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The influence of lubrication on tribological properties of Si_3N_4/1045 steel sliding pairs

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Compared with cermet cutting tools, ceramic cutting tools have much better thermal stability and higher hardness. Si_3N_4-based composite ceramics have been used progressively more for machining cast iron at very high speed. However, they have been found to be unsuitable for machining steel. One of the factors influencing this difference in behaviour is thought to be serious chemical wear of the ceramic at the high temperatures reached at the cutting tools. Lubrication could reduce the friction and the high temperature of the cutting tool/workpiece contact zone. A simulation test was carried out on a pin-on-disc tribometer in order to investigate the effect of lubrication on the friction and wear of Si_3N_4/1045 steel sliding pairs; the effects of load and speed on friction and wear were also investigated. The results show that suitable lubrication could greatly reduce the friction coefficient and wear rate of Si_3N_4 ceramic. Scanning electron microscopy, Auger electron spectroscopy and X-ray photoelectron spectroscopy were used for examinations of the worn surfaces. A wear mechanism of the Si_3N_4 ceramic in sliding contact with 1045 steel is proposed.

1. Introduction

Si_3N_4-based ceramics have attracted much attention as structural materials because of their excellent thermal and mechanical properties. In recent years, they are used more and more in machining cast iron and nickel-based alloys at high speeds [1–3]. However, they have been found to be unsuitable for machining steel because of the chemical dissolution of the ceramic in the chip at the high temperatures reached at the cutting edge [4]. The interdiffusion of elements and chemical dissolution between workpiece material and ceramic tool is much smaller when machining cast iron [5]. The wear rate of a silicon nitride cutting tool is two orders of magnitude lower when machining grey cast iron than when machining AISI1045 steel [6]. While steel is one of the most widely used class of materials, silicon nitride cutting tools would have greatly increased potential use, if they could perform as well on steel as they do on cast iron, by taking some effective measures. In this test, lubrication was used to reduce the friction and temperature in the contact zone between the ceramic and the steel; consequently, the chemical wear of the ceramic which occurred at high temperature could be controlled. The test was conducted on a pin-on-disc tribometer, which could simulate well the real cutting process. The friction and wear of the cutting tool usually depend on the properties of the tool materials, workpiece, machining conditions and environment. Under real machining conditions, it is often difficult or impossible to control all operational parameters, such as cutting speed, contact stress and environment. In addition, the measurement of friction force and wear of the tool is less accurate than it is on a tribometer. So the simulation test is very useful and effective for the friction and wear evaluations of the ceramic cutting tool materials.

2. Experimental procedure

2.1. Test machine and specimens

Wear tests were carried out on a pin-on-disc tribometer. The pin specimen was fixed; the disc specimen, driven by a motor, could rotate at different velocities. A schematic diagram of the tester is shown in Fig. 1. A line contact model was formed between the pin and the disc, which could simulate well the contact form of cutting tool and workpiece in real cutting practice. The pin was made from hot-pressed Si_3N_4 ceramic, 5 mm × 5 mm × 25 mm in size. The disc was machined from AISI 1054 steel (605 HV in hardness), 56 mm diameter and 6 mm thick. The frictional surface roughnesses of the pin and the disc were $R_a = 0.32$, 0.21 μm, respectively. Some properties of the Si_3N_4 ceramic are listed in Table I.

2.2. Test method

Friction and wear tests were operated under dry and lubricated conditions, respectively. The room

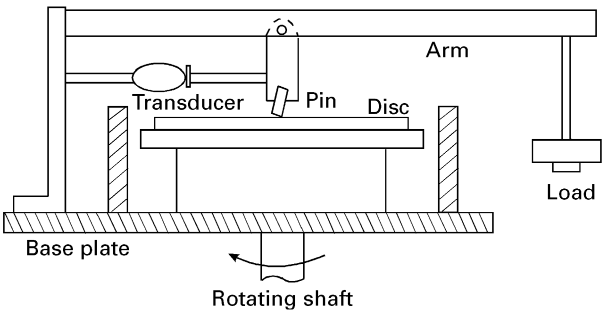

Figure 1 Schematic drawing of the contact model of the specimens.

TABLE I The physical and mechanical properties of the Si_3N_4 ceramic

Properties		Value
Amount	> 80	wt%
Density	3.5	$g\,cm^{-3}$
Hardness	1900	H_V
Bending strength	750	MPa
Elastic modulus	290	GPa
Fracture toughness	6.3	$MPa\,m^{1/2}$
Grain size	< 1.3	μm
Impurities		AlN, TiC, Y_2O_3

temperature was about 20 °C. The lubricants used were distilled water and a pure liquid paraffin. The kinematic viscosity of the liquid paraffin at 25 °C is $30\ mm^2\,s^{-1}$. During the operating process, the water or the oil were fed into the contact point between the pin and the disc by natural falling flow from a reservoir. The average rate of flow was about $0.01\ l\,min^{-1}$. The sliding speed between the rubbing surfaces varied over the range $0.8–3.2\ m\,s^{-1}$; a load range of 58.8–235.2 N was selected. Each pair had a 30 min running time under selected speed and load; at least two tests were performed and the results deviated by less than 6%. Before and after testing, the specimens were cleaned in an acetone bath for 15 min and then in a hexane bath for 2 min.

The wear scar width of the pin was measured under a photomicroscope, in order to calculate the volume and wear rate. The friction force was transmitted by a transducer to a recorder continuously during the test, from which the friction coefficient could be obtained. The worn surfaces were examined by scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS) and Auger electron spectroscopy (AES). An MgK_a line was used, the pass energy being 35.75 eV, and the binding energy C ls (284.6 eV) was used as reference.

3. Results and discussion

3.1. Effect of load on friction and wear

The effects of load on the friction and wear of Si_3N_4/1045 steel sliding pairs are shown in Figs 2 and 3, respectively. The sliding speed was $1.6\ m\,s^{-1}$. It can be seen from Fig. 2 that the friction coefficient increased gradually with load, and the lowest friction occurred under oil-lubricated conditions. Water had almost no effect on the friction coefficient. Under dry conditions, the wear rate was much higher than under lubricated conditions with both water and oil; in addition, it increased rather rapidly with load.

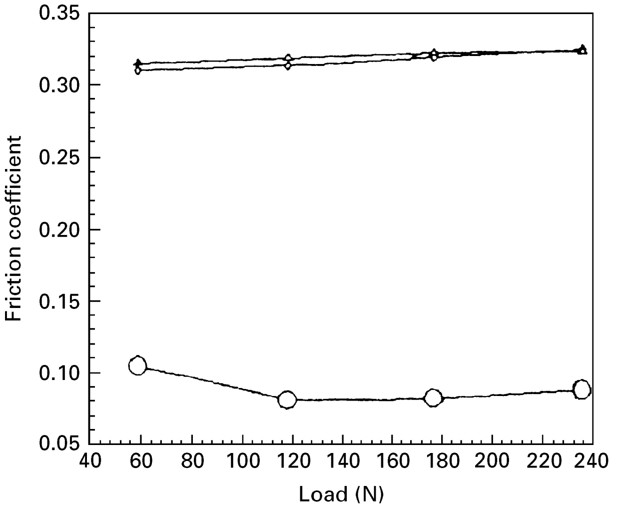

Figure 2 Friction coefficient as a function of load at $1.6\ m\,s^{-1}$, in (○) oil, (◇) water and (△) unlubricated.

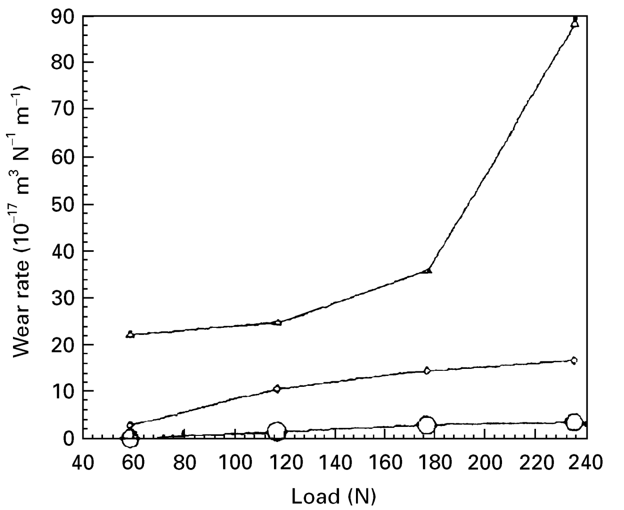

Figure 3 Wear rate as a function of load at $1.6\ m\,s^{-1}$, in (○) oil, (◇) water and (△) unlubricated.

Under boundary lubrication conditions, the carrying capacity of the water film is quite limited, it could not lubricate well the Si_3N_4/1045 steel sliding pairs, so no evident improvement in the friction coefficient was observed. However, water has a lower boiling point and higher specific heat than oil, so its good cooling property could reduce the temperature of the rubbing surfaces. Consequently, the element diffusion and chemical interaction between Si_3N_4 and 1045 steel could be decreased greatly, the adhesion wear and chemical wear could be controlled. In addition, the existence of water on the rubbing surfaces could accelerate the oxidation of 1045 steel surface; the formation of Fe_2O_3 (see Fig. 4) prevented adhesion of the rubbing surfaces to some extent. Compared with water, an oil film has a higher load-carrying capacity and better boundary lubricity, so the friction coefficient and the wear rate of Si_3N_4/1045 steel sliding pairs were improved significantly under oil-lubricated

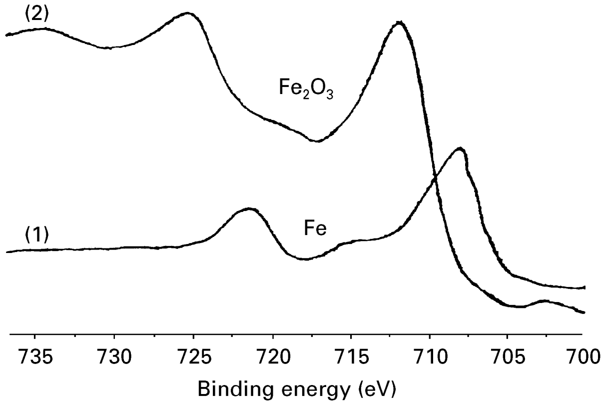

Figure 4 XPS spectrum of a worn steel surface: Fe 2P spectrum. (1) Original surface spectrum, (2) worn surface.

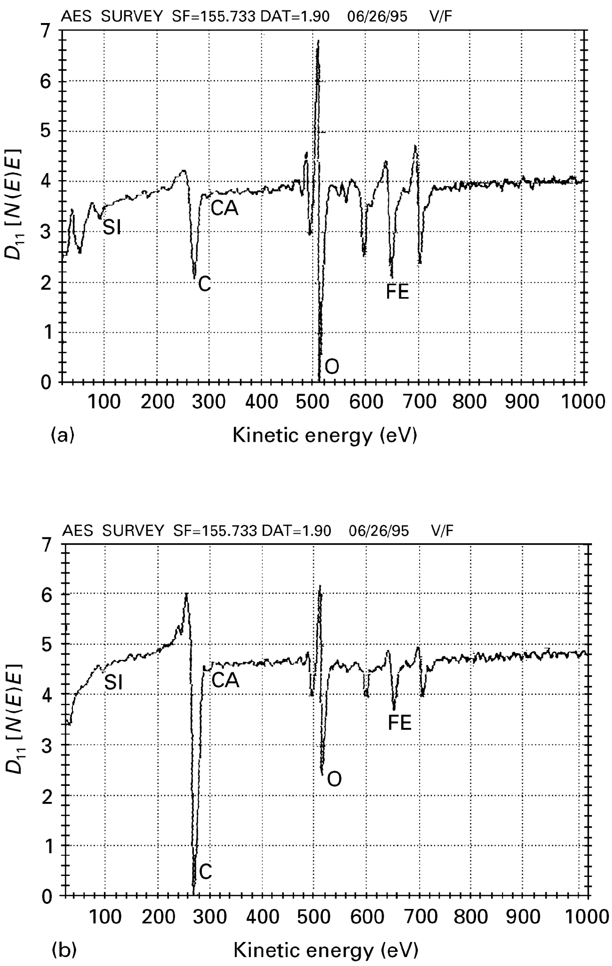

Figure 5 AES spectra of the worn steel surfaces. (a) 58.8 N, 1.6 m s^{-1}, 30 min, (b) 235.2 N, 1.6 m s^{-1}, 30 min.

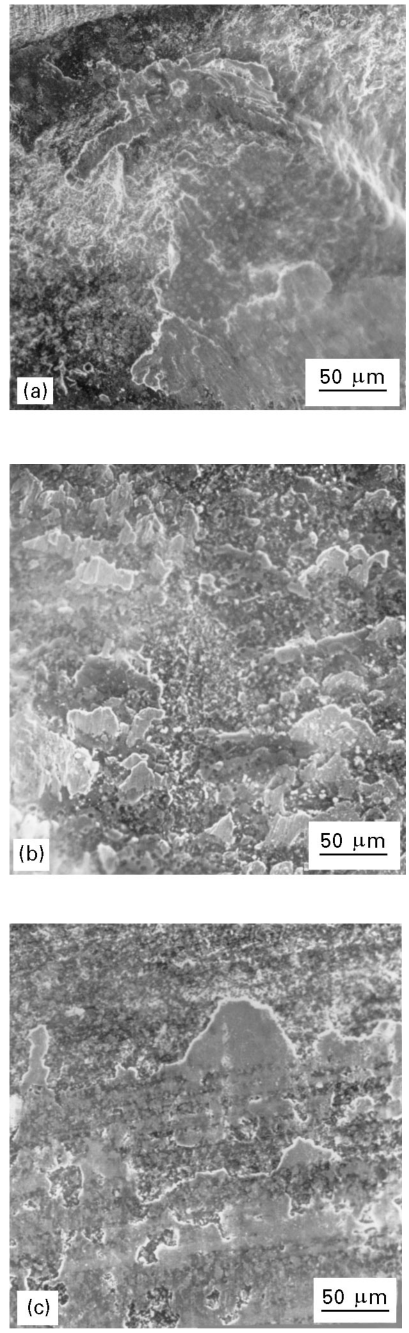

Figure 6 SEM morphologies of the worn Si_3N_4 surfaces: (a) dry friction, (b) water lubrication, (c) oil lubrication.

conditions. Moreover, it has been reported [7] that serious frictional conditions and catalysis by iron can cause the lubricating oils to become partially carbonized or graphitized; a carbon-rich polymer film formed on rubbing surfaces could improve boundary lubrication conditions. Fig. 5a and b indicate the formation of the carbon-rich film on the 1045 steel rubbing surface; the higher load brought about a larger amount of carbonized polymer. Under dry conditions, the rapid increase of wear rate at the high load range (beyond 180 N in this test) may be caused by the microfracture of the ceramic, which was proved by the SEM examination of the worn Si_3N_4 surface, see Fig. 6a. Fig. 6b and c show the SEM morphologies of the worn Si_3N_4 surfaces of lubricated conditions; obvious differences between them could be found. Lubrication could increase the critical fracture load of the ceramic surface [8]. Microfracture of the ceramic surface occurred much more easily under unlubricated conditions than under lubricated conditions.

Observations by SEM showed that wear debris produced at different frictional conditions differed in shape, see Fig. 7. Dry frictional conditions produced creeping deformation wear debris, block-shaped and larger in size, especially at higher load, while under oil-lubricated conditions, most of the particles were long and belt-shaped. When water was used for lubrication, small-sized wear particles were produced. The shapes of the wear particles could also explain, to

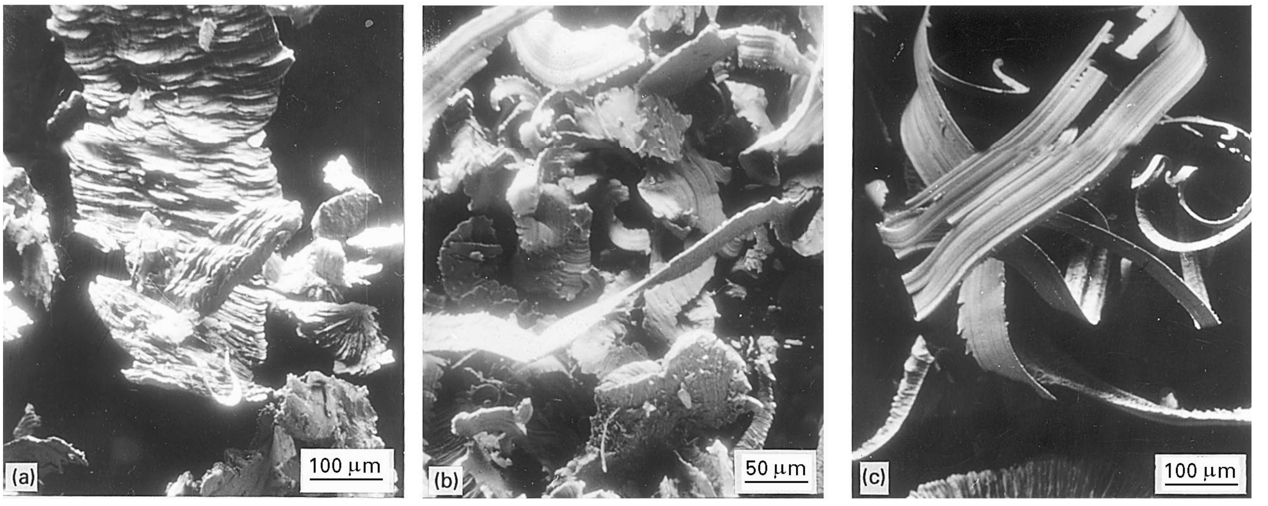

Figure 7 SEM morphologies of the wear debris: (a) dry friction, (b) water lubrication, (c) oil lubrication.

some extent, the different friction and wear properties of Si_3N_4/1045 steel sliding pairs under different conditions.

3.2. Effects of speed on friction and wear

Figs 8 and 9 show the effects of speed on the friction coefficient and wear rate of Si_3N_4/1045 steel sliding pairs, respectively. Under dry conditions, higher sliding speeds (more than 2.4 $m\,s^{-1}$ in this test) gave rise to higher friction coefficients and wear rates. High sliding speed produced a large amount of frictional heat and raised the temperature of the rubbing surfaces greatly, consequently, the element diffusion and chemical interaction between the Si_3N_4 and steel rubbing surfaces were accelerated, thus increasing the friction coefficient and wear rate. The chemical degradation of Si_3N_4 ceramic, caused by the chemical dissolution of Si_3N_4 grains at high temperature, followed by pull-out of Si_3N_4 grains from the glassy intergranular phase, was thought to be responsible for the high cratering wear found during the machining of AISI 1045 steel with Si_3N_4 ceramics [9]. Compared with Figs 2 and 3, it could be seen that the lubricated conditions have a more evident effect on the friction coefficient and wear rate at high sliding speeds, both being reduced to a greater extent. The cooling and lubricating actions of water and oil decreased the element diffusion and chemical interaction between the Si_3N_4 and steel rubbing surfaces which occurred at high sliding speeds. Tan [10] thought that element diffusion could increase by times with temperature, after the basic temperature for element diffusion had been reached. So suitable lubrication is very effective and important for the wear control of ceramic cutting tools in cutting practice.

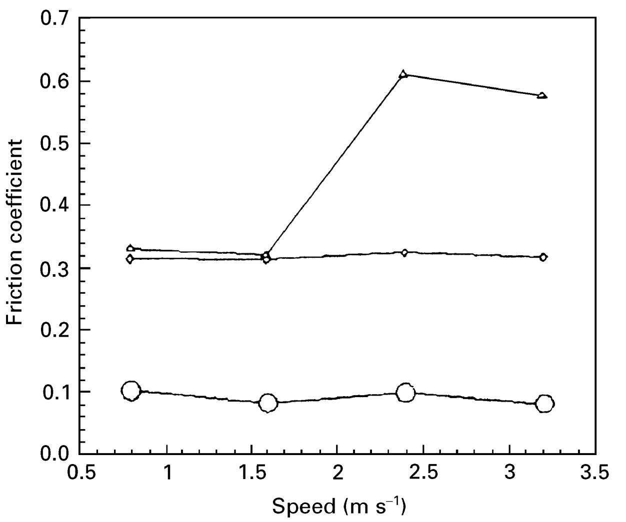

Figure 8 Variation of friction coefficient with speed at a load of 117.6 N, in (○) oil, (◇) water and (△) unlubricated.

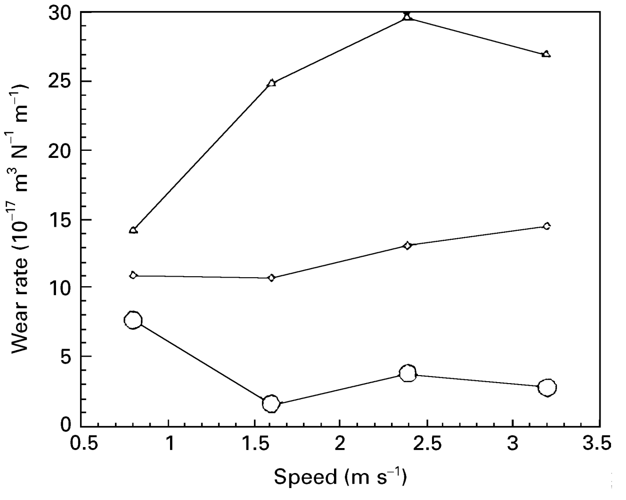

Figure 9 Variation of wear rate of Si_3N_4 with speed at a load of 117.6 N, in (○) oil, (◇) water, and (△) unlubricated.

3.3. Wear mechanisms of Si_3N_4 ceramic

SEM morphologies of the worn Si_3N_4 and 1045 steel surfaces show that serious adhesive transfer of 1045 steel on the ceramic surfaces occurred under dry frictional conditions; the worn surface of 1045 steel was rather rough, and many deep grooves were formed on it, see Fig. 10. The X-ray energy dispersion spectra of both the worn ceramic and steel surfaces are shown in Fig. 11. The rather intensive silicon peak in Fig. 11b may be caused by elemental silicon diffusion or

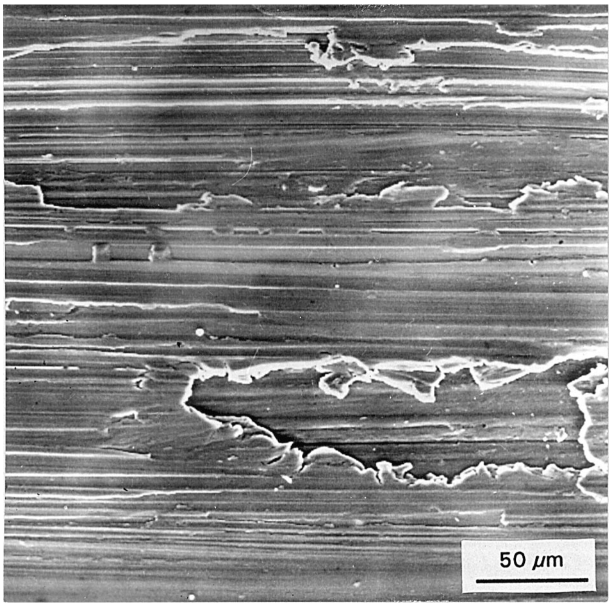

Figure 10 SEM morphology of the worn steel surface: dry friction at 117.6 N, 1.6 m s^{-1}, 30 min.

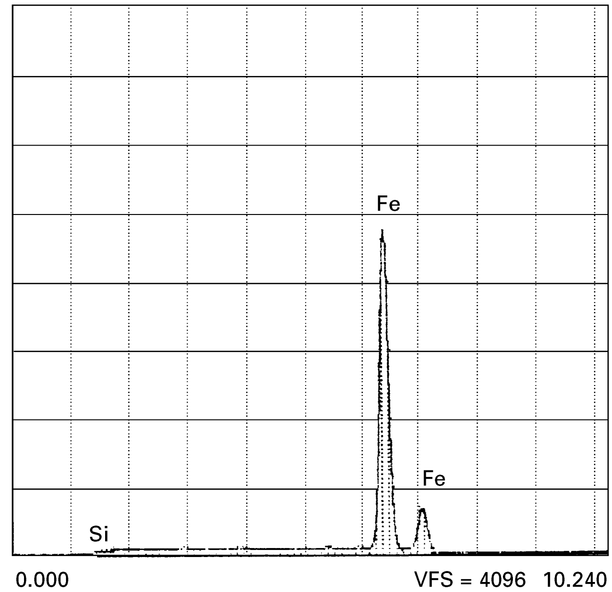

Figure 12 The energy dispersive X-ray spectrum of the original 1045 steel surface.

chemical dissolution of Si_3N_4 grains in the 1045 steel surface. Under lubricated conditions with water or oil, no elemental silicon was found on the worn steel surfaces. For comparison, the X-ray energy dispersion spectrum of the original 1045 steel surface is shown in Fig. 12.

From the examinations, the wear of Si_3N_4 ceramic in Si_3N_4/1045 steel sliding pairs under dry frictional conditions was mainly caused by adhesion between the rubbing surfaces and the microfracture of the ceramic, although chemical interaction between the rubbing surfaces was observed, which mainly aggravated the adhesion between the rubbing surfaces. In the rubbing process, the steel would be transferred to the ceramic surface because of adhesion; the transferred steel layers then were subjected to pressing stress and shearing stress (caused by friction force). Consequently, whether the subsurface of the ceramic covered by the transferred steel fractured, or the ceramic grains were pulled out, the transferred steel layers were peeled off the ceramic surface and caused the ceramic wear. With the relative movement between the ceramic and steel surface, the newly produced ceramic surface would be quickly covered again by the newly transferred steel layers. These newly transferred steel layers would be peeled off again. This process occurred repeatedly and continuously, resulting in the wear of the ceramic. This wear process could be described schematically as in Fig. 13. The lubricating and cooling actions of lubricants could prevent the chemical interaction and adhesion between the rubbing surfaces from occurring to a great extent; thus the friction coefficient and wear rate of Si_3N_4 ceramic were greatly reduced.

Ishigaki *et al.* [11] and Fischer and Tomizawa [12] thought that tribochemical reactions would occur on Si_3N_4/Si_3N_4 rubbing surfaces when water was used for lubrication. The suggested reaction process was $Si_3N_4 + 6H_2O \rightarrow 3SiO_2 + 4NH_3$, $SiO_2 + 2H_2O \rightarrow Si(OH)_4$. The $Si(OH)_4$ film formed on the rubbing

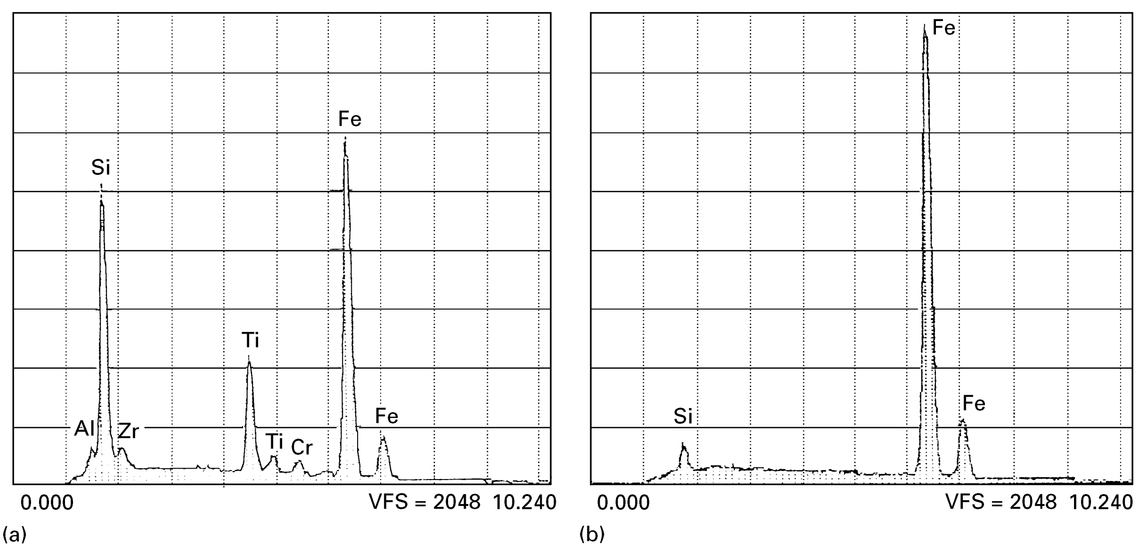

Figure 11 The energy dispersive X-ray spectra of the worn surfaces under dry friction (a) for Si_3N_4 ceramic, (b) for 1045 steel.

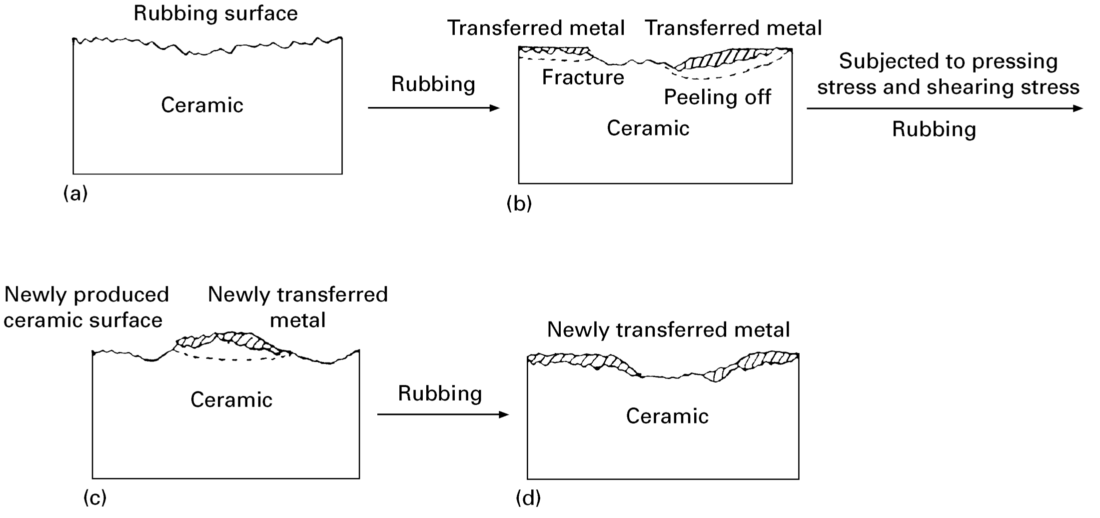

Figure 13 A schematic illustration of the wear mechanism of the Si_3N_4 ceramic.

surfaces could be sheared easily, so the boundary lubrication conditions could be improved. However, in this test, no $Si(OH)_4$ was found on the water-lubricated worn Si_3N_4 surface when the surface was examined by XPS. This result could be ascribed to the following factors: (1) the transferred steel layers reduced the direct contact area between water film and Si_3N_4 surface, the possibility of the tribochemical reactions between them was also reduced; (2) most of the areas where direct contact between water and Si_3N_4 occurred, were in low-lying areas of the ceramic surface, at which the friction conditions were relatively easy; the possibility of the formation of $Si(OH)_4$ film was also small. So the lubricating action of water was very limited in this test; the wear-reducing action mainly resulted from its cooling effect on the rubbing surfaces.

4. Conclusions

1. Under dry friction conditions, serious adhesion between the ceramic and the steel surfaces, and microfracture of the ceramic, occurred, which resulted in a high friction coefficient and a high wear rate.

2. A high load could cause the microfracture of the ceramic to occur more frequently, so the wear rate of the ceramic increased rapidly when the load was above a certain value. Lubrication could increase the critical fracture load. High sliding speeds caused a large amount of frictional heat under dry conditions, which could accelerate the element diffusion and chemical interaction between the rubbing surfaces, so the friction and wear properties were aggravated.

3. Lubrication could reduce the friction coefficient of Si_3N_4/1045 steel sliding pairs and the wear rate of Si_3N_4 ceramic. When lubricants were present on the rubbing surfaces, the element diffusion and chemical interaction between the rubbing surfaces could be prevented from occurring, so the adhesion and wear were reduced.

4. Compared with water, oil is more effective in reducing the friction coefficient and wear rate of Si_3N_4 ceramic. So in a real cutting process, suitable lubricating oils should be selected for reducing the wear of Si_3N_4 ceramic tools and raising their lifetime.

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