JOURNAL OF MATERIALS SCIENCE 29 (1994) 773–777

The abrasive wear of borosilicate glass

C. PANAGOPOULOS, E. FASOULA, A. MICHAELIDES
Laboratory of Physical Metallurgy, National Technical University of Athens, Zografou Campus, 157 73 Athens, Greece

The abrasive wear of borosilicate glass was studied. Under dry wear conditions, the weight loss of borosilicate glass was not found to be a linear function of the sliding distance. The debris from the worn glass areas was observed to consist of glass particles, silicon carbide particles from the abrasive wheel and agglomerates of glass and silicon carbide. This showed that the wear of borosilicate glass by silicon carbide wheels is mainly abrasive but also adhesive to a lesser degree.

1. Introduction

Ceramic materials, because of their excellent technological properties such as strength, hardness, chemical inertness and thermal shock resistance, are being considered in various tribological applications. In particular, the various glasses are promising for use in complicated technological areas. However, several aspects need to be addressed before they can be widely used. One of those aspects is the tribological behaviour of different glasses.

Up to now only limited research work has been reported about the general tribological behaviour of various glasses. Billinghurst *et al.* [1] deformed the surface of glass specimens with a hard metallic indenter; these investigators observed that under a static load of 2 kg no ring cracks were formed on the glass surface, but if the applied tangential force increased to 1.5 kg then sliding occurred and the friction tracks were covered with overlapping arced tracks. More detailed and similar results have been also reported by Gilroy and Hirst [2].

Bickermann and Rideal [3] found that the coefficient of friction of glass on brass, chromium and tin plate is equal to 0.18, 0.16 and 0.29, respectively. On the other hand, Claypoole [4] showed that fatty acids (stearic, oleic and palmitic) can reduce the coefficient of friction of glass on various metallic materials by 20–40 %. The same investigator also suggested that water-dispersible liquids, when applied on the glass surface form a resistant film that greatly protects the glass surface from abrasion. Finally, Chen *et al.* [5] examined the sliding indentation of borosilicate and fused-silica glasses by a sharp rigid indenter, and observed that various active lubricants are useful for controlling the wear and the vent crack depths of deformed glasses.

The present work examines the abrasive wear of borosilicate glass under different experimental conditions.

2. Experimental procedure

The specimens used in this study were made from borosilicate glass having the following chemical composition (wt %): 80 SiO_2, 13 B_2O_3, 4 Na_2O_3, 3 Al_2O_3. The specimens for wear measurements were squares 10 cm × 10 cm and 0.5 cm thick. In the centre of the glass specimens a hole with 0.6 cm diameter was opened.

The wear behaviour of borosilicate glass specimens was examined with the help of a Taber abrasion machine (Frank Co, Germany). This machine consists of two rotating abrasive wheels which produce a circular wear track of 1.1 cm width and 6.0 cm inner diameter. The glass specimen rotated about a vertical axis at a constant speed of 60 r.p.m. against the sliding rotation of the two abrasive wheels. These wheels were driven by the glass specimen under test about a horizontal axis displaced tangentially from the axis of the specimen. Wear was quantified by weight loss which was measured every 100 cycles.

Teledyne H18 wheels (Calibrade Co, USA), which consist of rubber impregnated with silicon carbide particles, were used for all the wear tests. The abrasive wheels were cleaned every 200 cycles to avoid contamination. Surface profiles of the wear tracks, parallel and perpendicular to the direction of the abrasive wheels, were taken with the aid of a Perthen profilometer. Surface examination of the worn glass specimens were also made with a Zeiss optical microscope. The wear debris was also examined with the above microscope and with a Philips X-ray diffraction machine using a CoK_α radiation ($\lambda = 0.1791$ nm) and an iron filter.

Most of the abrasive wear measurements were made under dry conditions at 20 °C. In addition, some of the wear experiments were carried out with the dropping of ethanol (10 mg per cycle) and a BP lubricant oil (16 mg per cycle) on the glass specimens. The lubricant oil consisted of two basic components plus two additives and a booster. The booster, which is the main anti-wear substance of the lubricant oil, was zinc dialkythiophosphate (Zddp).

3. Results and discussion

Fig. 1 shows the weight loss as a function of sliding distance during the abrasive wear testing of borosilicate glass under the action of two applied loads, 1.25

0022-2461 © *1994 Chapman & Hall*

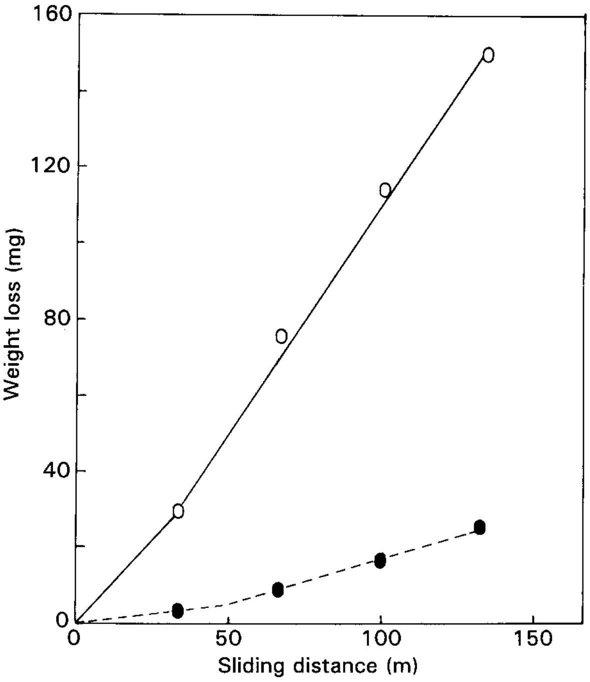

Figure 1 Weight loss as a function of sliding distance during abrasive wear testing of borosilicate glass for applied load (○) 5 N and (●) 1.25 N.

and 5 N. As observed, the variation of weight loss with sliding distance is not linear but consists of two linear segments.

The dimensionless wear rate $\dot{W}$ was calculated according to the formula

$$\dot{W} = \frac{\Delta m}{AL\rho}$$

where Δm is the weight loss, A the contact area ($24.5\,\mathrm{cm}^2$), L the sliding distance and ρ the density of borosilicate glass ($2.23\,\mathrm{g\,cm}^{-3}$).

Fig. 2 shows the variation of the wear rate of borosilicate glass with sliding distance for applied loads of 1.25 and 5 N. In the case of 1.25 N applied load, the dependence of wear rate on sliding distance seems to consist of two linear segments which increase with increasing sliding distance. In the case of 5 N applied load, the wear rate increases with increasing sliding distance between 67.5 and 135 m. The lower values of wear rate recorded during the first stages of wear measurements might be explained by the assumption that the top layers of borosilicate glass specimens had undergone hardening after thermal treatment during production of the glasses.

A significant portion of reported studies that have examined the abrasive wear of various ceramics have proposed that their abrasive wear resistance follows the general relationship

$$\text{Abrasion resistance} \propto K_{\mathrm{IC}}^{m} H^{n}$$

where K_{IC} is the fracture toughness and H the hardness of the ceramic material; m and n are constants. From the results given in Fig. 2 one can notice the low values of wear rate. These values must mainly be defined by the product of the relevant values for borosilicate glass: $K_{\mathrm{IC}} = 0.77\,\mathrm{MPa}$ and $H = 580\,\mathrm{kg\,m}^{-2}$.

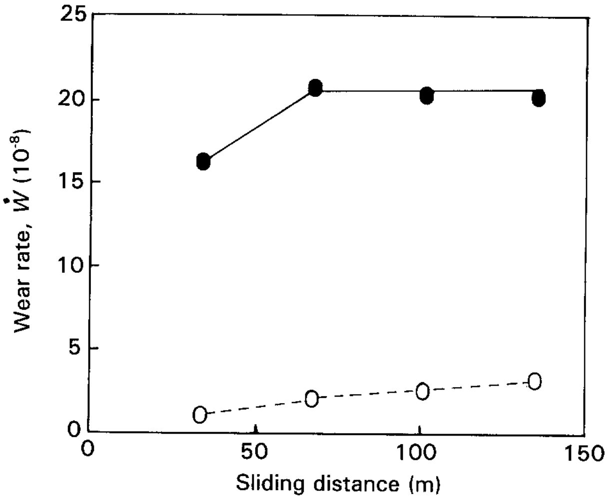

Figure 2 Variation of wear rate of borosilicate glass with sliding distance for applied load (●) 5 N and (○) 1.25 N.

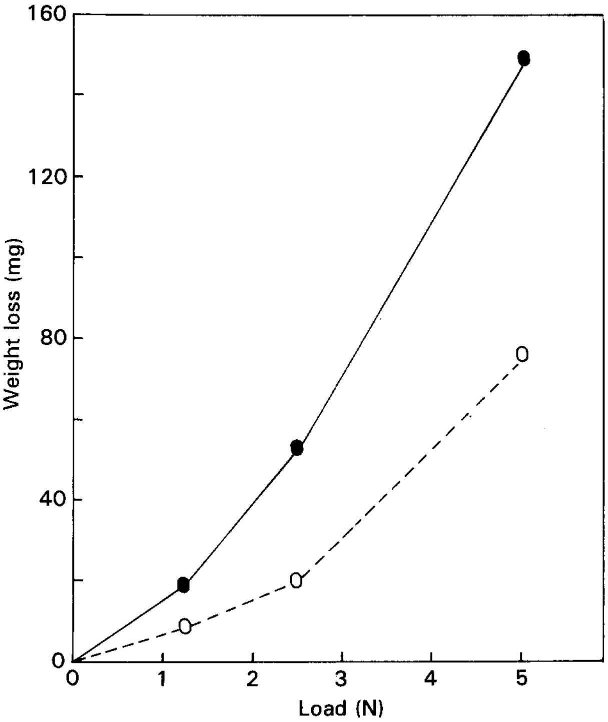

Figure 3 Variation of weight loss of borosilicate glass with applied load for sliding distance (○) 67.5 m and (●) 135 m.

Fig. 3 shows the weight loss of borosilicate glass as a function of applied load for two sliding distances, 67.5 and 135 m. This figure shows that the weight loss due to the abrasive wear of glass increases exponentially with increasing applied load. In addition, it can be noted that for a constant value of applied load the weight loss of borosilicate glass is higher at 135 m sliding distance than at 67.5 m.

The surface roughness measurements on the wear tracks, expressed as the average roughness R_a, were taken in directions transverse and parallel to the abrasive wheel movement. Fig. 4 shows profilometer traces on the wear tracks of borosilicate glass after 67.5 and 135 m sliding distance, with 1.25 N applied load. These traces were taken transverse to the sliding direction. From this figure it is observed that the surface roughness on the worn borosilicate glass increases with increasing applied load.

The values of surface roughness on the wear tracks, transverse and parallel to the sliding direction, were always found to be only different by about ± 10%. This is explained by the observation made on the wear tracks, which showed a pattern of crossed arcs generated by the abrasive wheels. One wheel rubs the glass outwards towards the periphery and the other inwards towards the centre of the specimen. Fig. 5 shows the surface roughness on the wear tracks to decrease with increasing sliding distance for a constant value of applied load.

Fig. 6 shows the surface morphology of the area next to the periphery of a circular wear track after 135 m sliding distance with 5 N applied load. As observed, fracturing of the worn borosilicate glass specimen occurred and some generated cracks propagate outwards of this track. Fig. 7 shows the surface area in the centre of the wear track after 135 m sliding distance with 5 N applied load. In this figure extensive fracturing and microchipping at the surface of worn specimens can be clearly observed. Figs 8 and 9 show the worn surfaces of two glass specimens when the applied load was 1.25 and 2.5 N, respectively, and the sliding distance 67.5 m. Comparing the surface morphology of these figures, it can be seen that the increase of applied load leads to increasing fracturing, ploughing and microchipping of the worn areas of borosilicate glass.

Observing the above figures, it can be said that the surfaces of the worn glass specimens exhibit a series of grooves, each of which was produced by an individual silicon carbide particle from the abrasive wheels. Mulhearn and co-workers [6, 7] have shown that material is removed by a chip being cut only if the attack angle, i.e. the angle between the working surface of the particle and the direction of sliding, is greater than a characteristic critical angle; if not, then the abrasive particle rubs the surface of the specimen

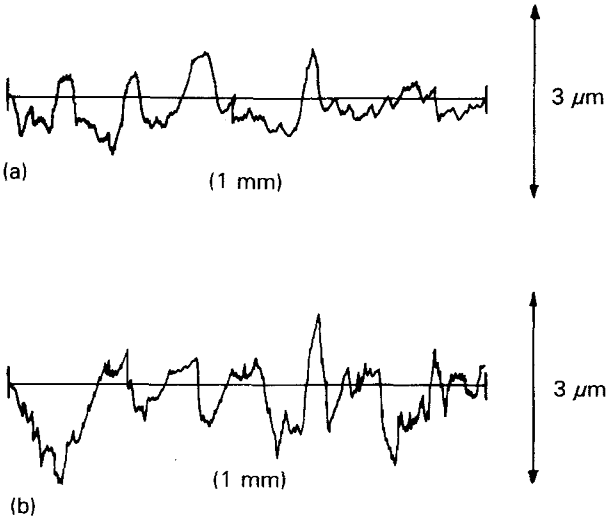

Figure 4 Profile traces on wear tracks of borosilicate glass after (a) 67.5 m and (b) 135 m sliding distance with 1.25 N applied load.

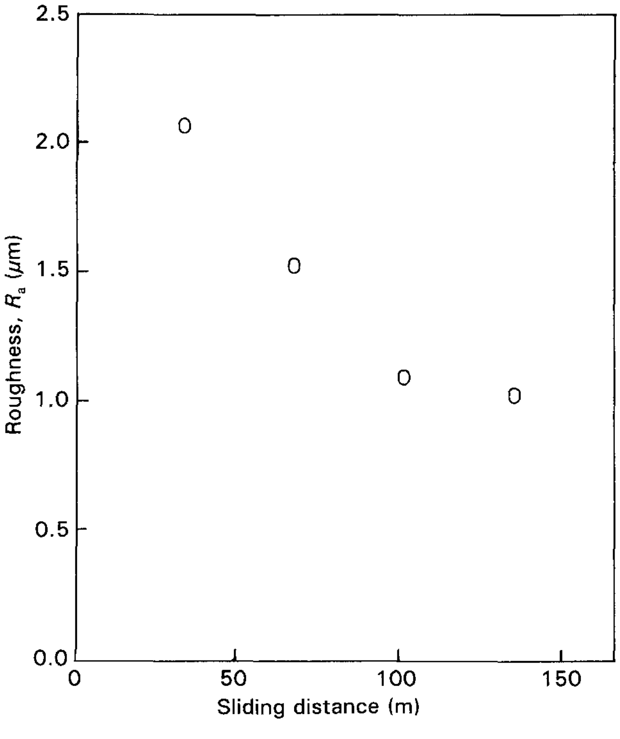

Figure 5 Roughness on wear tracks during the abrasive wear testing of borosilicate glass, as a function of sliding distance with 5 N applied load.

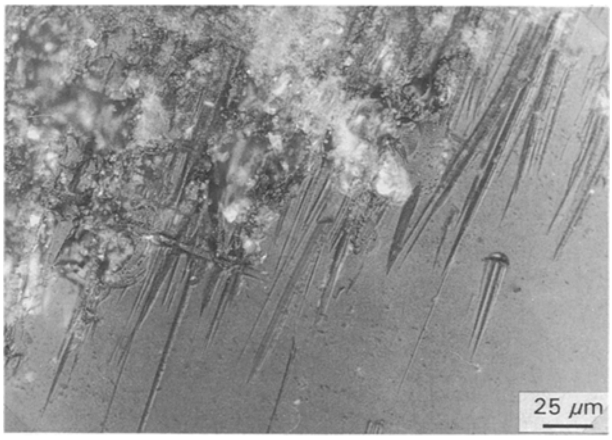

Figure 6 Surface morphology of the area next to the periphery of a circular wear track of borosilicate glass after 135 m sliding distance with 5 N applied load.

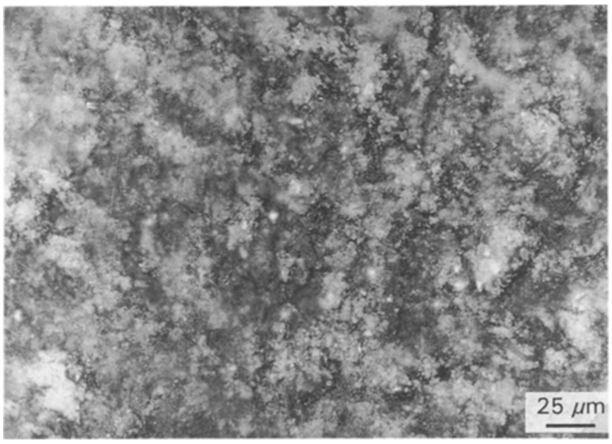

Figure 7 Surface morphology in the centre of a wear track of borosilicate glass after 135 m sliding distance with 5 N applied load.

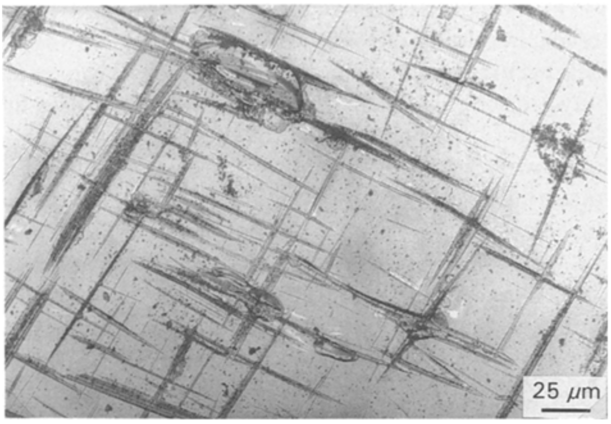

Figure 8 Surface morphology in the of centre of a wear track of borosilicate glass after 67.5 m sliding distance with 1.25 N applied load.

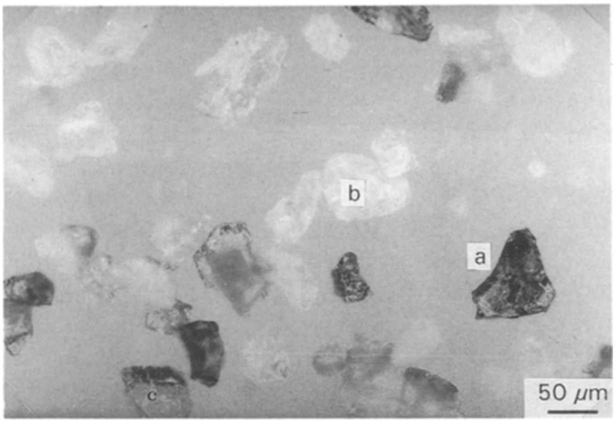

Figure 10 Optical micrograph of the wear debris of borosilicate glass; the sliding distance was 135 m and the applied load 5 N. (a) Silicon carbide particle, (b) borosilicate glass particle, (c) agglomerate of silicon carbide and glass particles.

Figure 9 Surface morphology in the centre of a wear track of borosilicate glass after 67.5 m sliding distance with 2.5 N applied load.

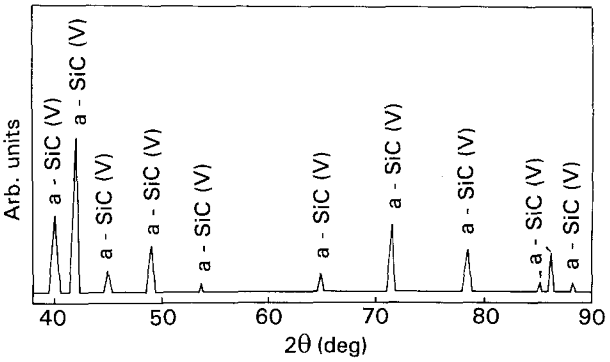

Figure 11 X-ray diffraction spectrum of the wear debris of borosilicate glass; the sliding distance was 135 m and the applied load 5 N.

and imparts a ploughing action. The silicon carbide particles in the abrasive wheels are oriented over a wide angular range and will present a distribution of attack angles to the borosilicate glass surface, some of which will be above the critical angle, according to the above ideas, and microchipping will occur in the sliding glass specimens. The above deductions are in full agreement with the observations shown above in Figs 6–9.

Fig. 10 shows the wear debris collected after a wear experiment in which the sliding distance was 135 m and the applied load was 5 N. A detailed examination of the wear debris showed the presence of glass particles, silicon carbide particles and agglomerates of glass and silicon carbide particles. This suggests that in addition to the main abrasive wear of borosilicate glass, an adhesive wear process may be operating between the glass and the silicon carbide particles in the Taber abrasion test. Additional evidence for the occurrence of adhesive wear during sliding contact of the borosilicate glass with the silicon carbide particles is given in Fig. 11. In this figure the X-ray diffraction spectrum of the wear debris is given. As shown, only diffraction peaks from the silicon carbide particles are detected whereas peaks from the glass particles are absent due to the non-crystalline structure of borosilicate glass.

It must also be pointed out that some reported investigations [8] have shown that adhesive transfer of nickel to silicon carbide particles occurs during contact. Furthermore, Date and Malkin [9] observed that material loss occurred by an adhesive wear mechanism between alumina abrasive particles and steel, especially if the experimental conditions gave rise to particle sliding. In the present investigation, those silicon carbide particles with sub-critical attack angles will slide against the glass surface, inducing glass particle transfer. Once this has occurred the resulting roughened surface will give rise to higher local attack angles and stresses, resulting in fracture within the scratch grooves.

Fig. 12 shows the variation of weight loss with sliding distance during the abrasive wear of borosilicate glass, under various experimental conditions, when the applied load was 5 N. The wear measurements on the glass specimens were performed under the following conditions: dry wear testing, dropping of ethanol during wear testing and dropping of lubricant oil during wear testing. From the figure it can be seen that the wear rate, i.e. the ratio of weight loss to sliding distance, increases according to the above series of experimental conditions, i.e. first, dry wear testing and last, dropping of lubricant oil during wear testing.

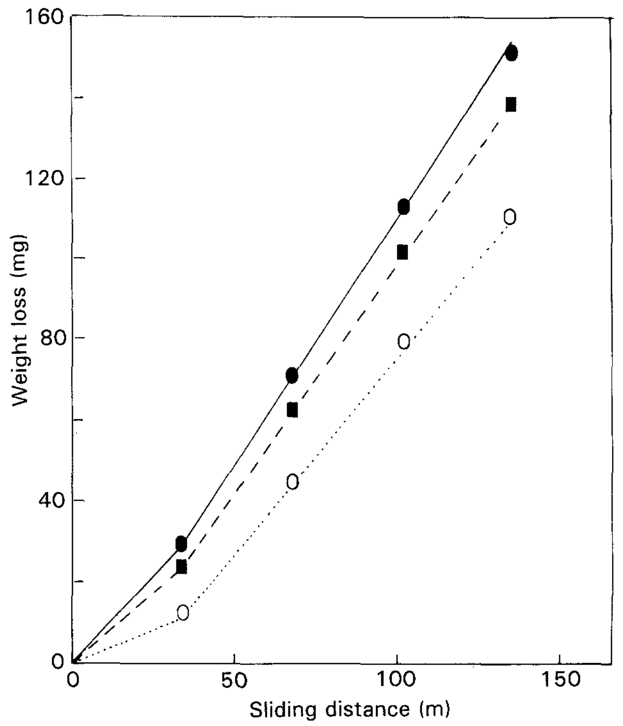

Figure 12 Weight loss as a function of sliding distance during the abrasive wear testing of borosilicate glass with applied load 5 N: (●) dry conditions, (■) ethanol, (○) lubricant oil.

Once again, it is observed that the variation of weight loss is not a linear function of sliding distance under different conditions of sliding contact of the borosilicate glass (Fig. 12). The decrease of wear conditions might be attributed to increasing surface wear resistance [10]. The influence of alcohols on the strength of glass has attracted much attention since the investigations reported by Westwood and Huntington [11], who showed that alcohols increase the indentation hardness and have a pronounced effect on diamond bit drilling rates.

In the same Fig. 12 it is seen that the wear rate of borosilicate glass under wear conditions of lubricant oil dropping is the lowest among the three wear conditions examined. This experimental observation must be due to the highly wear-resistance Zdpp booster which was added to the general lubricant oil.

4. Conclusions

The abrasive wear of borosilicate glass was studied and the main conclusions are given below.

1. During the abrasion of borosilicate glass with wheels contained silicon carbide particles, the weight loss was not found to be a linear function of the sliding distance.
2. The surface roughness of the worn areas of borosilicate glass was observed to decrease with increasing sliding distance for a constant value of applied load.
3. The weight loss of borosilicate glass was noticed to increase exponentially with increasing applied load for a constant value of sliding distance.
4. The wear debris was analysed and founded to consist of glass and silicon carbide particles and agglomerates of glass and silicon carbide particles.
5. The wear rate of borosilicate glass was observed to decrease according to the following sequence of conditions of wear testing: dry conditions, ethanol dropping and lubricant oil dropping during the wear experiments.

References

1. P. BILLINGHURST, C. BROOKS and D. TABOR, "Physical Basics of Yield and Fracture" (London, 1966) Ch. 4.
2. D. GILROY and W. HIRST, *J. Phys. D: Appl. Phys.* **2** (1969) 1784.
3. J. BICKERMANN and E. RIDEAL, *Phil. Mag.* **27** (1959) 687.
4. W. CLAYPOOLE, *Trans. ASME* **65** (194) 317.
5. S. CHEN, T. FARRIS and S. CHANDRASEKAR, *Tribol. Trans.* **34** (1991) 161.
6. T. MULHEARN and L. SAMUELS, *Wear* **5** (1962) 478.
7. A. SEDRIKS and T. MULHEARN, *ibid.* **7** (1964) 451.
8. K. MIYOSI and D. BUCKLEY, *ASLE Trans.* **22** (1979) 245.
9. S. DATE and S. MALKIN, *Wear* **40** (1976) 223.
10. G. CHEREPANOV, "Mechanics of Brittle Fracture" (McGraw-Hill, New York, 1979).
11. A. R. WESTWOOD and R. D. HUNTINGTON, in Proceedings of International Conference on Mechanical Behaviour of Materials (Society for Materials Science, Kyoto, 1972) p. 383.

Received 11 December 1992
and accepted 12 August 1993