A Comparative Study of Alumina Wear in Air and Distilled Water

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Wear behaviour of high density high purity alumina against itself was studied at low speeds in air as well as in distilled water using a pin-on-disc machine. Depending on the apparent contact pressure and environment used, different wear mechanisms were identified. It was observed that in dry sliding (ie, without lubrication), abrasive ploughing and grain boundary microcracking causing grain pull out were dominant mechanisms at low contact pressure while at higher contact pressure, asperity melting due to high flash temperature was found. In wet sliding, the mechanism was different and associated with the formation of aluminium hydroxide that acted as a solid lubricant between the contacting surfaces reducing the wear at lower contact pressure. At higher pressure, clear intergranular fracture was noticed.

Keywords: Alumina; Wear; Friction; Intergranular fracture

INTRODUCTION

Advanced engineering ceramics offer unique capabilities as tribo-materials. Structural ceramics particularly relatively low cost alumina has sought diverse applications due to its chemical stability and high hardness that leads to enhanced wear resistance. Today alumina is extensively used in cutting tools, industrial pump seals, spark plugs, high precision biomedical implants and many other applications.

It is widely accepted that wear resistance of alumina primarily changes with load [1, 2], speed [3, 4], temperature [5, 6], environment [7-9] and grain size[10, 11]. Different wear mechanisms, such as, chipping due to extension of sub-surface radial and lateral cracks[12,13], grain dislodgement following grain boundary microcracking [10, 14], plastic ploughing [15, 16], fatigue induced wear [17], chemical reaction induced wear [7-9,18,28] have been identified for alumina-alumina couple. Most of these studies are important in addressing the effect of different parameters on wear but they often differed in their investigative approach — either they employed different methodology or excluded the effect of one or more parameters, considered by other workers. So the combined effect of different parameters as well as their relative importance *vis-à-vis* hierarchy of influences which is so important for understanding the wear mechanisms often remained unaddressed though most of these studies have played a very important role in identifying the wear mechanisms associated to that particular study.

In the present paper, wear behaviour of alumina has been studied with conformal contact geometry at different contact pressures and speeds by using a pin-on-disc machine. The coefficient of friction and wear volume have been correlated with load and speed for dry as well as water lubricated sliding. It has also been tried to develop a comprehensive understanding regarding the sequence of wear mechanisms involved in each case.

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MATERIALS AND METHODS

Commercially available 99.8% pure Alcoa, A-16 SG alumina powder was used to prepare the samples for this study. The chemical composition of the powder is shown in Table 1. The same alumina was used to manufacture ceramic femoral head. The powder was pressed isostatically at a pressure of 150 MPa, turned to the shape of cylindrical pins and disc which were sintered at 1600°C with 2 h soaking time. The physical and mechanical properties of the alumina used in this experiment were determined as per the ASTM norms and the values are listed in Table 2. Separate alumina test-pieces were polished and thermally etched at 1500°C to study their microstructure by employing the secondary electron mode of a scanning electron microscope (Model No LEO 430i STEROSCAN, UK). The pho-tomicrograph of the samples (Figure 1) shows well defined angular alumina grains with an average size of 4 μm, as determined by line intercept method (ASTM E112). The disc, 125 mm ϕ and 8 mm thickness with a central hole of 35 mm ϕ, was fitted with the pin on disc type wear and friction testing machine and was used as the sliding counterface. As wear could be correlated to the apparent contact pressure[19-21], the experiments were conducted with two different apparent contact pressures of 2.5 MPa and 8.5 MPa. A flat-on-flat test configuration was used for the present set of experiments. Both the surfaces of the disc and the pins were made parallel to ensure their maximum contact. The surface roughness of the pins and the disc before and after the experiment was measured by using a profilometer (Surtronic 3p, Form Talysurf Plus, Rank Taylor Hobson Ltd, UK). The surface roughness (Ra) of the pins was found to be 0.3 mm- 0.1 mm while the corresponding value for the disc was 0.6 mm.

Simple pin-on-disc unidirectional wear and friction testing machine (model no. TR 20LE) manufactured by M/s Ducom, Bangalore, India was used for this study. All the pin samples were ultrasonically cleaned and dried before and after the experiment. Volumetric wear of pin was calculated from gravimetric measurement. Frictional force between the pin and the rotating disc during test was measured by a load cell attached to the side of the pin-holding lever arm and the values were shown instantaneously in the digital display. The coefficient of friction was calculated simply by dividing the frictional force value with the corresponding axial load on the pin. All the

Table 1 Chemical composition of the high purity bio-grade alumina used in the present study, %

Al_2O_3 by difference	99.8
Na_2O	0.06
Fe_2O_3,	0.02
MgO	0.03
SiO_2,	0.03
CaO	0.02

Table 2 Mechanical properties of alumina used in the experiment

Density, g/cm³		Young's modulus, GPa	Flexural strength, MPa	Vicker's hardness, GPa (Indentation load=100 N)
Disc	Pin			
3.78	3.84	385	392	16 ± 0.6

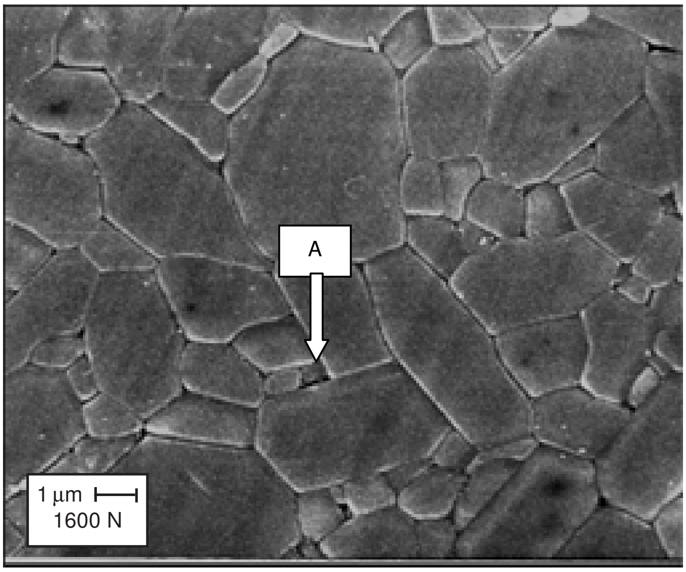

Figure 1 Microstructure of the alumina used in the experiments

investigations were performed at laboratry at temperature (*ie*, 25°C-30°C). Experiments were conducted with two different low sliding speeds of 0.2 m/s and 0.3 m/s under a constant rotational speed of 50 rpm of the disc and were carried out up to a sliding distance of 6 km in air as well as in distilled water. The samples were weighed before and after the test on a 'Shimadzu' electronic microbalance with an accuracy of four decimal places. Each experiment was repeated at least thrice to check the reproducibility of data.

RESULTS AND DISCUSSION

The results of the wear test are shown in Figure 2. In dry sliding test, it was found that the coefficient of friction (m) was higher at lower load whereas in case of water lubricated sliding, the reverse trend was evident (Table 3). In dry sliding, at 8.5 MPa contact pressure, the coefficient of friction was found to be in the range of 0.19-0.22 whereas, at 2.5 MPa it was 0.35-0.42 (Figure 2(a)). For water lubricated sliding, at higher pressure, the m varied between 0.326-0.356 and at lower contact pressure it was in the range of 0.086-0.113 (Figure 2(b)). In almost all the cases, coefficient of friction remained more or less constant throughout the distance of sliding. The volumetric wear loss for the test pin samples before and after experiment is shown in Figure 3. It was observed that volume wear loss was maximum when the test was conducted at highest pressure (8.5 MPa) in distilled water environment. Surprisingly, the wear loss was found to be extremely low in the case of dry sliding even with highest contact pressure. A detailed SEM observation of surface topography for the corresponding pin samples was carried out to identify the wear mechanisms associated in each case.

Figure 4 shows the surface topography of the worn out pin samples after 6 km of sliding under 2.5 MPa apparent contact pressure in dry condition. At 2.5 MPa, abrasive ploughing along with incomplete grain boundary micro cracking (Figure 4; Zone 'B') was observed. The possible reasons for micro cracking might be due to the micro structural defects, such as, pores, inclusions and weak grain boundaries (Figure1; Zone 'A') which acted as the nucleation sites of these micro cracks.

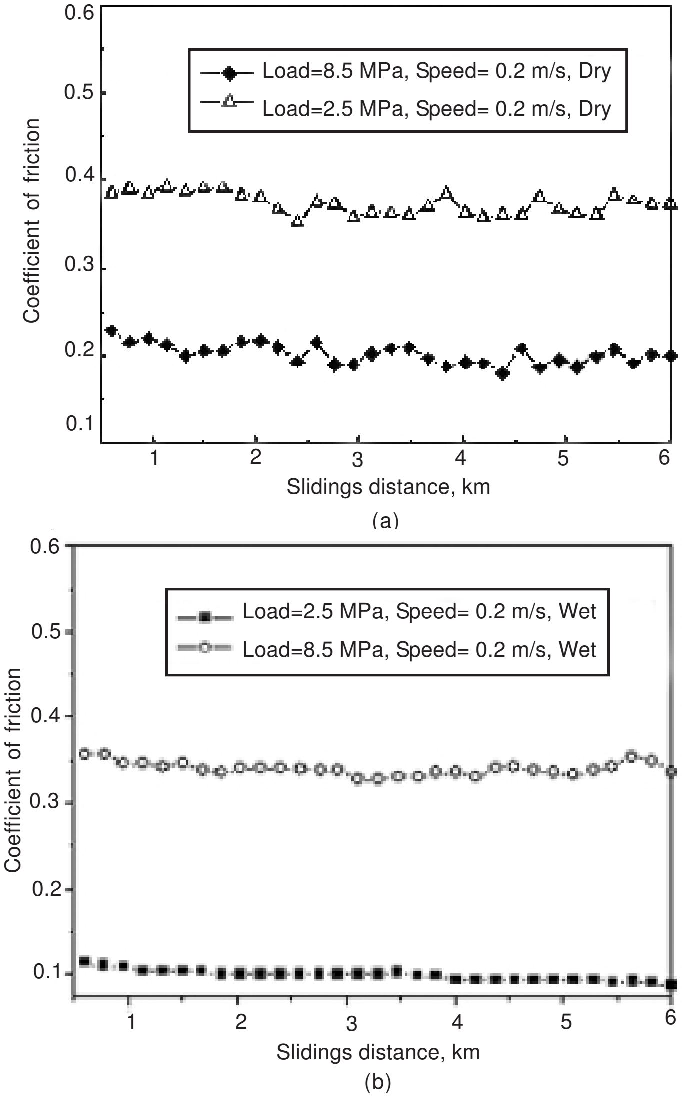

Figure 2 Variation of coefficient of friction in (a) air and (b) distilled water

Table 3 Coefficient of friction(μ) at different loads in dry and wet condition

Apparent contact pressure, MPa	Coefficient of friction (Sliding speed = 0.2 m/s)	
	Dry	Wet
2.5	0.35-0.42	0.086-0.113
8.5	0.19-0.22	0.326-0.356

Presumably, high contact pressure and temperature on the asperities might have resulted in dislocation movements under the influence of normal and tangential forces, which piled up against these defects and thus blocked slip band propagation. This probably generated microcracks at those observed sites [22-24]. At 8.5 MPa, a different wear mechanism was observed to be involved. SEM pictures of the pin samples showed widespread zones of smearing (Figures 5-6) for 0.2 m/s as well as 0.3 m/s sliding speeds. The reason of smearing might be the effect of local melting of the asperities on the surfaces due to high interfacial flash temperature generated from the sliding at a high-localised stress. Since wear mechanism and subsequent temperature rise at the sliding interfaces differs grossly for flat-on-flat test geometry compared to ball-on-flat configuration [25], sliding at low speed may even give rise to a very high temperature (>1350°C) at contact surfaces for conformal test configuration [26]. Depending upon the surface roughness, dimension and geometry of the asperity tips, sliding velocity and sliding time, the flash temperature may be sufficient to melt the asperity. A mathematical calculation (details presented elsewhere) [27] suggests that for alumina-alumina flat-on-flat contact with the prevailing range of stress, speed and surface roughness, flash temperature in excess of 1350°C could be generated which is well in accordance with the data reported in literature [26]. Moreover, in the present case, owing to flat-on-flat configuration, dissipation of heat (*eg*, radiation) was also low from the confined area of contact [25], which has aggravated the smearing action even further. The surface roughness of the alumina plate before and after the experiment with nominal contact pressure of 8.5 MPa, was measured by employing a profilometer which clearly indicated a progressive decrease of surface roughness (R_a) from 1.27mm - 0.96 mm to 0.73 mm- 0.52 mm . This also indicated melting and softening of asperities, which effectively reduced the surface roughness. Owing to this smoothening effect, wear volume as well as coefficient of friction in dry condition was low in the case of highest contact pressure in both the sliding speeds (Figures 2-3).

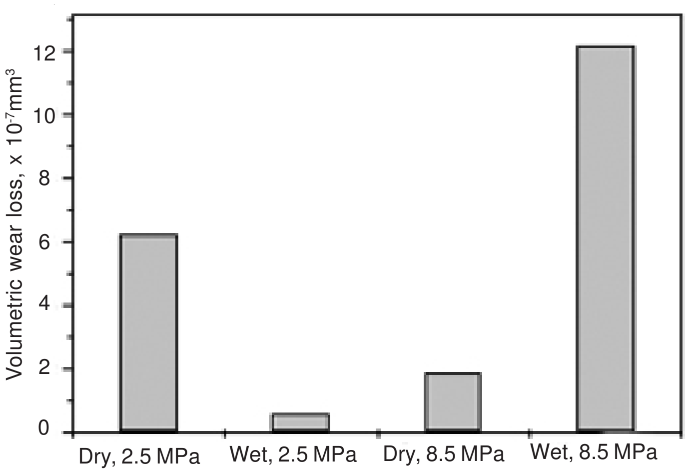

Figure 3 Volumetric wear loss of the wear pin samples with sliding speed of 0.2 m/s

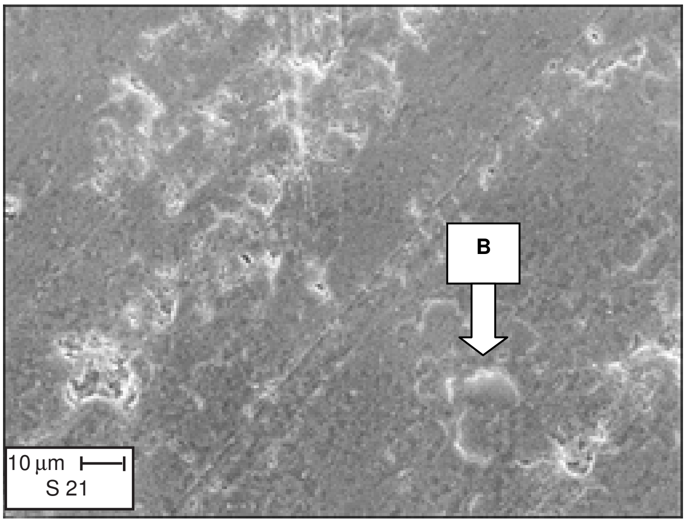

Figure 4 SEM images showing abrasive ploughing and incomplete grain boundary micro-cracking (Zone 'B') (2.5 MPa, 0.2 m/s, dry)

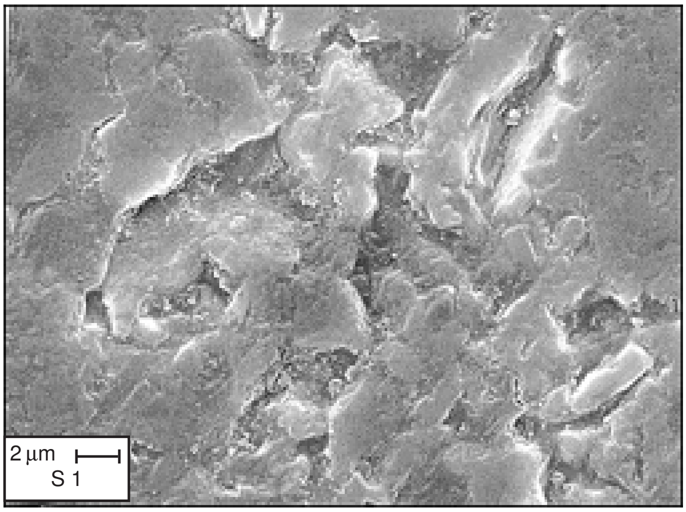

Figure 5 SEM images of pin samples showing widespread smearing zones(test conditions: 8.5 MPa, 0.2 m/s, dry)

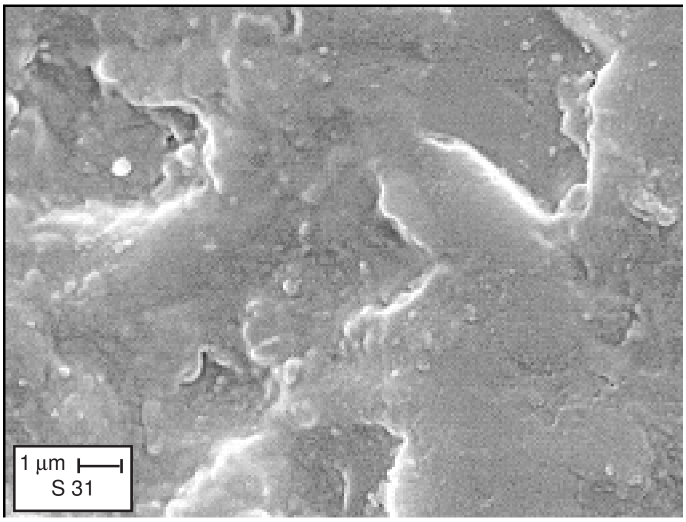

Figure 6 SEM images of pin samples showing widespread smearing zones(test conditions: 8.5 MPa, 0.3 m/s, dry)

Scanning electron micrographs of the wear pin samples reveal a different wear mechanism of alumina in water environment. At lower pressure, occasional grain pull-out and transgranular fracture were observed, (Figure 7(a)). The grooves thus created were found to be filled up with wear debris of different contrast level even after the ultrasonic cleaning of the test samples before SEM observation. The coefficient of friction and the wear volume loss in these cases

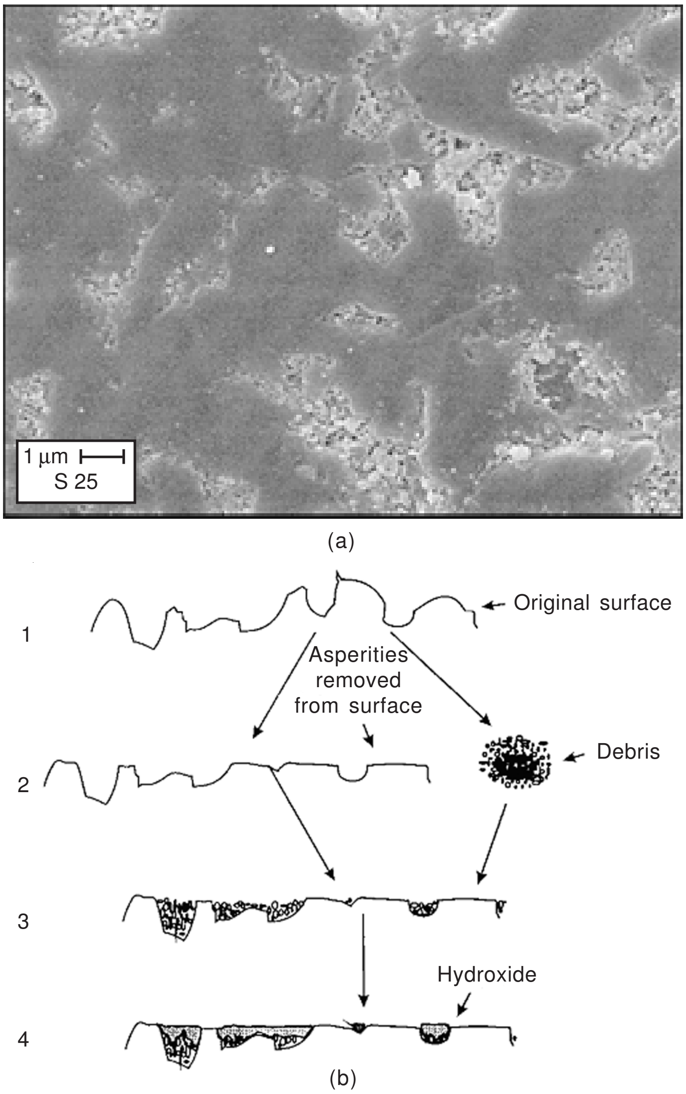

Figure 7 (a) Surface topography of the test pin samples showing transgranular fracture and wear debris of different contrast level filled up the grooves and (b) Wear mechanism of alumina in water: low friction due to formation of aluminium hydroxide (courtesy: M G Gee) (test condition: 2.5 MPa, 0.2 m/s, distilled water)

were also observed as lowest through out the experiments. This was due to the formation of aluminium hydroxide at the sliding interfaces in the presence of distilled water [9,18, 28] (Figure 7). The aluminium hydroxide is formed by chemical reaction between very fine alumina wear debris (produced by the fracture of the comparatively larger size asperities) and water which is promoted due to combined effect of the frictional heat generation and higher interfacial pressure during sliding. These hydroxides are accumulated in the wear grooves (Figure 7(b)) and are obviously beneficial to reduce the wear events significantly. Due to the layered crystallographic structure of the aluminium hydroxide like graphite, they act as a lubricative layer [28] in between the sliding surfaces and reduced the coefficient of friction as well as volumetric wear to a considerable amount. When the same experiment was conducted with higher presure (*ie*, 8.5 MPa), clear intergranular fracture was noticed (Figure 8). Probably, at the higher pressure, the hydroxide layer failed to maintain any lubricative effect and in the presence of water, severe intergranular fracture took place. As a result, the coefficient of friction increased substantially compared to the test with lower contact pressure (Figure 2). In water environment even at higher pressure, effective dissipation of frictional heat took place through the circulating water resulting reduction in localized heating and therefore melting of the asperities didnot take place though it occurred in dry sliding.

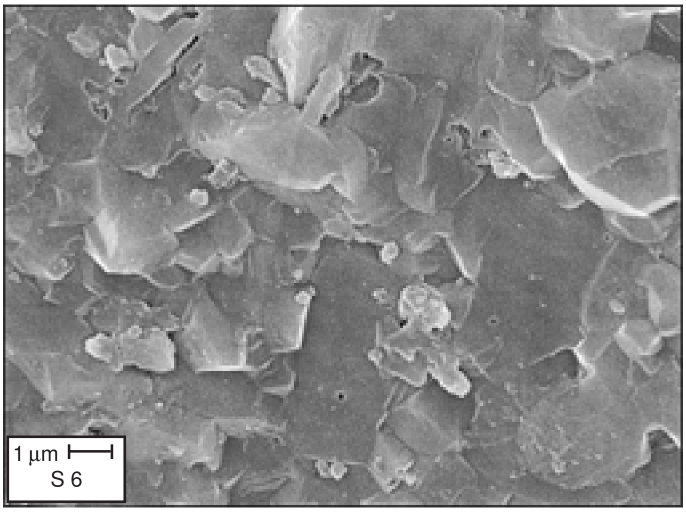

Figure 8 Optical micrograph shows clear intergranular fracture (8.5 MPa, 0.2 m/s, distilled water)

The surface topographies and the coefficient of frictions were found to be almost identical for the test samples of 0.2 m/s and 0.3 m/s while the other parameters are kept constant. One possible reason might be the speed ranges selected in the present set of experiments were too close to show any significant variations in the wear mechanism.

CONCLUSIONS

Wear of alumina is greatly dependent on test load as well as test environment. In air, at 2.5 MPa apparent contact pressure, abrasive ploughing and incomplete grain boundary microcracking were noticed while at 8.5 MPa, the wear mechanisms involved were asperity melting and subsequent smearing owing to very high flash temperature. In water environment, at an apparent contact pressure of 2.5 MPa, formation of aluminium hydroxide probably reduces the coefficient of friction and volumetric wear loss. At higher pressure, intergranular fracture was found to be the dominant wear mechanism in distilled water.

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