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Surface Damage Accumulation in Alumina under the Repeated Normal-Tangential Contact Forces

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Abstract : Surface damage accumulation of alumina ceramics under the cyclic stress state was analyzed. The alternating stress state in repeat pass sliding contact was simulated by a synchronized biaxial (normal and tangential) repeated indentation technique. Wear debris formation mechanism through damage accumulation and fatigue grain failure in both alumina ceramic balls and flat disks was confirmed, and the contact induced surface degradation due to fatigue cracking accumulation was quantified by measuring vertical contact displacement. Variation of structural compliance (slope of load-displacement curve) of two contacting bodies was expressed as a variation of the apparent elastic property, called pseudo-elastic constant, of the contact system.

Key words : alumina, surface damage accumulation, fatigue wear

Introduction

Early studies on the wear of ceramic materials classified the wear mechanisms in terms of conventional phenomenological expressions: abrasive, adhesive, erosive, and corrosive wear, etc. In recent times, more fundamental modes: brittle fracture, plastic deformation, and fatigue, have been suggested. When two ceramic surfaces are brought into sliding contact, they inflict mutual damage on each other, resulting in loss of material. This material removal essentially involves the fracture process where the crack nucleation and propagation depend on the loading history and environment.

Although it has always been generally believed that ceramics materials are not susceptible to fatigue degradation under cyclic stress state since they have limited crack-tip plasticity, there exist conventional tension/compression fatigue data indicating that fatigue effect may be possible in wear process in alumina ceramics [1,2]. Lathabai *et al.* [3] and Cho *et al.* [4] showed the effect of microstructure, especially, grain size on the fatigue cracking and wear of alumina. And also Ajayi *et al.* [5] suggested that surface fatigue may be responsible for the micro-damage wear mechanism having an incubation period; after this period wear rate increased.

It is clear that any point below the sliding track experiences a cyclic stress history as the contact region moves along the surface repeatedly. The fatigue can occur under the repeating combined shear-compressive and shear-tensile stresses. These cyclic stresses will induce the surface damage accumulation time-dependently.

Recently, a simple technique based on repeated indentation with a sharp indenter has been proposed as a method for studying cyclic fatigue effects in ceramics [6]. Lu *et al.* [7] conducted indentations with a sphere to analyze the damage induced by cyclic tangential loading of contacting elastic bodies. Guiberteau *et al.* [8] tested the indentation fatigue with a simple Hertzian contact producing the cumulative mechanical damage on ceramic surfaces. Lee *et al.* [9] developed the synchronized biaxial repeated indentation technique and confirmed the fatigue wear mode of alumina consisting of three different wear stage, i.e. asperity-scale fragmentation, loosening of grain at the crack opening edge, and grain break-out by bridging of the series cracks formed at the trailing edge of contact.

In this work, the surface damage accumulation in alumina ceramic through fatigue cracking under cyclic stress states was analyzed by synchronized alternating normal and tangential contact loading, and this surface degradation was also quantified by measuring contact displacement.

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Method

Specimen

Alumina-based ceramic cutting tool inserts (84% alumina, 12% zirconia, and 3% titanium diboride, $12.7 \times 12.7 \times 47.5$ mm, GTE Valenite Crop.) were used for the flat specimens and 99.5% alumina oxide (diameter of 6.35 mm, Industrial Tectonics Inc.) were used for the ball specimens. Some mechanical properties of ball and flat specimens are listed in Table 1.

The surface of the flat specimens were ground by SiC disc papers and then polished with diamond paste. The measured arithmetic average roughness heights, Ra, of flat specimens are 0.05 μm. The ball specimens were used as-received; the

Table 1. Material properties of the ball and flat specimens.

Material Properties	Ball	Flat
Young's Modules (GPa)	370	400
Poisson's Ratio	0.23	0.24
Vickers Hardness (Kg/mm^2)	1400	1800
Fracture Toughness (MN/m$^{3/2}$)	3.2	3.0
Density (g/cm^3)	3.86	4.2
Grain Size (m)	7.0±4.0	2.0±1.0

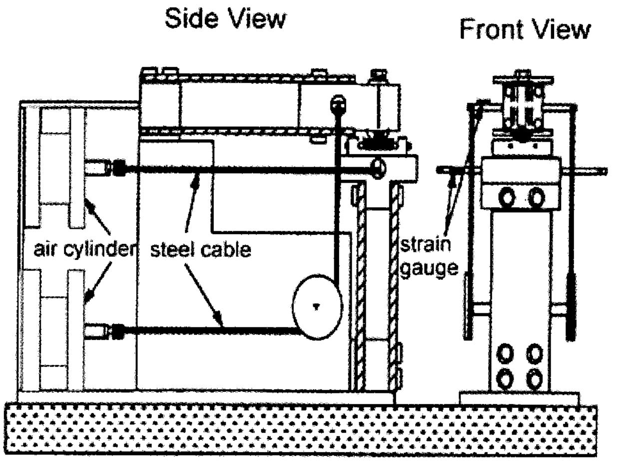


Fig. 1. Schematic diagram of the Cyclic Fatigue Indentation Device.

manufacturer quotes the roughness of the balls as 0.04 μm.

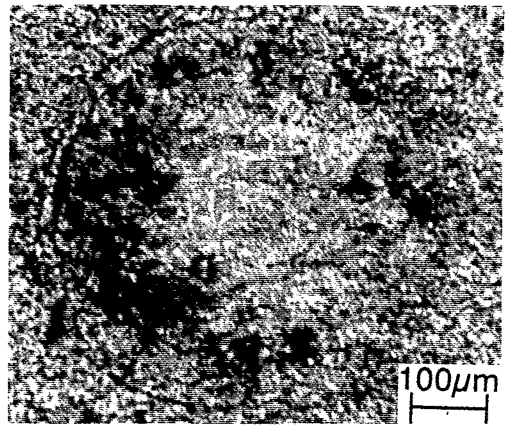
Device

Synchronized biaxial repeated indentations were performed using the newly designed machine, named Cyclic Fatigue Indentation Device [9]. Fig. 1 shows a schematic diagram of this test machine. The normal and tangential loads were applied by two air cylinders, respectively.

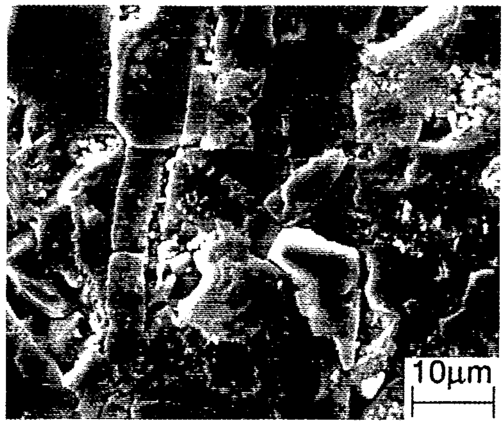
The load amplitudes were measured with strain gages attached on the loading bars. The working pressure of the air cylinder was regulated by an electro-pneumatic pressure servo-valve whose electric input was generated in an isosceles waveform by a computer. A MicroProx proximity probe was mounted on a ball holder and placed at a right angle against the top surface of the flat specimen holder so as to measure contact displacement. Indentation load data and contact displacement data were stored with a multi-channel scan data acquisition program in a computer during the tests.

Test protocol

Four peak normal contact loads, 480 N, 530 N, 590 N, 730 N, were applied. The highest load was set to a critical load for cone crack formation in a fully elastic brittle fracture theory by a single normal indentation [10]. Four peak tangential loads were synchronously applied for each normal load with load ratios ($L = P_t/P_n$) of 0.0, 0.05, 0.14, and 0.23. The tangential force was limited far below the static coefficient of friction



(a) flatl specimen



(b) ball specimen

Fig. 2. Optical and SEM photos showing the contact damage of micro-scale debris and macro-scale cracks with 730 N and L = 0.23 after 960 indentation cycles on the (a) flat and (b) ball specimens.

value of 0.5.

All tests were conducted in air using a frequency of 0.04 Hz. The number of cycles ranged up to 960 cycles. These test conditions were determined from preliminary tests to produce definitive surface damage. After tests, the contact surface damage was examined with optical and scanning electron microscopes.

Results

In repeated indentation tests, two kinds of surface damage were observed. At first, under the low load combination the material removal in micro-scale of grain size level or less was observed within the contact area without visible macro-cracks. As the applied loads increases, the area covered with debris spreads over the contact region.

Under the high contact stress, macro-scale (ring/horse shoe) cracks were also seen near the contact edge. An additional horizontal traction remarkably increases the amount of debris (Fig. 2.a) and develops the closely spaced macro-scale horseshoe cracks at the trailing edges of contact surface (Fig. 2.b). These damage accumulated through fatigue as the

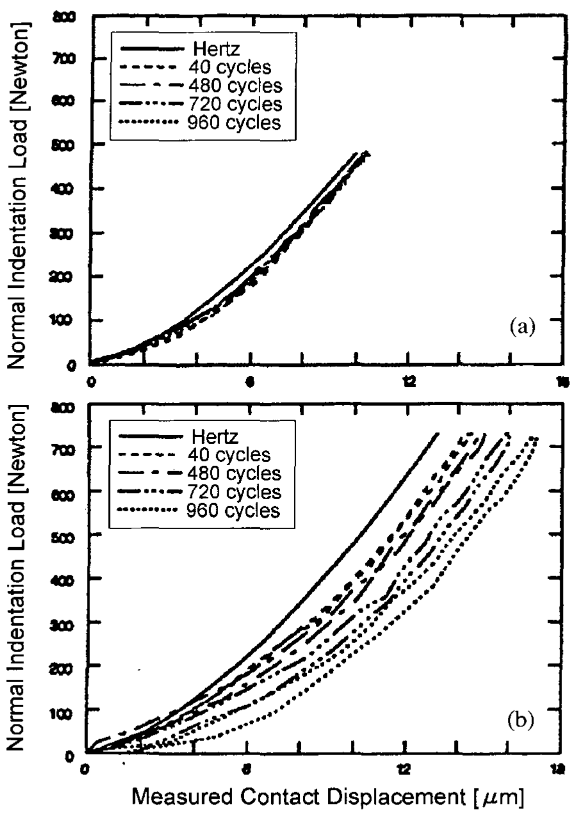


Fig. 3. Variation of hysteresis loops with (a) 480 N and (b) 730 N and L = 0.23.

number of indentation increased.

Surface degradation due to contact damage accumulation was detected by the change of slope in contact load-displacement curves (hysteresis loops). Figure 3 shows the changes of loading and unloading curves at each specific number of cycles.

Under a low normal indentation load of 480 N (Fig. 3.a), there was little change in each hysteresis loops which is very close to a theoretical elastic Hertzian contact curve. After the macro-crack formed under the given load combination, the slope down of hysteresis loop became large as the number of indentation increased.

Under the severe load combination of 730 N and L = 0.23, broadening of loop between the loading and unloading paths as well as a very large decrease in slope occurred (Fig. 3.b). This phenomenon was accompanied by a series of macro-cracks and large micro-scale wear debris pile-up (Fig. 2).

Discussions

The decreases in the slopes of hysteresis loops due to the increasing number of repeated indentations are caused by the increases of contact displacement, which involve the macro-scale cracking and surface damage accumulation in two contacting bodies. A noticeable increase of contact displacement with increasing load ratio (coefficient of friction) is interpreted by the formation of a series of macro-cracks. The

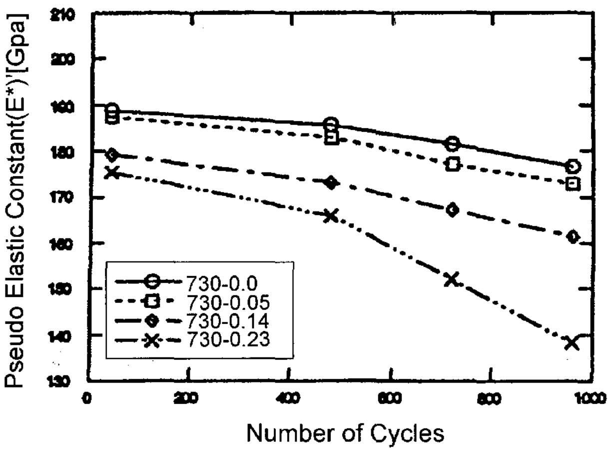


Fig. 4. Changes of pseudo-elastic constant of two contacting bodies under 730 N and each load ratio.

addition of horizontal traction increases the crack driving force with increased tensile stresses near the trailing edge, promotes the crack formation, and makes the hysteresis loop decline. The gap between loading and unloading paths may arise from the additional fracture during the unloading process. The possible mechanism of crack growth during unloading is a crack tip opening with wedge action of existing particles on the crack faces under reverse loading [2].

As the first step for quantifying the degree of surface damage accumulation, a trial is made to correlate the variation of measured contact displacement with the change of apparent elastic constant. Provided all assumptions of Hertzian contact are retained on each cycle, apparent radius of curvature, R, is fixed (R_1 and R_2 are radii of curvature of each contact body) and applied load, P, is known. Therefore, the variation of measured contact displacement, δ, enables to estimate the change in apparent elastic constant E* of two contact bodies according to the surface damage accumulation under the repeated indentations. It can be expressed in the following simple formula from Hertzian theory [11].

$$E^* = \left(\frac{9}{16R}\frac{P^2}{\delta^3}\right)^{1/2}$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

But, because contact failure may occur within a localized thin layer, and because the decrease of stiffness is not a change of bulk elastic property, the apparent elastic constant calculated from above equation will be called the "pseudo-elastic constant," (E*)'.

The variations of pseudo-elastic constant, (E*)', to the number of indentation cycles at a peak load of 730N with each load ratio are plotted in Fig. 4.

Test methodology used in this research could be used to indicate the structural integrity of ceramic surfaces.

Conclusion

Under the synchronized repeated normal and tangential forces the actual wear of alumina ceramics occurs in a fatigue mode by grain failure and macro-cracking at the contact interface. Fatigue wear mode was confirmed by the increase of material removal rate as the number of cycles increases in connection with increase of load ratio.

Surface damage accumulation via fatigue failure under the synchronized repeated normal and tangential forces was quantified by the decrease of slope in the hysteresis loops. This stiffness change is expressed as a variation of the apparent elastic properties of the contacting bodies within a localized thin contact layer.

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