POINT CONTACT FATIGUE IN POLYCRYSTALLINE ALUMINA

J. L. Henshall*, M.-O. Guillou*, and R.M. Hooper**

Polycrystalline alumina has many applications in load bearing situations. The soft impresser method (1) is a technique which has been devised to be able to introduce controlled plasticity into nominally brittle materials at low temperatures. This has been developed to allow fatigue testing of ceramics at room temperature (2). This paper briefly describes the technique and its application to a commercial polycrystalline alumina. The sequence of events that are observed is that plasticity occurs at the edge of the contact zone between the steel impresser and the flat alumina substrate, followed by predominantly transgranular localised fracture leading to surface fragmentation and radial crack propagation away from the contact. This paper demonstrates the manner in which a softer material causes fatigue, and thus wear, in a harder material.

INTRODUCTION

Polycrystalline alumina has been used in wear resistant applications such as dies for threads etc. for many years. The applied loads in these situations are generally minimal, but more recent applications, such as prosthetic joints, require significant load bearing capacity. In these circumstances the alumina may fail either due to the propagation of a pre-existing flaw, which gives relatively short lifetimes, the tribochemically assisted removal of surface layers or surface fatigue crack initiation and fracture. The present study is concerned with ascertaining the mechanics and mechanisms of the latter mode of failure.

The soft impresser method has been used to measure the contact fatigue behaviour of a commercial polycrystalline alumina, designation SP96. Tool steel cones have been used as the soft impressers.

* Department of Mechanical Engineering, Brunel University, Uxbridge, UK, UB8 3PH
** School of Engineering, Exeter University, Exeter, Devon, UK, EX4 4QF

contact pressure, the mean and cyclic pressure amplitude and the corresponding values of the maximum tensile stresses, which are in the radial direction at the edge of the contact between the steel and alumina.

TABLE 1 - Values of Applied Loads and Resultant Pressures in the Contact Zones and Radial Tensile Stresses at the Edges of the Contact Zones.

Applied Loads N	Maximum Pressure GPa	Mean ± Cyclic Pressure GPa	Mean ± Cyclic Maximum Radial Stress GPa
20.1 ± 9.3	7.62	5.21 ± 2.41	1.51 ± 0.70
29.4 ± 14.7	6.96	4.64 ± 2.31	1.34 ± 0.67
38.3 ± 20.6	6.69	4.35 ± 2.34	1.26 ± 0.68
19.6 ± 14.7	6.45	3.69 ± 2.76	1.07 ± 0.80
11.3 ± 10.3	4.08	2.13 ± 1.95	0.62 ± 0.57
22.1 ± 20.1	6.25	3.27 ± 2.98	0.95 ± 0.86
32.4 ± 30.2	7.47	3.86 ± 3.61	1.12 ± 1.05

For all the conditions detailed in Table 1 the alumina substrate did not immediately observably plastically deform or crack. However as the load was cycled, fatigue of the alumina was observed with a similar sequence of events being noted for each loading condition. The number of cycles to a given stage varied with the magnitude of the applied load. The main features of the fatigue process are described below.

The first observable signs of fatigue effects are discernible at the edges of the contact zones. In figure 1 the outline of the contact circle can just be detected. The initial deformation at the edge of the contact zone, figure 2, shows the formation of small steps within the alumina grains. These steps are slightly curved, and are therefore unlikely to be formed by twinning and thus this localised plasticity occurs presumably as a result of dislocation glide. From the top left hand corner in an arc downwards can be seen some metal (steel) that has been transferred from the cone to the substrate.

The next stage in the process, figure 3, is associated with a relative further downward displacement within the contact zone and the concomitant continued plastic deformation of the alumina grains leading to localised cracking. Figure 4 shows that this fracturing takes the form of transgranular fracture of occasional grains with the formation of small scale debris in isolated regions. The transgranular cracks are similar to those observed in the indentation fracture of sapphire, which would appear to

EXPERIMENTAL

The soft impresser method utilises a similar technique to the conventional indentation hardness test, but with the significant alteration that the rigid indenter is replaced by an impresser that is softer than the test piece. The advantages of this approach are:

- the deformation of the softer impresser ensures good conformity and alignment,
- by varying the hardness of the impresser, the degree of induced deformation and/or cracking can be varied and controlled, unlike diamond indentation where there is a substantial degree of localised deformation and/or fracture,
- the volume of tested material is relatively small.
- the contact area does not vary with load after the first application of the maximum load, as it would for example with classical Hertzian ball contact, and
- the stress pattern that is obtained is similar to that in many operational situations.

Details of the apparatus and procedure are described in Maerky (3). Briefly, the procedure uses a 120° apical angle cone which was attached to a beam by a threaded fixture. The other end of the beam was attached to a spring and cam, so that as the cam was rotated at constant speed by a small d.c. electric motor, the spring length was varied, and thus the force on the cone. The load was continually monitored by a load cell placed beneath the test block. The initial application of the load is crucial to ensure reproducible results, and a hydraulic piston was used to control the initial rate of descent of the cone onto the flat substrate at minimum load, with the cam subsequently being rotated by hand to give the maximum load. Thereafter the frequency of loading was 2 Hz.

The polycrystalline alumina was a commercial grade SP96 (Swallow Ltd, UK), containing ~5% MgO as sintering aid and ~3.5% residual porosity. X-ray diffraction showed that it was completely α-phase Al_2O_3. The mean linear intercept grain size was 9 μm, and the Vickers hardness (2.9 N load) = 13.6 GPa and indentation critical stress intensity factor = 3.6 MPa $m^{1/2}$ (using the Anstis et al formula (4), with E = 375 GPa). The flat specimens were ground and polished, using $^1/_4$ μm diamond polishing as the final stage. The impressers were ground from 5 mm round tool steel rod into a 120° apical angle cones with tip radius ~1 μm. A new cone was used for each test. The loads were applied for between 100 and 5 x 10^6 cycles.

RESULTS AND DISCUSSION

The range of applied loads used in these tests is given in Table 1. It was observed that the tip of the cone flattened to give a conforming circular contact zone on the first application of the maximum load, and there was no systematic variation of cone diameter with increasing number of cycles. Also included in this table are the values of the maximum

Figure 1. Surface of alumina substrate tested for 100 cycles at 19.6 ± 14.7 N. The outline of the circular contact zone can just be discerned. The first clear signs of permanent deformation can be seen towards the top left.

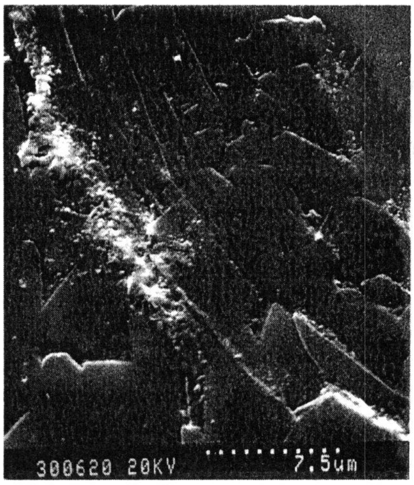

Figure 2. Specimen tested for 5000 cycles at 29.4 ± 14.7 N. The contact zone is towards the right hand side of the figure.

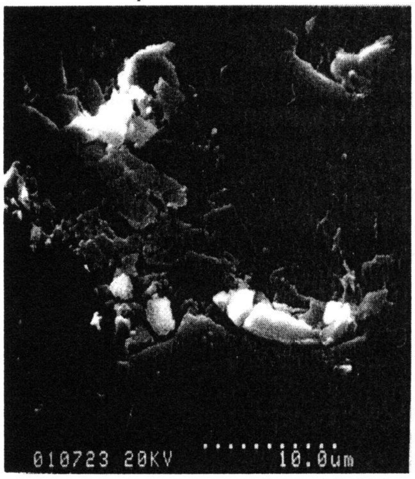

Figure 3. 1000 cycles at 38.8 ± 20.6 N at edge of contact zone

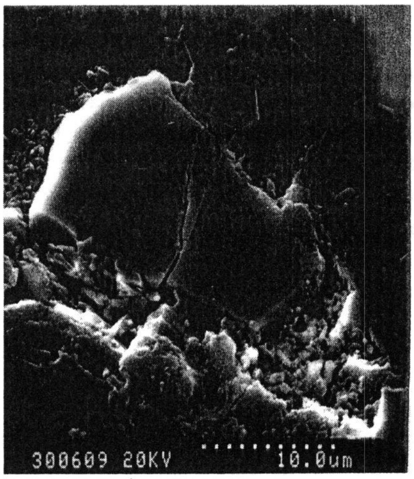

Figure 4. 10^4 cycles at 29.4 ± 14.7 N at edge of contact zone.

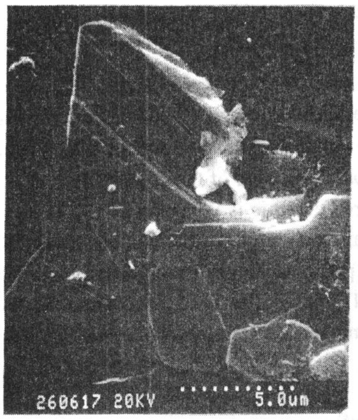

Figure 5. Twinning in alumina substrate within the contact zone, 10^5 cycles with loads of 20.1 ± 9.3 N.

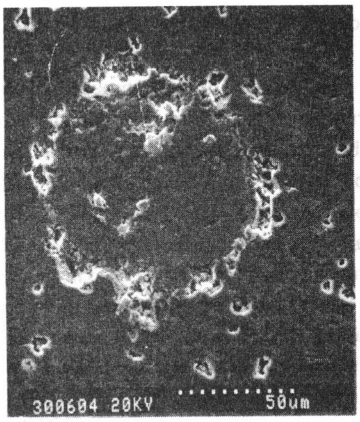

Figure 6. 5×10^5 cycles with loads of 29.4 ± 14.7 N showing almost complete ring crack around contact zone edge.

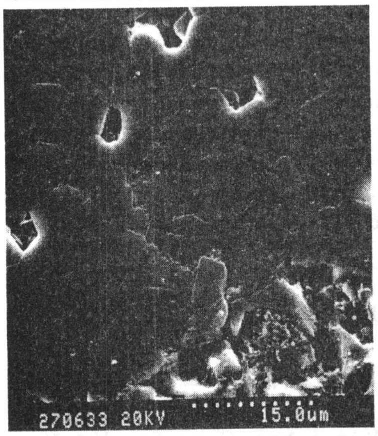

Figure 7. Radial crack propagating from edge of contact zone, 5×10^6 cycles at 29.4 ± 14.7 N.

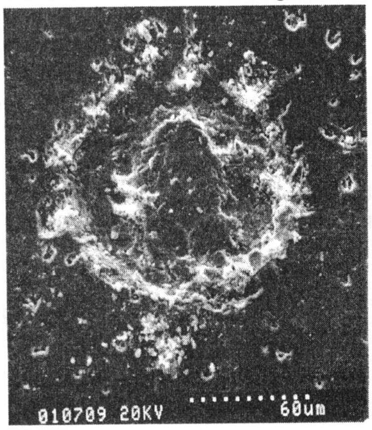

Figure 8. 10^5 cycles at 38.3 ± 20.6 N showing formation of a circular 'trench' of material removed.

be initiated by a combination of slip and twinning (5). Small particle debris formation, similar to that shown in figure 4, has been observed in the sliding wear of alumina (6) and explained in terms of the small agglomerate sizes formed in the manufacture of the alumina powders being carried through into the final product and surface hydrolysis of the alumina. At this stage the first clear signs of deformation in the centre of the contact zone, i.e. twinning, are observed, figure 5. It is noteworthy that these effects do not appear to be controlled or affected by the presence of the fairly large pores, 1-5 μm, even when the edge of the contact zone traverses one.

The fatigue process proceeds further by the formation of several localised deformation and fracture sites forming around the periphery of the contact zone. These then begin to interlink, figure 6. For all the test conditions outlined above the ratio of the number of cycles to produce observable deformation at the edge of the contact zone to the number required to form a complete ring of fractured ceramic is in the range 0.01 - 0.05. Towards the end of this stage, radial cracks propagate away from the contact zone to a distance of 10-30 μm, figure 7. These cracks are predominantly intergranular, although there is some degree of transgranular fracture. The final phase of the fatigue is the formation of a relatively deep circular trench of removed ceramic which grows both into the contact zone and to a lesser extent away from it, figure 8.

CONCLUSIONS

The soft impresser method has been used to demonstrate the manner in which a softer material (steel) may cause fatigue wear in a much harder material (alumina). The fatigue deformation and fracture initiate at the edge of the contact zone, where the maximum tensile stresses occur. The initial deformation appears to occur by slip, followed by twinning. The first stages of cracking are a combination of transgranular fracture, initiated by the plastic deformation, and small particle debris formed by the mechanisms described by Gee (6). Further loss of material occurs as a result of radial crack propagation away from the contact zone and gradual progression of a wear 'trench' into the contact region.

REFERENCES

(1) Brookes, C.A. and Green, P., Nature Vol. 246, 1973, pp. 119-122.

(2) Guillou, M.-O., Henshall, J.L. and Hooper, R.M., J. Amer. Ceram. Soc., Vol. 76, 1993, pp. 1832-1836.

(3) Maerky, C., PhD Thesis, University of Exeter, UK, 1998.

(4) Anstis, G.R., Chantikul, P., Lawn, B.R. and Marshall, D.B., J. Amer. Ceram. Soc., Vol. 64, 1981, pp. 533-538.

(5) Guillou, M.-O. and Henshall, J.L., in preparation

(6) Gee, M.G., J. Hard Materials, Vol. 3, 1992, pp. 363-377.