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Y-TZP sliding reciprocatively against various AlON ceramics

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The friction and wear characteristics of various yttria tetragonal zirconia polycrystalline (Y-TZP)–aluminium oxynitride (AlON) sliding systems were examined. These systems consisted of a Y-TZP sphere reciprocating against three different translucent AlON plates. The fully dense AlONs used contained 67.5, 73.0 and 77.5 mol % Al_2O_3 and had a grain size of 28 to 56 μm. The tests were performed at a constant track length, two loads, two frequencies and two different time intervals at room temperature. The humidity was controlled by flushing with dry nitrogen. The total vertical displacement and the friction coefficient were measured continuously and sampled. The worn surfaces were observed microscopically. It was concluded that there is no difference in wear behaviour between the three AlON types. It was also concluded that the amount of wear increases approximately linearly with load at a frequency of 1 Hz. The tests at 4 Hz show a stochastic transition between relatively mild wear and severe wear. The observations and data were used to derive a wear mechanism.

1. Introduction

Ceramics are materials which are still under development. New types of ceramic are being made and existing ceramics are continuously being improved. The field of applications for ceramics is very wide, ranging from the conventional brick and porcelain cups to the most sophisticated superconducting layers. Research is being conducted to develop materials with very specific characteristics. Once these materials are made, they have to be studied in respect of their properties. Wear-resistant behaviour is one of the fields in which structural ceramics are expected to perform better than other materials. Such ceramics are, for instance, alumina, zirconia, silicon nitride, silicon carbide and sialon. The counterparts of these ceramics in a wear-resistant application can be other ceramics, metals, plastics or composites. Various material combinations must therefore be investigated to obtain some understanding of the wear behaviour of ceramics.

Zirconias are well-known materials fabricated in several varieties. One of these varieties is yttria tetragonal zirconia polycrystalline (Y-TZP). Some of the properties of the material have been described (e.g. [1, 2]). The material has often been investigated as a wear-resistant material (e.g. [3–5]).

For this study, wear systems of a Y-TZP sphere sliding reciprocatively against three different AlON plates were investigated. The three AlONs, which were processed with different amounts of Al_2O_3, are a new kind of translucent ceramic [6–8]. Wear tests between Y-TZP and AlON could provide interesting information about the wear behaviour of comparable systems like Y-TZP–sialon, or more generally systems of TZP against harder and more brittle ceramics.

2. Experimental procedure

The pin material used was in all tests a commercially available Y-TZP sphere (Dynamic Ceramic, Stoke-on-Trent) with a radius of 2 mm and a polished surface. In Table I the properties of Y-TZP, measured on a plate of the same material from the same supplier, are given. These values are assumed to be comparable to the properties of the spheres. The AlONs were fabricated at the Centre for Technical Ceramics. Details about the processing and characteristics of these AlONs are given elsewhere [8]. A summary of some of their properties is given in Table I. In all cases the surfaces of the AlONs were ground.

The wear tests were performed on a pin-on-plate tribometer (Central Technical Workshop, Eindhoven University of Technology). In this set-up, a spherical Y-TZP pin reciprocates with a sinusoidal velocity on the flat AlON plate. The track length for the tests was chosen as 10 mm. The pin frequencies, f, of 1 and 4 Hz correspond to maximum velocities of 0.02 and 0.08 m s^{-1}, respectively. Normal loads, P, of 2 and 8 N

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TABLE I Characteristics of the materials used (most data for AlONs taken from [8]).

	Y-TZP	AlON 1	AlON 2	AlON 3
Al_2O_3 content (%)	–	67.5	77.5	73
ρ (g cm^{-3})	5.86	3.68	3.65	3.67
E (GPa)	208	333	306	314
ν	0.32	0.30	0.26	0.25
d (μm)[a]	1.15	33	56	28
σ_{3pb} (MPa)[b]	966	376	408	413
K_{Ic} (MPa m$^{1/2}$)[c]	7.9	2.3	2.3	2.2
HV_{2N} (GPa)	13.0			
HV_{10N} (GPa)		17.7	16.1	17.7

[a] Mean linear intercept for AlONs; for Y-TZP the average maximum grain size is given.

[b] Measured in a three-point bend test.

[c] Measured in a single edge-notch beam test.

were used. The duration was 24 h for most tests performed at 4 Hz and 72 h for most tests performed at 1 Hz. Some of the tests were performed twice. The experiments were performed in a flow of dry nitrogen at room temperature. This gives an approximately constant environment of less than 1% relative humidity. The reproducibility of the testing method had been examined in an earlier study [9].

The total vertical displacement of the pin during sliding was measured by an extensometer (Sangamo DG1). Continuous measurement of the vertical displacement is not recommended in the ASTM standard [10] because of the effects of debris and film formation. It does give, however, relevant information about the wear system during the test.

The friction force was measured by a force transducer. The displacement and friction force were simultaneously sampled under external triggering control with a computerized data acquisition system. Further details about the data acquisition are given elsewhere [9].

The worn surfaces were visually examined with optical microscopy (OM) and scanning electron microscopy (SEM). The data and observations were used to derive a wear mechanism which also explains some phenomena of other wear systems.

3. Results

The results are presented with examples which are characteristic of the conditions under which the tests were performed. The other graphs for tests performed under comparable conditions were similar in shape and reasonably similar in respect of their quantitative aspects.

Fig. 1a and b are examples of a vertical displacement graph and a friction graph, respectively, for a test performed at 8 N and 1 Hz for 72 h. All samples showed relatively mild wear, characteristic for a polishing mechanism.

The tests performed at 4 Hz all showed a transition of relatively mild wear to severe wear with a corresponding increase in friction coefficient after a few hours. As an example the graphs of the test at 8 N and 4 Hz are given in Fig. 2a and b, where the transition is

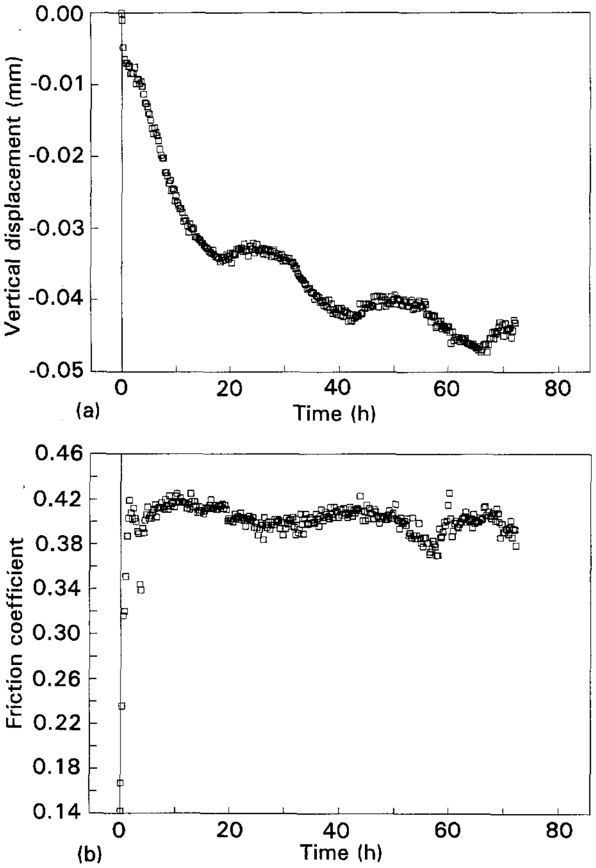

Figure 1 Characteristic examples of (a) a vertical displacement graph and (b) a friction coefficient graph of a test performed at 8 N, 1 Hz for 72 h on AlON 2. The periodic behaviour is due to a 24 h cycle in temperature.

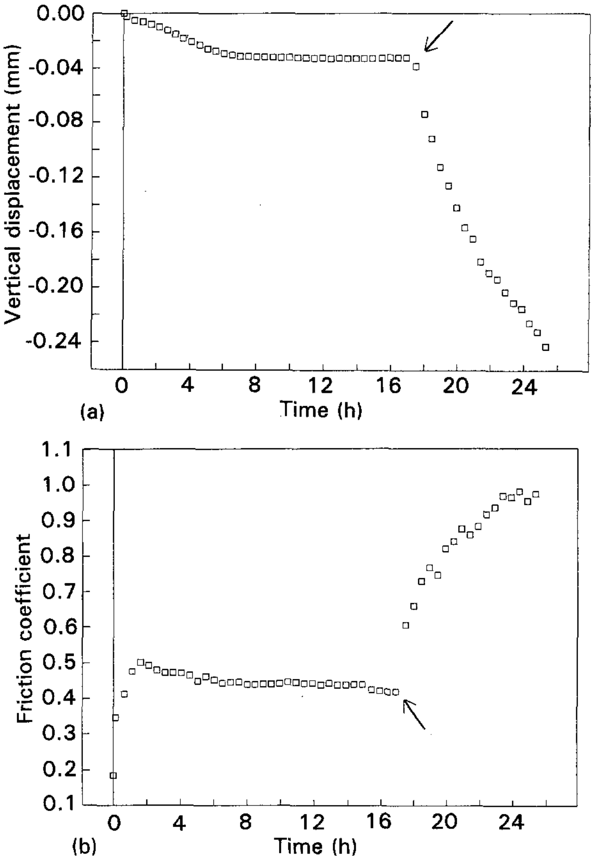

Figure 2 Characteristic examples of (a) a vertical displacement graph and (b) a friction coefficient graph of a test performed at 8 N, 4 Hz for 25 h on AlON 1. The arrows point at the transition to severe wear.

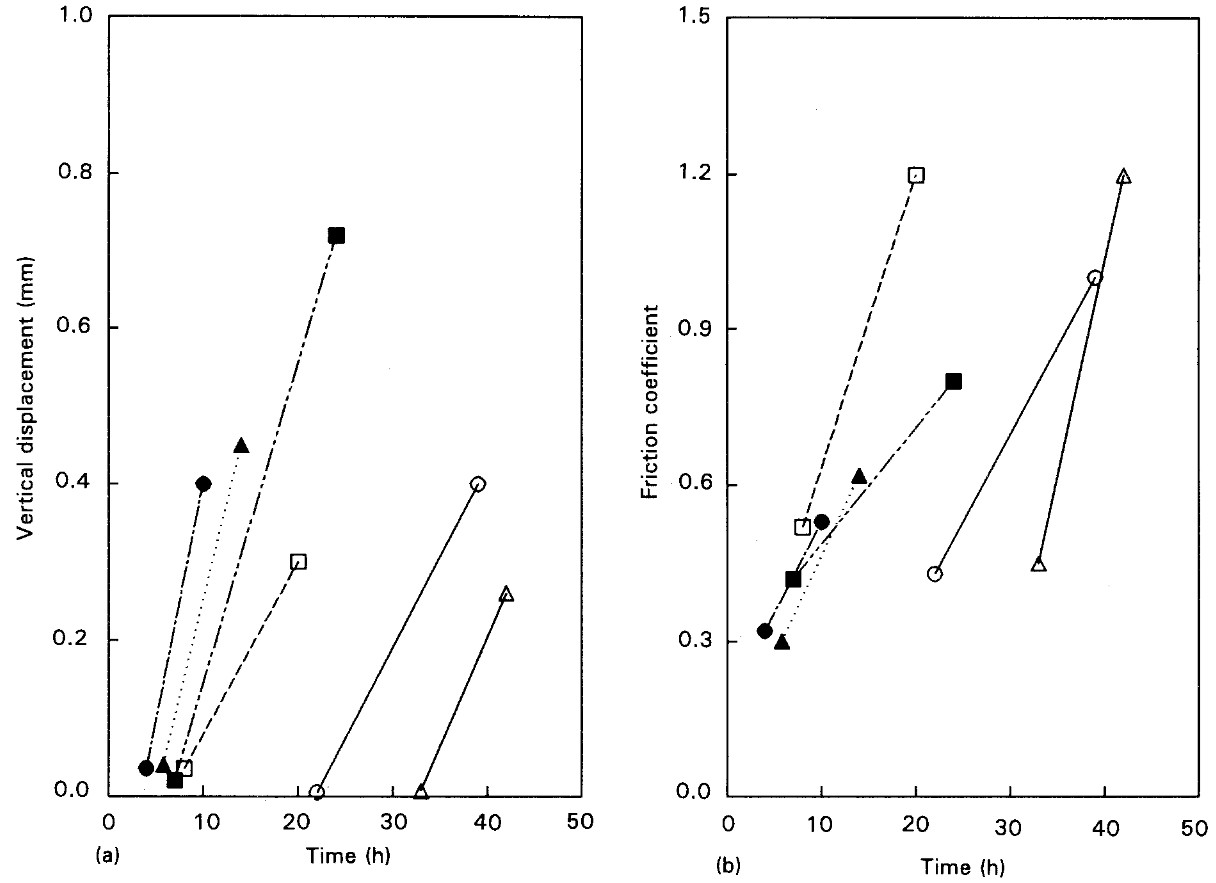

Figure 3 Graphical representations of the discontinuities in (a) vertical displacement and (b) friction coefficient occurring during tests performed at 4 Hz: (△) AlON 1, $P = 2$ N; (○) AlON 2, $P = 2$ N; (□) AlON 3, $P = 2$ N; (▲) AlON 1, $P = 8$ N; (●) AlON 2, $P = 8$ N; (■) AlON 3, $P = 8$ N. The lower points represents the transition while the higher points represent the end of the test.

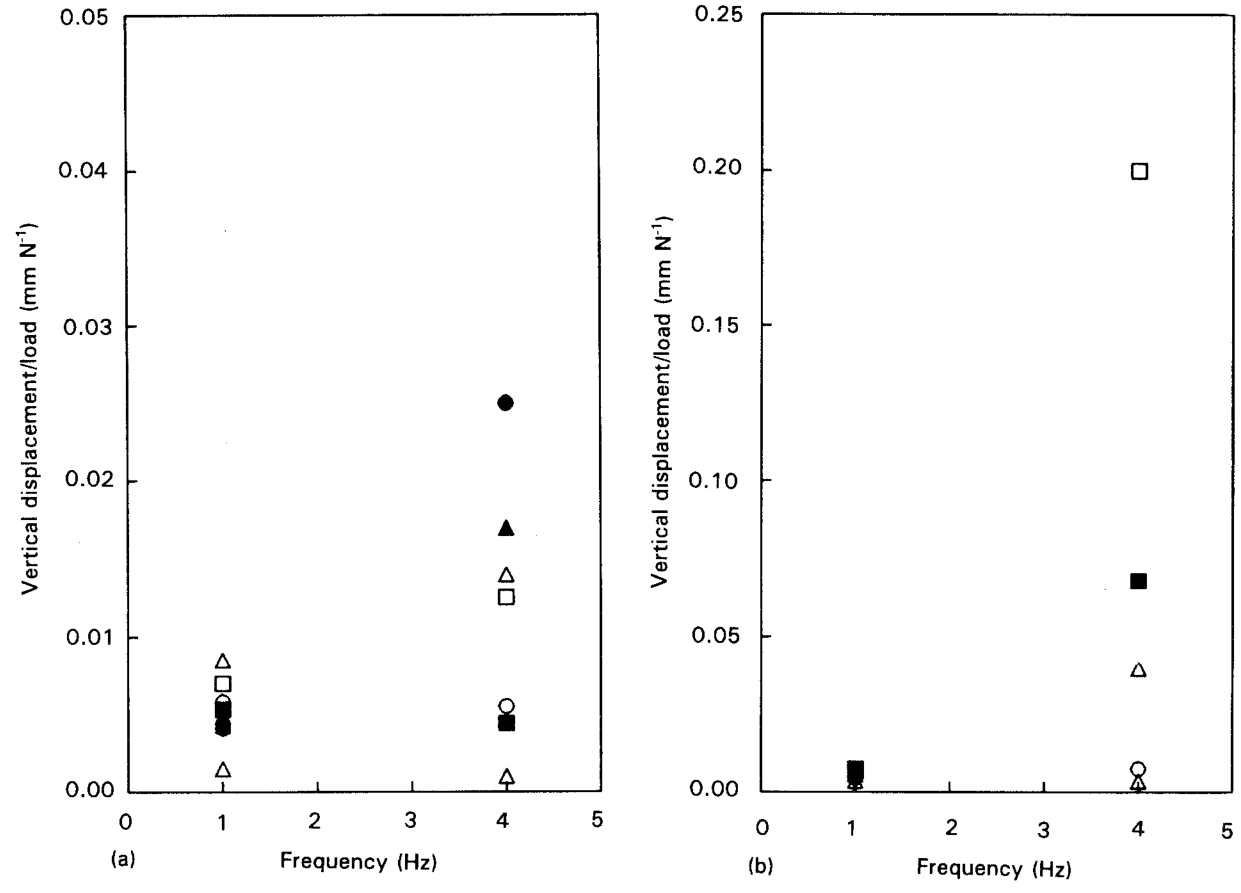

Figure 4 Summary of results from vertical displacement graphs after a sliding distance of (a) 1.73 km and (b) 5.18 km: (△) AlON 1, $P = 2$ N; (○) AlON 2, $P = 2$ N; (□) AlON 3, $P = 2$ N; (▲) AlON 1, $P = 8$ N; (●) AlON 2, $P = 8$ N; (■) AlON 3, $P = 8$ N.

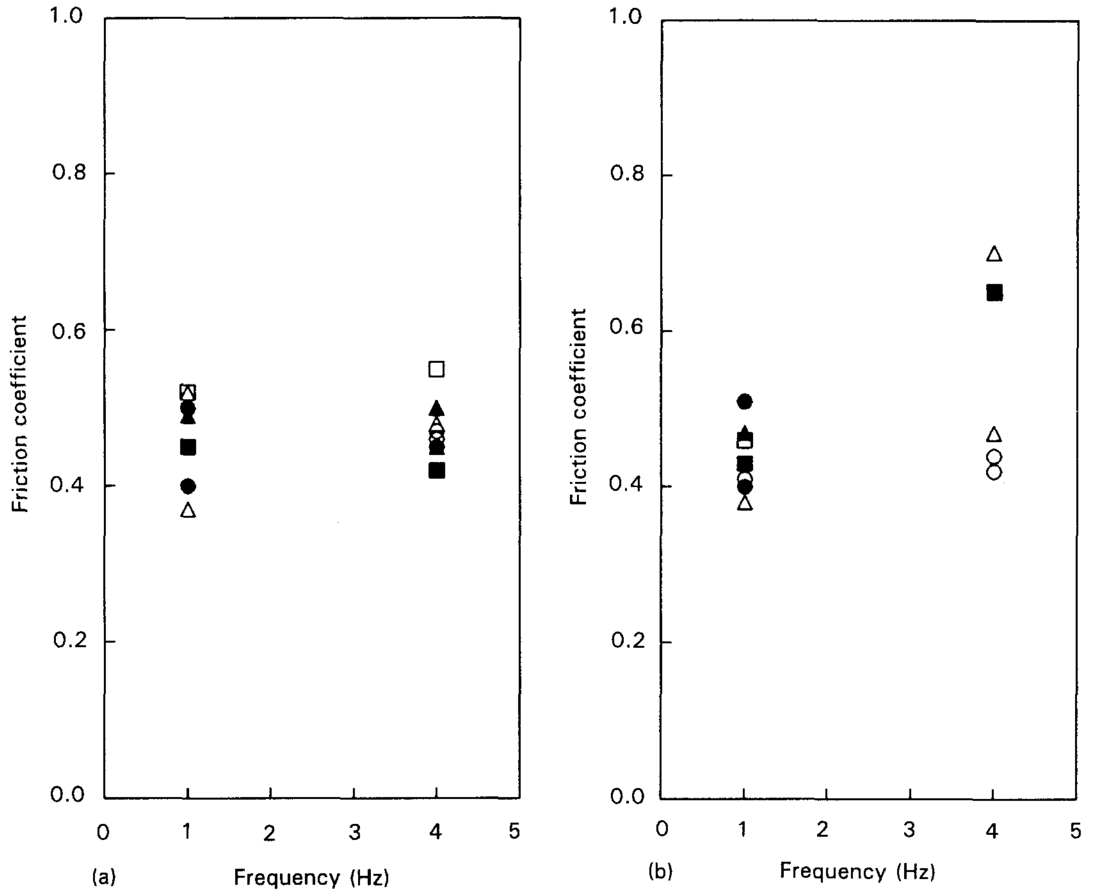

Figure 5 Summary of results from friction coefficient graphs after a sliding distance of (a) 1.73 km and (b) 5.18 km: (△) AlON 1, $P = 2$ N; (○) AlON 2, $P = 2$ N; (□) AlON 3, $P = 2$ N; (▲) AlON 1, $P = 8$ N; (●) AlON 2, $P = 8$ N; (■) AlON 3, $P = 8$ N.

indicated by arrows. For other conditions different transition times were observed.

This transition for each experiment can be represented by a line in a displacement time plot as shown in Fig. 3a and b. The starting point of the line is the point at which the regime of severe wear begins, as indicated by the arrows in Fig. 2a and b. The end point represents the end of the test. In two cases it represents the point of total failure of the sample. Although the point at which the transition starts shows some scatter, it can be seen that the average time before the transition occurs is larger for tests at a load of 2 N than for tests at a load of 8 N.

In Fig. 4a and b the results of the vertical displacement measurements are summarized in vertical displacement–load graphs after 1.73 and 5.18 km, respectively. The clusters of points at 1 Hz illustrate the approximately linear dependence of vertical displacement on load and the independence of the vertical displacement on AlON type. The highest points for the test performed on AlON 1 at 1 Hz, and 2 N can be explained by a difference of 5 μm between the first two measurements of the vertical displacement. This could easily be caused, for example, by some foreign particles located accidentally on the wear surface in the initial stage of the test. The values at 4 Hz show a fair amount of scatter, but this is caused by the aforementioned scatter in the transition.

The results of the friction measurements are summarized in Fig. 5a and b. The points plotted are the values after 1.73 and 5.18 km, respectively. The data for tests at 1 Hz are well within a range of 0.35 to 0.55 and independent of load and AlON type. The scatter for the data at 4 Hz is again caused by the transition.

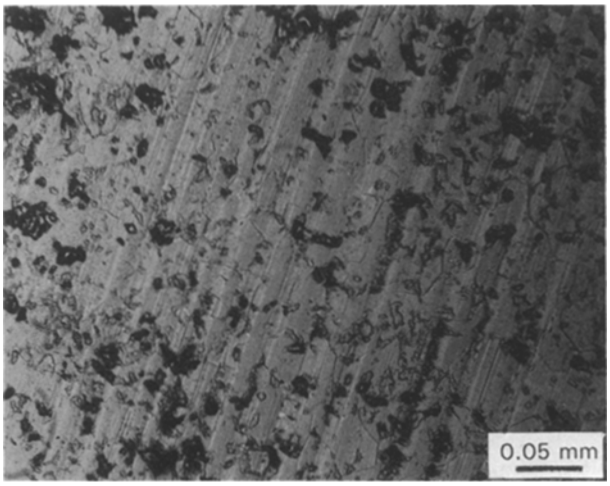

Figure 6 Worn surface of AlON 1 after a test at 8 N, 1 Hz for 72 h as observed by optical microscopy.

An example of a worn surface after a test under intermediate conditions, 8 N and 1 Hz, is shown in Fig. 6. This figure shows the microstructure of the AlON due to polishing. Some banding is also visible. In Fig. 7a and b this banding is examined in detail with SEM. These figures clearly show that the banding is formed by an alternation of bands with high and

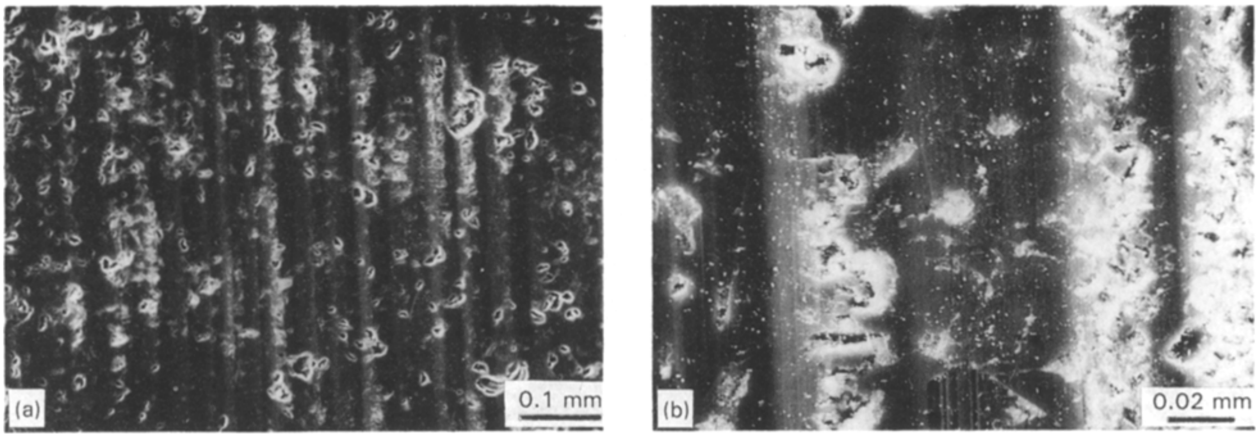

Figure 7 Worn surface of AlON 3 after a test at 8 N, 1 Hz for 72 h as observed with scanning electron microscopy: (a) overview, (b) detail.

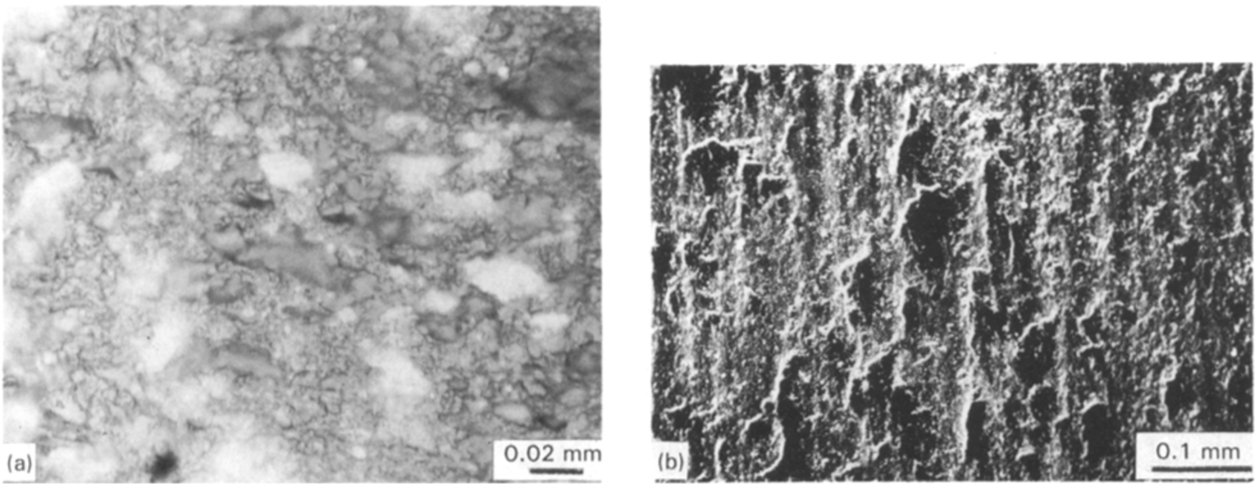

Figure 8 (a) Worn surface of AlON 2 plate after a test at 8 N, 4 Hz for 24 h as observed by optical microscopy. The light spots are due to debris adhering to the plate. (b) Worn surface of the Y-TZP sphere in the same test as observed by scanning electron microscopy. The dark spots are AlON particles adhering to the Y-TZP surface.

low concentrations of grains pulled out, or parts of grains which are pulled out. Fig. 8a and b present characteristic examples of the plate and the sphere, respectively, after a test at 4 Hz. The plate is covered with a layer of what appears to be debris without structure, and the sphere is covered with dark particles which were identified by X-ray energy-dispersive analysis (EDX) as AlON particles.

4. Discussion

In order to illustrate some of the relevant characteristics, a number of observations on this wear system are discussed.

The first part of the wear test is determined by the process of running-in. A conforming contact between the sphere and the plate has to be established, meanwhile reducing the local pressure.

The coherence of the grain boundaries and the strength of the material bonds of the AlONs appear to be very low. This is consistent with the relatively low fracture energy of 8 J m^{-2} as calculated from fracture toughness and Young's modulus. A ground surface is full of pits and holes and shows no grinding marks. This means that the initial wear surface of the AlONs can lose many AlON grains or parts of grains of various shapes and sizes.

The hardness of the AlONs is about 1.3 times the hardness of the Y-TZP. This means that the Y-TZP will not scratch or abrade the AlON plate. The banding on the AlONs as shown in Fig. 7a and b thus has to be caused by AlON particles localized at the sphere, either adhered or indented.

The phenomena observed and data obtained were used to develop a model. The experiments performed under intermediate conditions, 8 N and 1 Hz, provide information which explains most of the data. The worn surfaces after tests under these conditions show bands with a high concentration of grain pull-out. These bands are caused by AlON particles which are positioned at the sphere. The areas in between these bands support the load. These areas are thus supposed to be the wear-determining parts. The main mechanism of AlON removal in these areas is polishing. The amount of wear is thus simply linear with load, which is consistent with the results as shown in Fig. 4a and b. Running-in effects appear to have a minor influence in this respect. The friction coefficients are about equal for tests at 1 Hz, 2 N and 1 Hz, 8 N.

At a frequency of 4 Hz the whole process is greatly enhanced. More AlON particles are accumulated on the sphere until a threshold is reached and the contact between sphere and plate is practically an AlON–AlON contact with regular grain pull-out in the plate and the continuous removal of Y-TZP grains together with AlON particles from the sphere. A debris layer is formed containing Y-TZP grains and abrasive AlON particles.

A comparison with earlier studies on Y-TZP–sialon systems under approximately the same conditions [9] shows that a number of features are found in both systems. The amount of wear at a frequency of 1 Hz is about equal, the banding is found in both systems and a transition to severe wear was also observed in the Y-TZP–sialon system. The wear resistance of the AlONs at frequencies above 1 Hz is, however, much less than that of the sialons. The correspondence in observed phenomena does provide information which is probably useful in gaining insight into other systems with TZP sliding against harder ceramics.

5. Conclusions

1. There is no difference in wear behaviour between the three AlON types.
2. Polishing is the main wear-determining mechanism at a frequency of 1 Hz.
3. At 8 N and 1 Hz, AlON grains or parts of AlON grains are pulled out in bands but this does not influence the vertical displacement which is controlled by polishing.
4. At 4 Hz a transition occurs, at 2 N on average later than at 8 N, to severe wear characterized by many AlON particles attached to the Y-TZP sphere, resulting in mainly AlON–AlON contacts.

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