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Effect of Machining Damage on the Strength of a Glass-Ceramic

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A study has been made of the strength characteristics of machined glass-ceramic surfaces using an indentation flaw technique. The strength is found to decline or increase with progressive removal of the machining damage layer by a polishing procedure, depending on whether the indentation is made after or before the polishing. The results are interpreted in terms of a residual compressive stress in the initial machined surface. It is argued that failure to allow for the contribution of this stress in the fracture mechanics description of flaw growth could lead to significant errors in the evaluation of crack propagation parameters.

IN the course of a strength-testing program on a commercial glass-ceramic,* a surface-damage effect of significant proportions has become evident. Using a controlled indentation technique to introduce dominant flaws into flexure specimens, it was found that the strengths for as-machined surfaces were considerably higher, by ≈50%, than those for as-polished surfaces. An effect of this magnitude could have important repercussions in any prospective study of fracture and fatigue properties of ceramics, for it implies that the mechanics of flaw evolution are sensitive to the mechanical state of the surface. It was accordingly decided to run a simple series of strength tests to investigate this effect in a systematic manner.

Test pieces were prepared in bar form, 32 by 6 by 4 mm. A 400-mesh diamond-grit wheel was used to produce a uniformly machined surface on all the bars, to be taken as an "initial reference state". To eliminate portions of the machining damage layer thus incurred, subsequent removal of prescribed depths of material was effected by "polishing" with 1000-mesh SiC particles in a water slurry. The amount of material removed in each case was determined by simple before-and-after measurements of the specimen thickness, to a nominal accuracy of ±5 μm. A selected few specimens were polished in this way to a depth well in excess of that needed to remove the original machining damage (≫100 μm), and then given a further polish with 1 μm diamond paste to produce a mirror-smooth finish; these surfaces were to represent a "final reference state".

A standard Vickers diamond pyramid indenter was used to introduce a well-defined radial crack into each bar.[1] In most cases the indentation was made after completion of the polishing operation described above; however, some specimens were indented *prior to* the polishing. A peak load of 20 N was used for all the tests, chosen so that the radial cracks be small enough to experience the full influence of the machining damage layer without being dominated by the machining flaws themselves.[2] The indented bars were then broken in 4-point bending, with the indentation site centered on the tension side, at a stress rate of 2.5 $GPa \cdot s^{-1}$. At this rate the atmospheric test environment could be regarded as effectively "inert".[3]

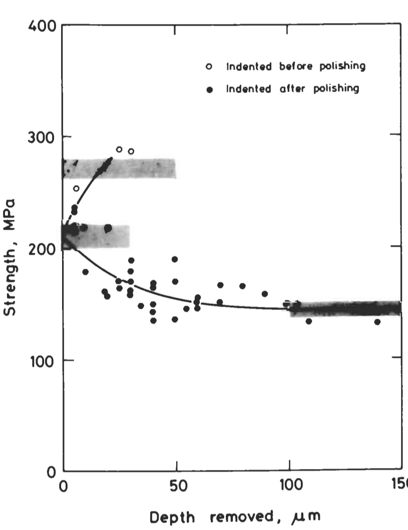

Fig. 1. Strength variation of machined commercial glass-ceramic surfaces containing indentation cracks at 20 N load as a function of depth of material removed.

The results of the strength tests are plotted in Fig. 1. Open and filled symbols distinguish between specimens indented *before* and *after* the polishing. All of these individual points represent failures from indentation sites. The solid lines are empirical fits to the data. Shaded bands indicate standard deviation limits for designated reference states: the central band represents the "initial" state (14 as-machined, indented specimens); the lower band represents the "final" state (14 as-polished, indented specimens); the upper band represents the strength level corresponding to failure from "natural" flaws (3 nonindented, as-machined specimens; 5 nonindented specimens, polish depth < 50 μm; 2 indented specimens, polish depth < 50 μm, which broke away from indentation site). The considerable scatter shown in the strength data is believed to reflect more on the effect of local microstructural variations on crack propagation[4,5] than on measurement errors. Notwithstanding this scatter, there are clear trends in the results which can be used in diagnosis of the nature of the machining damage layer.

The most direct evidence to this end comes from the filled-symbol data in Fig. 1. The systematic decrease in strength

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from 212±12 MPa to 145±7 MPa over a removal depth of ≈100 μm can only be explained in terms of a diminishing crack-closure force; that is, there must be a residual compressive stress associated with the initial, machined surface. The difference between the two strength levels, 67 MPa, is accordingly a measure of the effective compressive stress averaged over the crack plane, for 20 N indentations; at this indentation load the crack depth is ≈60 μm,[6] so the compression zone would appear to encompass the entire crack, although it is unlikely that the stress itself will be uniformly distributed over this depth.

In view of this interpretation, the rapid rise in strength indicated by the open-symbol data is instructive. It means that the polishing process must now be removing a vital portion of the radial crack system controlling the initial strength at a rate (per unit depth) significantly greater than that of the machining damage layer. Although the data presented here are limited, the designated upward trend is well substantiated by similar, more extensive studies on several other ceramics.[7-9] The strengthening effect is attributed to progressive removal of the local deformation zone about the immediate contact site, which acts as a source of intense residual *tensile* stress on the attendant cracks.[7-9] (Of course, the polishing must also reduce the crack size, but this is generally of secondary importance in the strengthening.)[9,10] After removal of ≈30 μm of material, the severity of the radial cracks is reduced to below that of the natural flaws.

The evidence presented above may be used to build a consistent picture of the machining damage mechanism. It is now well established that a single, point indentation gives rise to a radially outward compressive field, to accommodate the volume of the hardness impression.[11] The radial cracks formed by such indentations lie on median planes containing the load axis, and so derive their residual driving force from the tangential component of the field. Then, insofar as machining damage may be regarded as the cumulative manifestation of a vast number of related "indentation events", such that neighboring residual-contact fields show a high degree of overlap, it can be argued that the net force exerted on any individual median plane by the damage layer as a whole must be compressive.[12] In the present experiments, the divergence of the two sets of data points (Fig. 1) shows that the local opening force on the radial crack system exerted by the immediate indentation deformation zone outweighs the integrated closure force exerted by the surrounding surface damage.

It is interesting to contemplate the possibility that machining damage might offer an avenue of surface strengthening in ceramics fabrication. Comparison of our "initial" and "final" reference states in Fig. 1 would certainly seem to indicate that the glass-ceramic is less immune to strength degradation from post-preparation contact events when its surfaces are prepared with a relatively smooth finish. On the other hand, the presence of a surface compression layer must inevitably lead to a greater complexity in flaw response; it has already been suggested that the magnitude of the compressive stress will generally tend to some depth variation over the crack plane, and accommodation of such variation into an appropriate stress intensity factor formulation involves a highly detailed fracture mechanics analysis.[13] For this reason it is concluded that any attempt to evaluate material crack propagation parameters using surface flaws should make due allowance for this factor, preferably by removing the damage layer altogether.

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