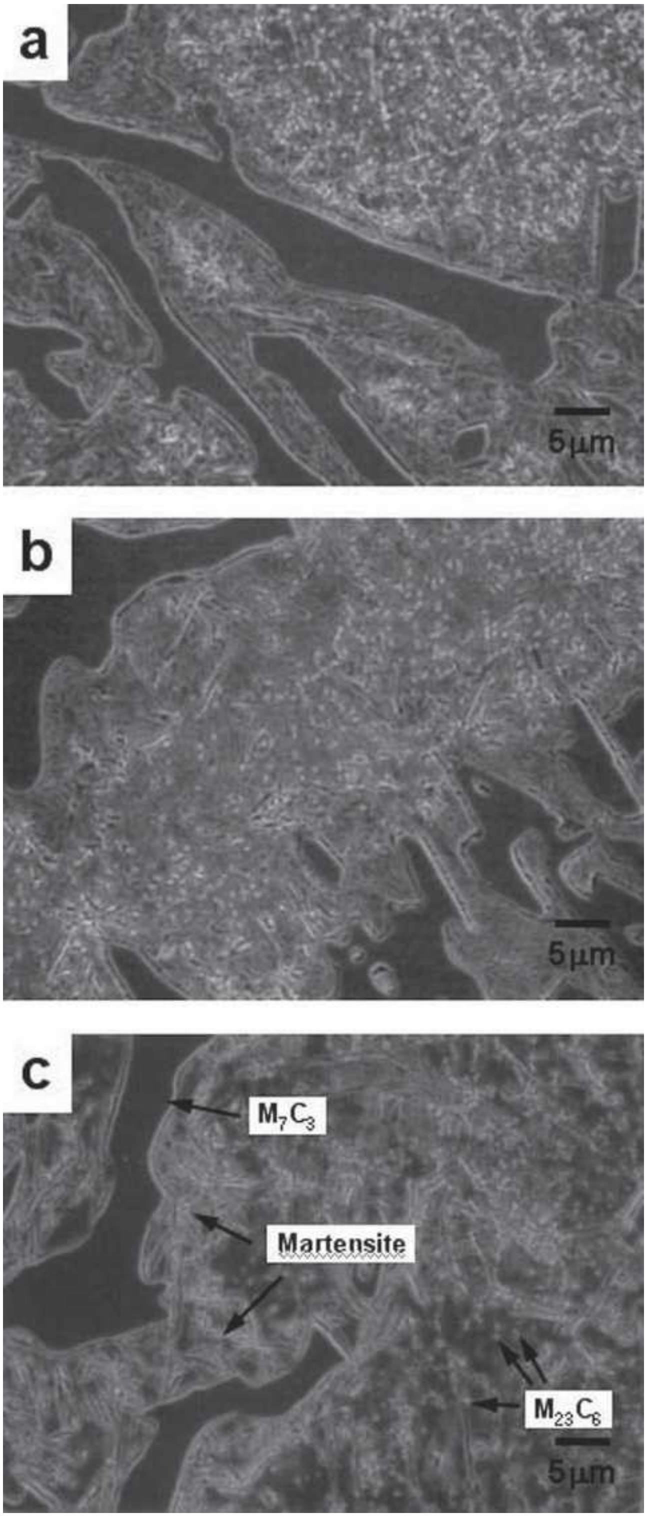


Fig. 5—SEM micrograph of the air cooled (*a*) A, (*b*) B, and (*c*) C alloys, showing martensite and fine $M_{23}C_6$ carbides in the austenitic matrix.

load is concentrated at carbides, which are then cracked or spalled off from the matrix.[22,23] On the other hand, few microcracks are found in the area beneath the worn surface of the C alloy (Figure 8(d)). The worn surface is in good condition because of the considerably simultaneous wear of the matrix and carbides and the existence of a few cracked carbides.

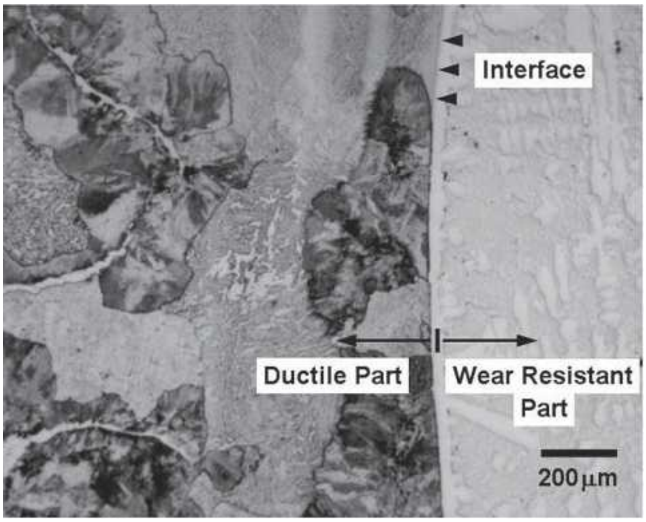


Fig. 6—Optical micrograph of the bonded interfacial region of the as-cast C alloy.

The wear loss of the heat-treated alloys is also shown in Table III. It is quite lower than that of the as-cast alloys, and the wear loss of the air-cooled alloys is slightly higher than that of the oil-quenched alloys. Figures 9(a) and (b) are SEM micrographs of worn surfaces of the air-cooled A and C alloys. The surface of the A alloy shows a typical abrasive wear mode in which grooves are formed in the wear direction (Figure 9(a)). Some carbide protrusions due to selective wear of the matrix are observed on the worn surface. The wear behavior of the C alloy is similar to that of the A alloy, but the size of carbide protrusions is finer in the C alloy (Figure 9(b)). The surface roughness of the air-cooled alloys is smoother than that of the as-cast alloys. Figures 9(c) and (d) are SEM micrographs of the cross-sectional area beneath the worn surface of the air-cooled A and C alloys. The worn surfaces are in good condition because the matrix and carbides are simultaneously worn because the cracking of precipitates hardly occurs.

D. *Apparent Fracture Toughness*

The apparent fracture toughness data of the wear-resistant alloys are shown in Table III. The fracture toughness of the as-cast wear-resistant alloys tends to decrease as the total carbide fraction increases with increasing chromium content. This indicates that carbides act as fracture initiation sites and reduce the fracture toughness.[24] The fracture toughness of the heat-treated alloys, particularly the oil-quenched alloys, is lower than that of the as-cast alloys because a considerable amount of brittle martensite is formed in the austenitic matrix after the heat-treatment.

Figures 10(a) through (e) are typical SEM fractographs of the fracture toughness specimens. The major fracture mode is cleavage fracture accompanied by a small amount of ductile rupture. The fractured surface of the as-cast A alloy is predominated by cleavage fracture with almost none of ductile fracture (Figure 10(a)). A number of large primary carbides, whose shapes are hexagonal and columnar, are pulled out or broken to form cleavage fracture facets. In the as-cast C alloy, the dimpled fracture regions exist between cleavage facets as shown in Figure 10(c), reflecting the improvement

Table III. Hardness, Bending Strength, Wear Loss, and Apparent Fracture Toughness of High-Chromium White Cast Iron Alloys Used for the Wear-Resistant Part of Duo-Cast Materials

Alloy	Heat-Treatment Condition	Hardness* (VHN)			Cr in M_7C_3** (Wt Pct)	Bending Strength (MPa)	Wear Loss (g)	Apparent Fracture Toughness $\left(\mathrm{MPa}\sqrt{\mathrm{m}}\right)$
		Bulk	Carbide	Matrix				
A	as cast	564	1491	333	66	649	0.177	24.7
	air cooled	794	—	665	—	—	0.107	20.4
	oil quenched	869	—	669	—	—	0.104	19.4
B	as cast	541	1319	331	61	635	0.145	25.9
	air cooled	808	—	669	—	—	0.095	23.5
	oil quenched	866	—	678	—	—	0.090	22.9
C	as cast	474	1177	291	51	592	0.136	27.4
	air cooled	741	—	566	—	—	0.115	24.6
	oil quenched	765	—	588	—	—	0.109	23.2

*The bulk hardness and microhardness of primary chromium carbides and matrix were measured under 30 kg and 100 g loads, respectively. The microhardness of fine eutectic chromium carbides present in the B- and C-alloys was measured under a 10 g load.

**The amount of chromium in M_7C_3 carbides was measured by EDS analysis.

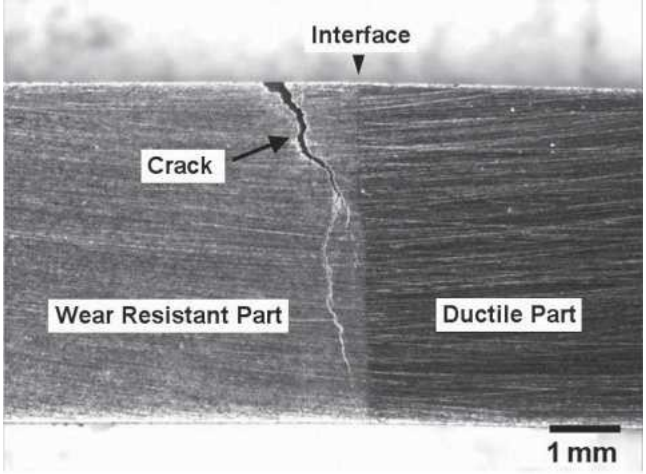


Fig. 7—Low-magnification optical micrograph showing the fracture mode of the four-point bend specimen of the as-cast C alloy. Note that cracking occurred inside the wear-resistant part, instead of in the bonded interfacial region.

of the apparent fracture toughness. This ductile fracture mode indicates that fracture proceeded partly to the austenite matrix as well as to carbides. In the heat-treated C alloys, cleavage fracture predominantly occurs because brittle martensite in the austenitic matrix plays a role in promoting the cleavage crack propagation (Figures 10(d) and (e)).

IV. DISCUSSION

Thus, in order to evaluate wear resistance under various wear environments, an understanding of wear mechanisms is required. Hypereutectic high-chromium white cast irons have excellent wear resistance since they have a high volume fraction of M_7C_3 chromium carbides. Wear mechanisms can be roughly classified into abrasion, erosion, adhesion, and surface fatigue. Considering that most of them are associated with microfracture occurring in materials, the wear resistance is closely related with fracture toughness. In order to improve both the wear resistance and fracture toughness simultaneously, the size, volume fraction, and distribution of chromium carbides, together with the role of the matrix, should be studied in detail. In the current study, three wear-resistant alloys having different size, volume fraction, and distribution of carbides were fabricated by varying the chromium content, and then heat treated to change the volume fraction of martensite in the austenitic matrix.

The formation of M_7C_3 carbides present in high-chromium white cast irons can be predicted from the solidification process. During solidification, primary carbides are first formed, and the residual liquid phase near solidification cells is decomposed into eutectic carbides and austenite as a result of eutectic reaction. When the chromium content exceeds 30 wt pct, a significant amount of large primary carbides are formed, whereas the eutectic carbide formation is promoted when the amount of primary carbides is reduced as the chromium content decreases. Because of the high volume fraction of hard primary M_7C_3 carbides, the bulk hardness in the as-cast A alloy is the highest (Table III). However, the wear test data show an opposite trend to the general understanding that wear resistance improves with increasing hardness.[25] This can be associated with the hardness variation between carbide and matrix and with a selective wear of the matrix. A number of hard primary carbides near the surface are spalled off as they are cracked, as shown in Figure 8(c). Thus, the wear resistance of the as-cast A alloy deteriorates because primary carbides are easily cracked or removed during the wear process, despite the high hardness. Because these primary carbides are readily fractured even under a low wear load, the fracture toughness also deteriorates (Table III, Figure 10(a)).

On the contrary, the as-cast C alloy composed of eutectic carbides instead of primary carbides shows a lower hardness than the as-cast A alloy because of the decrease in the volume fraction of M_7C_3 carbides, but it has better wear resistance. This is because eutectic carbides are uniformly distributed among dendritic arms to form an interdendritic structure, which effectively prevents carbides from easy cracking under an applied load and leads to wear relatively homogeneous wear, as shown in Figures 8(b) and (d). Eutectic carbides are hardly cracked or spalled off during the wear process or the fracture process, and thus, both the abrasive wear resistance and fracture toughness improve.

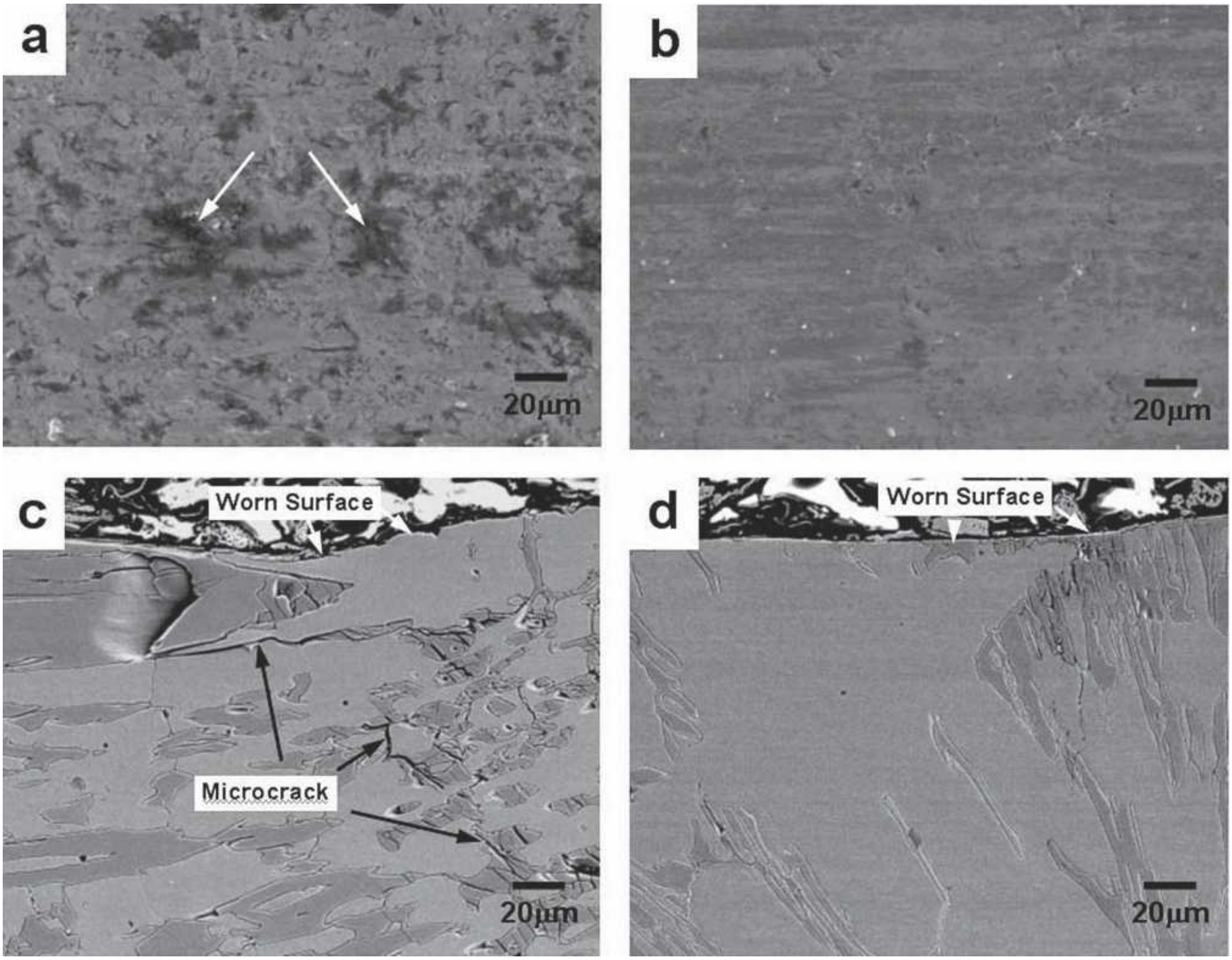


Fig. 8—SEM micrographs of the worn surface of the wear specimens of the as-cast (*a*) A and (*b*) C alloys. (*c*) and (*d*) are SEM micrographs of the cross-sectional area beneath the worn surface of the as-cast A and C alloys, respectively.

Considering that the distribution of carbides of the heat-treated alloys is the same as that of the as-cast alloys, the wear resistance of the heat-treated alloys is greatly affected by characteristics of the matrix. Parts of the austenitic matrix formed during duo casting are transformed to martensite after austenitization followed by oil quenching or air cooling (Figure 4(c)). Thus, the matrix hardness increases after the heat treatment, and that of the oil-quenched alloys is higher than that of the air-cooled alloys (Table III). The increased matrix hardness improves the overall bulk hardness and consequently the wear resistance of the heat-treated alloys. In the case of the wear resistance, the wear test results of the heat-treated alloys are quite different from those of the as-cast alloys. This implies that the wear resistance cannot be well explained by only the matrix hardness or the overall hardness.

The correlations between the matrix hardness, volume fraction of martensite present in the matrix, matrix/carbide hardness difference, and wear loss are shown in Figures 11(a) through (c). The wear loss decreases proportionally with increasing matrix hardness or volume fraction of martensite present in the matrix (Figures 11(a) and (b)). The wear resistance of the wear-resistant alloys can be more reasonably explained by taking into consideration the hardness difference between M_7C_3 carbides and matrix. The wear loss increases proportionally with the increasing matrix/carbide hardness difference (Figure 11(c)), and its correlation is better than that between the wear loss and matrix hardness or volume fraction of martensite. The matrix/carbide hardness difference is large in the as-cast alloys, but decreases as the matrix hardness increases after heat treatment, thereby greatly improving the wear resistance of the heat-treated alloys. Particularly, in the A alloys, the heat-treated alloys have greatly enhanced wear resistance because the matrix/carbide hardness difference is much reduced after the heat treatment. Thus, the matrix/carbide hardness difference plays a major role in determining the wear resistance, although other parameters such as hardness and volume fraction of carbides and matrix hardness influence it simultaneously.

In the as-cast alloys, the matrix/carbide hardness difference is large, the matrix is selectively worn during the wear process, and carbides are easily cracked or spalled off from

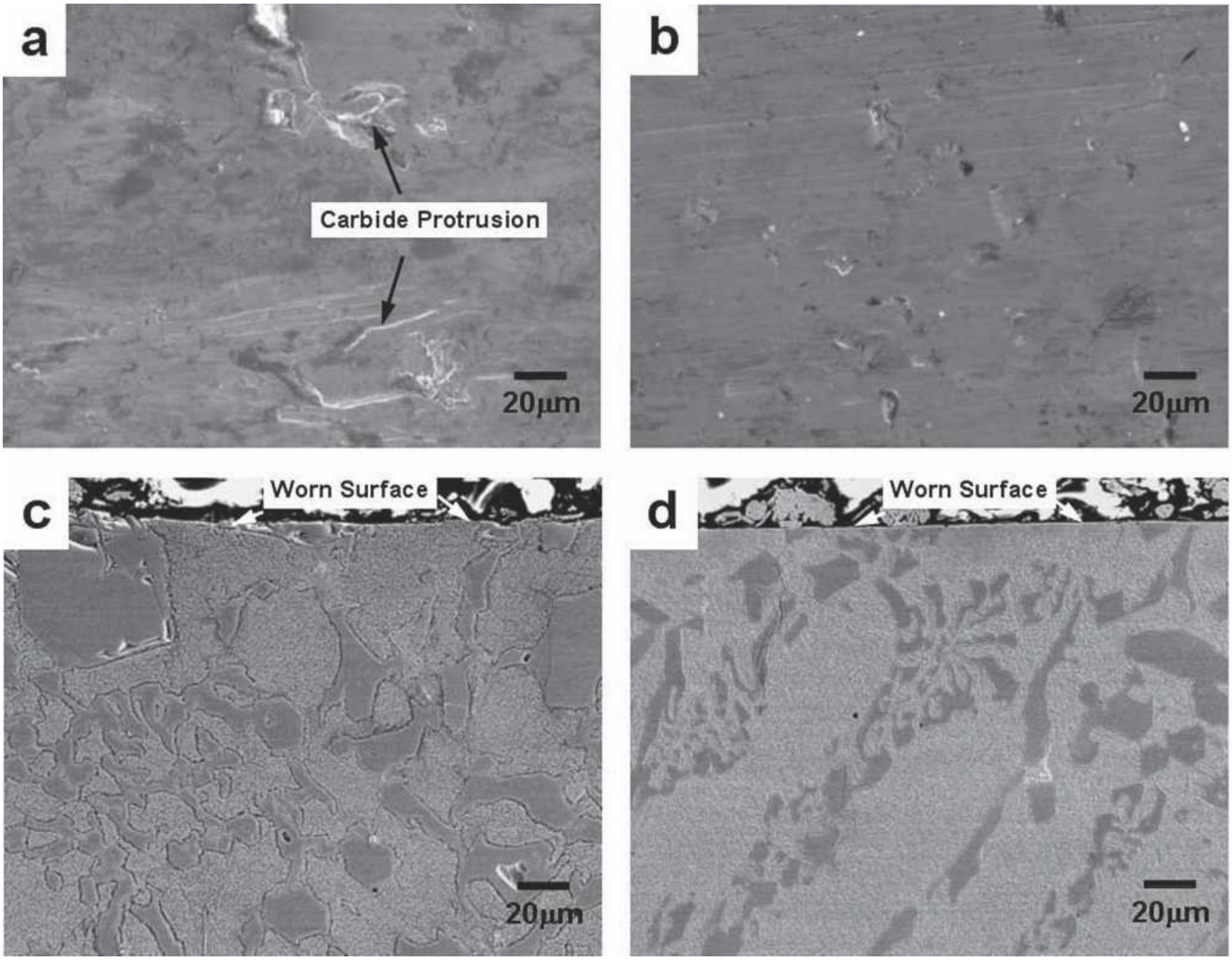


Fig. 9—SEM micrographs of the worn surface of the wear specimens of the (*a*) A and (*b*) C alloys air cooled after austenitization. (*c*) and (*d*) SEM micrographs of the cross-sectional area beneath the worn surface of the air-cooled A and C alloys, respectively.

the matrix. Spalled-off carbides work as wear debris, and accelerate the abrasive wear, resulting in a decrease in the wear resistance.[26] In the heat-treated alloys, on the other hand, the selective wear of the matrix and the cracking or spalled-off carbides are considerably reduced because the matrix/carbide hardness difference decreases by the increase in the matrix hardness, thereby leading to the improvement of the wear resistance. It is observed from the SEM micrographs of the cross-sectional area beneath the worn surface of the heat-treated alloys (Figures 9(c) and (d)) that the almost flat worn surface is maintained and the carbide cracking decreases after the heat treatment. However, the fracture toughness of the heat-treated alloys is lower than that of the as-cast alloys, whereas both the hardness and wear resistance are higher (Table III). This is because the matrix containing a considerable amount of martensite does not effectively prevent the propagation of cracks initiated at carbides.[24]

These results indicate that wear resistance and fracture toughness of the wear-resistant part of the duo-cast materials are closely related with the size, volume fraction, and distribution of M_7C_3 chromium carbides and with the volume fraction of martensite in the austenitic matrix. The matrix/carbide hardness difference also plays an important role in analyzing the wear resistance. Considering the improvement of both wear resistance and fracture toughness of the as-cast alloys, it is desirable to add less than 30 wt pct chromium in order to avoid the formation of primary carbides and to form an interdendritic structure of eutectic carbides. It can be concluded that the as-cast C alloy is the one with most excellent wear resistance and fracture toughness. In the case of the heat-treated alloys, the wear resistance and fracture toughness of both the B and C alloys are similarly excellent because the matrix/carbide hardness difference decreases after the heat treatment.

V. CONCLUSIONS

Effects of the size, volume fraction, and distribution of M_7C_3 carbides and the matrix characteristics on the wear

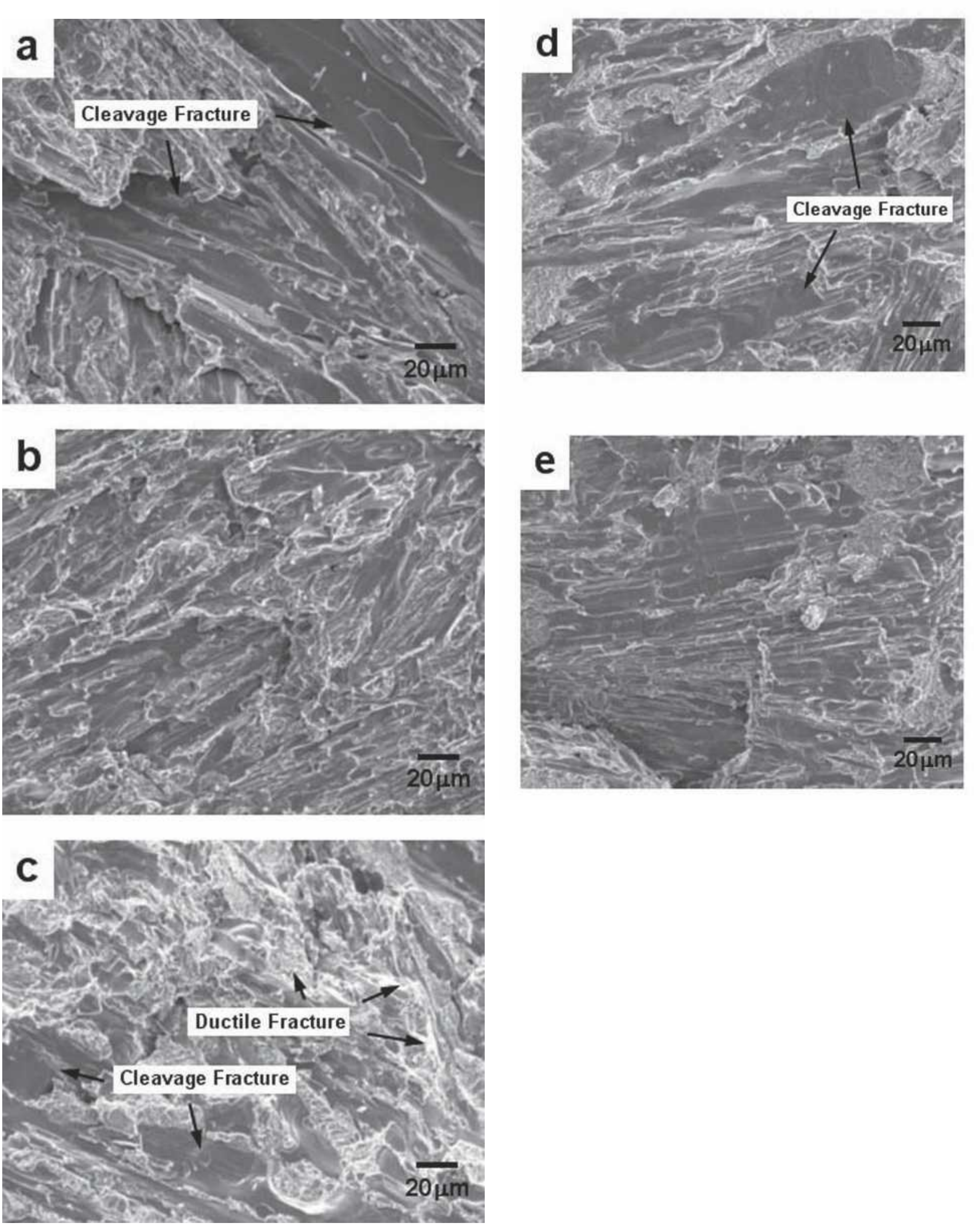
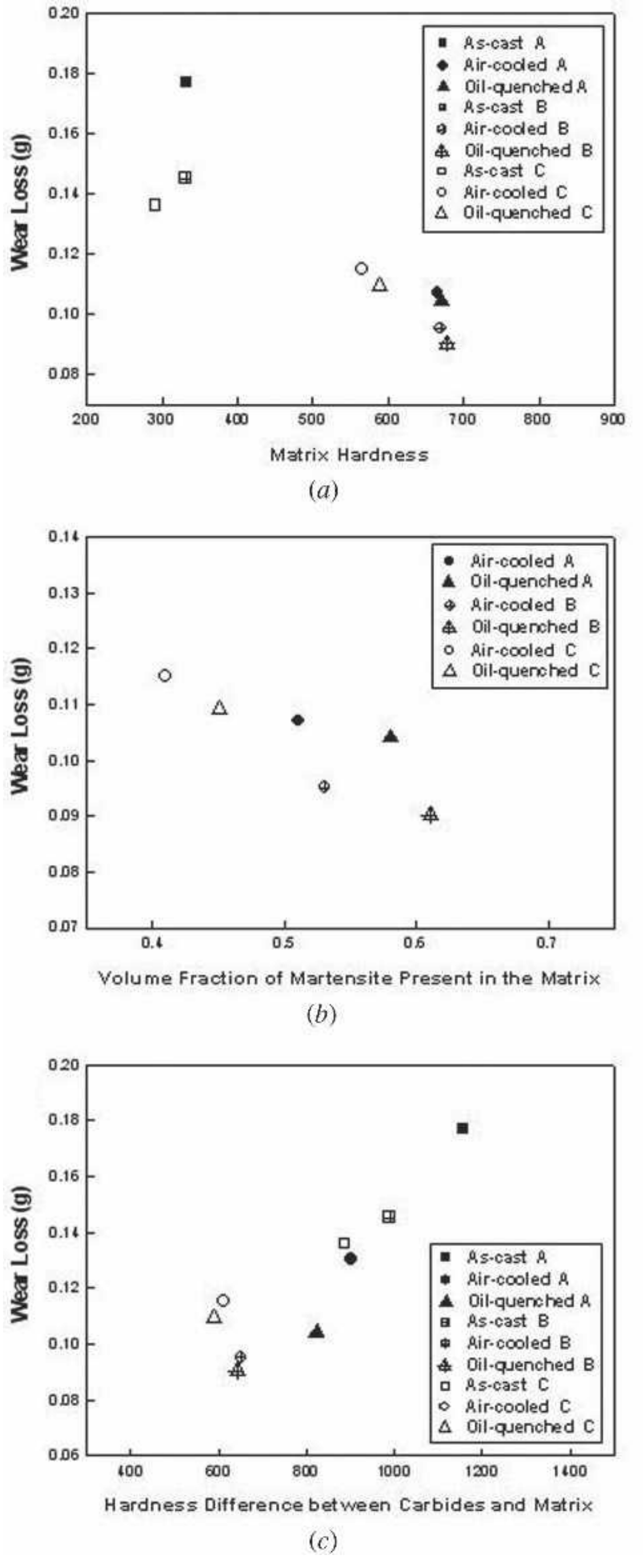


Fig. 10—SEM fractographs of the fracture toughness specimens of the (*a*) as-cast A, (*b*) as-cast B, (*c*) as-cast C, (*d*) air-cooled C, and (*e*) oil-quenched C alloys.

resistance and fracture toughness in duo-cast materials composed of a high-chromium white cast iron and a low-chromium steel were investigated in this study.

1. In the alloy containing chromium over 30 pct, both hexagonal-shaped, large primary M_7C_3 chromium carbides and fine eutectic M_7C_3 chromium carbides were present



(*a*)

(*b*)

(*c*)

Fig. 11—(*a*) Matrix hardness, (*b*) volume fraction of martensite present in the matrix, and (*c*) hardness difference between carbides and matrix *vs* wear loss of the high-chromium white cast iron alloys.

in the austenitic matrix. With decreasing the chromium amount, the fraction of primary carbides decreased, whereas that of eutectic carbides increased. After the heat treatment, a considerable amount of martensite was formed in the austenitic matrix, while M_7C_3 carbides were maintained.

2. Since large primary M_7C_3 carbides formed by the high chromium addition were brittle and readily spalled off from the matrix during the wear process, they worked adversely on the wear resistance and fracture toughness. On the other hand, in the alloys containing a smaller amount of chromium, an interdendritic structure of eutectic M_7C_3 carbides having lower hardness than primary carbides was formed, thereby enhancing both the wear resistance and fracture toughness simultaneously.
3. In the heat-treated alloys, the selective wear of the matrix and the cracking or spalled-off carbides were considerably reduced since the hardness difference between the carbides and matrix decreased by the increase in the matrix hardness after the heat treatment, thereby leading to the improvement of the wear resistance. However, their fracture toughness was lower than that of the as-cast alloys because the matrix containing a considerable amount of martensite did not effectively prevent the crack propagation.

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