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The Effect of the Third Body on the Fretting Wear Behavior of Coatings

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The formation, oxidation, and agglomeration of wear debris of coatings were investigated in this study. The rheology of the third body and its influence on the fretting wear behavior were studied in depth and systemically. The results showed that the shape and nature of the debris were the essential factors determining the mobility of the third body. All factors that could make the debris layer or third body remain on the contact surfaces would decrease the friction coefficient and fretting wear. The soft and large plate-like debris particles were apt to remain in the contact region. Conversely, the hard and sphere-shaped debris particles tended to be squeezed from the contact surfaces and to increase the fretting wear.

Keywords fretting wear behavior, rheology, third body

1. Introduction

Fretting damage is a very complex phenomenon, which involves adhesion, abrasion, fatigue, and corrosion on the contact surfaces. Under different conditions, it can be exhibited as fretting fatigue, fretting wear, and fretting corrosion.[1,2] Compared with ordinary sliding wear, one of the important tribological characteristics of fretting wear is the effect of the wear debris trapped on contact surfaces on the fretting process.[3] Studies on the effect of debris on fretting wear have been reported and discussed in the literature.[4-9] Iwabuchi[10] found that the compacted oxide on a softer surface prevented the wear of the oxide and abraded a harder opposing surface. The research conducted by Colombie[11] proved the beneficial effect of the compacted oxide layer by its quick formation when oxide particles or chalk powder were supplied artificially. Iwabuchi[12] also found that the loose oxide wear particles and surface oxide film formed in the preheating had no significant effect on the wear process; instead, the most important factor was the formation of the compacted oxide layer on the surface. Such an oxide layer was called "the third body" and had a good load-carrying capacity to prevent metal-metal contact.[13] The complexity of the fretting wear process originated mainly from the influence of the formation and evolution of the third body on fretting wear. The formation of the third body resulted from the adhesion and transfer of first bodies and the ploughing of asperities.[14] Strictly speaking, the loose debris particles coming from adhesion, transfer, and degradation of materials in the initiation of fretting wear should not be regarded as the third body. Indeed, the third body is the debris bed comprising compacted oxide particles, which could separate the rubbing surfaces and decrease the friction coefficient and wear. The formation of the third body implies that fretting wear reaches the steady stage, when the rheology of the third body will determine the wear behavior of the later fretting process. This study attempted to investigate the formation of the third body of coatings based on the analysis of production, oxidation, and agglomeration of wear debris. The influence of rheology on the fretting wear behavior was then examined in depth and systemically.

2. Experimental Detail

2.1 Substrate Materials and Surface Modification Techniques

The substrate material chosen for applying the surface modification was 1045 steel. First, samples with the dimensions of $10 \times 10 \times 20$ mm^3 were machined from the 1045 steel rod. Then the samples were heat treated at 860 °C for 20 min, water quenched, and tempered at 600 °C for 30 min. Subsequently, the samples were ground and lapped with diamond paste to $R_a = 0.07$ μm.

The surface modification coatings investigated here included: shot peening and ion sulfuration (PS duplex), ion plating TiN, and RF sputtering MoS_2. The ion sulfuration coating with the thickness of 10 μm was obtained using low-temperature sulfuration equipment at 180 °C for 2 h. The shot-peening process was conducted with the Almen intensity strength of 0.25 Amm, and ϕ0.6 mm steel balls. TiN coating with the thickness of 2.5 μm was deposited on 1045 steel substrate in an ion-plating device (model MIP-800, Mechanics Research Institute, Beijing, China) using a bias voltage of −100 to −150 V and a nitrogen atmosphere of 6×10^{-1}Pa. An MoS_2 coating with the thickness of 2.5 μm was produced by the radiofrequency (RF) sputtering process. Before deposition, the target, which was compacted using pure MoS_2 powder (purity ≥99 wt.%) with a small amount of LaF_3, was RF-presputtered and the substrate was ion-etched for 15 min at a dc power of about 100 W in pure Ar gas (purity ≥ 99.9%). The coatings were deposited to a thickness of about 2.5 μm by RF sputtering

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under the following conditions: anode voltage of 2.0 kV, substrate biased with a negative dc current of -100 V, and Ar pressure of 5.3 Pa. Before surface modification, the substrates must be ultrasonically cleaned in Analytical Reagent (AR)-grade acetone.

The counterpart was a 52100 steel ball with diameter of 40 mm. The composition and main characteristics of the 1045 steel substrate specimen and 52100 steel are listed in Tables 1 and 2.

2.2 Fretting Wear Tests and Analyses

Fretting wear tests were conducted on a tension-compression hydraulic machine.[11] The scheme of the fretting testing machine is given in Fig. 1. The coated flat specimen was stationary and the 52100 steel ball was vibrated with small reciprocating amplitude. All specimens were cleaned in an ultrasonic bath of alcohol before tests. The fretting experiments were conducted under unlubricated, ambient temperature of 18 ± 3 °C and relative humidity of 60% ± 10%. Because the debris detachment is the fretting damage mechanism in the gross slip regime, the experimental parameters were determined as normal load 300 N, slip amplitude 60 μm, and frequency 5 Hz. After tests, the wear debris stuck on the stationary specimens was collected using gummed tape. Then the morphologies and composition of fretting wear scars and wear debris were examined by scanning electron microscope (SEM) with energy dispersive spectroscopy (EDX).

3. Results and Discussion

3.1 The Formation of the Third Body of the Coatings

The variation of friction coefficient of PS duplex, ion-plated TiN, and RF-sputtered MoS$_2$ coatings with the number of cycles are shown in Fig. 2. The time necessary to form the third body varied with the coatings. Except for MoS$_2$ coating, PS duplex coating and TiN coating had begun to transit to the steady state when the third body formed around 10,000 cycles. Figure 3 displays the morphologies of fretting wear scars of PS duplex, TiN, and MoS$_2$ coatings under the experimental conditions of normal load 300 N, amplitude 60 μm, frequency 5 Hz, and 10,000 cycles. The analysis indicated that there existed a large amount of debris on the fretting wear scars. The plate-like oxide debris was shown on the wear scar of the PS duplex coating (Fig. 3a). A lower yield strength and larger surface roughness of the PS coating led its wear debris to be produced during the work hardening process. The continuous formation, movement, oxidation, and fragmentation

Table 1 **The Chemical Composition of 1045 Steel Substrate and 52100 Steel Ball (wt.%)**

	C	Si	Mn	Cr	S	P	Ni
1045 Steel	0.45	0.27	0.65	0.25	0.02	0.04	0.25
52100 Steel	0.95	0.25	0.30	1.50	0.02	0.04	0.20

Table 2 **The Main Characters of 1045 Steel Substrate and 52100 Steel Ball**

	E (GPa)	σ_s (MPa)	σ_b (MPa)	Hardness (HRC)	Surface Roughness
1045 Steel	210	650 to 750	850 to 900	25 to 29	Ra = 0.07 μm
52100 Steel	210	1700	2000	60 to 63	Ra = 0.02 μm

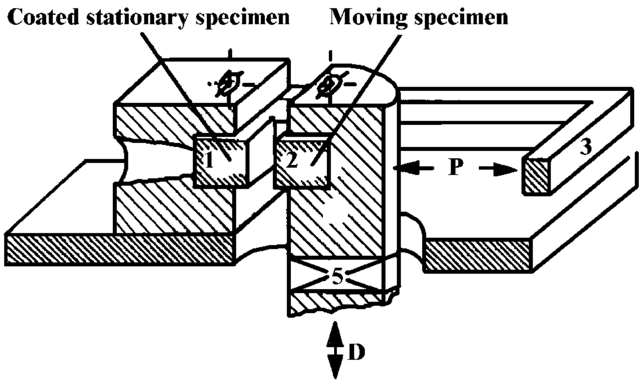

Fig. 1 The scheme of the fretting testing machine

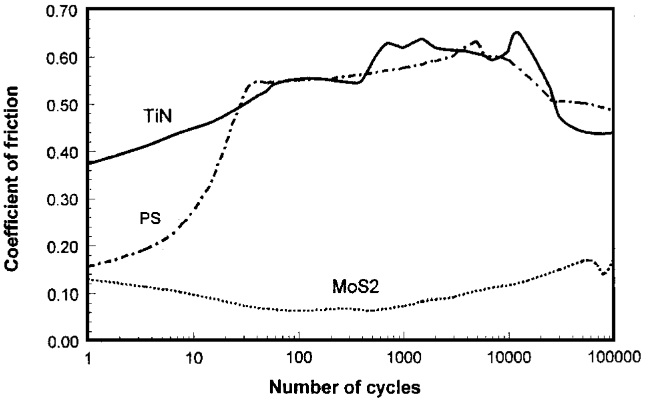

Fig. 2 The variation of friction coefficient of shot peening and ion sulfuration duplex (PS), TiN, and MoS$_2$ coatings with number of cycles (normal load 300 N, amplitude 60 μm, and frequency 5 Hz)

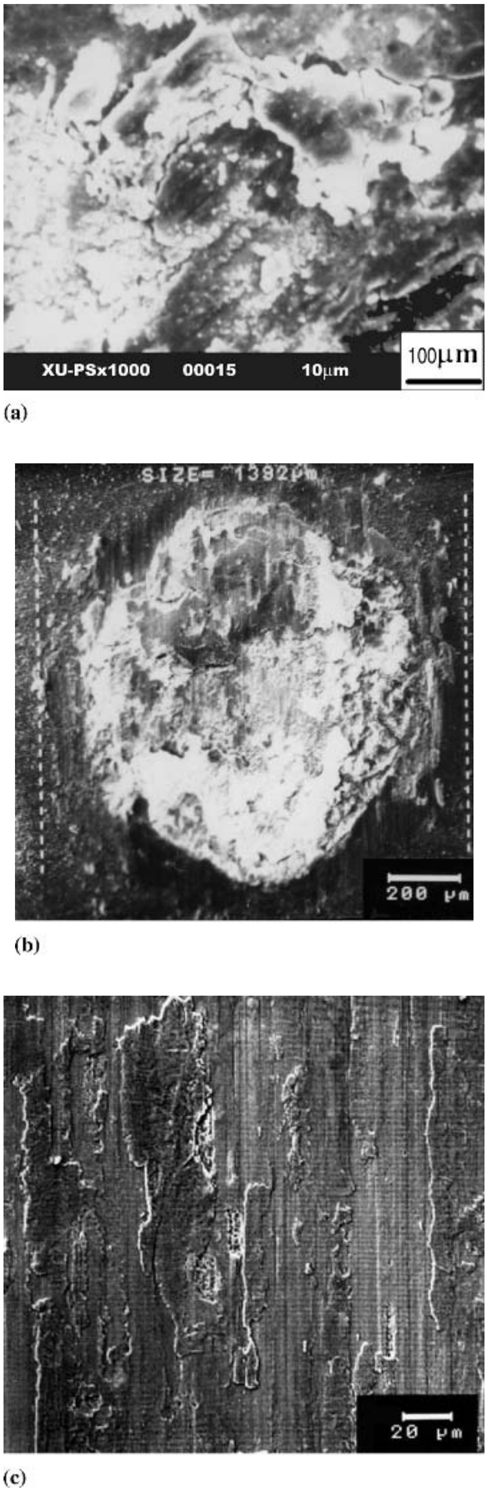

Fig. 3 The morphologies of fretting wear scars of the coatings (normal load 300 N, amplitude 60 µm, frequency 5 Hz, and 10,000 cycles): **(a)** PS composite coating, **(b)** TiN coating, and **(c)** MoS_2 coating

of a lot of debris particles resulted in the formation of a debris bed or third body composed of iron oxides. The morphology of wear scar of TiN coating (Fig. 3b) shows the heap of materials, which probably came from the compacted debris and transferred material of the counterpart. During the fretting wear, plastic deformation and fracture frequently occurred on this thick debris layer comprising Ti, Fe, and Cr oxides. At the same time, the loose debris particles oxidized severely on the contact surface and became more brittle and smaller. The morphology of the fretting wear scar of the MoS_2 coating (Fig. 3c) shows that a lot of MoS_2 debris transferred from the coating to the counterpart was smeared on the coating undegraded. Obviously the third body composed of MoS_2 debris played an effective lubricating role. This not only kept the friction coefficient at a low level throughout the process, but also minimized the damage to the substrate.

3.2 The Effect of Rheology of the Third Body on the Fretting Wear Behavior of the Coatings

The formation of the third body was a virtual process, in which the loose debris particles produced by various damage mechanisms were trapped, compacted, deformed, oxidized, broken, and aggregated continuously and alternatively on the contact surfaces. After the formation of the third body, the reciprocating movement of fretting wear still kept it moving and evolving. Therefore, the nature and rheology of the third body affected the wear behavior of the whole fretting wear system.

The morphologies of the debris eliminated from the contact surface of PS duplex coating at 10,000 and 100,000 cycles, respectively, are shown in Fig. 4. Analysis indicated that the fine plate-like debris ($d \approx 50$ nm) had aggregated to larger lumps ($d \approx 1$ µm) (Fig. 4a) at 10,000 cycles. The debris bed of steady state (100,000 cycles) comprised finer sphere-like particles ($d \approx 30$ nm) (Fig. 4b), which were Fe oxides according to the EDX analysis (Fig. 5). The variation of debris shape of the PS duplex coating from plate to sphere greatly improved the mobility of the third body. This promoted the delamination of the substrate and brought the friction coefficient of the PS duplex coating to a higher level than that of the other coatings at steady state.

Figure 6 shows the morphologies of debris squeezed from the contact surface of TiN coating at 10,000 and 100,000 cycles, respectively. It can be seen that the debris of both 10,000 and 100,000 cycles looked like fine plate-like aggregation. However, the particles of 100,000 cycles ($d < 50$ nm) (Fig. 6b) were smaller than that of 10,000 cycles ($d > 50$ nm) (Fig. 6a), and the former seemed looser than the latter. It was possible that the debris eliminated earlier included part of the TiO_2, which adhered the other oxides to form the large aggregation, and they were not fragmented completely because of the short period they remained on the contact surface. At steady stage, a large amount of the substrate debris composed mainly of incompletely oxidized metal particles was eliminated from the contact area, which made the debris look loose. EDX analysis of the debris at 100,000 cycles (Fig. 7) indicated that the content of Ti in the debris squeezed out of the contact surface was smaller than that of the debris remaining on the wear scar (Fig. 8). Results suggested that TiO_2 was apt to stay in the interface. TiO_2 was also beneficial for forming the third body

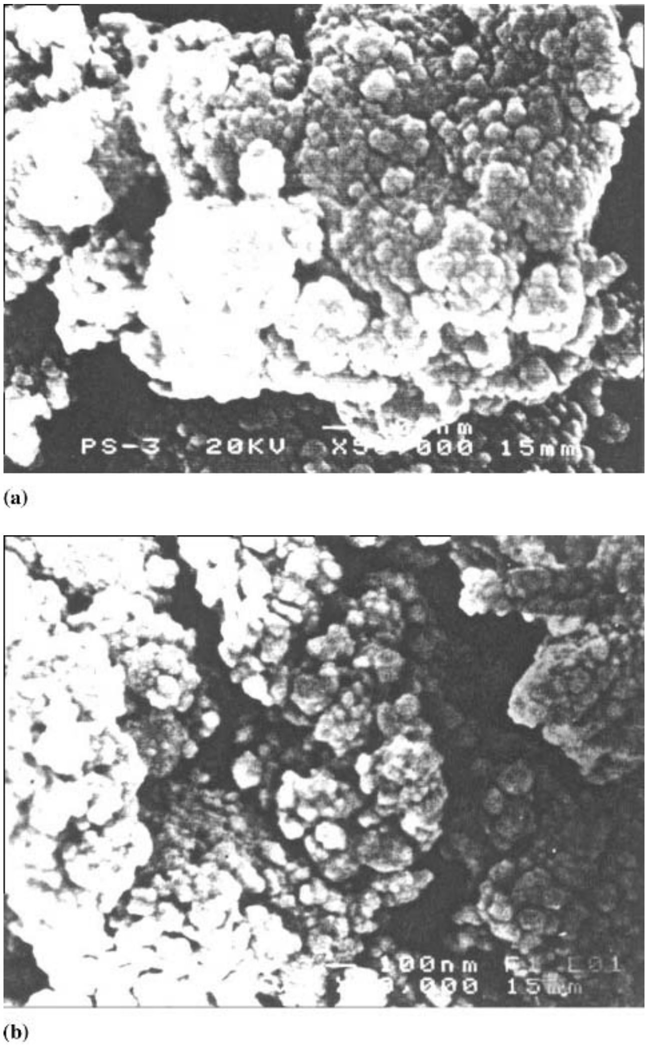

Fig. 4 The morphologies of the wear debris of the PS composite coating at different stages: **(a)** 10,000 cycles, and **(b)** 100,000 cycles

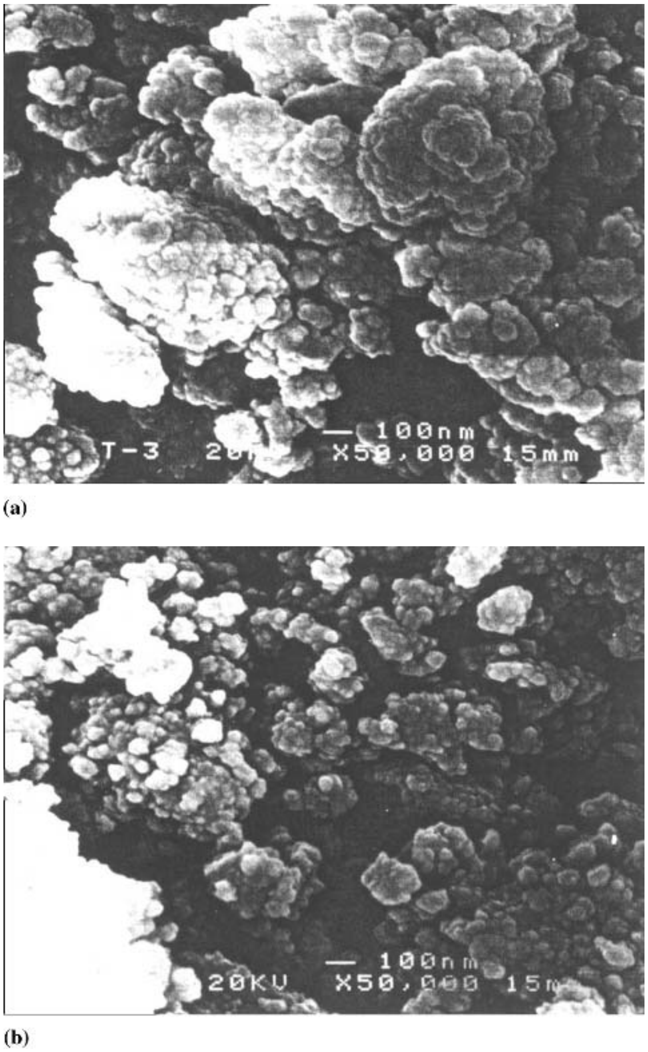

Fig. 6 The morphologies of the wear debris of the TiN coating at different stages: **(a)** 10,000 cycles, and **(b)** 100,000 cycles

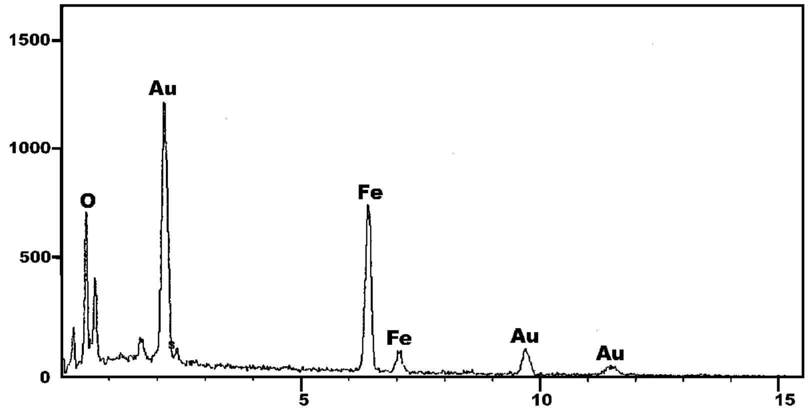

Fig. 5 The EDX analysis of the wear debris of the PS composite coating at 100,000 cycles

and decreasing the friction coefficient of TiN coating at steady stage of fretting wear.

The morphology and composition of the debris eliminated from the contact surface of MoS_2 coating at 100,000 cycles are shown in Fig. 9. It showed clearly that the debris of the MoS_2 coating were large plate-like particles composed of MoS_2 and

MoO_3, which still played a marked lubricating role. In addition, MoS_2 debris existing as large plates remained more easily in the interface to form the third body, the good load carrying capacity of which effectively restrained the damage of the substrate and kept the friction coefficient of the MoS_2 coating at a low level until the end of the fretting experiment.

On the basis of these analyses, it can be summarized that the third body, which is apt to remain on the contact surface or cling to the first bodies, can restrain the fretting wear from progressing because of the lubricating effects and separation of counterparts. Conversely, the wear debris that is eliminated from the contact surface will increase the fretting wear by its abrasion. The nature and rheology of the third body are mostly affected by the properties of materials and environmental conditions. Under the same environmental conditions, the mechanical and physicochemical properties of first-body materials and contact regime are the essential factors determining the formation and evolution of the third body.

4. Conclusions

- The third body of the PS duplex coating comprised Fe oxides. TiO_2, transferred material of the counterpart, and the substrate debris made up of the third body of TiN coating. The third body of the MoS_2 coating presented itself by MoS_2 debris smearing on the coating.
- The formation and rheology of the third body determined the fretting wear behavior of the coatings at steady stage. All the factors that made the debris layer or third body remain on the contact surface were able to decrease the friction coefficient and fretting wear. Conversely, the fretting wear resistance would be lowered if the debris particles were easily eliminated from the contact surfaces.
- The shape and nature of the debris were the essential factors to determine the mobility of the third body. The soft and large plate-like debris particles were apt to remain in the contact region. In contrast, the hard and sphere-shaped

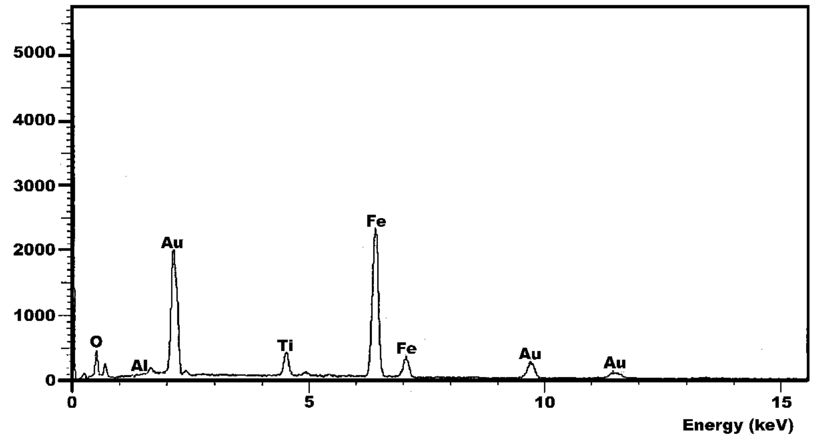

Fig. 7 The EDX analysis of the wear debris of the TiN coating at 100,000 cycles

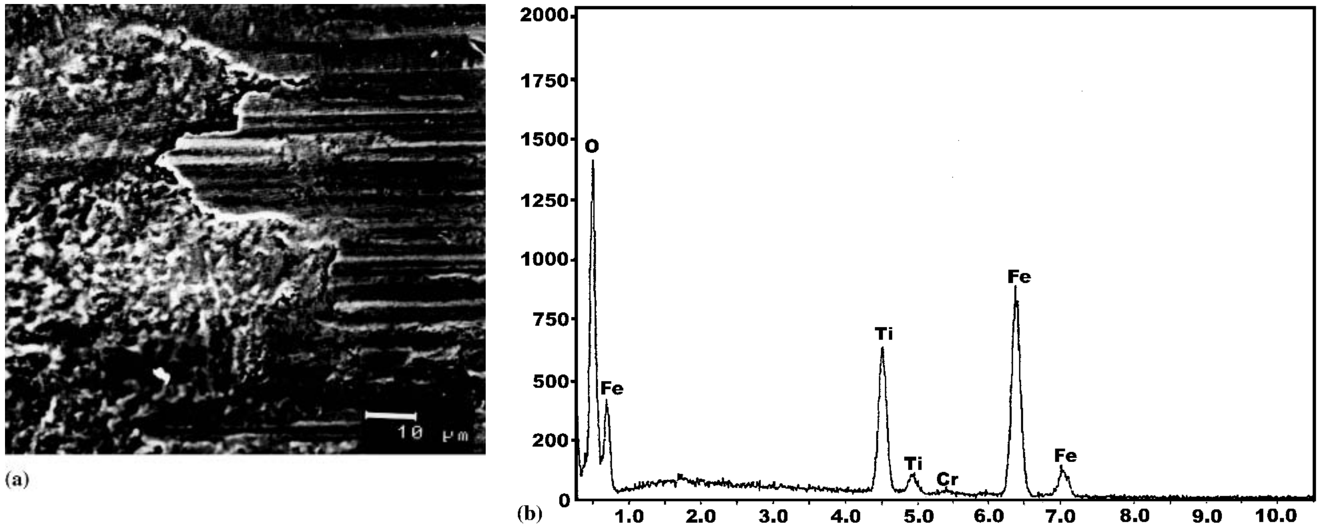

Fig. 8 The morphology and composition of the debris layer on the contact surface of the TiN coating. **(a)** The morphology of the debris layer on the contact surface of the TiN coating, and **(b)** the EDX analysis of the debris layer

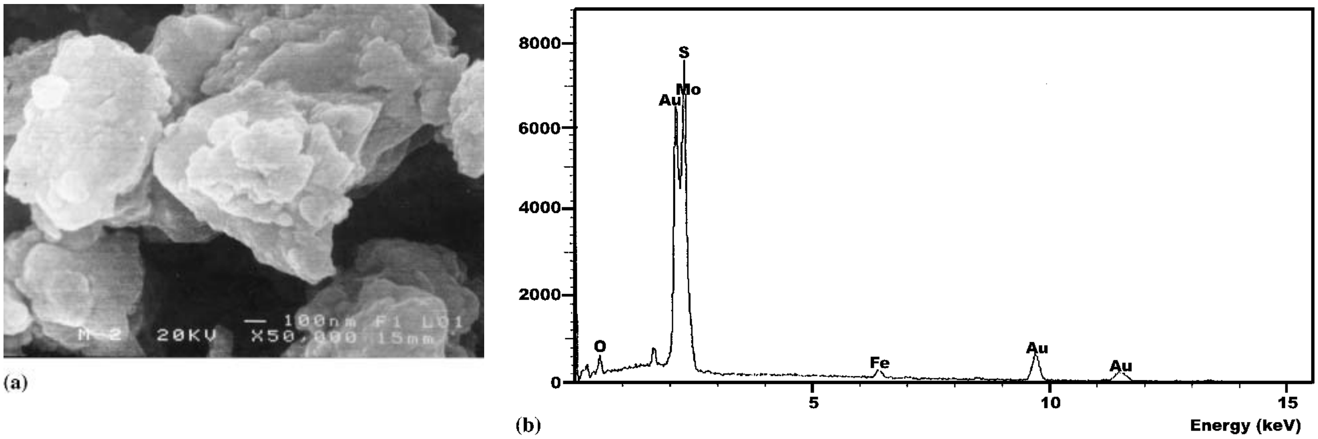

Fig. 9 The morphology and composition of the wear debris of the MoS_2 coating. **(a)** The morphology of the wear debris of the MoS_2 coating, and **(b)** the EDX analysis of the wear debris

debris particles tended to squeeze from the contact surfaces and increased the fretting wear.

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