JTTEE5 15:323-328
DOI: 10.1361/105996306X92541
1059-9630/$19.00 © ASM International

Technical Note

Dry Sliding Wear Behavior of Ceramic-Metal Composite Coatings Prepared by Plasma Spraying of Self-Reacting Powders

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(Submitted 15 April 2005; in revised form 18 October 2005)

Ceramic-metal composite (CMC) coatings were deposited on the surface of Fe-0.14-0.22 wt.% C steel by plasma spraying of self-reacting Fe_2O_3-Al composite powders. The dry sliding friction and wear character of the CMC coatings are investigated in this paper. The wear resistance of the CMC coatings was significantly better than that of Al_2O_3 coatings under the same sliding wear conditions. The tough metal, which is dispersed in the ceramic matrix, obviously improved the toughness of the CMC coatings. Wear mechanisms of the CMC coatings were identified as a combination of abrasive and adhesive wear.

Keywords: air plasma spraying, ceramic coating, wear and friction, wear mechanisms

1. Introduction

The deterioration of equipment parts, such as wear, corrosion, and high-temperature oxidation, usually begins at their surfaces when they work under high temperature, high pressure, and corrosive conditions (Ref 1-3). Surface engineering is a cost-efficient method for producing materials, tools, and machine parts that must resist severe wear conditions. To handle modern industry requirements, ceramic coatings prepared by thermal spraying are widely used to enhance the wear resistance of many types of equipment components (Ref 4). However, because the actual wear resistance of a coated part depends both on the hardness and toughness of the protective coating material, the application range of ceramic coatings is limited by the brittleness of ceramics. To improve the wear resistance of ceramic coatings, some tough phases, such as metals or other oxide ceramics, which can increase the coating toughness, are mixed with the ceramic powders for producing of composite sprayed coatings (Ref 5). However, the improvement in wear resistance obtained with this approach can be limited due to the segregation of the two different powders occurring during spraying, which results in a nonuniform distribution of the addition material in the coatings.

Ceramic-metal composite (CMC) coatings made by plasma spraying of Fe_2O_3-Al self-reacting composite powders possess higher toughness than single-phase ceramic coatings, because the metal and ceramic concurrently formed through reaction during spraying and, consequently, were dispersed uniformly in the coating. In the present work, sliding wear tests of these CMC coatings were performed under dry sliding conditions. For the sake of comparison, pure Al_2O_3 ceramic coatings made by plasma spraying were tested under the same conditions.

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2. Experimental Procedures

2.1 Materials

The agglomerated Fe_2O_3-Al composite powders prepared according to the technique described elsewhere (Ref 6). The powders were sieved to 40-80 μm and sprayed onto Q235 (Fe-0.14-0.22 wt.% C) steel substrates. The spray parameters were given in a previously published paper (Ref 6). Reaction of Fe_2O_3-Al took place in the plasma flame according to the following reaction equations:

$$Fe_2O_3 + 2Al = 2Fe + Al_2O_3 + 836\ kJ \quad \text{(Eq 1)}$$

$$4Fe_2O_3 + 6Al = 3FeO + 3Al_2O_3 + 5Fe \quad \text{(Eq 2)}$$

$$Al_2O_3 + FeO = FeAl_2O_4 + 39\ kJ \quad \text{(Eq 3)}$$

$$3Fe + Al = Fe_3Al \quad \text{(Eq 4)}$$

$$Fe + Al = FeAl \quad \text{(Eq 5)}$$

The reaction products, Al_2O_3, $FeAl_2O_4$ spinel, Fe-Al alloy, and metal Fe, formed the CMC coatings on the Q235 steel substrates.

Pure Al_2O_3 coatings were prepared by spraying commercially available α-Al_2O_3 powders, the size of which is 30-50 μm, supplied by Beijing Langqiao Technology and Trade Company Limited China. The spraying parameters of this powder are given in Ref 7.

2.2 Wear Tests

Dry sliding wear tests were carried out on a MM-200 wear test machine made in Xuanhua Material Test Machine Co. Ltd, China. Figure 1 shows the wear test configuration. The CMC-coated samples, 9 × 10 × 12 mm, were motionless during the

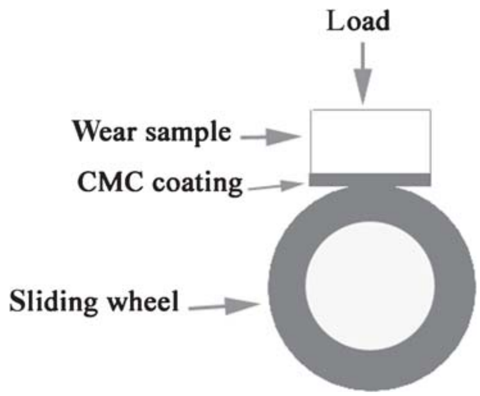


Fig. 1 Schematic showing the wear test configuration

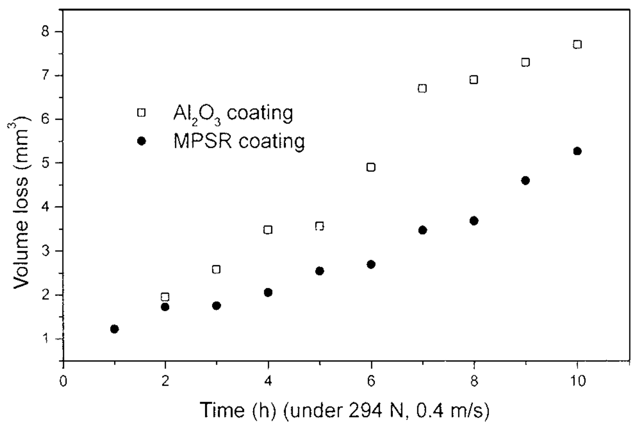


Fig. 2 Variation of volume losses of different coatings under same dry sliding wear condition

wear test. The sliding wheels, 38 mm in diameter and 10 mm in thickness, were made of GCr15 (Fe-1.0 wt.% C-1.5 wt.% Cr) steel. They were quenched, tempered to obtain HRC62 hardness, and then ground to obtain a Ra < 0.32 μm smooth surface finish. For every wear test, a new sliding wheel was used to ensure identical initial wear conditions. The wear test was performed under the following conditions: sliding speed of 0.4 m/s for 10 h and applied loads of 294 and 490 N (simulating the wear and friction conditions of exigent braking). Prior to wear testing, the surface of all specimens were polished with 800-grit Cr_2O_3 paper for a Ra < 0.63 μm surface finish, and cleaned with alcohol and dried in an oven at 80 °C for 30 min. The wear resistance was indicated by the volume loss calculated using Eq 6, in which b is the width of wear trace measured under an optical microscope at 20× magnification, and it is the average value of five measurements. The antifriction characteristics were indicated by the friction coefficient, calculated using Eq 7. To take into account the variability of the wear and friction characteristics of the coated samples, the volume losses and friction coefficient under steady-state sliding conditions were obtained from the average of three samples. The worn surfaces and cross sections of the samples were examined using a Phillips (Eindhoven, The Netherlands) XL30TMP scanning electron microscope (SEM).

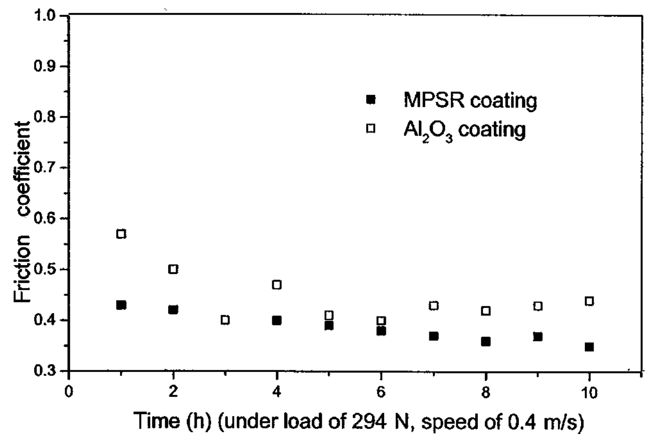


Fig. 3 Variation of friction coefficient of different coatings under same dry sliding wear conditions

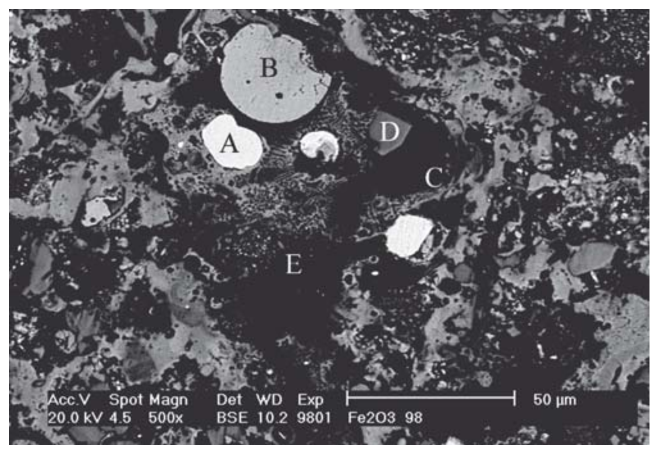


Fig. 4 SEM image of the CMC coating

$$V = B \times \left[r^2 \times \sin^{-1}\left(\frac{b}{2r}\right) - \frac{b}{2}\left(r^2 - \frac{b \cdot b}{4}\right)^{1/2} \right] \qquad \text{(Eq 6)}$$

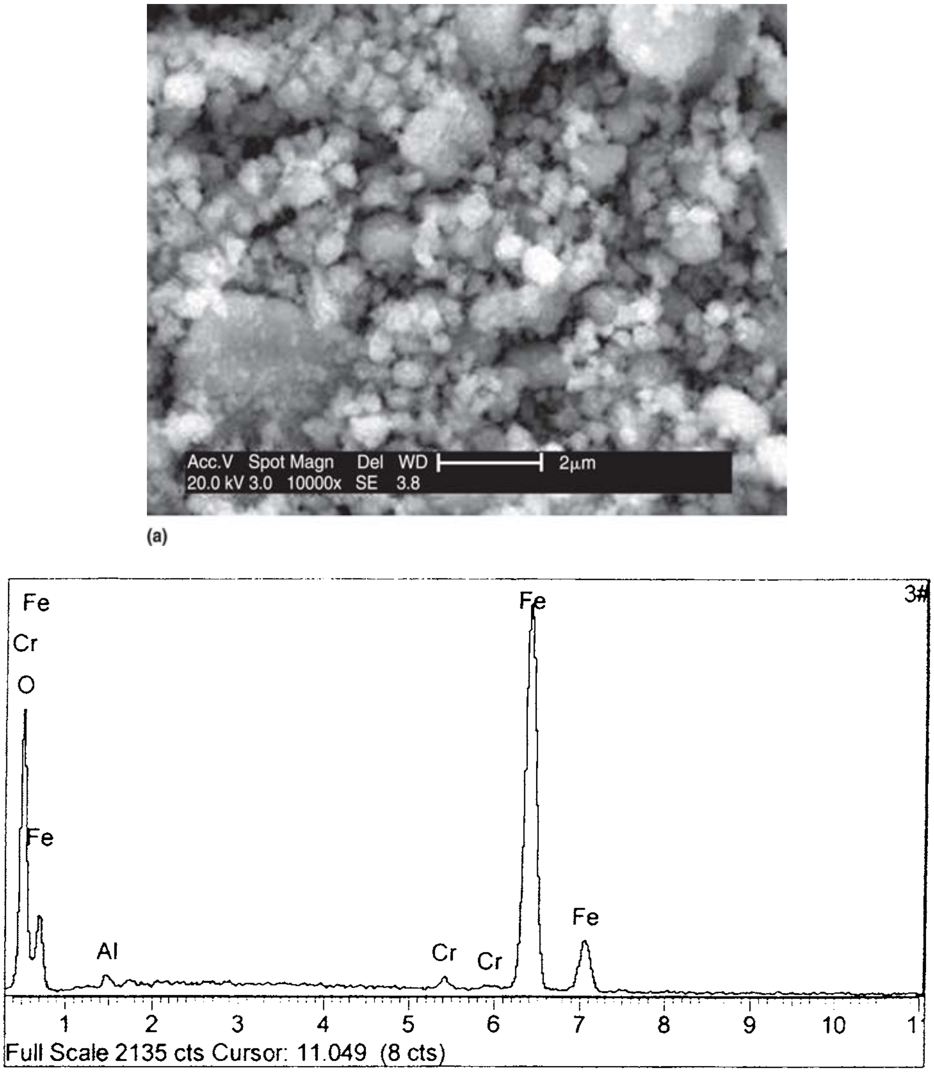
$$\mu = \frac{T}{r \cdot P} \cdot \frac{\alpha + \sin\alpha \cdot \cos\alpha}{2 \sin\alpha} \qquad \text{(Eq 7)}$$

where V is volume loss, μ is the friction coefficient, B is the thickness of sliding wheel (in mm), r is the radius of sliding wheel (in mm), b is the width of wear trace on the surface of wear test samples (in mm), T is the moment of friction recorded by test machine (N × mm), P is the load, and α is the contacting semi-angle ($\alpha = \sin^{-1}(b/2r)$).

3. Results and Discussion

3.1 Friction and Wear Characteristics of Coatings

Figure 2 shows the volume losses of CMC and Al_2O_3 coatings as the function of the wear time, obtained with a sliding speed of 0.4 m/s and an applied load of 294 N. It exhibits that volume losses of all specimens increased with increasing of the



Element	Apparent Concentration	Intensity Correction	Weight	Weight Sigma	At.%
C K	0.25	0.4816	0.89	0.63	2.20
O K	30.76	1.5427	33.52	0.79	62.35
Al K	0.26	0.5435	0.82	0.09	0.90
Cr K	0.69	1.1357	1.02	0.13	0.58
Fe K	34.93	0.9210	63.75	0.85	33.96
Totals			100.00		

(b)

Fig. 5 (a) SEM image of wear scraps of CMC coatings under sliding wear 5 h, with load of 294 N, (b) energy-dispersive spectrum analysis of wear scraps

wear time. At the beginning period of wear test, the volume losses of the two kinds of coatings increased very quickly, which indicates that the two kinds of coatings were in an unsteady wear stage. However, the volume loss of Al_2O_3 ceramic coating was much higher than that of the CMC coating after a 4 h wear test. When wear time increased up to 7 h, the volume loss of Al_2O_3 coating was twice that of the CMC coating. Although the Al_2O_3 ceramic coatings possessed the high hardness of 1089 HV_{100mg}, experimental results showed that it did not retain good wear resistance under high loads. The wear resistance of the CMC coating is better than that of Al_2O_3 ceramic coating after 8 h of wear testing, which attributed to the metal phase in the CMC coating reinforcing toughness of the coatings.

Figure 3 presents the friction coefficient of the two kinds of coatings. The coefficients of friction for all CMC coating samples were constant between 0.35 and 0.45 and smaller than

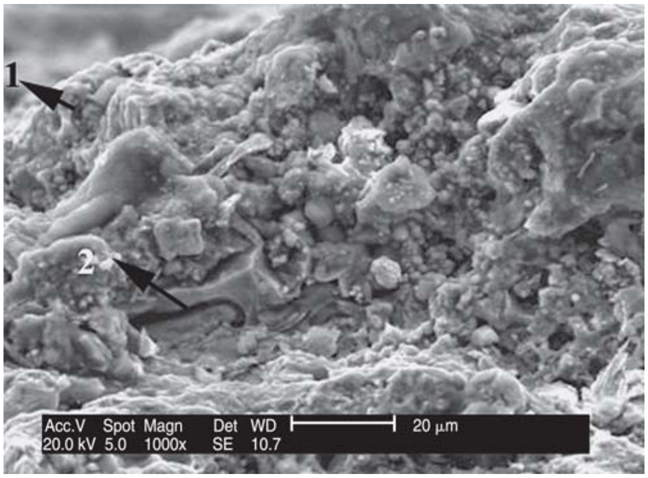


Fig. 6 SEM image of the subsurface cross section of worn surface under high load of 490 N for 10 h

that of the Al_2O_3 ceramic coatings in the stable friction stage. It could be seen from Fig. 3 that the CMC coating exhibited more stable friction and wear behavior than that of the Al_2O_3 ceramic coatings. A small quantity of unreacted Fe_2O_3, which was present as fine sheet powders in the starting feedstock, acted as a solid lubricant in this tribological system (Ref 8), improving the friction and wear characteristics of the CMC coatings.

3.2 Influence of Microstructure on Friction and Wear Characteristics

The microstructure of the CMC coatings (Fig. 4) has been investigated (Ref 6). Different phases were found in the CMC coatings: Al_2O_3 (zones C, E), $FeAl_2O_4$ spinel (zone D), metal Fe (zone B), Fe-Al alloy (zone A), and a small quantity of Fe_2O_3. The Al_2O_3 and $FeAl_2O_4$ spinel formed the supporting frame of the coating (the matrix), in which tough metal and alloy zones are found. The tough metal phases restrained crack propagation in the coating, improving its toughness and the wear resistance. During wear, unreacted Fe_2O_3 lubricated the wear surface.

Figure 5 shows the SEM micrograph and energy-dispersive spectrum analysis of wear scraps of the tribological system, the wear scraps contained Fe, O, Cr, and Al elements. The atomic percents of Fe, O, and Al were 33.96, 62.35, and 0.9, respectively, indicating that the main constituents of the wear scraps were ferric oxide. For this wear system, Fe element came from the CMC coating and the sliding wheel, and Al element in the wear scraps came only from the CMC coating. According to the proportion of Fe_2O_3 and Al in the composite powders (Ref 6), the quantity of Fe coming from the CMC coating should be the same with that of Al element, which was 0.9 at.%. Consequently, in the wear scraps, the Fe content coming from the CMC coating was 2.65% (100% × (0.9/33.96) = 2.65%) of the total Fe content, the balance coming from the sliding wheel was 97.35%. That is to say, the material wear losses in this tribological system came mainly from the sliding wheel.

To understand the wear behavior of the CMC coatings, the region below the worn surface (subsurface) of the CMC coating was examined by SEM (Fig. 6). Arrows 1 and 2 in Fig. 6 indicate the wear trace and the subsurface, respectively. Figure 6 shows that there is little microcracking and deformation in the subsurface of the worn surface.

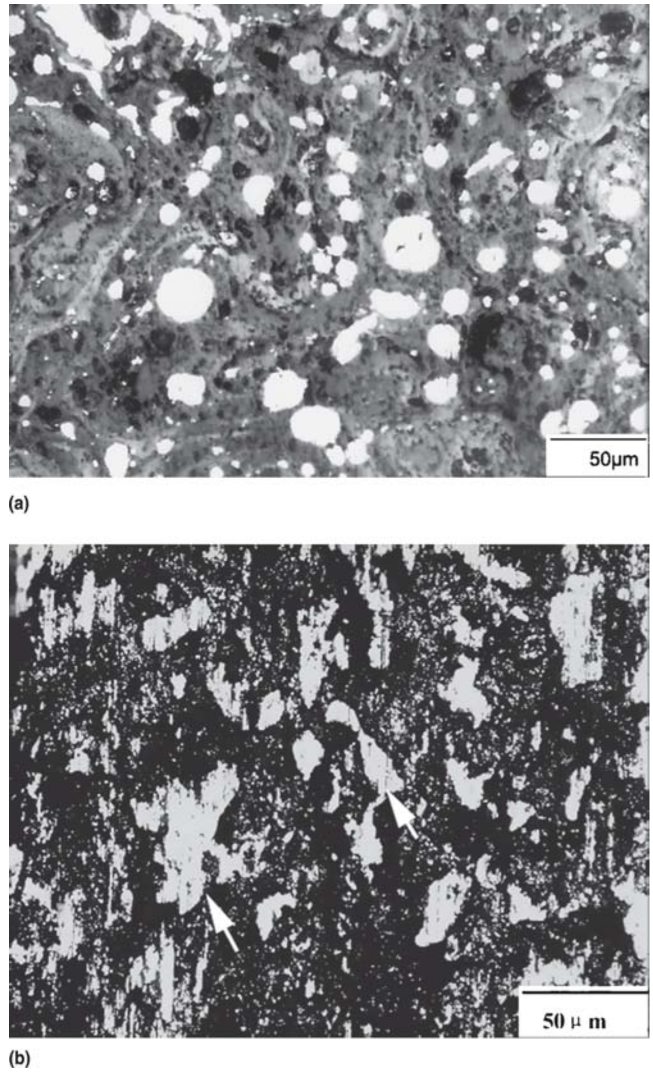
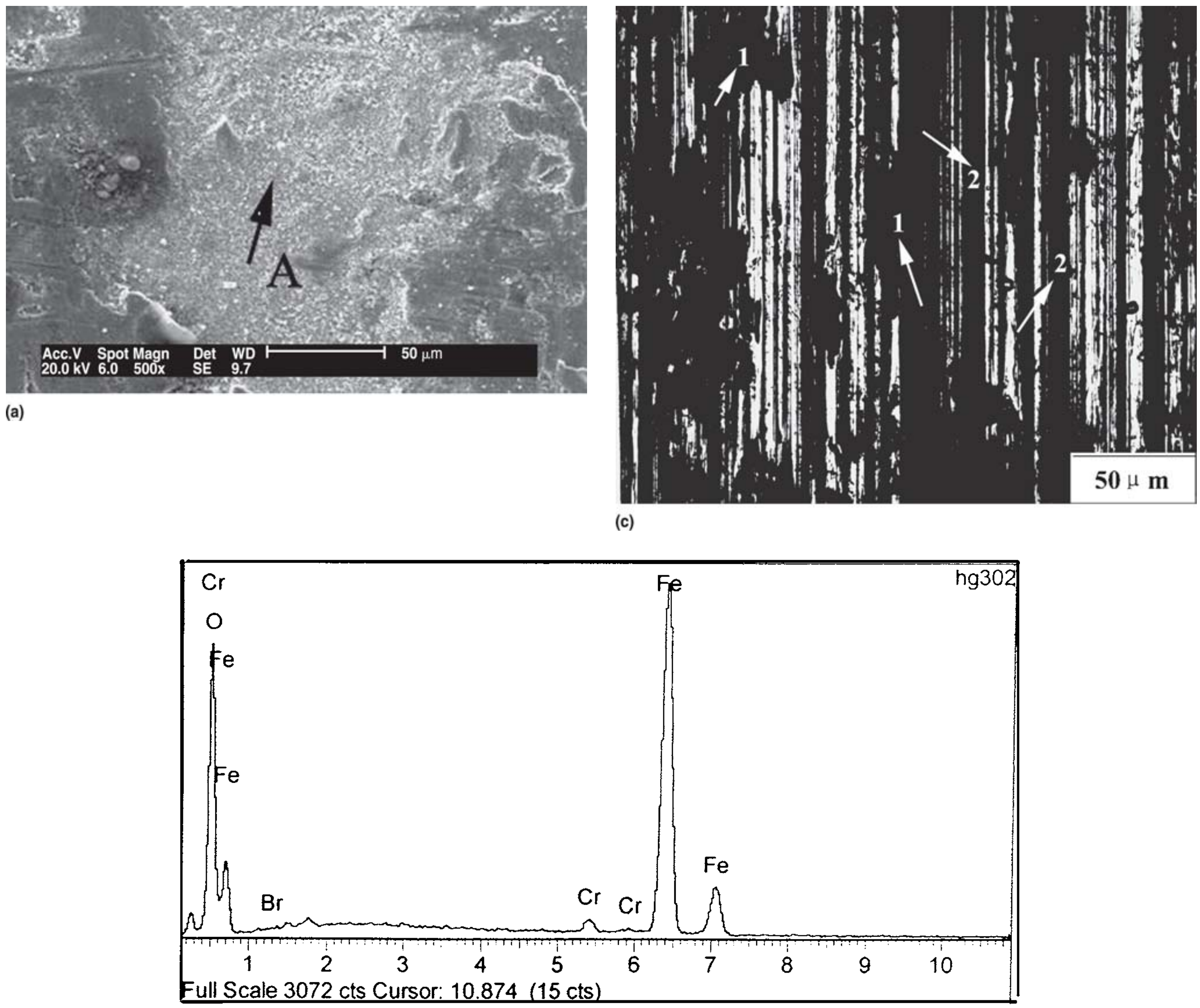


Fig. 7 Optical micrograph of the CMC coating (a) before the wear test and, (b) after testing for 10 h with load of 294 N

3.3. Wear Mechanism of the CMC Coatings

3.3.1 Adhesion. Figure 7 presents the SEM images of the CMC coating before and after wear. The shape and quantity of the metal phase distributed over the sample surface before and after wear were different. The metal, indicated by the arrow, was deformed and spread over the surface of the sample after wear. It is an indication of the partial metal adhesion occurring between the CMC coatings and sliding wheel during the wear test. Under high-load dry wear-testing conditions, the sliding wheels were tempered by friction heat in the tribological system, and microwelding appeared between the metal of the CMC coating and the sliding wheel. The welded metal was then torn by successive relative motions. The partially tempered metal detached from the sliding wheel and transferred to the CMC coating, which



Element	Apparent Concentration	Intensity Correction	Weight	Weight Sigma	At.%
O K	49.28	1.5926	35.36	0.62	65.65
Cr K	1.27	1.1309	1.28	0.12	0.73
Fe K	50.65	0.9203	62.89	0.62	33.44
Br L	0.20	0.4917	0.47	0.16	0.18
Totals			100.00		

(b)

Fig. 8 (a) SEM micrograph of the worn surface of the CMC coating after a 10 h wear test under a load of 294 N, arrow indicates the wear trace, (b) energy-dispersive spectrum analysis of the zone marked A in (a), (c) optical micrograph of the worn surface of the sliding wheel after a 10 h wear test under a load of 294 N

corresponded to a partial adhesion wear phenomenon (Ref 9-11). Figure 8(a) and (c) show the worn surface of the CMC coating and sliding wheel. Arrow 1 in Fig. 8(c) shows pits, left by microwelding and tearing away, where the metal transferred to the surface of the CMC coating. Figure 8(b) presents the energy-dispersive spectrum of the worn surface of CMC coating at the zone marked “A” in Fig. 8(a). It could be seen in Fig. 8(b) that Cr appeared at the worn surface. However, the CMC coating did not contain Cr, although the sliding wheel made of GCr15 steel did. Therefore, Cr came only from the sliding wheel, which confirmed that some metal material was transferred during the wear test. Therefore, the wear mechanism of metal in the CMC coating was of adhesive type (Ref 12).

3.3.2 Abrasion. The arrow in Fig. 8(a) and arrow 2 in Fig. 8(c) indicate one of furrows on the worn surface of the CMC coating and sliding wheel, respectively. During wear testing, the ceramic and spinel phases, which are relatively brittle phases, flaked off from the ceramic matrix, became abrasive particles, and ploughed or cut into the sliding wheel and the CMC coating. The furrows on the worn surfaces are indicators of the abrasion that occurs during the wear test.

In summary, abrasive and adhesive wear mechanisms coexisted for the CMC coating under dry sliding wear. For the ceramic phases in the CMC coating, the wear mechanism was abrasive model. For the metal phases in the CMC coating, the wear mechanism was adhesive type. For the sliding wheel, the wear mechanism was abrasion and partial adhesion. Therefore, abrasive and adhesive wear coexist for the CMC coatings under high loads and dry sliding wear conditions.

4. Conclusions

- Compared with plasma-sprayed Al_2O_3 coatings, the volume loss and the friction coefficient of the CMC coatings were lower during dry wear test under the same high loading conditions (294 N), i.e., the wear resistance and antifriction properties of the CMC coatings were superior than those of the Al_2O_3 coatings.
- The excellent wear resistance and antifriction characteristics of the CMC coatings resulted from the particular microstructure of the CMC coatings, in which the hard Al_2O_3 and $FeAl_2O_4$ spinel phases formed the support frame (the matrix), and the metal Fe and Fe-Al alloy increased the toughness of the coating.
- The wear mechanism of the CMC coating under dry sliding wear was abrasive and adhesive models in combination. For the ceramic phase in the CMC coatings, the wear was abrasive. For the metal phase, abrasive and adhesive models coexisted.

Acknowledgment

The work was financially supported by the Natural Science Foundation of Hebei China (grant 599031).

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