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Environmental effects on friction and wear of dry sliding zirconia and alumina ceramics doped with copper oxide

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Abstract

The influence of the addition of copper oxide on the friction and wear characteristics of dry sliding zirconia and alumina at various humidities and elevated temperatures is outlined in this article. At various humidities, it is found that the addition of CuO give a significant contribution in reducing the coefficient of friction of dry sliding zirconia against alumina (from 0.65 to 0.25) and alumina against alumina (from 0.55 to 0.35) systems. At elevated temperatures, zirconia and alumina doped with CuO exhibit high friction ($f > 0.6$). The experiments reveal that alumina doped with CuO exhibit superior resistance to wear even at high temperature.

Keywords: Zirconia; Alumina; CuO; Friction reduction

1. Introduction

Nowadays, most mechanical systems in, for instance, an engine use liquid lubricant to reduce friction and wear of the machine components. However, the strict exhaust emission regulations, the environmental issues and the demand of costumers to reduce maintenance costs have encouraged researchers to reduce the use of lubricants in engines and start to develop unlubricated engines [1].

The properties of low density in combination with high hardness and high elasticity modulus as well as the ability to preserve the mechanical properties at elevated temperatures has brought ceramics as the front end material to meet the challenge of unlubricated engines. Not only for machine components, with their high hardness, high elasticity modulus and chemical inertness, ceramics have been used as materials for cutting tools [2,3] and for biomedical applications [4].

The current developed ceramics has shown to be wear resistant in dry sliding contact conditions [5,6]. However, for sliding contact condition, these wear resistant ceramics still exhibit a high coefficient of friction which of course will cause large energy dissipation. Besides the energy loss, coefficient of friction effects the transition of mild to severe wear of ceramics at dry sliding contact conditions [7]. Therefore, low friction and wear resistant dry sliding ceramic systems are needed not only to reduce the energy loss but also to extend the operational conditions and still operating in the mild wear regime. To be considered as an interesting material for dry sliding contact applications, the material should be wear resistant (specific wear rate, $k \ll 10^{-6}\ \mathrm{mm^3\ N^{-1}\ m^{-1}}$) and reveals low friction ($f < 0.2$) [8].

In principle, a low friction system can be achieved by having hard materials to support the normal load and a soft thin interfacial material to provide easy shear, i.e. lubrication. For dry sliding systems, lubrication is

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implemented by hard materials coated with a soft thin coating or by dispersing soft second phase material in the base material which can act as a lubricant (self lubrication mechanism) when the system slides. For a well performing dry sliding system, a self lubricated material is preferred. It is found [10–12] that the addition of CuO as a second phase in zirconia can reduce the coefficient of friction from 0.7 (for a dry sliding zirconia system) down to 0.25. The presence of CuO in zirconia forms copper rich grains and these grains are squeezed out into the contact due to the high contact pressure and smeared along the wear track as the system slides forming a soft thin layer. Alumina ceramic doped with copper oxide is also developed and it is found that the addition of copper oxide into alumina reduces the coefficient of friction of pure alumina from 0.55 down to 0.4 [11]. All the dry sliding tests reported in our previous publications [5,6] were conducted at a temperature of 23 °C and a relative humidity of 40%. In practice, the temperature and the humidity can vary depending on the application. Therefore, in this article, results are presented showing the influence of the addition of CuO on the tribological behaviour of zirconia and alumina ceramics at various humidities and temperatures.

2. Material preparation and testing methods

Five percent weight (5% wt) of copper oxide powder (particle size < 5 μm, Alfa Chemical, Germany) was added to alumina (particle size ~ 0.23 μm, AKP50, Sumitomo, Japan) and 3Y-TZP powder (particle size 30–40 nm, Tosoh, Japan). The composite powders were mixed by wet milling for 24 h in a polyethylene bottle by using ethanol and zirconia balls as milling media. The mixed suspension was dried in an oven at 80 °C for 24 h and at 120 °C for 8 h. The mixed powder was ground lightly in a plastic mortar and sieved through a 180 μm sieve. The green compacts with a diameter of 50 mm and a thickness of 4–6 mm were produced by uniaxial pressing at 30 MPa and subsequently followed by isostatic pressing at 400 MPa. The composites of CuO and 3Y-TZP were sintered at temperatures of 1500 °C for 4 h and 1550 °C for 8 h. The composite of CuO and α-alumina was sintered at 1500 °C for 2 h. The heating rate and cooling rate used were 2 °C/min and the specimens were cooled down in the oven until 25 °C. The specimens have densities of more than 92%. The characterization of these materials is outlined in [11–13].

The materials ready for investigation were polished to a centerline surface roughness (R_a) of 0.1 μm. The samples were heated up to 850 °C for 2 h.

The experiments were performed on a pin-on-disc tribometer (CSEM, Switzerland). The tribometer has a special heater that can heat up the samples up to 700 °C. The tribometer was placed in a climate chamber which allow the user to set the humidity (up to 95%). The ball on disc geometry is chosen to avoid misalignment problems (see Fig. 1). The zirconia or alumina doped with CuO specimens are used as disc (see Fig. 1). In [10], it is observed that the reduction of friction is significant only when alumina or zirconia doped with CuO were sliding against alumina. Therefore, in this investigation we used a 10 mm diameter commercially available alumina ball as the counter body. The applied normal load is 5 N which corresponds to a maximum Hertzian pressure of 0.9 GPa for the case of zirconia sliding against alumina and 1.2 GPa for the case of alumina doped with CuO sliding against alumina. All the tests were conducted with 0.1 m/s sliding velocity. All specimens were cleaned ultrasonically in ethanol for 30 min and dried at 120 °C prior to the experiments. Each test was carried out for at least 1 km sliding distance.

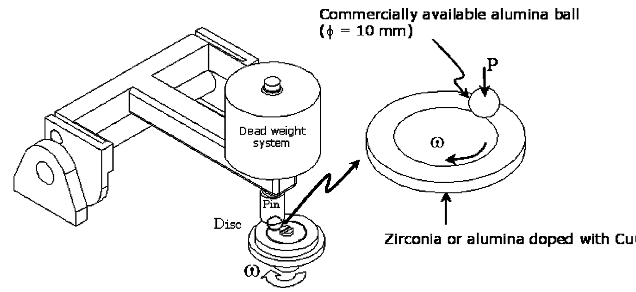

Fig. 1. Schematic representation of the pin-on-disc friction tester.

3. Results and discussion

3.1. Friction and wear of zirconia and alumina doped with CuO at various humidities

The coefficient of friction of alumina doped with 5% wt CuO sliding against alumina at various humidities is shown in Fig. 2. Fig. 2 shows the benefit of adding CuO into alumina where the coefficient of friction is reduced from 0.55 down to 0.4 at 23 °C and 40% relative humidity. At a higher humidity (95%), the coefficient of friction of dry sliding alumina doped with 5% wt CuO sliding against alumina decreases to 0.35 (see Fig. 2). For pure alumina sliding against alumina, Sasaki [14] reported that at various humidities, the coefficient of friction reduces from 0.6 at humidity of 20% down to 0.4 at humidity 75%. The results of Sasaki [14] and Gee [15] revealed that alumina absorb water when placed in humid air forming a hydroxide layer on the surface that consequently will reduce friction and wear. For all the tests performed at high humidity, there is hardly any wear observed of alumina doped with 5% wt CuO sliding

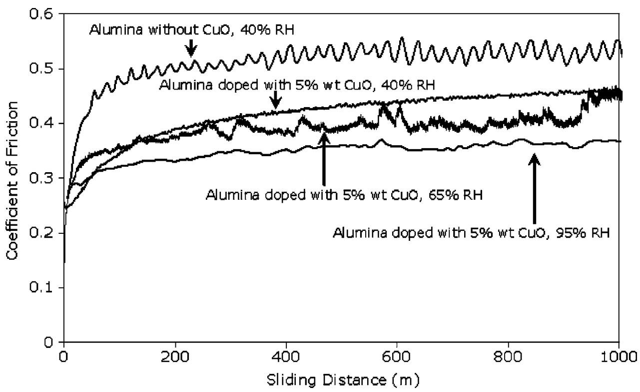

Fig. 2. Coefficient of friction of pure alumina and alumina doped with CuO sliding against alumina at different humidities. (Normal load: 5 N, sliding velocity: 0.1 m/s, temperature: 23 °C.)

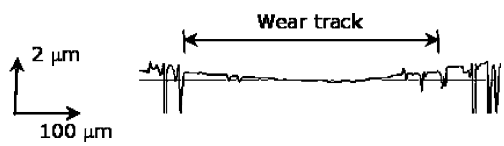

Fig. 3. Typical wear track profile of alumina doped with CuO sliding against alumina at 23 °C and different humidities.

against alumina (specific wear rate, $k \ll 10^{-7}$ $mm^3\ N^{-1}\ m^{-1}$). The wear track looks very smooth (see Fig. 3) and most probably the wear that took place happened at the very beginning of sliding (running-in process).

In contrast with alumina, humidity does not show any significant effect on friction and wear of pure zirconia (see Fig. 4a). The coefficient of friction of pure zirconia fluctuated around 0.7 (see Fig. 4a) and the specific wear rate is slightly less than $10^{-6}\ mm^3\ N^{-1}\ m^{-1}$ for all tests performed. Our experimental results are also in conformance with the observation of Sasaki [14]. Sasaki [14] reported that the coefficient of friction of zirconia only reduce from 0.7 down to 0.6 at humidities of 0–80% while the specific wear rate is reported between $5 \times 10^{-7}\ mm^3\ N^{-1}\ m^{-1}$ to $10^{-6}\ mm^3\ N^{-1}\ m^{-1}$.

In general, the coefficient of friction of zirconia doped with CuO sliding against alumina reduces as the relative humidity increases and the coefficients of friction as a function of sliding distance in general follow a certain characteristic. At the start, the coefficient of friction is low for a certain sliding distance then gradually increases and stay at a high value.

The addition of CuO into zirconia shows a significant influence on friction and wear at various humidities (see Fig. 4b and c). For zirconia doped with CuO sintered at 1500 °C, at 40% and 95% humidity the coefficient of friction can be as low as 0.3 for a sliding distance of 2 km whilst for 18% humidity the coefficient of friction is about 0.35 for 1 km sliding distance. After a certain sliding distance the low friction gradually increase to a higher value (see Fig. 4b). When the coefficient of friction of this material is low (about 0.2–0.35), there is hardly any wear observed. This is due to the fact that soft copper rich grains [12,13] at the surface of zirconia doped with CuO can be squeezed out due to the high contact pressure and smeared along the wear track forming a patchy soft thin layer that principally will reduce friction, i.e. a self lubricating mechanism [9]. The presence of water vapor might reduce the interfacial shear strength between alumina and zirconia doped with CuO sintered at 1500 °C, as shown by Fig. 4b where the coefficient of friction varies from 0.35, 0.3 and 0.2 at 18%, 40% and 95% humidity, respectively.

For zirconia doped with CuO sintered at 1550 °C, at 18% and 40% humidity the addition of CuO does not show any contribution in reducing the friction of zirconia (see Fig. 4c), in contrary, the addition of CuO increase the friction as well as the wear compared to that of pure zirconia. However, at higher humidities (60% and 95%), the coefficient of friction is reduced from 0.7 down to 0.4 and 0.25 for a certain sliding distance (1–2 km) and after that, the coefficient of friction gradually increase again to a higher value (0.8). At 95% humidity, there is no significant wear observed when the coefficient of friction is about 0.3 or lower. In zirconia doped with CuO sintered at 1550 °C, the amount of amorphous copper rich compound is different from that of zirconia doped with CuO sintered at 1500 °C [12,13]. This difference may cause the different tribological behaviour between zirconia doped with CuO sintered at 1500 °C and the one sintered at 1550 °C.

3.2. *Friction and wear of zirconia and alumina doped with CuO at elevated temperature*

Alumina doped with 5% wt CuO sliding against alumina show an increase in friction with increasing temperature (up to 500 °C). The coefficients of friction increase from 0.4 to 0.8 as the temperature increases (see Fig. 5). The values of the coefficient of friction are in the same range with the values observed by Dong et al. [16] where the coefficient of friction of pure alumina increases from 0.4 to 0.8 as the temperature increases from 100 °C to 800 °C.

Specific wear rates, k, less than $10^{-7}\ mm^3\ N^{-1}\ m^{-1}$, were observed in the sliding tests of alumina doped with CuO sliding against alumina at elevated temperatures.

The steady state coefficient of friction of zirconia doped with CuO sliding against alumina tested at elevated temperatures are shown in Fig. 6. At elevated temperatures, the coefficient of friction of zirconia doped with CuO sintered at 1500 °C and 1550 °C, are about the same value as that of pure zirconia. In addition a lot of wear (severe wear) was observed when zirconia

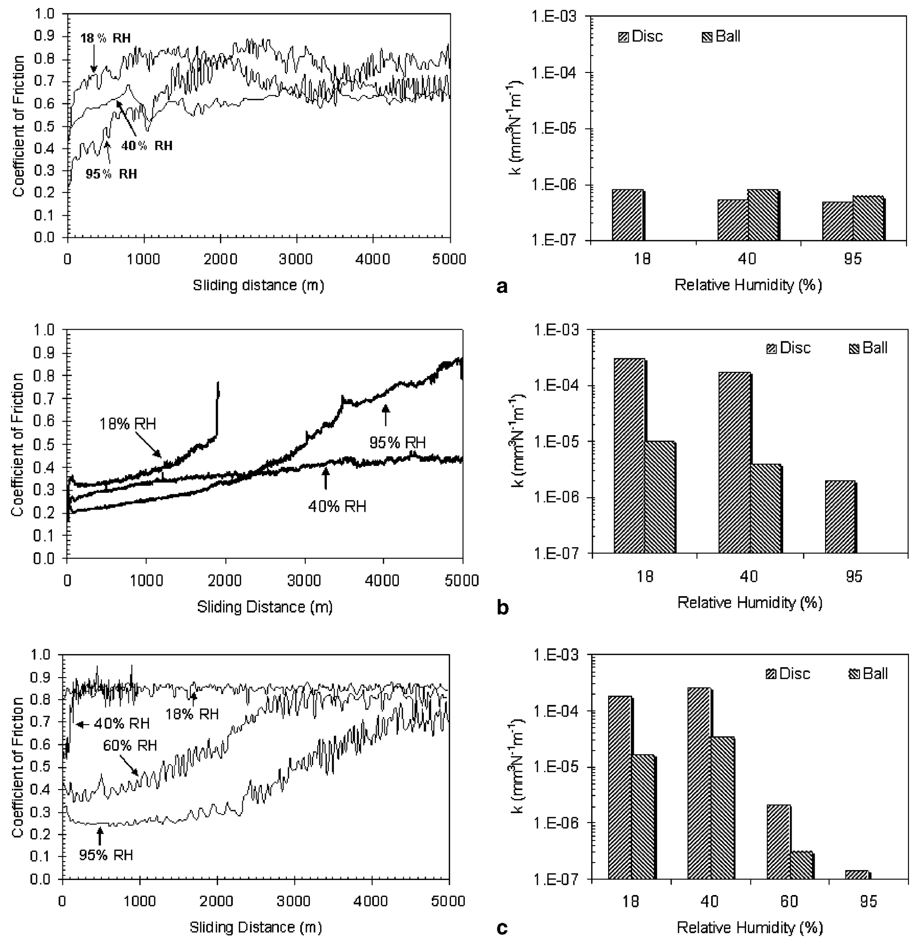

Fig. 4. Coefficient of friction and specific wear rate of pure zirconia (a), zirconia doped with CuO sintered at 1500 °C (b), and zirconia doped with CuO sintered at 1550 °C (c) sliding against alumina at different humidities. (Normal load: 5 N, sliding velocity: 0.1 m/s, temperature: 23 °C.)

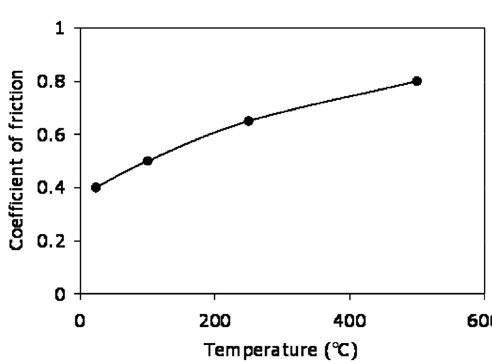

Fig. 5. Coefficient of friction of alumina doped with 5% wt CuO sliding against alumina at elevated temperatures. (Normal load: 5 N and sliding velocity: 0.1 m/s.)

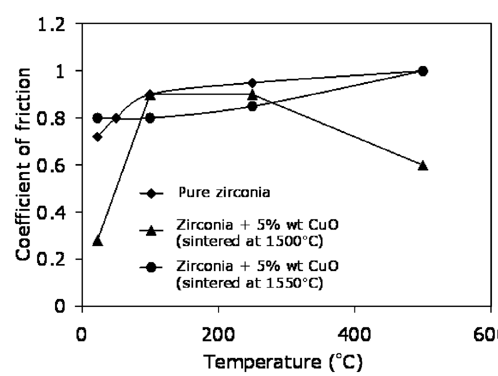

Fig. 6. Steady state coefficient of friction of pure zirconia and zirconia doped with CuO sliding against alumina at elevated temperatures. (Normal load: 5 N and sliding velocity: 0.1 m/s.)

doped with CuO were tested at elevated temperatures. For pure zirconia, our results show almost the same values as those reported by Stachowiak and Stachowiak [17]. They observed that the coefficient of friction of pure zirconia increase from 0.55 to 0.7 when the temperature was increased from room temperature to 400 °C. Stachowiak and Stachowiak [17] also reported high wear of zirconia tested at elevated temperatures.

The overall test results at elevated temperatures show that the addition of CuO does not give any significant reduction in friction and wear.

4. Conclusions

The addition of copper oxide (CuO) to alumina and zirconia ceramics shows a significant contribution in reducing friction when tested at various humidities. In general, the coefficient of friction is lower at higher humidity for zirconia doped with CuO. Zirconia doped with CuO sintered at 1500 °C, in particular, shows a low coefficient of friction (0.25–0.35) for the humidity range from 18% to 95%. However, the low friction only remain for a certain sliding distance (up to 2 km). Further research has to be conducted to maintain the low friction. Alumina and zirconia doped with CuO show high friction ($f \approx 0.6$–1) when tested at elevated temperatures (100–500 °C). Zirconia doped with CuO exhibit severe wear when tested at elevated temperatures whereas alumina doped with CuO shows superior resistance to wear even at high temperature (mild wear).

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