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# EROSION AND STRENGTH DEGRADATION OF AN ELASTIC MODULUS GRADED ALUMINA-GLASS COMPOSITE

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## ABSTRACT

Previous research has shown that Hertzian cone cracking is suppressed in ceramic composites whose elastic modulus increases with depth below the surface. The objective of this research was to determine if these modulus-graded composites would also exhibit superior resistance to particle impact damage. Therefore, impact damage with sharp and blunt particles was studied in monolithic and modulus-graded glassy alumina. The composite was fabricated by impregnating a dense, fine-grained alumina with an aluminosilicate glass having a lower elastic modulus than the alumina. This produced a functionally gradient composite with decreasing glass content below the surface, thus causing the elastic modulus to monotonically increase with depth. The aluminosilicate glass had a coefficient of thermal expansion and Poisson ratio the same as the alumina. Therefore, the composite had no macroscopic, long-range residual stresses.

The sharp multi-particle impact (erosion) experiments were conducted with a slinger type apparatus. The blunt single impact experiments were conducted with small stainless steel balls using a particle accelerator gas-gun. In the case of the sharp particle impact experiments, erosive wear and strength degradation was measured as a function of depth below the surface. For the single impact experiments, the onset of ring cracking was determined and compared to that for monolithic alumina. These experiments were designed to give an insight into the effect of the alumina-glass microstructure and the corresponding elastic modulus gradient on the particle impact damage resistance of this composite.

It was found that the modulus-graded alumina exhibited the same erosive wear, post erosion strength, and ring crack formation, as did the monolithic alumina.

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## INTRODUCTION

Ceramic components are frequently subjected to contact loads that can cause surface cracking and consequential degradation of performance, reliability and lifetime. Attempts to increase contact damage resistance include introduction of a compressive residual surface stress by coatings, layering materials with different thermal expansion coefficients[1], novel hot pressing techniques[2], among others. There are also techniques that use microstructural engineering to provide increased toughness at the surface.[3,4] Recently a new concept has been proposed to render ceramics more contact damage resistant.[5] This novel technique uses monotonically increasing elastic modulus gradation from the surface into the bulk to significantly increase the cracking threshold load by altering the stress field beneath a blunt indenter. Such modulus-graded specimens have been prepared by infiltrating alumino-silicate glass into alumina substrates. Time and temperature controlled the gradient and depth of infiltration. As the volume fraction of the lower elastic modulus glass decreased from the surface to the bulk, so did the effective elastic modulus. The specimens were used to show that modulus gradation suppresses Hertzian crack formation as compared to both the bulk glass and the alumina substrate.

Ceramic components may also encounter impact loading by sharp and blunt particles. The transient stress field generated by such impacts is likely to be different than under quasi-static loading. It is not clear if modulus gradation provides a similar increase in damage resistance under impact loading as it does in Hertzian contact. Therefore, the objective of the research presented in this paper was to evaluate the performance of elastic modulus graded alumina specimens under multiple sharp-particle impact condition (erosion) and impact by a small steel sphere. In the erosion study material removal as a function of depth and the corresponding strength changes were evaluated. In the single impact study the ring crack formation threshold was measured.

## EXPERIMENTAL PROCEDURE

Aluminosilicate glass* infiltrated fine-grained (3-5 μm) alumina** discs (25 mm diameter x 4.2 mm thick) were prepared in accordance with the processing procedure outlined in Ref. 5. Namely, an alumina disc with a piece of glass (14 mm square x 4 mm thick) placed on it was heated for two hours at 1690$^0$C. A schematic of the fabrication procedure is shown in Fig. 1. The treatment resulted in a monotonically decreasing volume fraction of glass starting with 0.4 at the surface and ending up zero at 2 mm below the surface. The corresponding modulus gradient was estimated on the basis of rule-of-mixtures with glass having a modulus of 72 GPa and the alumina 386 GPa. The resulting modulus gradient is

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* Code 0317, Corning Inc., Corning, NY.

** Greenleaf Technical Ceramics, East Flat Rock, NC.

shown on Fig. 2. The figure shows that the measured elastic modulus varies from approximately 250 GPa at the surface monotonically approaching 380 GPa at 2 mm below the surface. The solid line in the figure represents best fit to the data.

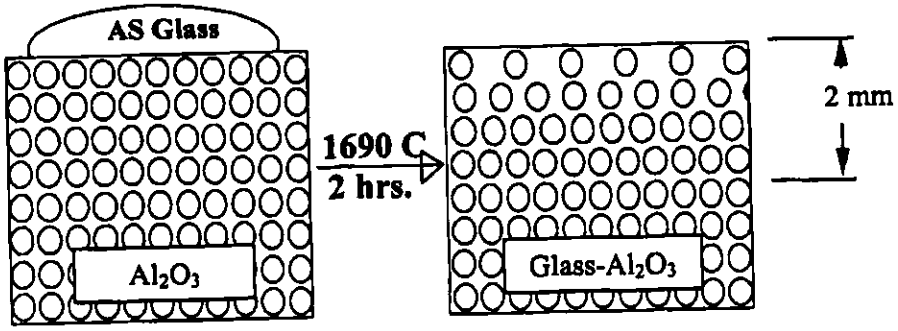

Figure 1. Schematic of the glass infiltrated alumina specimen processing.

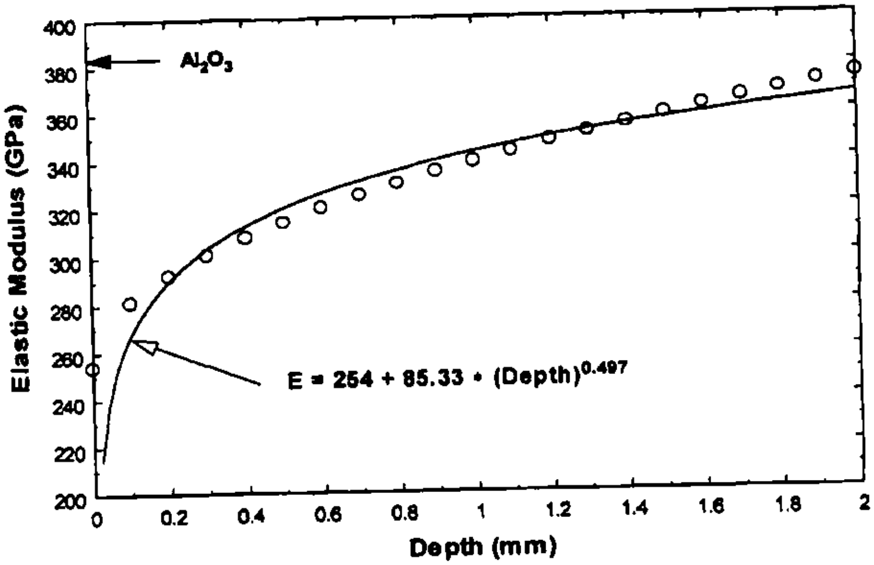

Figure 2. Elastic modulus variation in a glass infiltrated alumina specimen.

The erosion experiments were conducted in a slinger-type apparatus[6] where SiC abrasive grit was ejected from a rotating tube against target specimens. There were two grit sizes used with two different ejection velocities. Namely 46 grit (540 μm avg. dia.) with 53 m/s that resulted in an impact kinetic energy of

$2.8 \times 10^{-4}$J, and 16 grit (1,900 µm avg. dia.) with 79.5 m/s yielding $266 \times 10^{-4}$J of kinetic energy. Erosion testing entailed impacting the specimens with a given amount of grit, measuring the specimen's change in weight and dimensions, and repeating the process until no change was observed in the erosion rate. The biaxial strength of a number of specimens after the initial erosion cycle as well as after prolonged erosion were tested in a ring-on-ring apparatus.

The single impact experiments were conducted using a particle accelerator gas-gun. Small steel spheres (2 mm dia.) were accelerated with high pressure nitrogen gas against perpendicularly positioned target specimens. The velocity of the projectiles, hence their kinetic energy, was measured for each test using a time-of-flight device. The tests entailed impacting the target with increasingly greater kinetic energy until ring cracks were observed by microscopic examination.

## RESULTS AND DISCUSSION

Figure 3 shows the erosion rate of the modulus-graded alumina as a function of depth of erosion using the smaller of the abrasive particles (46 grit) at $2.8 \times 10^{-4}$J kinetic energy. The figure shows two sets of data. The group of data for less than 0.15 mm depth represent tests on specimens that were ground only to remove the residual processing glass from the surface. For data between 0.3 and 0.4 mm depth the specimens were ground to 0.3 mm depth before the erosion tests began.

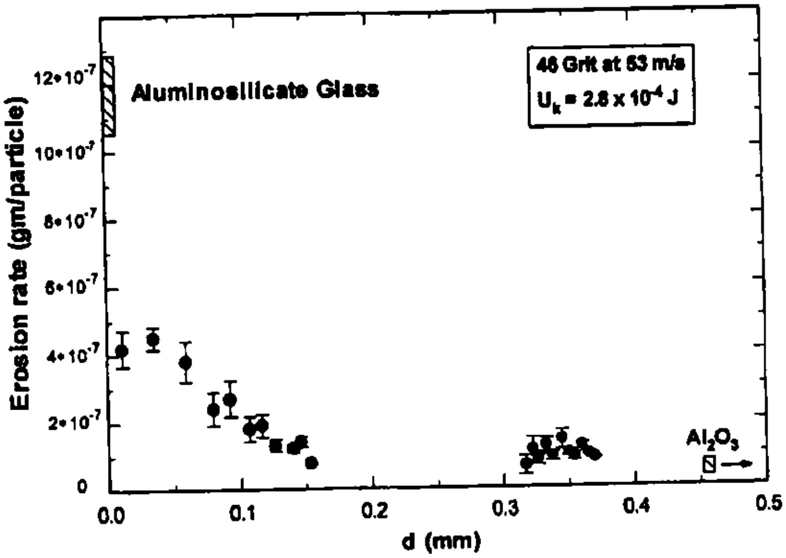

Figure 3. Erosion behavior of modulus-graded alumina using 46 grit particles.

This was done to determine the influence of the initial grinding procedure on the erosion rate. The figure also shows the erosion rate of aluminosilicate glass and the alumina substrate. It can be seen that the erosion rate asymptotes to that of alumina in less than 10% of the depth of the modulus gradation (2 mm). It could be surmised that the erosion rate of the modulus-graded alumina is essentially the same as monolithic alumina irrespective of the depth of erosion since the initial higher rates seen on the figure were attributed to the removal of residual process glass at the periphery of the specimens.

The erosion rate behavior with the larger abrasive particles (16 grit) is shown on Fig. 4. The figure includes two sets of data corresponding to the same initial grinding conditions as in Fig. 3. The trend in erosion behavior with this larger grit and higher kinetic energy is the same as with the smaller grit, although the overall erosion rate is more than an order of magnitude higher, as expected. Once again, the erosion rate of the modulus-graded material is approximately the same as that of the alumina substrate irrespective of the depth of erosion. The higher rates for depths less than 0.05 mm was once again attributed to the removal of residual processing glass.

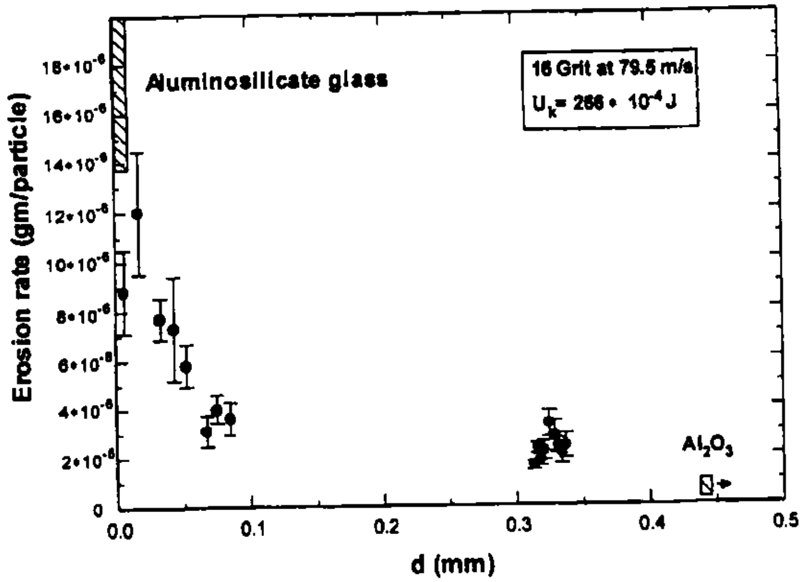

Figure 4. Erosion behavior of modulus-graded alumina using 16 grit particles.

The residual strength of the eroded modulus-graded alumina specimens is shown on Fig. 5. The figure shows data for two different kinetic energies corresponding to the two different grits used for the tests. It can be seen that the post erosion strength of modulus-graded alumina does not vary (within experimental scatter) with the depth of erosion. However, erosion does lower the strength with increasing particle kinetic energy, as expected.

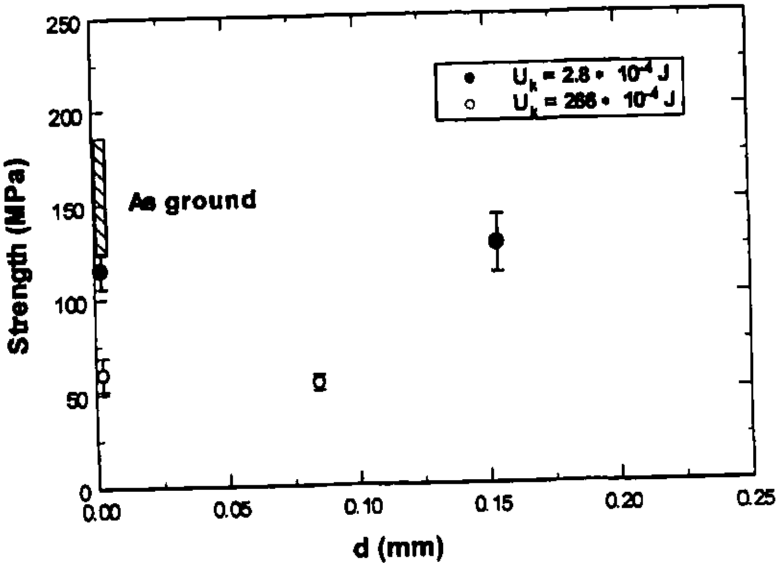

Figure 5. Post erosion strength of modulus-graded alumina.

Single impact with a spherical projectile results in classical Hertzian crack morphology[7]. Namely, ring cracks appear on the surface that extend into cone cracks below the surface. Figure 6 shows a micrograph of typical ring cracks in monolithic alumina. This is an optical micrograph with illumination from the backside of the specimen.

The results of the single impact tests are shown in Fig. 7. In the figure Hertzian ring crack diameter is plotted as a function of impacting kinetic energy for the monolithic and the modulus-graded alumina specimens. It can be seen that ring cracks

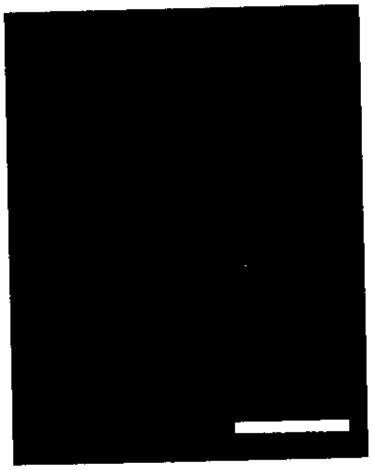

Figure 6. Typical ring cracks in monolithic alumina. (Scale 200 μm)

form at approximately 0.001 J of kinetic energy (~25 m/s with 2 mm steel sphere) in both of the materials. Once this ring crack threshold is exceeded, the diameter of the ring cracks does not seem to depend strongly on kinetic energy.

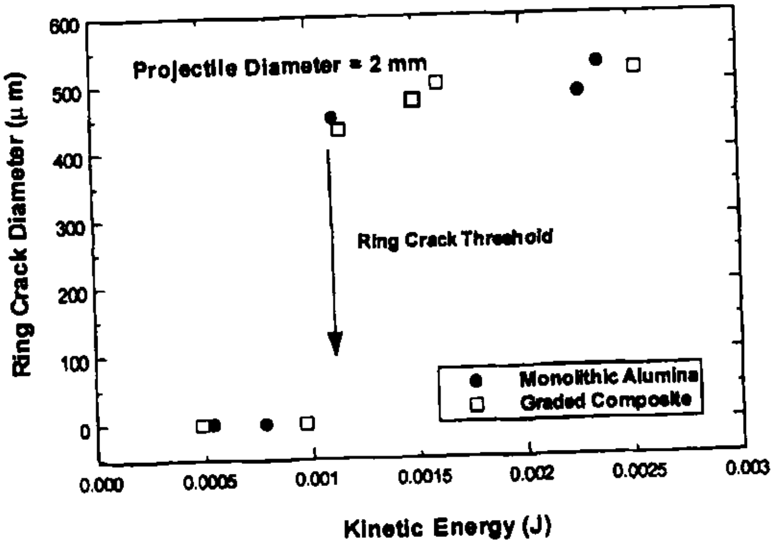

Figure 7. Hertzian ring crack formation in modulus-graded and monolithic alumina.

## CONCLUSIONS

Elastic modulus gradation in alumina has been shown to suppress the tendency for Hertzian crack formation under quasi-static indentation loads. This occurs because the modulus gradient alters the stress field beneath the spherical indenter such a way that the magnitude of the tensile stress in the vicinity of the contact ring is reduced. For the modulus gradient to have this beneficial effect its scale needs to be on the order of the scale of the Hertzian stress field, that is the diameter of the contact radius needs to be comparable to the depth of the gradation. In the single impact tests performed in this study this condition may not have been satisfied since the contact radius as indicated by the ring cracks were in the order one fourth of the depth of the gradation. The relatively small contact radius might explain why the ring crack formation threshold was found to be the same for the monolithic and the modulus-graded alumina specimens.

Although the scale of the stress field produced by the impact of the abrasive particles during erosion is believed to be smaller than the depth of modulus gradation, there seems to be another reason why the varying modulus did not affect the erosive wear. Upon infiltration the glass was not distributed homogeneously throughout the alumina material. Instead, it tended to form glass pockets at triple junctions and left relatively large interconnected alumina regions intact. Initially, the impacting particles dislodged the glass from the pockets that were situated near the surface. After this initial phase, the particles encountered only the hard alumina regions. Consequently, the material removal rate was close to that of the substrate irrespective of the glass in the pockets. This argument leads one to believe that erosion is primarily controlled by toughness instead of elastic modulus, hence modulus gradation is not likely to yield substantial benefits against erosive wear. The positive aspect of the results is that modulus gradation did not make the material erode faster than the substrate.

## ACKNOWLEDGEMENT

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