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The Wear Characteristics of Silicon Nitride

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Abstract

Friction and wear properties of silicon nitride were investigated using ball-on-disk tribometer under various relative humidity levels (RHL). Friction tests were conducted against various metals (copper, nickel, titanium, aluminium). The results show that the influence of humidity depends on the material of the couples. Tribological behaviour of silicon nitride sliding on very reactive metals such as titanium and aluminium is not influenced by RHL. In contrast, the friction coefficient and wear mechanism of nickel and copper are strongly affected by adsorbed films of water vapour. Tribological properties of Si_3N_4/Si_3N_4 couple were also studied and the effect of humidity was analyzed. © 1998 Elsevier Science Limited. All rights reserved

1 Introduction

Ceramic materials are increasingly being used in tribological applications. Among these materials, silicon nitride appears to be a good candidate for high temperature applications because of its high strength at elevated temperature.[1–3] In various industrial machines, silicon nitride roller bearings were advantageously used instead of steel ones.

Silicon nitride was also successfully applied to sliding elements of cars. One important aspect of the tribological behaviour of Si_3N_4 deals with its sensitivity to water in both gaseous and liquid states. Previous work does not give any clear evidence as to how water affects friction and wear of silicon nitride. Many authors reported that when sliding, an amorphous hydrated film forms at the surface which reduces friction coefficient and protect the material from further wear.[3–6] In other papers, it has been reported that the presence of small amounts of water in lubricating oil lead to increase both friction and wear.[7]

In the present paper, we have analyzed the effect of humidity and the influence of the microstructure of silicon nitride when this ceramic is in sliding contact against itself or against metals (copper, nickel, titanium, aluminium).

2 Experimental Details

Sliding tests were carried out using a pin-on-disc tribometer, working in a controlled atmosphere. The experiments were conducted in air, at room temperature (19°C), with various relative humidity levels (10 to 95%). The riders were spheres of Si_3N_4 without porosity in sliding contact with discs. The discs were polycrystalline samples of copper, nickel, titanium and aluminium. Si_3N_4/Si_3N_4 couples were also tested. Two types of silicon nitride were used as discs. The first type was without porosity [(Si_3N_4(W)], while the second type [Si_3N_4(P)] had a porosity of 20%. Some properties of these ceramics are listed in Table 1. Figure 1(a) and (b) show the topographies of the ceramics.

During the wear test, the motion was reciprocating with a frequency of 0·5 Hz. The length of the sliding distance was 15 mm and the test duration was 25 min. The applied load was 5 N for Si_3N_4/metal couples while a higher load of 30 N was used in the case of silicon nitride in sliding contact against itself. Worn surfaces were investigated by scanning electron microscopy (SEM), and profilometry.

3 Results and Discussion

3.1 Metal/Si_3N_4 couples

Values of friction coefficients for various metal/Si_3N_4 couples are shown in Table 2.

Increasing the humidity leads to decrease the friction coefficient for copper and nickel, indicating a reduction in the interfacial bond strength. In contrast, for aluminium and titanium, the friction coefficient is not affected by humidity.

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Table 1. Some properties of the ceramics used

Material	*Si_3N_4 (W)*	*Si_3N_4 (P)*
Hardness (Hv)	1600	1400
Fracture toughness (MPa $m^{1/2}$)	7	2·5
Young modulus (GPa)	300	150
Open porosity (%)	0	20

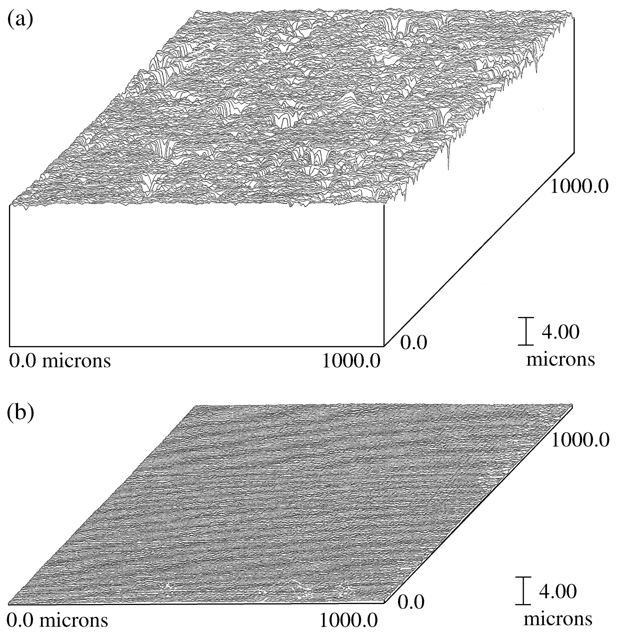

Fig. 1. Topographies of the two types of silicon nitride used in this study: (a) Si_3N_4 (P), porosity of 20%; (b) Si_3N_4 (W) without porosity.

Table 2. Values of friction coefficients of Si_3N_4 against various metals under several humidity levels

Metal	*Humidity (%)*						
	10	*33*	*50*	*66*	*76*	*86*	*95*
Cu	0·60	0·40	0·40	0·35	0·30	0·25	0·20
Ni	0·80	0·75	0·70	0·60	0·60	0·55	0·50
Ti	0·60	0·60	0·60	0·60	0·60	0·60	0·60
Al	0·80	0·80	0·80	0·80	0·80	0·80	0·80

When sliding, aluminium and titanium adhere strongly to silicon nitride at any relative humidity level (RHL). A large amount of transfer was detected in each case (Fig. 2) and the topography of the wear scar is characteristic of adhesive wear (Fig. 3).

Examination of the wear track on copper revealed evidence of a very thin transfer film at RHL of 10% and 33%, whereas no transfer was detected at higher humidity level. The surface of wear was smooth, indicating that copper did not suffer adhesive wear (Fig. 4).

3.2 Si_3N_4/Si_3N_4 couple

Figure 5(a) and (b) show the value of friction coefficient as a function of sliding distance for the two types of silicon nitride. The first type was without porosity [Si_3N_4(W)] and the second had a porosity of 20% [Si_3N_4 (P)].

Wear tests have been conducted at various RHL. The starting values of friction coefficient are 0·2 for Si_3N_4 (P). When sliding, after a certain time, the friction coefficient increases sharply from 0·2 to 0·8 ± 0·1. The latter value corresponds to a plateau. The only difference in specimen behaviour is in the time (or sliding distance) before the abrupt change in friction coefficient occurs. It increases with increasing humidity. The only exception is the test conducted under a humidity level of 95%. In this case, the friction coefficient has a constant value of 0·2.

For Si_3N_4 (W), the starting values of friction coefficient are higher than for Si_3N_4 (P), but the former shows a better resistance to wear. The surface profile of the wear scar on Si_3N_4 (P) is shown in Fig. 6.

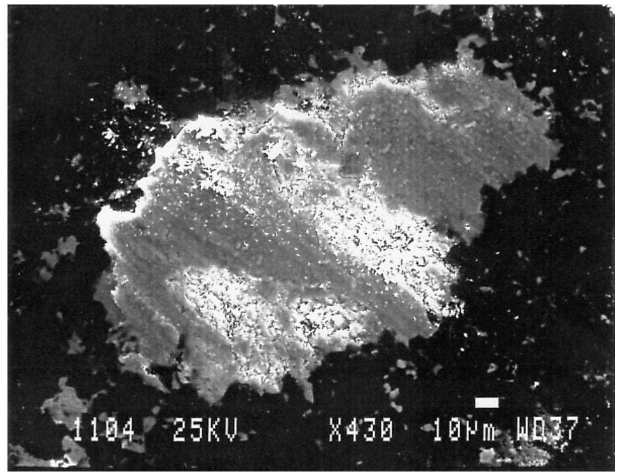

Fig. 2. SEM image of Si_3N_4 surface after sliding against aluminium. A large amount of metal transfer is shown. An identical result was obtained with the Si_3N_4/Ti couple.

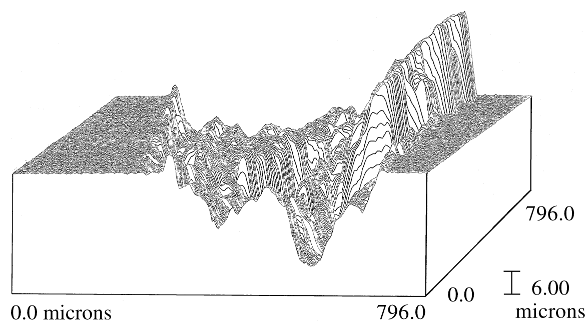

Fig. 3. Topography of wear track in aluminium after sliding against a sphere of Si_3N_4 under an applied load of 5 N.

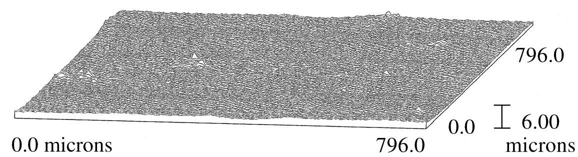

Fig. 4. Topography of wear track in copper after sliding against a sphere of Si_3N_4 under an applied load of 5 N.

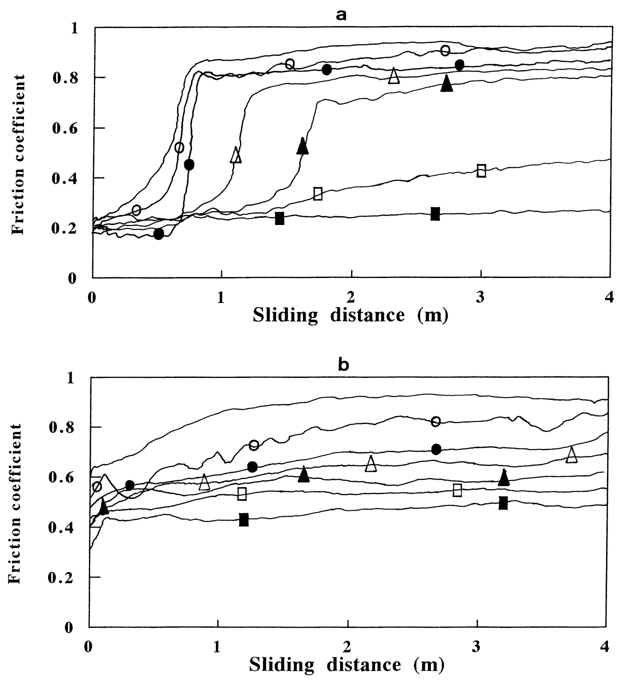

Fig. 5. Variation of friction coefficient with sliding distance for the two types of silicon nitride: (a) Si_3N_4 (P), (b) Si_3N_4 (W). The relative humidity is: —— 10%, —○— 33%, —●— 50%, —△— 66%, —▲— 76%, —□— 86%, —■— 95%.

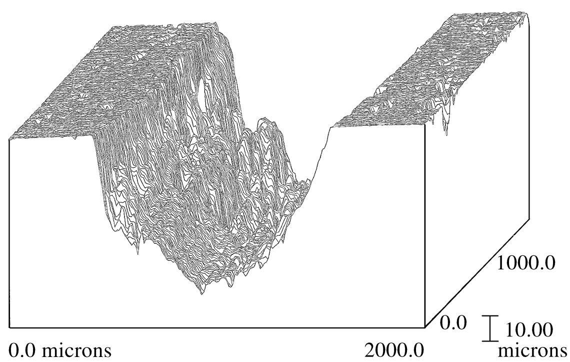

Fig. 6. The surface profile of the wear scar in Si_3N_4 (P) at the end of a sliding test conducted under RHL = 33%.

The evolution of wear rate as function of humidity for the two types of ceramics is reported in Fig. 7. The volume of material removal has been measured by tridimensional profilometry at the end of wear tests.

Under low RHL, Si_3N_4 (W) shows a better resistance to wear (Fig. 7) due to its better mechanical properties (Table 1). In the contrary, the two types of ceramic have identical wear resistance at the highest humidity level, this could be due to the formation of a protective lubricating film on the surface of silicon nitride in the presence of water.[3] The possible reactions between silicon nitride and water are:

$$Si_3N_4 + 6H_2O \rightarrow 3SiO_2 + 4NH_3$$

$$SiO_2 + 2H_2O \rightarrow Si(OH)_4$$

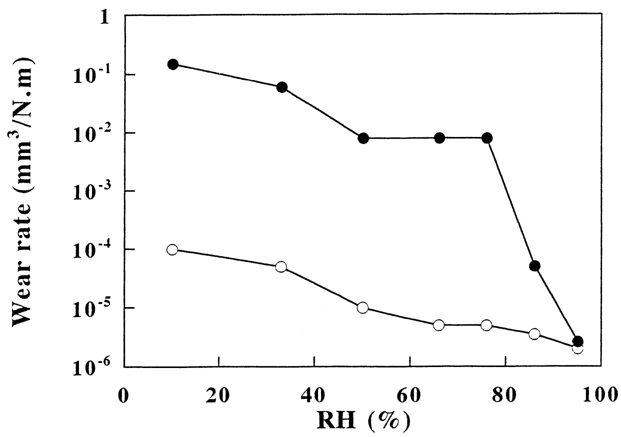

Fig. 7. Variation of the wear with relative humidity. —○—: Si_3N_4 (W), —●—: Si_3N_4 (P).

These reactions lead to the formation of a protective film of hydrated amorphous silica which are known to reduce friction and wear.

The results reported above show clearly that the formation of these films has a beneficial effect even in the case of porous silicon nitride.

4 Conclusion

Friction and wear properties of silicon nitride in sliding contact against various materials (Cu, Ni, Ti, Al, Si_3N_4) were studied using ball-on-disc technique, in air, with various relative humidity levels.

The following is a summary of the results obtained:

1. Increasing the residual humidity level (RHL) leads to a decrease in friction coefficient against copper and nickel. Adhesive wear takes place at low RHL while metal wear by ploughing, at high RHL.
2. In the case of aluminium and titanium, the friction coefficient is not affected by RHL. Friction coefficients are $\mu(\mathrm{Ti}) = 0{\cdot}60$ and $\mu(\mathrm{Al}) = 0{\cdot}80$ whatever the RHL. Aluminium and titanium adhere strongly to silicon nitride at any relative humidity level leading to an important metal transfer to the ceramic.
3. The results concerning Si_3N_4/Si_3N_4 couple indicate that friction and wear decrease with increasing humidity, due to the formation of a silicon hydroxyde film which reduce friction and wear.

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