Journal of University of Science and Technology Beijing
Volume 11, Number 6, December 2004, Page 549

Materials

Dry wear behaviors of wear resistant composite coatings produced by laser cladding

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(Received 2004-06-08)

Abstract: Using different proportional mixtures of Ni-coated MoS_2, TiC and pure Ni powders, new typical wear resistant and self-lubricant coatings were formed on low carbon steel by laser cladding process. The microstructures and phase composition of the composite coatings were studied by SEM and XRD. The typical microstructure of the composite coating is composed of multi-sulfide phases including binary element sulfide and ternary element sulfide, γ-Ni, TiC and Mo_2C. Wear tests were carried out using an FALEX-6 type pin-on-disc machine. The friction coefficient and mass loss of three kinds of MoS_2/TiC/Ni laser clad coatings are lower than those of quenched 45 steel, and the worn surfaces of the laser cladding coatings are very smooth. Because of high hardness combined with low friction, the laser cladding composite coating with a mixture of 70% Ni-coated MoS_2, 20%TiC and 10% pure Ni powder presents better wear behaviors than the composite coating with other powder blends. The composition analysis of the worn surface of GCr15 bearing steel shows that the transferred film from the laser cladding coating to the opposite surface of GCr15 bearing steel contains an amount of sulfide, which can change the micro-friction mechanism and lead to a reduced friction coefficient.

Key words: laser cladding; MoS_2/TiC/Ni; wear resistance and self-lubricant; wear behavior

1 Introduction

With the development of aerospace and vacuum industries, the components in an engine or in general machinery must be required to meet with severe environment, such as high temperature, high loading, strong radiation *etc*. Under these conditions, the presence of liquid lubricant is not possible or may be forbidden to avoid contamination (*e.g.* in food industry). Particularly, dry machining could have a detrimental effect on the tool performance (high tool wear or damage). The risk of this can be drastically reduced or eliminated by a solid lubricant. In special circumstances, the solid lubricant deposited where a traditional lubricant cannot perform will allow lower liquid lubricant flow and increase the performance of tools and components [1-3]. As the restriction imposed by environmental legislation tightens, solid lubrication provides a viable solution. Lasers are powerful tools for the surface modification of metals in improving their corrosion and tribological properties. Laser cladding is a novel surface treatment technology which takes possession of advanced features, such as the integrity of fusion bond between the cladding coating and substrate, high process flexibility, high working speeds and no requirement for post process treatment.

Considerable attention has been previously given to hard particle reinforced clad coatings [4-9]. However, such coatings are not good option for some applications. From the viewpoint of tribology, the hardness is not the only factor which decides the wear resistant behavior of the surface coating. There are other reasons why typical hardfacing coatings are not used more widely. The coatings are not always low friction and may not provide necessary protection for the opposing surface. Indeed, the coatings are very hard and if the coated surface or coating is rough then they can cause abrasion and rapid wear of the opposing surface. If the coating is removed, it becomes a source of abrasive particles during the friction process. In order to provide optimum wear protection for easily worn components, it is necessary to use a solid lubricant coating with low friction and the ability to protect the opposite surface. The metal matrix composites containing sulfide have a low friction coefficient and low wear rate from room temperature to 600°C, which can be used as solid lubricant coating materials [10, 11].

In the present study, a new hard lubricant composite coating with an amount of Ni-coated MoS_2 powder has been prepared by laser cladding technology. The purpose of this work is to produce a composite

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coating which is characterized by high hardness combined with low friction coefficient, leading to very high load-bearing capacity.

2 Experimental procedures

A low carbon steel plate with a dimension of 10 mm×10 mm×50 mm was used as the substrate. Before laser cladding, the surfaces were ground to a surface finish of Ra=0.2 μm, and rinsed with ethanol followed by acetone. A mixture of Ni-coated MoS_2, TiC and Ni powders was used as the coating materials for MoS_2/TiC/Ni coating and the proportion of powder blend used in laser cladding is given in **table 1**. The particles of Ni-coated MoS_2 powder are less than 10 μm in size and the ratio of Ni to MoS_2 is 4/6 in mass. The particles of TiC powder are less than 15 μm in size and polygon in shape. The powders were mixed by hand using a spoon in a glass and preplaced on the low carbon steel. The laser cladding was carried out with a defocused laser beam of 3 mm in diameter using a PRC-3 kW continuous wave CO_2 laser processing system in an argon shielding atmosphere. The laser cladding parameters were the laser power, 1.25 kW and the traverse scan speed, 12 mm/s.

Table 1 Proportion of the powder blend used in laser cladding experiments

Powder label	Powder type (wt%)		
	Ni-coated MoS_2	TiC	Pure Ni powder
p1	80	20	—
p2	70	20	10
p3	60	20	20

The metallographic cross-section of clad samples was prepared in the plane perpendicular to the scan direction. The chemical composition and microstructure of laser cladding coating were analyzed by a LEO-1450 scanning electron microscope (SEM), and the worn surface of the coatings observed by a CSM-950 scanning electron microscope and X-ray energy dispersive spectroscopy (X-EDS). The phase structure identification was conducted by D/Max-RB X-ray diffraction (XRD). The radiation source was Cu K_α, the working voltage at 40 kV with a scan rate of 15°/min. The microhardness measurement was done on an HX-200 micro-Vickers machine with a load of 0.2 kg.

Dry sliding friction and wear tests without lubricant were performed in a pin-on-ring mode on a Falex-6 model friction and wear testing machine (Falex corporation, Sugar Grove, Illinois, USA). The pin specimens were machined in the form of cylinders with a diameter of 4.8 mm and a length of 12.7 mm. The counterpart discs were made of a quenched and tempered GCr15 bearing steel with a nominal chemical composition (wt%): C, 1.0; Cr, 1.5; Si, 0.25; Mn, 0.30; Ni, 0.20; Mo, 0.05; V, 0.15, and a surface hardness of HRC 60 and a surface roughness of Ra=0.2 μm. The applied load was varied from 17.8 to 44.5 N (17.8, 26.7, 35.6 and 44.5 N) and the sliding speed was kept constant at 0.24 m/s. The friction coefficient μ was calculated using the expression: $\mu=T/RP$, where T is the friction moment, R the ring radius, and P the normal load acted on the pin specimen. The specimens were thoroughly cleaned with acetone in an ultrasonic cleaner before and after the wear test. The mass loss during the wear test was measured using a photoelectric balance 1712MP8 with the resolution of ±0.01 mg.

3 Results and discussion

3.1 Microstructure characterization and microhardness

Figure 1 presents a typical X-ray diffraction profile of the laser cladding composite coatings with different proportions of Ni-coated MoS_2, TiC, pure Ni powder blend. The results indicate that the major constitutional phases of the laser clad composite coatings with p1 and p2 powder blends are multi-sulfide phases including binary element sulfide and ternary element sulfide, γ-Ni, TiC and Mo_2C. Because of the low content of Ni-coated MoS_2 powder added to the powder blend, $Ni_{2.5}Mo_6S_6$ phase has not been found in the laser cladding composite coating with p3 powder blend. According to the XRD results, it is demonstrated that MoS_2 decomposes completely due to the thermo-reaction by laser heating, and the decomposed sulfur reacts with Ni and Ti in the laser clad coating.

Figure 2(a) shows the scanning electron images of longitudinal section of the clad coating at a laser beam speed of 12 mm/s and an output power of 1.25 kW. The SEM observation reveals that the microstructure of the clad coating is very complicated and several different brightness contrast zones that represent different constituent phases of the microstructure are found. The composition of various microzones by energy dispersive X-ray (EDX) is given in **table 2**. Combining the XRD results and the composition of phases in the coating, it can indicate that the black particles (marked A in figure 2(a)) are partially dissolved TiC cermaic particles, which are embraced by Mo_2C carbide (marked B in figure 2(b)). Owing to the irradiation of laser beam, the MoS_2 particles are heated to reach the temperature higher than the melting

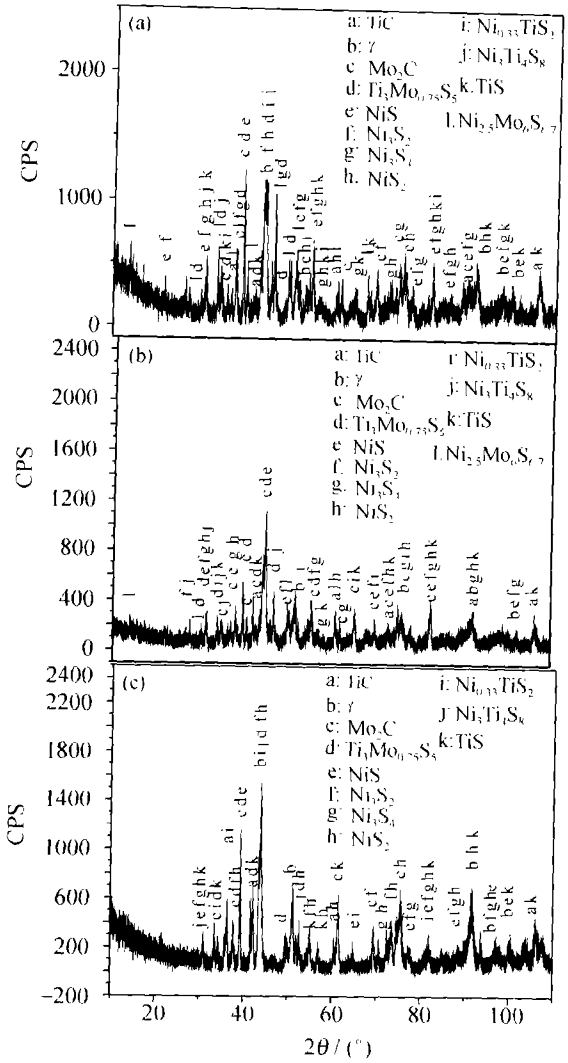

Figure 1 XRD patterns of laser cladding MoS_2/TiC/Ni composite coatings: (a) p1 powder blend; (b) p2 powder blend; (c) p3 powder blend.

point of the particles and the dissociation of MoS_2 to Mo and C occurs briefly. The white block phase (marked C in figure 2(a)), which mainly consists of Mo, S and Ni elements, is identified $Ni_{2.5}Mo_6S_{6.7}$ ternary sulfide. During the laser cladding process, there are convective flows of the molten metal, which results in the reaction of Mo, S, Ti and Ni to form ternary or binary element sulfide such as $Ni_{0.33}TiS_2$, $Ni_3Ti_4S_8$, $Ti_3Mo_{0.75}S_5$ and NiS. It is noted that there are two kinds of distribution features of Mo_2C, namely, the surrounding structure of the exterior of TiC particles and in shape of particles or needle-like homogeneous distribution in clad coating. The surrounding structure contained an amount of Ni and Ti can be confirmed as the composite carbide of Mo_2C type, and which plays an important role in bonding the TiC particles with a matrix of clad coating. Owing to supersaturation of Mo and C in the matrix, the Mo_2C precipitate from the matrix in particle-like or needle-like (figure 2(c)) during the period subsequent to the solidification. Under the condition of rapid heating and cooling during the laser treatment, Ni reacts with decomposed MoS_2 to form $Ni_{2.5}Mo_6S_{6.7}$ in the place of Ni-coated MoS_2 powder due to diffusing insufficiency. With increasing the outpower density or decreasing the content of Ni-coated MoS_2 powder in the powder blend, $Ni_{2.5}Mo_6S_{6.7}$ phase has not been found. The microzone of grey strip phase (marked D) and dark grey phase (marked E) is multi-sulfide eutectic.

The hardness profiles of the laser clad coatings with different proportions of Ni-coated MoS_2/TiC/Ni powder blend along the depth direction are depicted in **figure 3**. It can be seen that the hardness of three kinds of clad coatings decreases gradually as the distance from the surface increases. The distribution of hardness is relative to the gradient distribution of TiC fraction along the depth direction, which is responsible for the hardness of laser clad Ni-coated MoS_2/TiC/Ni composite coatings. The microhardness of the laser clad coating with p2 powder blend is the highest of the surface layer among the three kinds of powder blends.

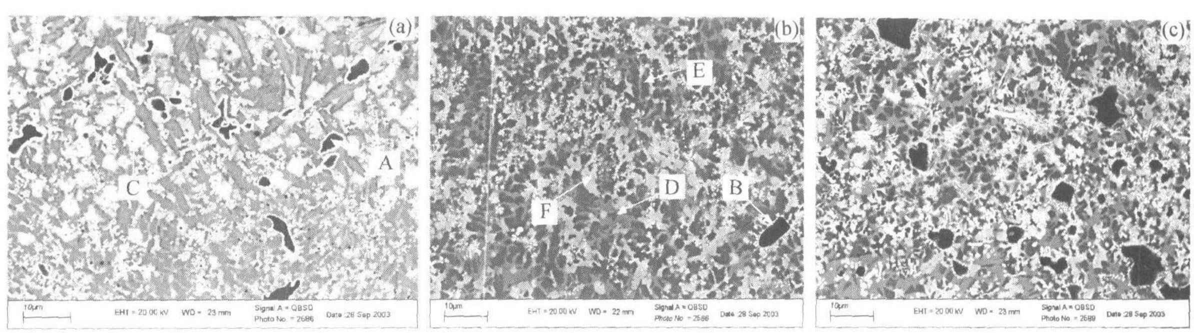

Figure 2 SEM micrographs showing the microstructures of laser clad MoS_2/TiC/Ni composite coatings: (a) p1 powder blend; b)p2 powder blend; (c) p3 powder blend.

3.2 Sliding friction and wear behaviors

Figure 4 shows the friction coefficients of the composite coating with different proportions of Ni-coated MoS_2/TiC/Ni powder blends and hardened AISI 1045 steel as a function of the normal load at a given sliding velocity of 0.24 m/s and a wear time of 10 min. The friction coefficients of three kinds of clad composite coatings are considerably lower than that of the hardened AISI 1045 steel, which demonstrates that the clad MoS_2/TiC/Ni composite coatings have lower friction coefficients than the hardened AISI 1045 steel. The friction coefficient of the clad composite coating with p2 powder blend is appreciably lower than that of the other powder blends, which is relative to the content of sulfide and hardness of cladding coatings.

Table 2 EDAX analyses result of the laser cladding MoS_2/TiC/Ni composite coating (at%)

Phase lable	Phase	Ni	Mo	S	Ti	Fe	C
A	TiC	—	—	—	94.0794	—	5.9236
B	Mo_2C	10.2393	86.7650	1.6194	1.3757	—	—
C	$Ni_{2.5}Mo_6S_{6.7}$	14.5537	24.7327	60.4144	—	0.2992	—
D	$Ni_{0.33}TiS_2$, $Ni_3Ti_4S_8$, $Ti_3Mo_{0.75}S_5$, TiS	22.4454	21.9407	49.8493	5.7646	—	—
E	NiS_2, NiS, Ni_8S_2, Ni_3S_4	60.5509	1.4560	36.7667	0.4858	0.7406	—
F	γ-Ni	83.9130	0.9374	12.4436	0.5606	2.1453	—

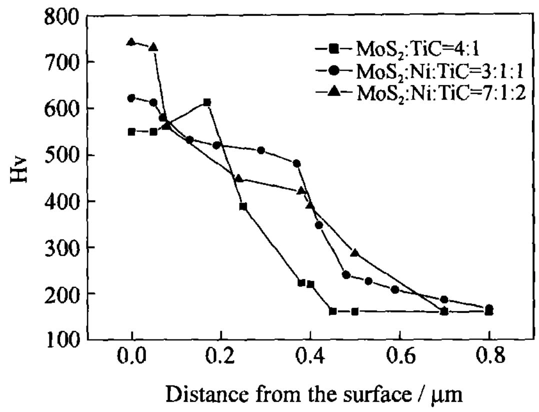

Figure 3 Microhardness distributions of the laser cladding coatings.

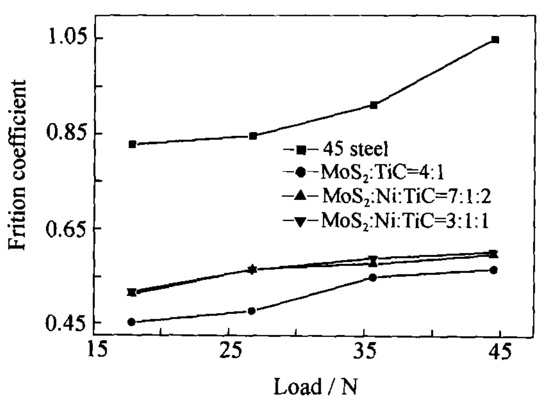

Figure 4 Friction coefficients of cladding coatings and 1045 steel as a function of the normal load at a given sliding velocity of 0.24 m/s and a wear time of 40 min.

The wear mass losses of the clad coatings with different proportions of MoS_2/TiC/Ni powder blend and hardened AISI 1045 steel as a function of the normal load at a given sliding velocity of 0.24 m/s and a wear time of 10 min are shown in **figure 5**. It is noted that the wear mass losses of the tested materials increase with increasing the applied normal load. In the entire applied load range, the mass losses of the three kinds of clad coatings are lower than one sixth of that of AISI1045 steel and show better wear resistance than AISI 1045 steel. After dry sliding wear 10 min under an applied load of 44.5 N, the mass loss of the clad coating with p2 powder blend is lower than that of the other kinds of clad coatings and only about one eighth of that of 45 steel. It is also proved that the laser clad coating with p2 powder blend has high load-bearing capacity than the other powder blends and is an optimum option for the preparation of wear resistant clad coatings with different proportions of Ni coated MoS_2/TiC/Ni powder blend.

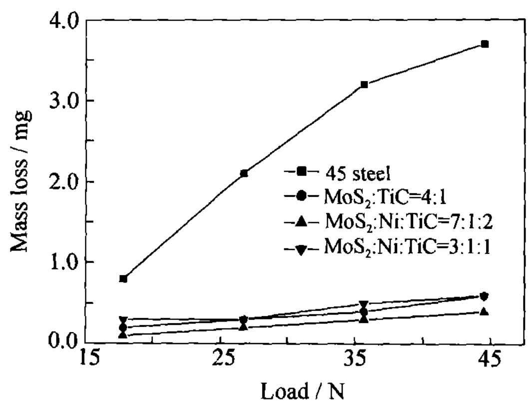

Figure 5 Wear mass losses of clad coatings and AISI 1045 steel as a function of the normal load at a given sliding velocity of 0.24 m/s and a wear time of 10min.

The morphologies of the worn surface of hardened AISI 1045 steel and the clad coating with different proportions of MoS_2/TiC/Ni powder blend are shown in **figure 6**. Figure 6(a) shows that the worn surface of harden AISI 1045 steel is very rough and deep plowing grooves and adhesive flake debris can be observed. Because of the low resistance of plastically deformation and hardness, the surface of 1045 steel has not enough ability to resist the indentation of hardness particles of the opposite surface. It can be clearly seen from figures 6(b)-(d) that the morphologies of the worn surface of the clad coating with different proportions of MoS_2/TiC/Ni powder blend are so smooth that the microstructures of the clad Ni-coated MoS_2/TiC/Ni composite coatings can be clearly determined after a dry sliding wear test of 10 min under an applied load of 44.5 N. The undissolved TiC particles play an important role in increasing the harness and acts as hard barriers to resist the plastic deformation of coatings. The surrounding structure of Mo_2C type carbide is effective to improve the bonding of hard particle (TiC) and soft matrix. It is not found that the hard particles are worn out by flaking off, which illuminate the strong bonding of carbide and matrix. The multi-sulfide eutectic under dry sliding wear test conditions, such as binary element sulfide TiS, NiS, Ni_3S_2 and ternary element sulfide $Ni_{2.5}Mo_6S_6$, $Ni_{0.33}TiS_2$, makes a contribution to reducing friction as a self-lubricant in the clad coatings. Comparing with other powder blend, the laser clad coating with p2 powder blend is smoother.

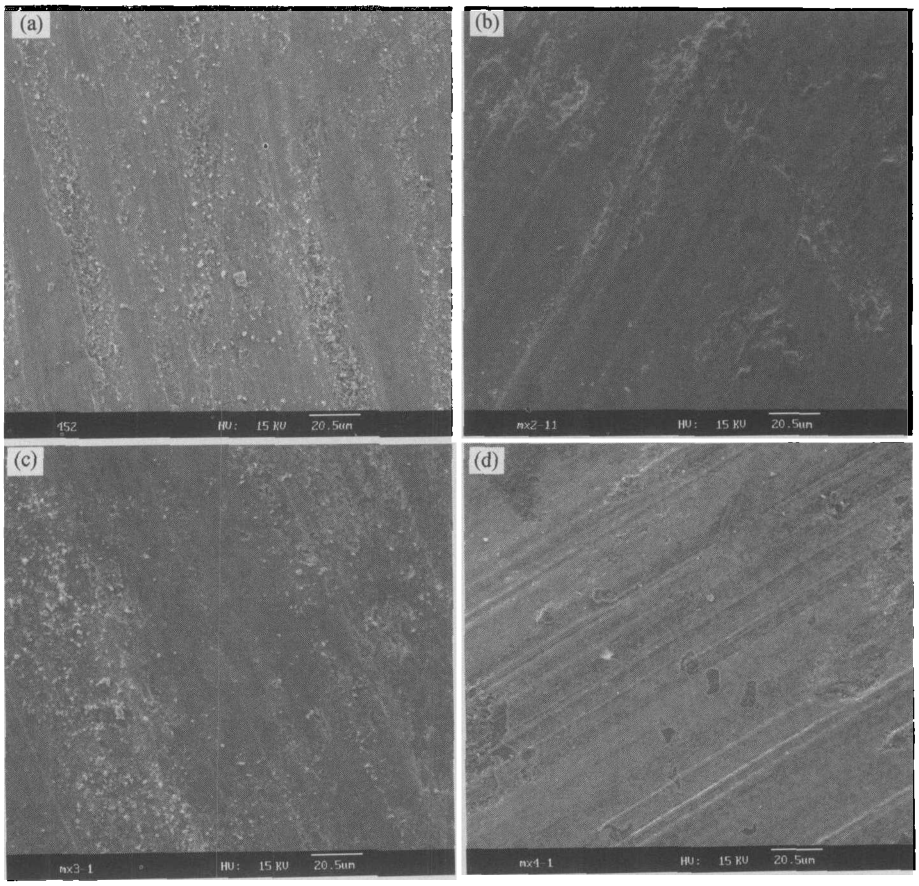

Figure 6 SEM micrographs showing the worn surface morphologies (the wear test of 10 min under an applied load of 44.5 N): (a) quenched 45 steel; (b) p1 powder blend; (c) p2 powder blend; (d) p3 powder blend.

The morphologies of the worn surface of GCr15 bearing steel coupled with the clad coating with p2 powder blend are shown in **figure** 7. It shows that there is a transferred film distribution on the worn surface of GCr15 bearing steel after sliding for 10 min under a load of 44.5 N. The composition of the transferred film is listed in **table** 3. The results show that an amount of sulfide of the clad coating is transferred to the opposite surface, and which proves that the clad coating is self-lubricant and has the ability to form transfer film and protect the opposite surface. The single applied hard particle reinforced laser coatings are provided with high hardness, but they can cause the abrasive of opposite surface and do not offer any protection for the opposite surface. The difference between the laser clad coatings with Ni-coated MoS_2, TiC and pure Ni powder and the conventional hard particle reinforced clad composite coating is that the former reduces the friction and protects both its own surface and the opposite surface.

3 Conclusions

(1) The novel wear resistant and self-lubricant laser clad composite coatings have many advantages over hardened AISI 1045 steel because of their hardness, wear resistance, low friction and load-bearing capacity.

(2) The typical microstructure of the composite coatings with p1 and p2 powder blends is composed of multi-sulfide phases including binary element sulfide and ternary element sulfide, γ-Ni, TiC and Mo_2C. The laser clad composite coatings with p3 powder blend do not include $Ni_{2.5}Mo_6S_6$ phase due to the low content of Ni-coated MoS_2 powder added to the powder blend.

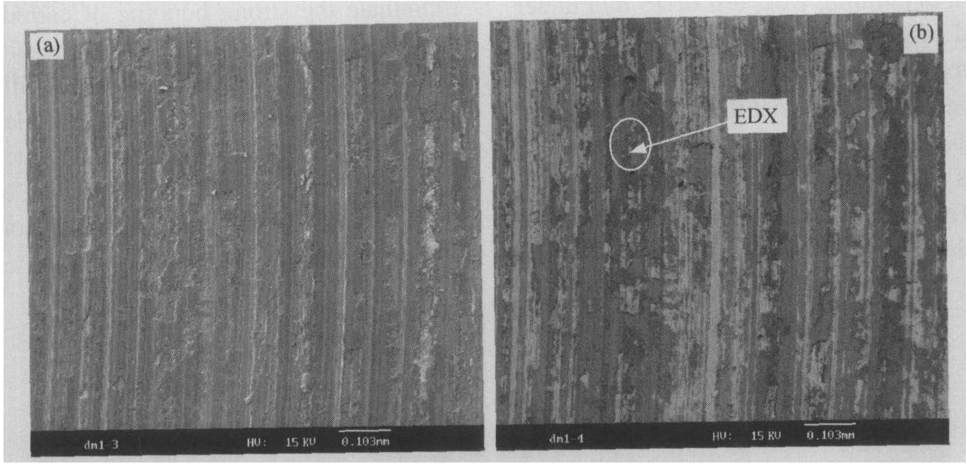

Figure 7 Surface wear morphologies of GCr15 bearing steel: (a) secondary electron image; (b) backscattered electron image.

Table 3 EDAX analysis results of the adhesion of GCr15 bearing steel

Element	Content / wt%	Content / at%
S	3.7633	6.3725
Ti	2.3983	2.7184
Cr	1.5131	1.5801
Fe	83.2367	80.9238
Ni	9.0886	8.4052

(3) After dry sliding wear of 10 min under different loads, the mass loss and friction coefficient of the clad coatings with different proportions of MoS_2/TiC/Ni powder blend are considerably lower than that of hardened AISI 1045 steel. The wear resistance of the laser clad composite coating with p2 powder blend is appreciably lower than that of the other powder blends and is the optimum option for the preparation of wear resistant coating with different proportions of MoS_2/TiC/Ni powder blend.

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