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Controlled wet erosive wear of sapphire

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Abstract

Controlled wet erosive wear tests were performed on sapphire specimens. The erosion rates were 5.68 ± 0.67 nm/s, 5.81 ± 0.72 nm/s and 5.85 ± 0.81 nm/s due to impacts produced normal to (0 0 0 1) basal plane and $(1\,\bar{1}\,0\,0)$, $(1\,1\,\bar{2}\,0)$ prismatic planes, respectively. On the contrary to wear due abrasion and sliding, the erosion of sapphire did not depend on the crystal orientation. Scanning electron microscopy (SEM) micrographs of worn areas were analysed. The main erosion mechanism of sapphire appears to be by both plastic deformation and brittle fracture.

Keywords: Erosion; Sapphire; Plastic deformation; Brittle fracture; Al_2O_3

1. Introduction

It is known that sapphire is one of the hardest natural minerals (9 on the Mohs' scale) with excellent chemical stability at high temperature and high wear resistance. The hardness of sapphire is anisotropic[1–6] and depends on the indentation load,[3,6] surface finishing[3] and temperature.[4]

Plastic deformation in sapphire is well known as evidenced by slip (basal and prismatic) and twinning[7–11] at high temperatures. The basal slip system is more common and it is activated at the (0 0 0 1) planes in the $[1\,1\,\bar{2}\,0]$ direction at 900 °C. The prismatic slip system is activated on $(1\,\bar{2}\,1\,0)$ planes in the $[1\,0\,\bar{1}\,0]$ direction at 1800 °C.

Nevertheless, Hockrey[12] has reported the observation of slip on the basal planes at room temperature. By using transmission of electron microscopy (TEM), he observed that high dislocation densities on well defined permanent Vickers hardness impressions were direct evidence of plastic deformation due to slip on the basal planes. Furthermore, other researchers[10–13] have also reported the observation of plastic deformation (both basal and prismatic planes become activated) on worn surfaces of sapphire during sliding wear tests at room temperature.

The wear of sapphire due to sliding on a steel surface[14,16] is strongly dependent on the crystal orientation. The maximum wear rate occurs when the sliding (rubbing) is on the basal plane but is independent of the sliding direction. Whereas when sliding on the prismatic planes wear rate depends on the sliding direction,[14] less wear resistance is found when the sliding direction is normal to the basal planes. Also wear resistance of sapphire due to abrasion depends on crystal orientation.[13,15–17]

Here we present results of wet erosive wear tests performed on surface of sapphire due to normal particle impacts. The crystal planes chosen for this study were (0 0 0 1) basal plane and $(1\,\bar{1}\,0\,0)$, $(1\,1\,\bar{2}\,0)$ prismatic planes. The choice of these planes was based on their importance to deformation and fracture process as previously summarised. The basal plane is one on which dislocation motion and deformation twinning[7–11] occurs and the prismatic planes have been reported to fracture easily.[18]

2. Experimental procedure

2.1. Sample preparation

Specimens were prepared from a 1 in. diameter white sapphire boule grown by the Czochralski process supplied

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by the National Physical Laboratory. Cuboid specimens of 10 mm × 10 mm × 5 mm were cut from this boule using a high-speed diamond saw (CAPCO). Three crystal orientations were chosen: $(0\,0\,0\,1)$ basal plane and $(1\,\bar{1}\,0\,0)$, $(1\,1\,\bar{2}\,0)$ prismatic planes. Specimens were mechanically ground with 14 μm SiC slurry and polished on cloths impregnated with 1 μm diamond paste.

2.2. Wet erosive wear test

Wear tests were carried out by using an erosive wear tester[19] which basically consists of an electric motor, a jet body-sample holder and a slurry pot. The jet body-sample holder is mounted on one end of a arm attached to a shaft connected to the motor. At the other end of the arm, a paddle is attached to mix the slurry. Both the jet body and the paddle rotate in a groove delimited by the pot inner wall and a cylinder in the centre of the pot as shown in Fig. 5.2.1 in Ref. [19]. Tests were performed in a slurry medium of 1.5 kg SiC grit (irregular shape with blunt and sharp edges[19]), with a mean size of ~780 μm and a mean mass of 9.10×10^{-4} g, dispersed in 8 l of water. Particle impacts at ~2.4 m/s were normal to the specimen surface. Tests were performed for several intervals of 1.0 h and the erosion rate, R, was calculated as:

$$R = \frac{\Delta w}{A_{\mathrm{imp}} \Delta t} \tag{1}$$

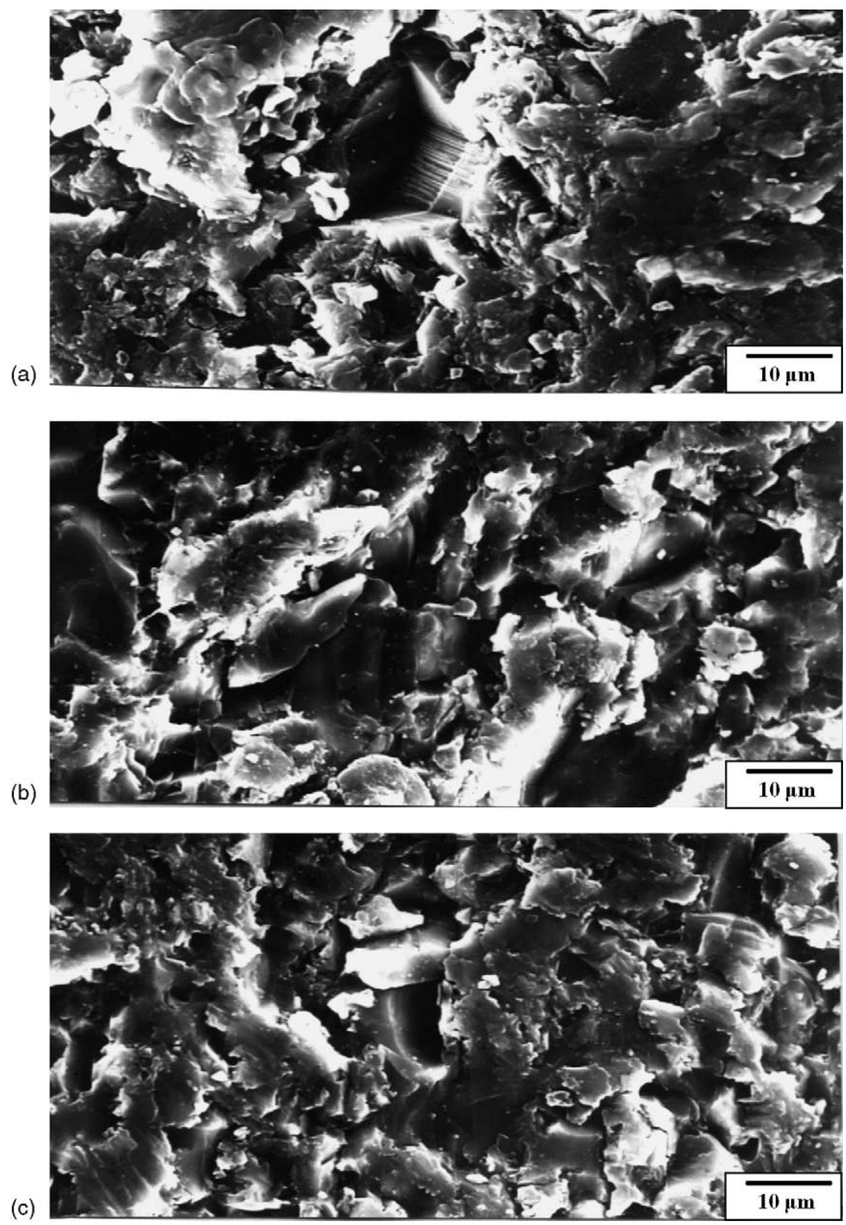

Fig. 1. Typical eroded surface of sapphire due to normal particle impacts. (a) $(0\,0\,0\,1)$ basal plane, (b) $(1\,\bar{1}\,0\,0)$ prismatic plane and (c) $(1\,1\,\bar{2}\,0)$ prismatic plane.

where $\Delta w = w - w_0$. w_0 is the specimen weight before testing (t_0) and w is the specimen weight after testing for a time t. A_{imp} is the impacting area (worn area) and ρ is the specimen density.

3. Experimental results and discussion

Fig. 1 shows SEM micrographs of worn surfaces after 6.0 h of normal particle impacts. Both plastic deformation and brittle fracture are present in the worn areas. The scars on the basal planes (Fig. 1a) are similar to those plastic impression produced by a sharp indenter. Whereas for the prismatic planes (Fig. 1b and c), the scars are similar to those of brittle fracture with looser debris and those produced by a blunt indenter. It can be noticed that looser debris are more present on worn areas of prismatic planes than basal planes. Also the blunt indenter impressions on prismatic planes are much bigger than the sharper indenter impressions on basal planes.

The weight loss versus impacting time due to normal particle impacts for each crystal orientation is shown in Fig. 2. The weight loss increases linearly with impacting time and does not depend on crystal orientation. The presence of both blunt and sharp indenter impressions can be attributed to the shape of the impacting particles. SiC grits used in this study were of irregular shape with blunt and sharp edges.[20]

Table 1 summarises the erosion results of each crystal orientation: mean weight loss, w_{mean} and mean erosion rate, R_{mean}, was calculated using Eq. (1), where $A_{imp} = 2.82 \times 10^{-5}$ m^2 and $\Delta t = 1.0$ h. The particle impacting velocity was ~2.4 m/s and specimen density $\rho = 3.965$ g/cm^3.

On the contrary to wear due to abrasion and sliding,[13–17] the erosion rate of sapphire does not depend on crystal orientation. For instance in sliding wear tests, the basal planes are less resistant, then prismatic planes is attributed to the fact that during sliding on the basal planes very high temperatures are locally produced (at the sliding contact) which activate the basal slip system making this plane less resistant to sliding. In the present erosion tests, these locally high temperatures do not occur because the striking particles have low impacting energy (impacts velocity is up to 2.4 m/s) and erosion tests are performed in a water medium. Furthermore, after several impacts the worn area is being roughened up (Fig. 1), then the particle impacts cease to be normal to any sapphire crystal plane. At larger time wear rate become independent of crystal orientation.

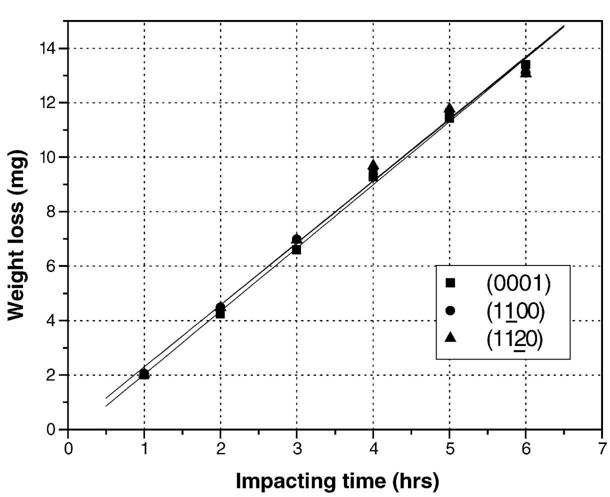

Fig. 2. Weight loss vs. impacting time (normal impacts). The weight loss increases linearly with test duration, and does not depend on crystal orientation.

Table 1
Erosion rate results of sapphire

Impacts normal to planes	Weight loss, w_{mean} (mg)	Wear rate, R_{mean} (nm/s)
(0 0 0 1)	2.28 ± 0.28	5.68 ± 0.67
(1 $\bar{1}$ 0 0)	2.34 ± 0.29	5.81 ± 0.72
(1 1 $\bar{2}$ 0)	2.55 ± 0.30	5.85 ± 0.81

The damages areas produced by single impacts (Fig. 1) are due to both plastic deformation and brittle fracture that does not depend on the hardness of crystal orientation, which is anisotropic.[1–6] Thus, the main erosion mechanism of sapphire appears to be by both plastic deformation and brittle fracture.

On the other hand, wet erosive wear tests of polycrystalline Al_2O_3 was extensively studied by Franco and coworkers[19–21] at the same tests conditions as here. They reported that the erosion rate for specimens of grain size G = 1.2, 3.8 and 14.1 μm was 1.83 ± 0.7 nm/s, 8.36 ± 0.8 nm/s and 11.30 ± 0.6 nm/s, respectively. The erosion results of single crystal Al_2O_3 can be compared to erosion rate of Al_2O_3 with grain size ranging from 1.2 to 3.8 μm. The main wear mechanism of polycrystalline alumina is by linking of crack systems from closely spaced impacts.

4. Conclusions

Controlled wet erosive wear of sapphire were studied. The weight loss due to normal particle impacts on basal and prismatic planes of sapphire increased linearly with impacting time and does not depend on crystal orientation. The erosion rates were 5.68 ± 0.67 nm/s, 5.81 ± 0.72 nm/s and 5.85 ± 0.81 nm/s due to impacts produced normal to (0 0 0 1) basal plane and (1 $\bar{1}$ 0 0), (1 1 $\bar{2}$ 0) prismatic planes, respectively, also does not depend on the hardness of crystal orientation. On the contrary to wear due abrasion and sliding, the erosion of sapphire did not depend on the crystal orientation. The main erosion mechanism of sapphire appears to be by both plastic deformation and brittle fracture.

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