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Journal of the European Ceramic Society 26 (2006) 2407–2412
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The interfacial and tribological properties of Ni–Cr alloy/ceramic tribo-couples under dry sliding contact

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Received 28 December 2004; received in revised form 18 April 2005; accepted 29 April 2005
Available online 13 June 2005

Abstract

In this paper, the tribological behaviors of Ni–Cr alloy sliding against Si_3N_4 and WC–Co at 20 °C and 600 °C were investigated on a tribometer with a ball-on-disk configuration. The experimental results indicated that Ni–Cr alloy sliding against WC–Co exhibited higher wear resistance than that sliding against Si_3N_4. From the viewpoints of the interfacial interactions between metal and ceramic (chemical reaction, wetting, adhesion, transference), the wear mechanisms were elucidated. The tribological behaviors of Ni–Cr alloy/ceramic tribo-couples were well correlated with the interfacial characteristics, namely the reactive interface and the non-reactive interface. Ni–Cr alloy/Si_3N_4 tribo-couple showed severe adhesive wear as a result of the interfacial reaction between Ni and Si_3N_4, while the non-reactivity of Ni/WC interface is the most important factor corresponding to the moderate adhesive wear in Ni–Cr alloy sliding against WC–Co. Finally, the relations among the interfacial characteristics, wear behavior, and temperature were discussed. The results may provide some experimental evidences on the design and optimization of metal/ceramic tribo-couples.

Keywords: Wear resistance; Interfaces; Si_3N_4; WC–Co

1. Introduction

Study on metal/ceramic interfaces plays significant roles in many engineering applications, such as advanced structural composites, microelectronic packaging, coatings, joints, and oxide-supported catalyst.[1,2] Therefore, many experimental and theoretical studies have been conducted on the fundamental behaviors for metal/ceramic interfaces. In recent years, these researches have focused on three aspects: chemistry, physics and materials science.[3]

Unlike these interfaces mentioned above, metal/ceramic tribo-couples belong to a sort of dynamic contact interface.[4] Many results have been published on metal/ceramic tribo-couples with emphasis on that wear is a function of many variables such as speed, load, temperature, contact geometry, surface roughness, lubrication, and environment, and eventually described their wear maps under different conditions.[5–8] Generally speaking, the tribological behaviors of metal/ceramic tribo-couples under unlubricated sliding contact are mainly determined by plastic deformation, adhesion, delamination and fracture, which are responsible for relatively high friction coefficient and wear rate. All the metal/ceramic tribo-couples with “clean” surfaces exhibited a correlation between the Young’s or shear modulus of metal and the adhesion, friction, and wear behavior of the metal. The tribological behaviors for metal/ceramic tribo-couples, including adhesion, coefficient of friction, metal wear, and metal transference to the ceramic, decrease with an increase in the Young’s or shear modulus of the metal.[9] In addition, when ceramics are in sliding against a metal, the chemical and metallurgical properties of the surface are directly related to their frictional properties.[10] Metal/ceramic interface may be broadly categorized as reactive and non-reactive. So far there is less information about interfacial reaction/tribological property relation for metal/ceramic tribo-couples.

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doi:10.1016/j.jeurceramsoc.2005.04.019

The objective of the present work was to study the tribological behaviors of Ni–Cr alloy sliding against Si_3N_4 and WC–Co at 20 °C and 600 °C, respectively. The worn surfaces of tribo-couples were analyzed by SEM/EDS. From the viewpoints of interfacial interaction (chemical reaction, wetting, adhesion, transference), the wear mechanisms of Ni–Cr alloy/ceramic tribo-couples were elucidated.

2. Experiment details

Ni powder (Shanghai No. 2 Metal Smeltery, AR. 99.4%, 200 mesh) and Cr powder (Shanghai No. 2 Metal Smeltery, AR. 99.8%, 200 mesh) were used as the initial components. The composition of the initial powders was 80 wt.% Ni and 20 wt.% Cr. The Ni and Cr powders were mixed in double cone blender for 3 h. The powder mixture was kept in a graphite die and then hot-pressed at 1200 °C for 15 min under a pressure of 15 MPa in inert atmosphere. The hot-pressed samples, namely Ni–Cr alloy, were machined and polished for microstructure observation and wear testing. The density measurement of Ni–Cr alloy was made using Archimeds method, and Ni–Cr alloy had a relativity density of >99%. The microstructure image of polished Ni–Cr alloy is shown in Fig. 1. Together with the EDS result, the microstructure of Ni–Cr alloy shows the existence of two phases: the grey area and the dark area were identified as Ni–Cr solid solution and chromium rich phase.

The friction and wear test were performed with a THT07-135 ball-on-disk high-temperature tribometer (CSM Instruments SA, Switzerland). The upper specimen was a commercially available ceramic ball with 3 mm in diameter, and the lower specimen was Ni–Cr alloy disk with a size of 25 mm in diameter and 8 mm in thickness. The surfaces of Si_3N_4 ball (Harbin Institute of Technology, China) and WC–Co ball (CSM Instruments SA, Switzerland) were of a ball-bearing quality, and the mechanical properties of ceramic balls are listed in Table 1. The surface roughness (R_a) of Ni–Cr alloy was 0.09 μm. Prior to commencing a wear test, the specimens were ultrasonically cleaned in an alcohol bath and then dried by hot-air. The experiment was done in ambient condition (relative humidity is 30%–50%), sliding velocity is 0.5 m/s and normal load is 5 N. Selected test temperatures were 20 °C and 600 °C. Wear rates were calculated by measuring the worn volume of the ball and the area of wear track cross section on the disk, using optical microscopy and surface profilometry. The friction coefficient was recorded continuously during the test by a computer. The worn surfaces and the composition of wear track as well as original surface were analyzed by SEM with EDS.

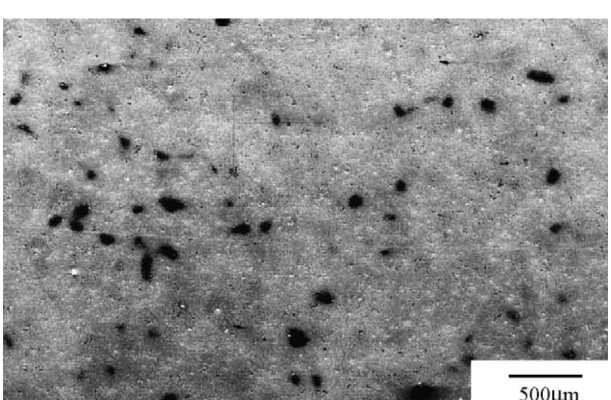

Fig. 1. Fig. 1 Microstructure image of Ni–Cr alloy polished.

3. Results and discussion

3.1. Tribological behaviors of Ni–Cr alloy sliding against Si_3N_4 and WC–Co

Fig. 2 shows the friction coefficients of Ni–Cr alloy sliding against Si_3N_4 and WC–Co, respectively. As shown in Fig. 2, the two tribo-couples exhibit high friction coefficient in the range of 0.6–0.8. For Ni–Cr alloy sliding against Si_3N_4, the friction coefficient at 20 °C is higher than that at 600 °C. The situation is reversed for Ni–Cr alloy sliding against WC–Co. The friction coefficient of Ni–Cr alloy/Si_3N_4 tribo-couple at 20 °C is shown in Fig. 3. It can be found that the friction coefficients showed some fluctuation around the aver-

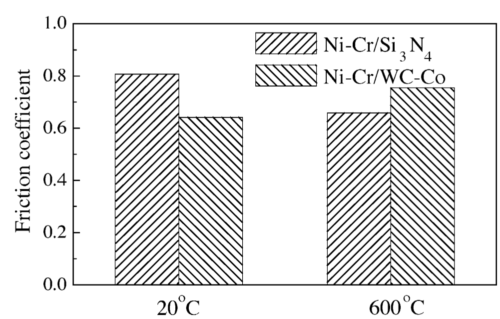

Fig. 2. Friction coefficients of Ni–Cr alloy sliding against ceramics at 20 °C and 600 °C.

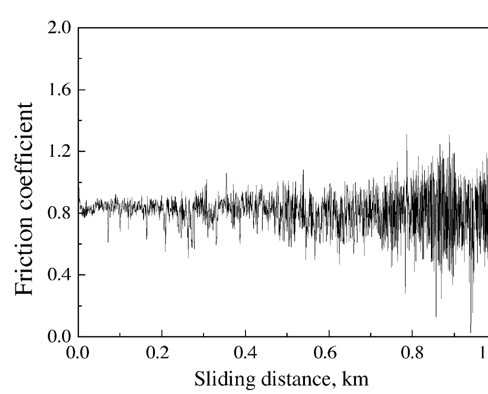

Fig. 3. Friction coefficient of Ni–Cr alloy/Si_3N_4 tribo-couple as function of sliding distance at 20 °C.

Table 1
The physical and mechanical properties of the selected ceramics

Ceramics	Density (g/cm^3)	Hardness HV (GPa)	Compressive strength (GPa)	Bending strength (GPa)	Tensile elasticity modulus (GPa)
WC–6% Co	15	15.5	5.3	1.6	610
Si_3N_4	3.2	14–17	–	–	320

age value, with a tendency to increase with increasing the sliding distance. The fluctuation of friction coefficients at 600 °C were particularly noticeable compared at 20 °C after shorter running-in period, and generated much big frictional noises during test. Actually, the frictional characters of Ni–Cr alloy/ceramic tribo-couples are related to their interfacial and transfer behaviors of tribo-couples interfaces.

Fig. 4 shows the wear rates of Ni–Cr alloy sliding against Si_3N_4 and WC–Co, respectively. It is noticeable that the two Ni–Cr alloy/ceramic tribo-couples exhibit apparent difference in wear resistance. The wear rates of Ni–Cr alloy/Si_3N_4 tribo-couple are much higher than that of Ni–Cr alloy/WC–Co tribo-couple, especially at 20 °C a difference of about two orders of magnitude in wear rate of Ni–Cr alloy for the two tribo-couples. In addition, the two tribo-couples exhibit two similar features: the wear rates of ceramic are lower than that of Ni–Cr alloy, and the wear rates of both ceramic and Ni–Cr alloy at 600 °C are higher than that at 20 °C. However, the previous studies have shown that the wear resistances increase at high temperature when a precipitation-hardened Ni-based super alloy (Inconel 718) sliding against ceramics, due to the formation of lubricious oxides.[11] Compared with Inconel 718, Ni–Cr binary alloy exhibit relatively low strength, which is unfavorable to the formation of a sufficiency thick oxide layer at high temperatures. Thus the Ni–Cr alloy is readily transferred to the ceramic surfaces, and lead to severe adhesion and high wear. This will be described later in this paper.

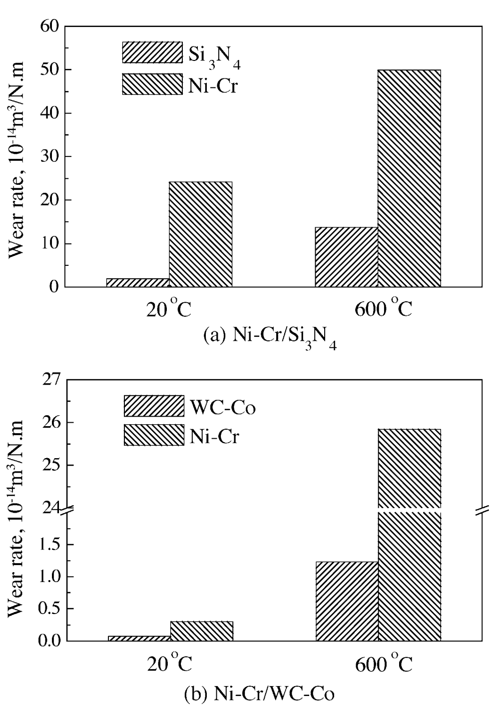

Fig. 4. Wear rates of Ni–Cr alloy/ceramics tribo-couples at 20 °C and 600 °C.

3.2. SEM/EDS observations

3.2.1. Ni–Cr alloy/Si_3N_4 tribo-couple

The SEM images of the worn surfaces of Ni–Cr alloy/Si_3N_4 tribo-couples are shown in Fig. 5. Worn surfaces of Ni–Cr alloy at both 20 °C and 600 °C show severe ductile deformation and flow along the sliding direction. At 600 °C, large wear debris on the worn surface probably result from adhesion and delamination, and is smeared onto the worn surface (see Fig. 5c). Due to strong bonding between metal and ceramic, transferred adhesive metal on the worn surface of Si_3N_4 at both 20 °C and 600 °C are clearly observed. Temperature is a significant factor to dominate the adhesion process. At 20 °C the built-up layer on the worn surface of Si_3N_4 appear flake-like (see Fig. 5b), whereas at 600 °C Si_3N_4 worn surface is entirely covered with continuous and thick metal transfer layer (see Fig. 5d).

3.2.2. Ni–Cr alloy/WC–Co tribo-couple

The SEM images of the worn surfaces of Ni–Cr alloy/WC–Co tribo-couples are shown in Fig. 6. The worn surface of Ni–Cr alloy at 20 °C shows typical characteristic of adhesive wear with a few white patches randomly located on the worn surface, as shown in Fig. 6a. The EDS results on the white patches (62.56% Ni, 14.10% Cr, 14.17% O, 6.67% W and 2.50% C) reveal the existence of metal oxides and WC particles on the worn surface. At 600 °C, severe plastic deformation of Ni–Cr alloy occurs, with some asperities and pits (shearing fracture). The EDS results of the worn surfaces of Ni–Cr alloy are listed in Table 2. According to Table 2, the concentration of oxygen of the worn surface at 20 °C is relatively higher than that at 600 °C. Therefore, it can be induced that at 20 °C some metal oxides are formed on worn surface due to the tribo-oxidation, which can greatly reduce adhesion and wear. However, at high temperature and contact stress conditions, the metal oxides are removed by the repeated slid-

Table 2
The EDS results of the worn surfaces of Ni–Cr alloy sliding against WC–Co in air

Temperature (°C)	Element (wt.%)			
	Ni	Cr	O	W
20	75.51	16.80	5.86	1.83
600	77.41	20.00	2.59	–

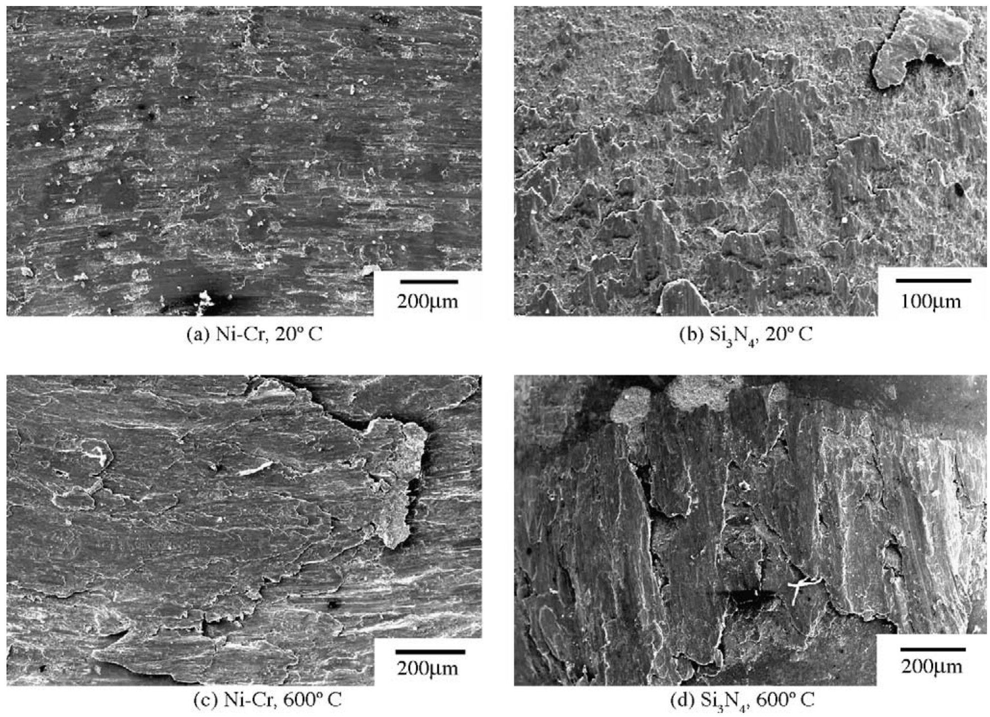

Fig. 5. SEM images of worn surfaces of Ni–Cr alloy/Si_3N_4 tribo-couples at 20 °C and 600 °C.

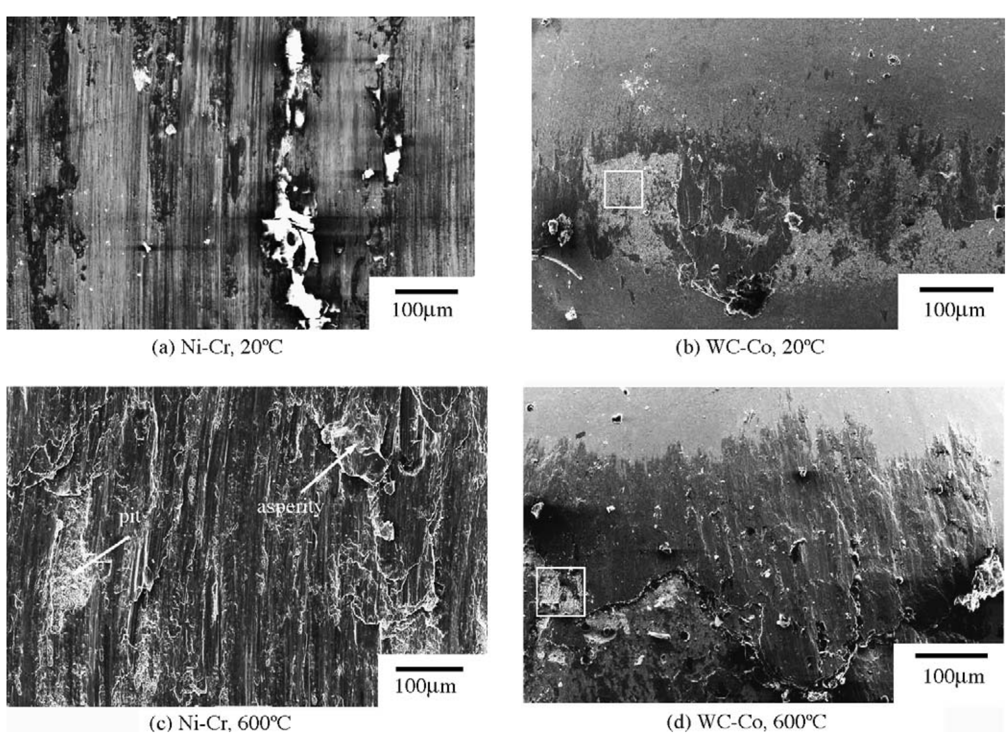

Fig. 6. SEM images of worn surfaces of Ni–Cr alloy/WC–Co tribo-couples at 20 °C and 600 °C.

ing and consequently adhesive wear is unavoidable.[9] Like the Ni–Cr alloy/Si_3N_4 tribo-couple, it is also found that the transferred material from Ni–Cr alloy onto WC–Co worn surfaces was found at both 20 °C and 600 °C. As labeled □ in Fig. 6b and d, the transferred films on the WC–Co worn surfaces are unstable, and locally peeled off.

3.3. Wear mechanisms

For the two kinds of metal/ceramic tribo-couples, it can be obviously observed that metallic films are readily transferred onto the ceramic surface, and thereby control the friction and wear behaviors of metal/ceramic tribo-couple. During metal sliding against ceramic, the interfacial bond strength between the metal and ceramic is generally greater than the cohesive bonding of the metal. Thus, the fracture of the cohesive bonds in the metal results when shearing occurs.[9] These strong interfacial bonds and the mechanical properties are the main causes of the observed wear behavior and the transfer of the metal to the ceramic.[12] It can be considered that the wear mechanisms of metal/ceramic tribo-couples are explored on the basis of theory of adhesion recently developed for metal/ceramic systems.

The work of adhesion (W_a) of the metal/ceramic interface was calculated using the following equation:

$$W_a = \gamma_{lv}(1 + \cos\theta) \quad (1)$$

where γ_{lv} is the interfacial free energy of liquid–vapor and θ the contact angle. When chemical reactions take place at metal/ceramic interface, the expression for W_a becomes:

$$W_a = \gamma_{lv}(1 + \cos\theta) + (\gamma_{ss} - A\Delta G) \quad (2)$$

where γ_{ss} is the energy of the solid-reaction layer interface, A a constant related to the moles of product and ΔG the Gibbs energy. Thus, a thermodynamically favorable reaction (negative ΔG) increases the work of adhesion and should result in a lower contact angle.[13] According to these adhesion theories, it can be inferred that reactive metal/ceramic interface suffers more severe adhesion compared to non-reactive metal/ceramic interface.

It is well known that Ni/WC interface system have pronounced wettability. Contact angle of Ni on WC was as low as 0° at 1380 °C in vacuum.[14] However, this wetting is non-reactive, where the driving force of wetting mainly consists of physical force, such as van der Waals and dispersion force.[15] Hence, the bonding strength of Ni/WC interface is not as strong as that of chemical-bonding interface. Considering the work of adhesion is a function of temperature (the work of adhesion increase with the increasing temperature), the fact that the tribological properties of Ni–Cr alloy/WC–Co tribo-couple at 20 °C are much better than that at 600 °C can be well explained.

Generally Ni does not readily wet Si_3N_4 and generate a high contact angle (120°).[14] On the other hand, Ni/Si_3N_4 interface system at high temperature is thermodynamically unstable (negative ΔG), some reactions between Ni and Si_3N_4 occur, which enhance the wetting and adhesion and produce brittle intermetallic compounds such as NiSi and Ni_3Si.[16,17] Furthermore, it is noted that alloy element Cr has minor influence on the reaction between Ni and Si_3N_4.[18] During Ni–Cr alloy sliding against Si_3N_4, some reaction mentioned above can take place due to tribo-induced chemical and temperature effects. This is unfavorable for the tribological behavior of Ni–Cr alloy/Si_3N_4 tribo-couple and leads to severe adhesive wear. These results may provide experimental evidences on the design and optimization of metal/ceramic tribo-couples

4. Conclusions

The following conclusions could be drawn:

(1) The wear rates of Ni–Cr alloy/Si_3N_4 tribo-couple are much higher than for Ni–Cr alloy/WC–Co tribo-couple, especially at 20 °C, a difference of about two orders of magnitude in wear rate of Ni–Cr alloy for the two tribo-couple.

(2) The tribological behaviors of Ni–Cr alloy/ceramic tribo-couples were well correlated with their interface characteristics. Ni–Cr alloy/Si_3N_4 tribo-couple showed severe adhesive wear due to their interfacial reaction, while the non-reactivity of Ni/WC interface is an important factor corresponding to mild adhesive wear in Ni–Cr alloy sliding against WC–Co.

Acknowledgement

The authors acknowledged with thanks for the financial supports from Xibuzhiguang of Chinese Academy of Sciences.

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