Journal of the European Ceramic Society 15 (1995) 1193–1199

0955-2219/95/$9.50
0955-2219(95)00103-4

Wear Resistance of Stabilized Zirconias

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(Received 27 January 1995; revised version received 31 May 1995; accepted 31 May 1995)

Abstract

The wear resistance of stabilized zirconias was investigated on both a pin-on-disk machine and a Dangoumeau apparatus under dry and lubricated (water) conditions. Under the experimental conditions (80 N load and 12 mm/s speed) the wear mechanism can be described as initial plastic deformation and then grain pull-out. The role of the third-body in the interface of friction has been demonstrated with asymmetric couples where one of the antagonists is made of alumina. If for pure friction it is not easy to differentiate the magnesia partially stabilized zirconias (MgPSZ) from the yttria tetragonal zirconia polycrystal (YTZP), after shock tests we can conclude that the YTZP have a better wear behaviour than the MgPSZ, especially in the case of attrition applications.

1 Introduction

Recently, considerable attention has been applied to stabilized zirconia ceramics, because of their special mechanical, chemical and thermal properties. For the application of high capacity attrition mills for fine grinding and homogeneization millings, beads with a large surface and high energy input are required. High density, good sinterability and improved fracture toughness make stabilized zirconias very attractive as wear-resistant materials. However, their potential applications are still limited by the lack of reliable data concerning the wear behaviour and mechanism. Although a number of studies have been carried out to investigate the wear characteristics in a variety of conditions, most of them deal with metal/ceramic contacts and ceramic/ceramic friction is not well known as yet.

Scott[1] studied the wear behaviour of MgPSZ and suggested that their particular wear resistance depended on the amount of transformable phase in the sample. Aronov[2] also observed a range of temperature where the wear of MgPSZ decreased by three orders of magnitude. He proposed a phenomenological model to explain this wear by phase transformation due to frictional heating. Fisher *et al.*[3] examined the wear behaviour of tough and brittle zirconias in different environments. They concluded that water has a deleterious effect on wear resistance. Stachowiak *et al.*[4] found similar wear for both MgPSZ and YTZP in a pin-on-flat test despite their significant difference in grain size. The delamination and plastic deformation were considered as the main wear mechanisms. For Chen *et al.*[5] rapid wear of MgPSZ and YTZP was found in a special range of sliding speed, wear resistance of MgPSZ, however, remained better than that of YTZP. Lee *et al.*[6] carried out an extensive study on YTZP zirconias by setting wear maps. They identified wear transitions depending on the environment. In mild-wear regimes plastic deformation and microcutting are dominant. Thermal-shock-induced brittle fracture is the predominant mechanism causing severe wear in the high-speed regimes. Probable moisture-induced destabilization of YTZP is evident specifically under water-lubricated conditions.

Considering the results above, the wear behaviour of zirconia ceramics seems to be very sensitive to the structure of the material, and to the test parameters, such as temperature, environment and sliding speed as underlined by Liang *et al.*[7]

2 Experimental

2.1 Wear apparatus

The first wear tests were conducted on a pin-on-disk tribometer described in Fig. 1. The linear speed was 12 mm/s and the load applied by a dead-weight system of 8 kg, i.e. about 80 N. Wear is measured with a rugosimeter which gives the profile of the track on the disk. With width W, depth D and length L of the track it is possible to calculate the removed volume V:

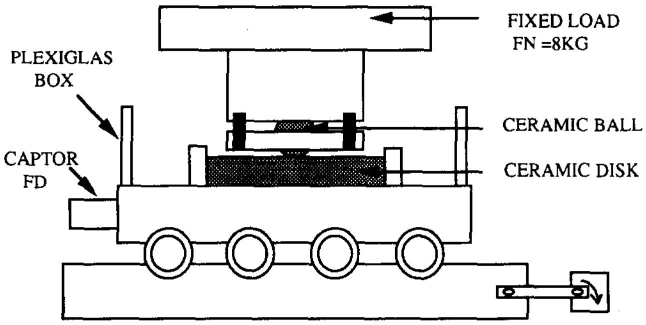

Fig. 1. Schematic representation of the pin-on-disk tribometer.

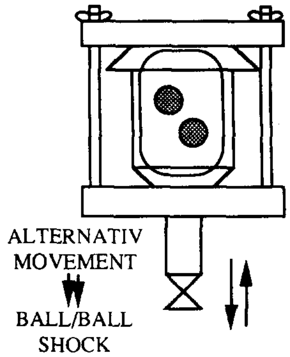

Fig. 2. Schematic representation of the Dangoumeau machine.

$$V = L\left(R^2 \arccos\left(\frac{R-D}{R}\right) - W\frac{R-D}{2}\right),$$

$$\text{where } R = \frac{D^2 + \frac{W^2}{4}}{2D}. \qquad (1)$$

For balls the wear volume is obtained from the scar diameter, knowing the radius of the ball:

$$V = \Pi\frac{R^3}{3}(2 - 2\cos\beta - \sin^2\beta\cos\beta),$$

$$\text{where } \beta = \arcsin\left(\frac{D}{2R}\right). \qquad (2)$$

A captor can measure the longitudinal force F_D, this leads to the coefficient of friction μ which is the ratio between the normal force F_N and the longitudinal force F_D.

Bearing in mind the attrition application we have chosen the Dangoumeau test which allows, by an oscillating movement, shock between two balls closed in a closed jar. This can be made both in air or in water, see Fig. 2.

2.2 Materials

The zirconias used for the investigations were of two kinds: either partially stabilized with magnesia (MgPSZ) or totally stabilized with yttria (YTZP) or a mixture of yttria and ceria (YCeTZP, YC). We have also studied alumina as a reference and a composite structure containing 80 wt% of YTZP and 20 wt% of Al_2O_3 (ATZ).

PSZ samples were sintered at 1700°C for 2 h then heat-treated at 1425°C to make the tetragonal phase precipitate in the cubic matrix. The average cubic grain size was about 30–50 μm, the tetragonal precipitates being submicronic. With long soaking times at 1425°C, these grew above the critical size[8] of ≈ 0·3 μm and become monoclinic on cooling. TZP ceramics were sintered between 1350 and 1500°C for 2 h and were constituted by grains of less than 1 μm. Phase contents were determined by X-ray diffraction analysis (XRDA).[9]

The surface roughness, R_a, of the disks was about 0·002 μm after polishing, the balls were as-sintered. Other properties of the materials are listed in Table 1.

3 Results

3.1 Wear results

Wear results of symmetric couples (ball and disk of the same ceramic) are given in Figs 3 and 4. In order to be clear we have only plotted data

Table 1. Properties of materials

Material	*Sintering route*	*Density (g/cm⁻³)*	*% Density*	*Ave. grain size (μm)*[a]	*Hardness GPa*	*Toughness (GPa√m)*	*% T*	*Symbol*
MgPSZ1	1700°C 2h 1425°C 4h	5·57	96	50/2 C/T	6·44	6·2	60[b]	○
MgPSZ2	1700°C 2h	5·65	98	50/0·3	10·22	6·13	97[b]	□
MgPSZ3	1700°C 2h	5·71	98	50/0·3	10·74	—	85[b]	×
YTZP1	1350°C 3h	5·83	99	0·766	10·68	5·2	100	◇
YTZP2	1475°C 2h	5·99	99	0·368	10·94	5·02	100	+
YTZP3	1450°C 2h	6·01	99	0·356	12·93	—	100	Δ
YTZP4	1450°C 2h	5·92	97	0·351	13·03	—	100	∇
YTZP5	1450°C 2h	6·05	100	0·367	13·55	5·46	100	⧅
YTZP6	1400°C 2h	6·08	100	0·333	13·60	—	100	⊞
YC	1450°C 2h	6·00	99	0·771	11·85	—	100	■
ATZ	1400°C 2h	5·45	97	0·454	16·10	—	100	⊡
Al_2O_3	1380°C 3h	3·95	99	≈ 1	18·23	—	—	⊙

[a] Interpolate method.
[b] Sum of cubic and tetragonal content.

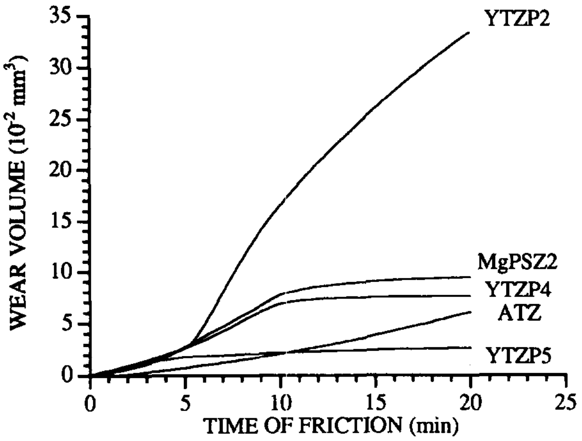

Fig. 3. Wear of disks in air (symmetric couples). (Schematic behaviour similar in air and in water).

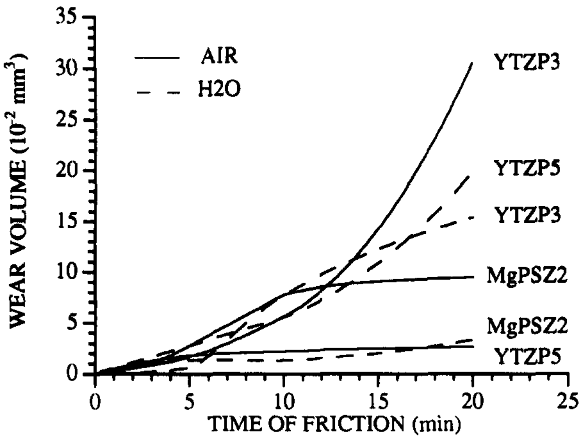

Fig. 5. Influence of water on disk wear. (Identical for balls and disks).

concerning some of the materials. No typical behaviour can be determined for MgPSZ or YTZP. The wear volume (for disks), or the scar volume (for balls), can remain quasi-constant, reach a steady-state value or increase with the friction time. A PSZ disk may react like a TZP one, whilst the wear of two TZP disks may be totally different. In fact we can only classify the ceramics according to the severity of wear, depending on the antagonist (ball or disk) and on the environment; no absolute classification is feasible. Concerning balls, however, the PSZ ceramics are less resistant than the TZP ones. We also note that the YTZP5 was the least worn TZP ceramic, both for disks and for balls and that the ATZ composite has one of the best wear behaviours.

The presence of water reduces the wear of PSZ ceramics, whereas in most cases it increases the wear of TZP ceramics as predicted by the literature[3,6] because of the destabilization of the tetragonal phase which transforms into the monoclinic one. When the tetragonal phase is very stable (YTZP3 and YTZP6) no transformation is possible and water has again a favourable effect on wear resistance (Fig. 5).

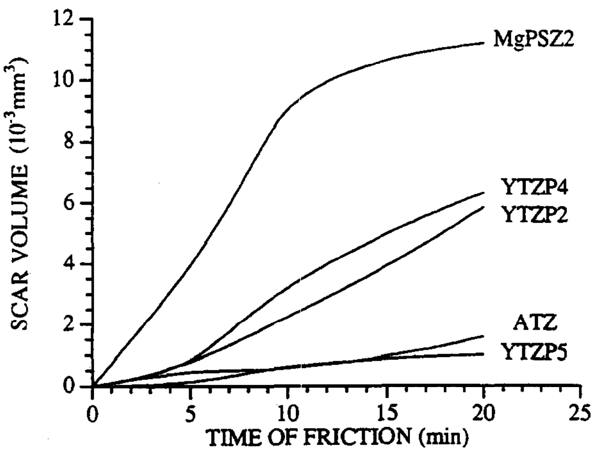

Fig. 4. Wear of balls in air (symmetric couples). (Schematic behaviour similar in air and in water)

The addition of alumina in the ATZ composite leads to a better resistance (Figs 3 and 4), because of the increase in hardness. In all configurations the wear of this composite is one of the lowest. Alumina disks are just polished during friction, whereas alumina balls reacts like TZP balls.

To really compare our materials, we studied asymmetric couples where either the disk or the ball is in alumina. The wear volumes are given in Figs 6 and 7. The wear of balls rubbed against an

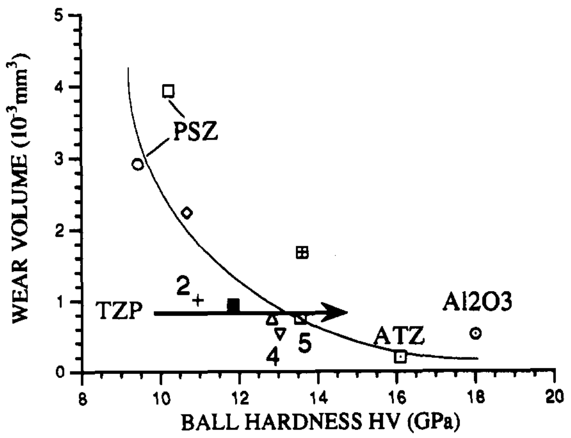

Fig. 6. Wear of balls on Al_2O_3 disk (water).

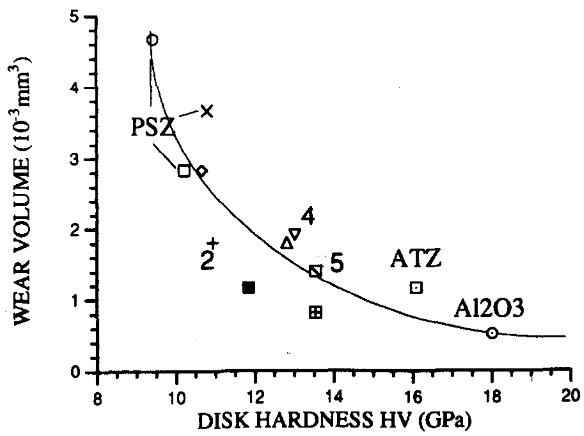

Fig. 7. Wear of Al_2O_3 ball on disk (water).

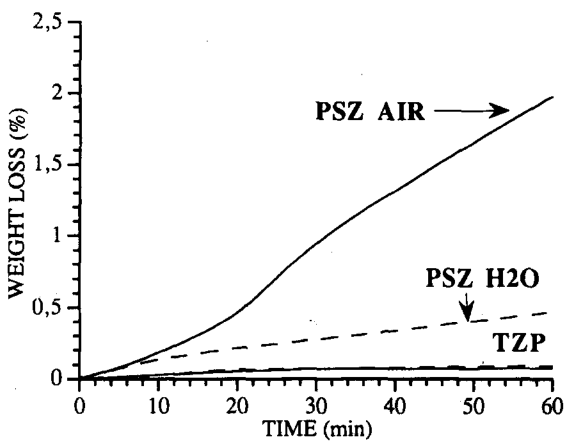

Fig. 8. Weight losses after Dangoumeau shock tests.

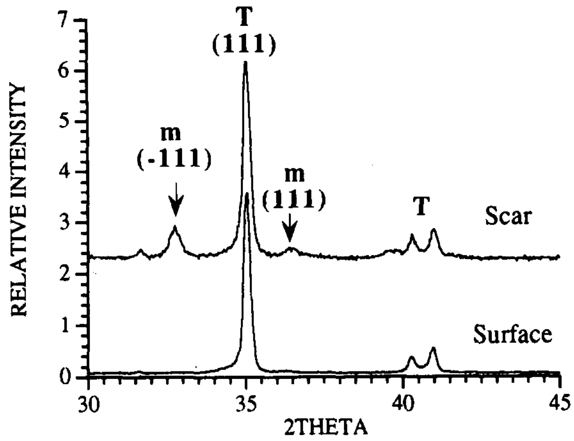

Fig. 9. Wear-induced surface transformation on a YTZP2 disk.

alumina plate had a tendency to decrease with increasing hardness, even when the wear of TZP seems to be independent of the material (except for YTZP1 and YTZP6 — see horizontal line in Fig. 6). The same tendency was observed for the wear of disks by an alumina ball: the harder the plate, the less worn. This was still true for the alumina ball which was worn more on smooth disks than on hard ones (Fig. 7). These results were valid both in air and in water.

After tests in the Dangoumeau[10] jar, the PSZ balls were strongly worn, especially in air where TZP are less sensitive. Water significantly reduces the wear of PSZ ceramics, whereas it has only a slight influence on TZP (Fig. 8). The ATZ balls were extremely spoilt and the alumina one totally destroyed (under the same experimental conditions).

3.2 Worn surface analysis

In order to understand the wear mechanisms of pins and disks, the worn surfaces were analysed both by a secondary electron microscope (SEM) with an EDAX attachment and by XRDA. A phase transformation can occur on the surface of the more transformable disks which reduces the wear rate (Fig. 9); wear debris are transformed into the monoclinic phase. When the surface of disks is too stable (no possible transformation) the disks are more worn because they are less able to absorb energy.

On the PSZ plate no real variation in the monoclinic content was observed. This can be explained by the reversal monoclinic → tetragonal transformation which takes place at the frictional interface. The tetragonal → monoclinic martensitic transformation occurs on cooling on the transformed monoclinic grains which results in a macroscopic steady-state.[11]

Wear of pins leads to the formation on the surface of a dense third body layer (Fig. 10) which consists of a mixture of the two antagonists (Fig. 11). After sliding on an alumina plate the presence of alumina on the surface of the TZP ball is obvious.

Different wear profiles are obtained after shock tests depending on the nature of the materials (Fig. 12). Grain pull-out is observed on TZP balls, transgranular fracture on PSZ balls (Fig. 12(a, b)) and macrochipping on ATZ balls with shearing of the alumina grains (Fig 12(c, d)).

4 Discussion

No significant difference between MgPSZ and YTZP can be observed after symmetric tests without shock, either in air or in water. The wear mechanism depends on the geometrical shape and not on the material. Wear of disks begins with

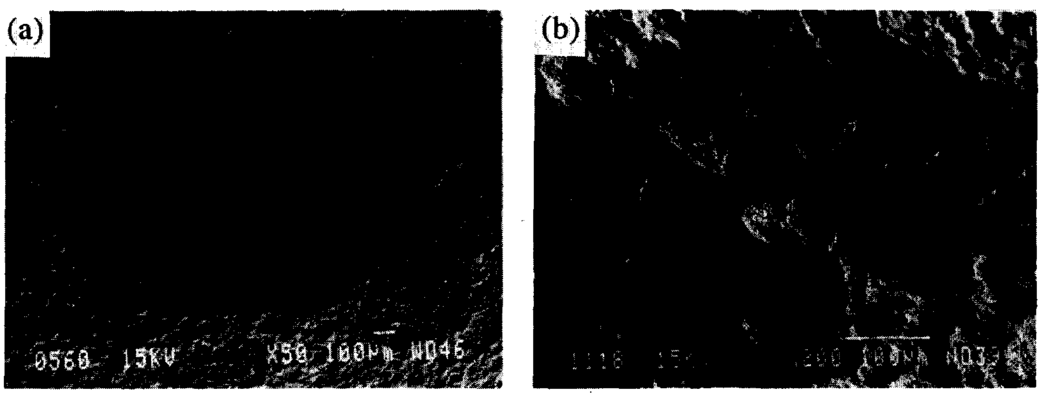

Fig. 10. Wear scar on a zirconia ball: (a) erosion of a YTZP2 ball; (b) dense layer on a YTZP4 ball.

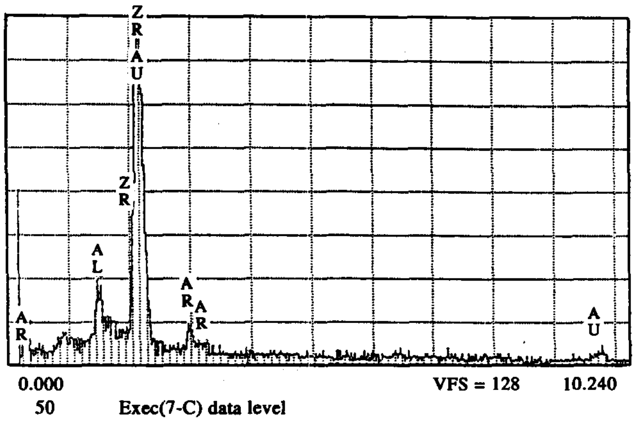

Fig. 11. Surface analysis of a YTZP2 ball rubbed on Al_2O_3. Presence of alumina on the ball.

plastic deformation or polishing of the surface, then above a typical critical strain value intergranular fracture occurs first along circular paths resulting from mechanical stresses (Fig. 13).

The properties of the materials (i.e. hardness, toughness, grain size, porosity, etc.) may influence the first steps in the wear process but then the adherence of the third body becomes the predominant factor. The constant load of 8 kg also has an influence, depending on the materials it can induce too high stress and cause severe wear.

Wear of balls starts with filing of the surface spheres and then wear is inversely proportional to the ability of debris to adhere to the surface and to form a dense protective layer. If debris cannot stick to the surface, extensive wear takes place. So the more easily the layer is formed, the less worn the pin. When these tests are conducted in water the PSZ properties are improved, those of the TZP are generally reduced (Fig. 5).

However, at this stage no real distinction can be seen between the different classes, even though the alumina–zirconia composite is in general less damaged. Friction tests with asymmetric couples clearly show the influence of material properties on wear: the soft PSZ ceramics are more worn and harder TZP ceramics are less worn against alumina, except the YTZP1 and YTZP6 balls which are less resistant.

Wear of an alumina ball on a disk confirms the important role of wear debris defined before as the third body in the interface. When sliding, the alumina ball creates abrasive debris which in turn can wear the alumina ball.

With shock tests (Dangoumeau) the TZP ceramics shows a better wear resistance than the PSZ, despite equivalent toughnesses. These tests also reveal the inadequacy of the ATZ ceramic because of the presence of brittle alumina. The analysis of the worn ball confirms that fracture occurs on alumina grains by pull-out or shearing.

Nevertheless, we can note that, for identical hardnesses and toughnesses, tribological properties can be very different. So we have to find other explanations: one may be the third body part because its adhesion to the surface is essential,

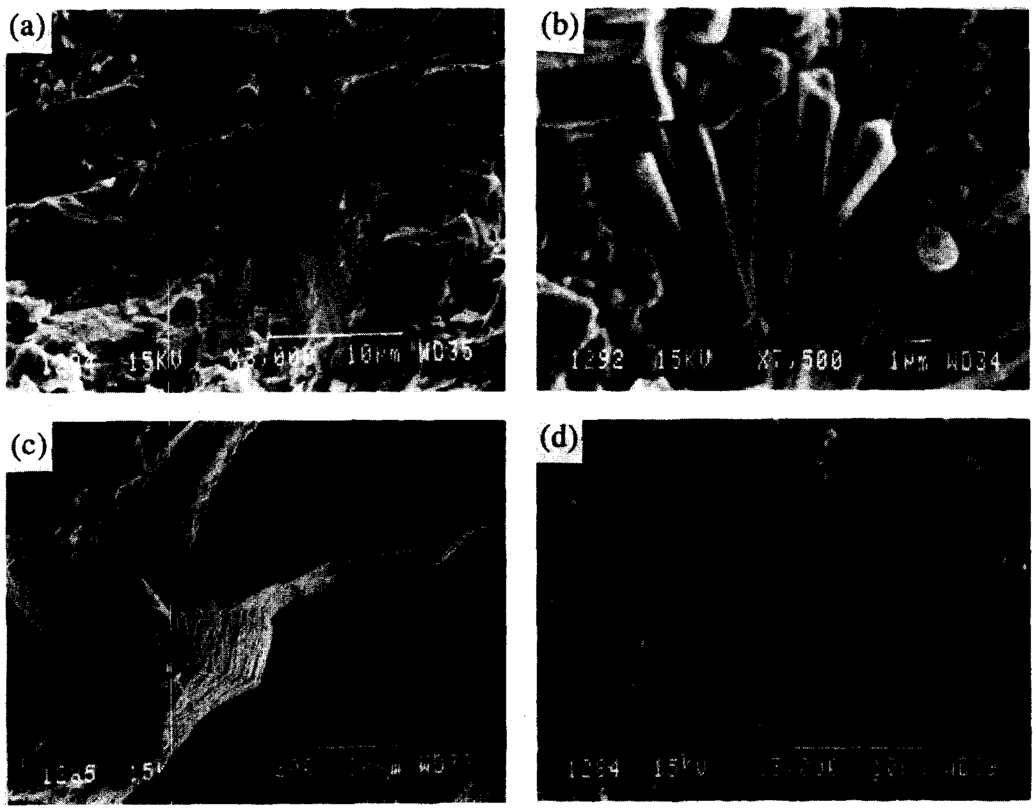

Fig. 12. Surface of worn balls after shock tests: (a, b) transgranular fracture for MgPSZ; (c, d) extensive macrochipping, shearing of Al_2O_3 grains for ATZ.

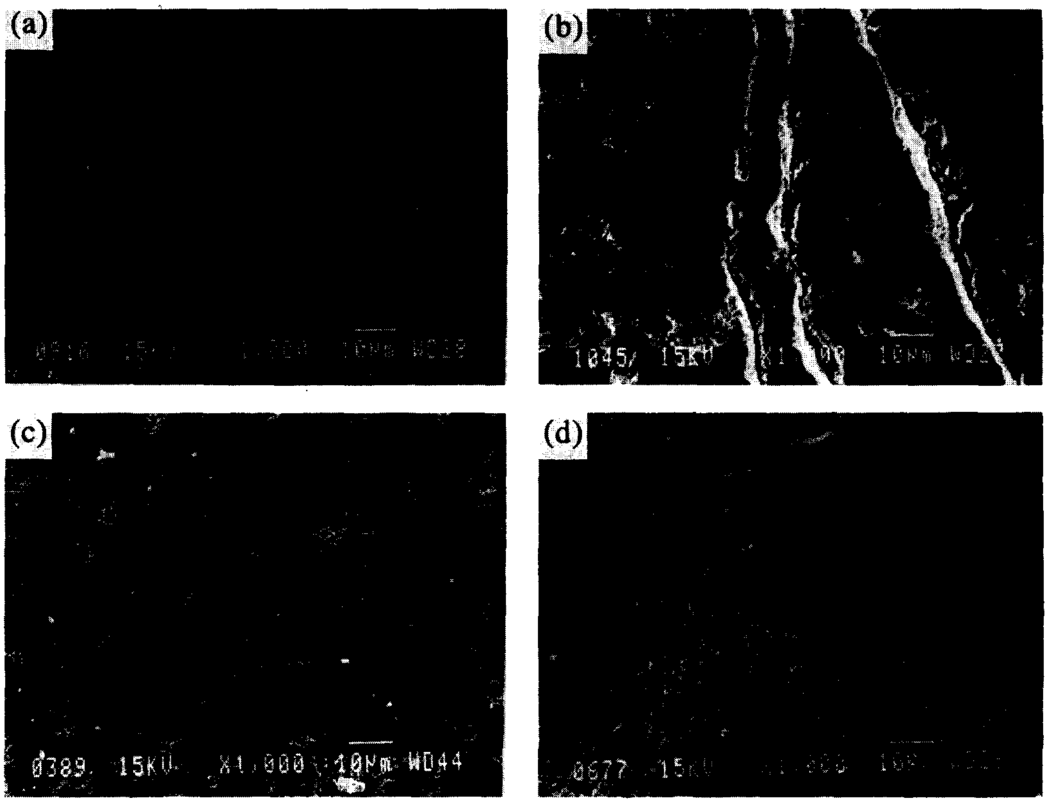

Fig. 13. Surface of worn disks after pin-on-disk tests (symmetric YTZP couple) Wear mechanism: (a) plastic deformation with micro-fracture and polishing; (b) circular fracture; (c) intergranular fracture with grain pullout; (d) failure.

however results may differ for equivalent compositions (TZP) so other properties interfere: the study of the influence of materials dielectrical properties (susceptibility) on wear is in hand. Thus electrostatic phenomena can affect:[12–14]

- the first steps of wear (stored polarization energy relaxation which induces cracks)
- the energetic balance of the martensitic transformation T → M
- the charge effects (triboelectrification) in the contact area which depend on the presence of water and modify the electrostatical adherence of the third body.

5 Conclusions

With continuous friction without shock (pin-on-disk) wear of disks occurs first by plastic deformation then by microfracture, the third body debris control the final wear steps. Wear of balls depends on the ability of the dense protective third body surface layer to form. The more stable the layer, the less worn the ball. Generally speaking MgPSZ and YTZP are equivalent when tested symmetrically on a pin-on-disk tribometer. Although water has an effect on their wear behaviour, it reduces the wear of PSZ, whereas it has only a slight influence on the TZP tested. When rubbed against alumina the TZP are less worn than the PSZ. Introduction of alumina in zirconia ceramics leads to a strengthening and reduces sliding wear. TZP have a better wear resistance to shock tests than the PSZ. The addition of alumina results in the failure of the material. These results cannot be explained by the intrinsic mechanical properties of the materials. So we have to consider other parameters such as dielectrical phenomena like polarization energy, contact charges which can modify fracture of ceramics or third body adhesion.

Acknowledgement

This work was partly sponsored by the EEC (Feasibility Award BRE2-CT93-0692).

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