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Friction and wear characteristics of binary and ternary zirconia ceramics

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The friction and wear behaviour of binary and ternary zirconia ceramics was studied in an unlubricated environment over a range of loads and sliding speeds. In these tests, ternary zirconia ceramics based on the ZrO_2–CeO_2–Y_2O_3 system were seen to show very low friction coefficients and wear rates compared with the other binary zirconia systems investigated, with a coefficient of friction typically about 50% that of other (binary) zirconia ceramics, and a wear rate of about 1% of that of tetragonal yttria-doped zirconia. During slide testing of zirconias a transition from a low wear regime to a high wear regime was observed with increasing sliding velocity and load. SEM was used to identify the wear mechanisms.

1. Introduction

Over the past ten years much effort has been devoted to developing the mechanical properties of yttria-doped tetragonal zirconia polycrystal (TZP) and cubic-stabilized zirconia (CSZ) ceramics (e.g. references in [1, 2]). The materials show high strength and fracture toughness values enhanced by transformation toughening. However, it is well known that the tetragonal phase readily becomes destabilized and transforms to monoclinic symmetry during low-temperature annealing, particularly in humid environments, at 120–300 °C, with consequent decreases of both fracture strength and fracture toughness [3, 4]. Such a combination of temperature and atmosphere is likely to be realized locally in zirconia wear parts during use, and so measures should be taken to inhibit this degradation. Alloying TZP with CeO_2 has proved effective in this regard [5], and thus it is of interest to investigate the wear properties of these ternary zirconia ceramics.

There is increasing interest in the use of high-grade technical ceramics for a variety of engineering and industrial applications, particularly where high wear resistance is required [6–10]. Magnesia-doped zirconias (Mg–PSZ) are already in use in wear parts, particularly in the paper industry and in metal drawing dies, but suffer readily from fatigue-related degradation [7, 11]. In contrast, the friction and wear properties of fine-grained ternary zirconia ceramics (e.g. TZP alloyed with 20%Al_2O_3 or ZrO_2–Y_2O_3–CeO_2 compositions) in particular, have not been reported. As a contribution to the study of friction and wear processes in binary and ternary zirconia ceramics, with a view to identifying potentially useful tribological materials, the friction and sliding wear of binary and ternary zirconia ceramics, without lubrication, under different loads and sliding speeds, were investigated.

2. Experimental procedure

Seven ceramic powders based on doped zirconias (see Table I for compositions) were uniaxially pressed at 100 MPa to form discs 30 mm diameter and 3 mm thick. These were sintered at 1500 °C for 4 h in air, heating and cooling at 5 °C min^{-1}. The discs were then ground and polished with 6 µm diamond paste.

Dynamic wear experiments were carried out using a pin-on-disc machine configuration in which a stationary pin, capped with a ceramic or metal ball, was loaded by a dead weight on to a horizontal rotating disc, describing a wear track of the order of 15 mm diameter. The diameter of the ceramic (TZP) balls was 5.9 mm and the metal bearing steel balls 6 mm. The wear tests were carried out at room temperature in air. The rotary speeds of discs were 50, 100 and 200 r.p.m. corresponding to linear speeds of 40, 80 and 160 mm s^{-1}. The pins were loaded to 80 and 100 N.

The wear rates on the discs were determined both by volume loss estimates from surface profile measurements (using a Talysurf-10) in four directions across the wear tracks, and by weight loss measurements.

TABLE I The ceramics investigated

Material	Composition	Source
N1	ZrO_2–Y_2O_3–CeO_2 (tetragonal)	Imperial College
N2	ZrO_2–Y_2O_3–CeO_2 (cubic + tetragonal)	Imperial College
N3	ZrO_2–Y_2O_3–CeO_2 (cubic)	Imperial College
20A	ZrO_2–3 mol % Y_2O_3–20 mol % Al_2O_3	Tosoh Co.
3Y-TZP	ZrO_2–3 mol % Y_2O_3	Tosoh Co.
8Y-CSZ	ZrO_2–8 mol % Y_2O_3	Tosoh Co.

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The worn surfaces were examined by scanning electron microscopy to assess the wear mechanisms operating.

Coefficients of friction (metal on ceramic, and ceramic on ceramic) were determined using a reciprocating friction test, rubbing a ball against a plane, polished ceramic surface. The frictional force was monitored by strain gauge transducers. The friction tests were carried out at room temperature in air, at approximately 52% relative humidity.

The pin cycle frequency varied from 10–50 Hz and the sliding distance varied from 0.1–0.3 mm under a load of 0.5 kg.

3. Results

3.1. Coefficient of friction

The coefficients of friction of the ceramics in contact with ceramic and metal balls are listed in Table II for a load of 5 N and a sliding speed of 20 mm s^{-1}. It is observed that two of the ternary zirconia–ceria–yttria ceramics (N1 and N2) show attractive friction properties with friction coefficients about 50% those of the other zirconia ceramics under these conditions.

3.2. Wear

The wear rates of seven zirconia ceramics loaded to 80 N abrading at a speed of 40 mm s^{-1} are listed in Table III. It was found that sample N1, a ternary zirconia–ceria–yttria ceramic showed the lowest wear rate in contact with a TZP ball. This rate was about 1% of that of the TZP, which in turn showed about 10% of the wear rate of a cubic 8% Y_2O_3-doped zirconia ceramic.

When the pin loading was increased from 80 N to 100 N, the wear rate of the TZP disc on the TZP ball approximately doubled, as shown in Fig. 1.

Fig. 2 shows the variation of the wear rate of the TZP disc and the TZP ball with sliding speed. It was found that there was a transition from a low wear regime to one of severe wear as the sliding speed was increased from 90 mm s^{-1} to 150 mm s^{-1}; during this interval the wear rate of the disc rose by a factor of 2, while the wear rate of the ceramic ball rose by a factor of 10.

Fig. 3 shows scanning electron micrographs of the wear tracks produced in tetragonal and cubic zirconia ceramics at a load of 80 N and a sliding speed of 40 mm s^{-1}. Evidence for plastic deformation was not observed; however, many microcracks could be seen. In comparison, Fig. 4 shows scanning electron micrographs of wear tracks in tetragonal and cubic zirconia discs loaded to 80 N but slid at a speed of 160 mm s^{-1}. Under these conditions, evidence of plastic deformation, regular grooves in the direction of sliding motion, was seen.

Comparative data showing the wear rates of these materials are presented in Table III.

TABLE II Coefficient of friction (unlubricated; load 5 N, sliding distance 0.2 mm, frequency 50 Hz)

Friction couple Disc/ball	Friction coefficient
N1/ceramic	0.198
N2/ceramic	0.202
N3/ceramic	0.414
20A/ceramic	0.414
3Y–TZP/ceramic	0.401
8Y–CSZ/ceramic	0.401
N1/ceramic	0.189
N2/bearing steel	0.202
N3/bearing steel	0.401
20A/bearing steel	0.401
3Y–TZP/bearing steel	0.396
8Y–CSZ/bearing steel	0.396

TABLE III Wear rate for the ceramics tested (load 80 N, speed 40 mm s^{-1})

Wear couple: Disc/ball	Wear rate ($m^3 N m^{-1}$)	
	Disc	Ball
N1/ceramic	0.15×10^{-15}	0
N2/ceramic	0.54×10^{-14}	0
20A/ceramic	1.90×10^{-14}	1.34×10^{-14}
N3ceramic	9.60×10^{-14}	2.70×10^{-14}
3Y–TZP/ceramic	2.12×10^{-14}	1.27×10^{-14}
8Y–CSZ/ceramic	21.90×10^{-14}	0.70×10^{-14}

4. Discussion

The wear process in materials is generally described in terms of one or more mechanisms; for example, adhesive and abrasive processes, microfracture, plastic deformation, delamination or fatigue [12–14]. Any one of these mechanisms can predominate, or several of them can combine to develop the wear surface and

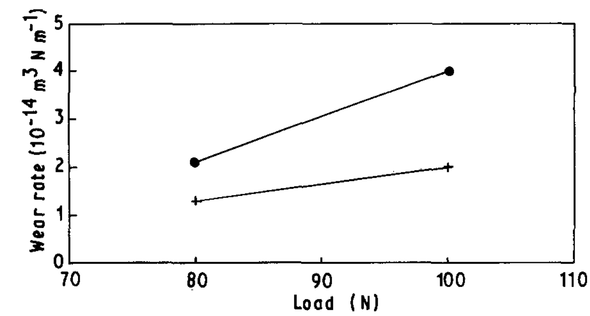

Figure 1 Variation of measured wear rate with applied load (sliding speed 40 mm s^{-1}). (—•—) Disc, (— + —) ball.

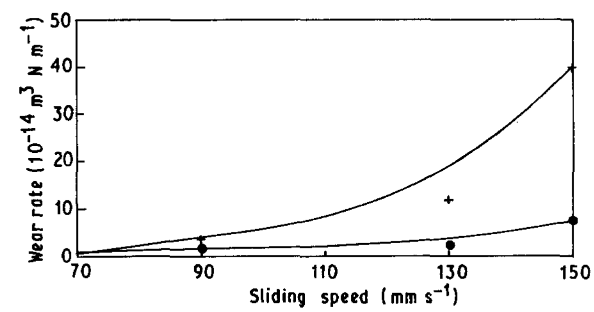

Figure 2 Variation of measured wear rate with sliding speed (load 80 N). (—•—) Disc, (— + —) ball.

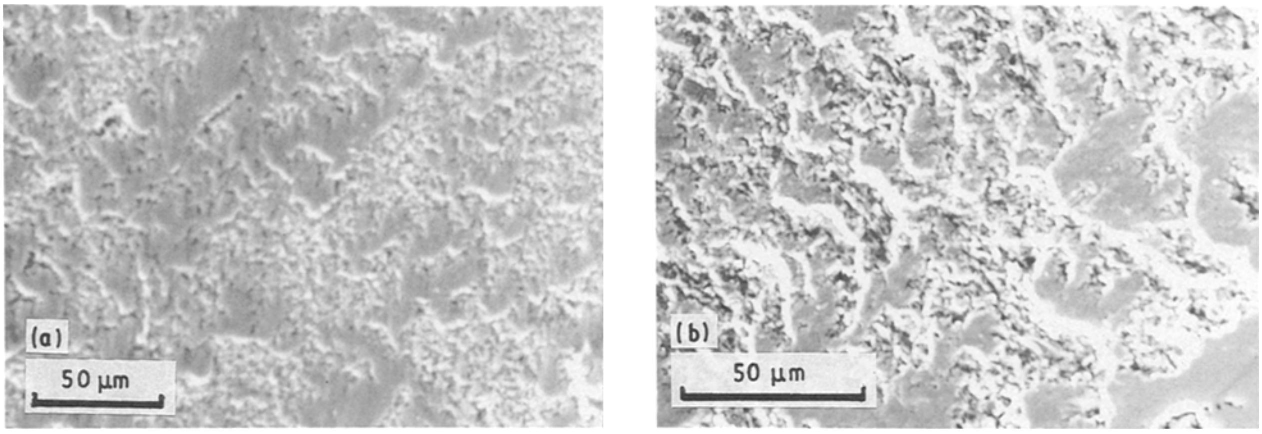

Figure 3 Scanning electron micrographs of the wear damage produced in ceramic ball on disc tests at an applied load of 80 N and a sliding speed of 40 mm s^{-1} for (a) 3Y–TZP, and (b) 8Y–CSZ.

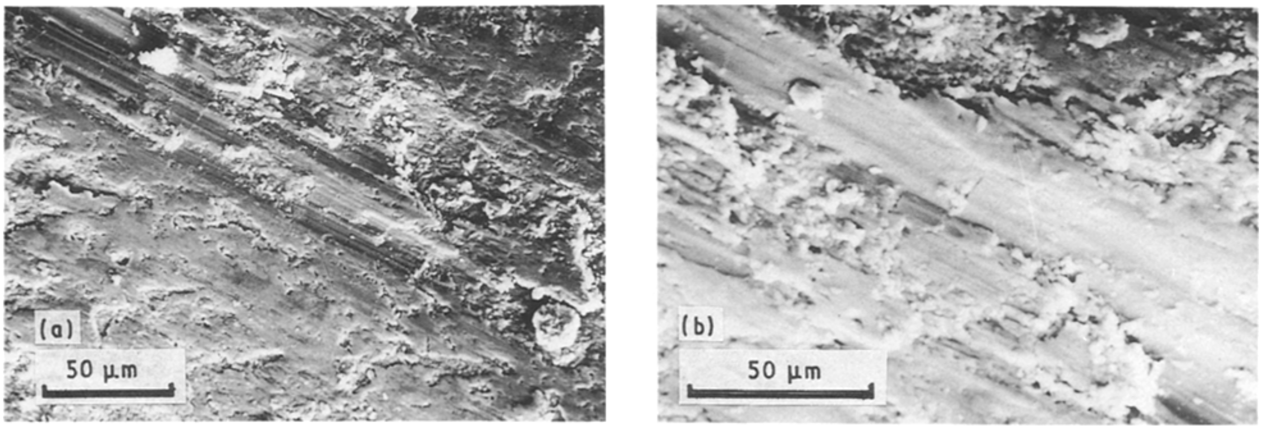

Figure 4 Scanning electron micrographs of the wear damage produced in ceramic ball on disc tests at an applied load of 80 N and a sliding speed of 160 mm s^{-1} for (a) 3Y–TZP, and (b) 8Y–CSZ.

subsurface. Generally, the dominant wear mechanism changes with the ceramic, or with varying the load or sliding speed. Microstructural observations of the samples worn in this study indicate that microfracture and plastic deformation are the dominant wear mechanisms for zirconia ceramics observed under these conditions.

At a load of 80 N and at a low sliding speed (40 mm s^{-1}), microfracture is the dominant wear mechanism observed in the binary and ternary zirconia ceramics. Plastic deformation is not observed under these conditions, probably due to the small amount of frictional heat generated. Fig. 3 shows the irregular microstructure formed by this wear process in tetragonal and cubic zirconia ceramics; wear scars being formed on the plate surfaces.

Table III emphasizes the difference in wear resistance between TZP and CSZ, the wear rate of CSZ being 20 times larger than that of the TZP, although they have similar hardnesses. This supports the suggestion that microfracture is the dominant wear mechanism in zirconia ceramics, with the enhanced toughness of TZP, minimizing the extent of microcracking that would normally result from the tensile stresses in the wake of the rubbing contact having an extraordinarily large influence on the wear resistance of these materials [15].

In the sliding tests a transition from a low wear regime to a high wear regime occurs when the sliding velocity increases from 90 mm s^{-1} to 150 mm s^{-1}, the dominant wear mechanism of 3Y–TZP changed from microfracture to plastic deformation concurrently with this. Scanning electron micrographs (Fig. 4) show some evidence for plastic deformation of TZP (there are very regular grooves along the direction of sliding); such morphological features are often observed in metals, where they are called ploughing grooves and are attributed to the plastic deformation of the substrate materials.

The low coefficient of thermal conductivity of ceramics gives rise to a limited ability to dissipate heat generated on surfaces during sliding contacts. The higher sliding velocity and the larger the load, in general the higher are the surface temperatures reached. If a critical temperature and stress are reached, then plastic deformation will occur.

In microfracture-dominated wear, the fracture toughness has a dominant influence on the wear resistance of ceramics, with the relatively brittle CSZ likely to be more susceptible to wear by surface microfracture. The toughened zirconia ceramics, for example TZP, ternary ZrO_2–Y_2O_3–CeO_2, or duplex ZrO_2–3%Y_2O_3–20%Al_2O_3, have superior wear resistance in the microfracture regime, due to the nature of the R-curve rendering it difficult for the crack to propagate beyond a certain length whilst permitting some energy to be absorbed by the generation of short, arrested cracks. At high sliding velocities or high loads, plastic deformation is seen to be the dominant wear mechanism for these ceramics, resulting in the degradation of their (lower level) wear resistance and a rapid increase in the observed wear rate.

5. Conclusions

1. The ternary zirconia–ceria–yttria ceramics show very attractive friction and wear properties under certain conditions. The coefficients of friction are about 50% of that of other zirconia ceramics, whilst its wear rate is about 1% of that of TZP.

2. The friction coefficient of zirconia ceramics are seen to increase with increasing sliding speed.

3. During sliding wear tests of zirconia ceramics, a transition from a low wear regime to a high wear regime occurs with increasing sliding velocity and load.

4. In the low wear rate regime, microfracture is the dominant wear mechanism for the binary and ternary zirconia ceramics; the toughness of the ceramics has a dominant influence on their wear resistance, in the high wear rate regime, plastic deformation is the dominant wear mechanism for tough zirconia ceramics under these experimental conditions.

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