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Cone cracks around Vickers indentations in fused silica glass

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Surface and subsurface deformation and cracking around Vickers identations in fused silica have been studied. The indentations were sectioned by making the Vickers indents on and near the tip of a pre-existing crack. The characteristic median and lateral cracks around the impression and shallow cracks within the surface of the indentation were observed on the specimen surface. The subsurface deformation showed compacted or densified zones, devoid of any flow line rosettes. The dominant cracks, similar to the Hertzian cone cracks observed around purely elastic spherical indentations, occurred outside the compacted zones. These cone cracks make angles of 30 to 40° with the specimen surface. Multiple cone cracks with shallower angles often formed outside the major cone cracks. It has been suggested that the expansion of the boundary of the compacted zone as the indenter load is increased can cause median cracks during loading while the mismatch of strain at this boundary may give rise to lateral cracks during unloading.

1. Introduction

The fracture mechanics analysis of the median crack, one of the crack systems that form around Vickers indentations, provides a method of characterizing the fracture toughness and the state of surface stress of brittle material (see [1–8]). The increasing use of this technique requires a proper understanding of the origins of the median cracks and the other system of cracks (radial and lateral cracks) that form around pyramidal indentations. Underlying such studies is the relevance of the median and radial cracks to the strength degradation and the lateral cracks to the erosion and wear of brittle materials in most contact situations.

Attempts have been made to investigate the problem of nucleation of the median, radial and lateral cracks around pyramidal indentations. Lawn and Evans [9] have analysed the fracture mechanics of the initiation of the median crack from "fortuitous" flaws at the expanding elastic–plastic boundary. More recently, Hagan and Swain [10] have examine in detail the cracking and deformation beneath Vickers indentations in soda-lime glass. The general features of the surface and subsurface cracking and deformation are illustrated in Fig. 1 which shows the damage around a 50 N load indentation. The surface damage shows the characteristic median crack pp, from the corners of the indentation and the cracks, cz, within the surface of the indent itself (as in Fig. 1a). The subsurface damage consists of the deformed zone, dz, and traces of the median and lateral cracks in the bulk. The deformed zone is made up of a series of intersecting shear flow lines, characteristic of materials undergoing radial flow [11]. These shear lines are clearer in the subsurface view of another 50 N load indentation illustrated in Fig. 1d to f. Some of these flow lines aa, bb, and cc, in Fig. 1c and e appear to degenerate into lateral cracks outside the deformed zone. These cracks are initiated during loading as shear cracks along the flow lines and are propagated by the unloading residual stresses. The dominant lateral cracks, lc in Fig. 1b, from the bottom of the deformed zone are also produced by the unloading stresses. Only one median crack is observed in Fig. 1b and it appears at the point t of two interacting flow lines. This inter-

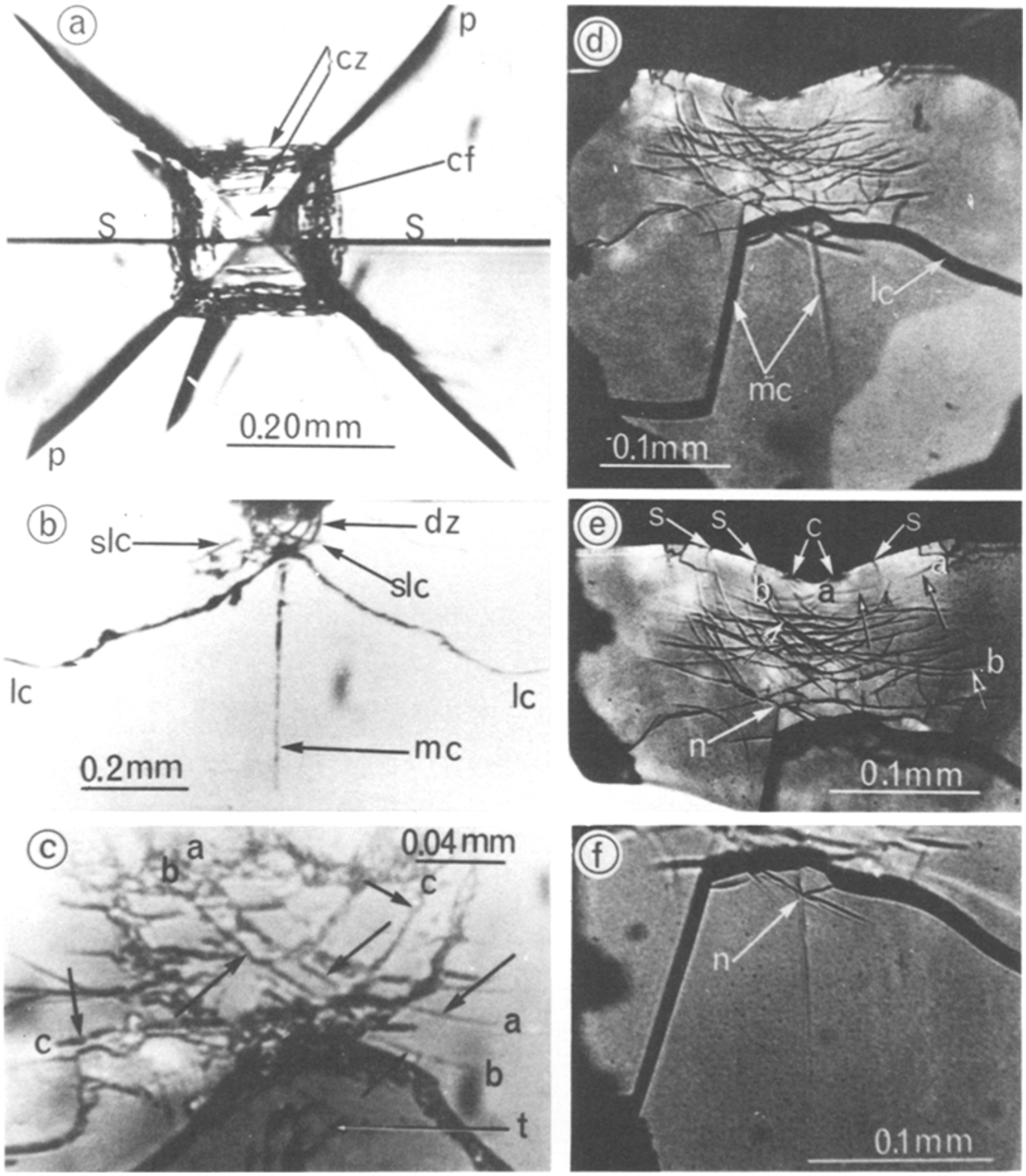

Figure 1 The surface and subsurface damage of 50 N Vickers indentations in soda-lime glass. The subsurface deformed zone consists of a network of shear lines aa, bb and cc as in (c) – the point t marks the start of median crack. (d), (e) and (f) show the subsurface fractures of another 50 N indentation.

section is clearer in regions n of Fig. 1e and f which show two well-developed median cracks. The formation of the median crack is similar in many respects to crack nucleation by the pile up of dislocations on two intersecting slip planes. Some of the surface cracks, cz, within the surface of the indentation, coincide with points of intersection s of the flow lines with the specimen surface, as in Fig. 1e; they are probably produced by the elastic contact stresses at the specimen indenter surface during loading. It is tempting to attribute the origins of the median and lateral cracks in different materials to the inhomogeneous nature of the subsurface deformation irrespective of the response of the material to the indenter constraints. This paper, however, illustrates the

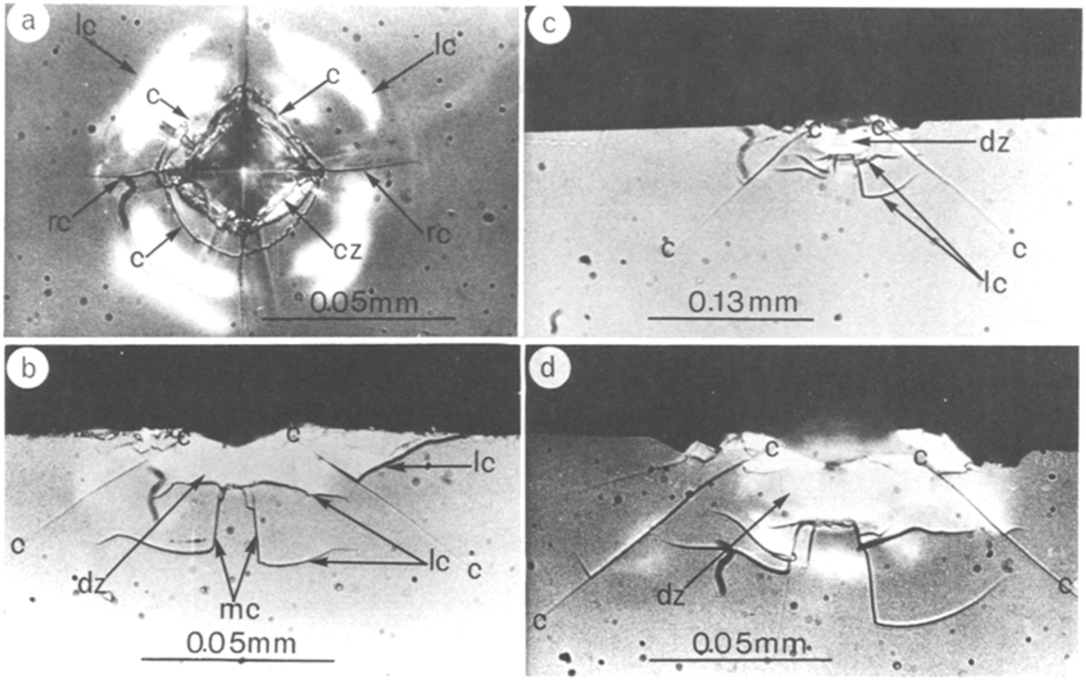

Figure 2 Surface (a) and sub-surface damage (b) to (d) around Vickers indentations in fused silica. The characteristic radial (median), lateral and ring cracks are marked rc, lc and c in (a). The subsurface of different Vickers indentations show the compacted zones, dz, and traces of median lateral and cone cracks in the bulk.

differences that can arise in fused silica glass compared with those in soda-lime glass.

2. Experimental

A heavy duty Vickers hardness tester was used to make indentations in thin plates of fused silica (typical dimensions 50 mm × 20 mm × 1 mm). The indentations were sectioned to allow a study of the subsurface deformation by making the indentations on and near the tip of a pre-existing crack. Details of the sectioning technique have been given elsewhere by Peter [12, 13] and Hagan and Swain [10].

3. Results

Details of the surface and subsurface deformation around 2 N load Vickers indentations in fused silica are illustrated in Fig. 2a. The surface damage, consisting of median and lateral cracks (rc and lc respectively) and cracks, cz, within the surface of the indentation, are similar to those in soda-lime glass illustrated in Fig. 1a. An additional feature, however, is a ring crack, c, which forms at or outside the contact area. Fig. 2b to d show the subsurface damage of other 2 N load indentations, and the dominant cracks are significantly different from those under Vickers indentations in soda-lime glass. The deformation and cracking are somewhat similar to those observed around spherical indentation in soda-lime glass [10, 14]. The subsurface damage consists of a compacted (deformed) zone, dz, illustrated in Fig. 2b to d (Fig. 2d is a higher magnification of Fig. 2c; it shows the crack patterns more clearly but "flaring" from the cracks makes the extent of the region dz less clear). These compacted zones are made visible by the pressure-induced changes in the refractive index and reflectivity of the glass. The compacted zones are devoid of any of the shear lines that occur in soda-lime glass. Sometimes median and lateral cracks develop from the bottom of the compacted zone; other lateral cracks arise from the tips of the median cracks as in Fig. 2b and c.

The surprising feature about the subsurface cracking in fused silica is the presence of dominant cone cracks, which are associated with the elastic loading of spheres on brittle solids. The cone cracks, cc in Fig. 2b to d, are associated with ring cracks, at c in the specimen surface shown in Fig. 2a. The cone cracks form at or outside the deformed zone and make an angle of about 30° with the specimen surface. In fused silica, however, the normal Hertzian cone cracks produced with spherical indenters make angles of 25° with the specimen surface. Multiple cone cracks making shallower angles also occur outside the major cone crack (see Fig. 2b and d). In fact, the feature arrowed lc in Fig. 2a is the reflection from the "skirt" of the cone crack. Sometimes the lateral cracks start from points along the "skirt" of the cone and propagate to the surface [15].

4. Discussion

As observed by Peter [12, 13], Mackenzie [16] and Ernsberger [17] the high hydrostatic and shear stresses under the indenter can compact or densify the "open" silicate structure; genuine flow-like processes occur only in soda-lime glass or in glasses containing a minimum of network modifiers [13]. This flow is inferred from the development of the system of 'rosette' flow lines which are similar to the elastic shear stress trajectories under conical indenters [18] and also the logarithmic spiral shear stress trajectories around an expanding cylindrical cavity [10, 13]. The use of the elastic shear stresses, although inadequate for the elastic–plastic indentation, does indicate the nature and points of initiation and extent of the deformation for spherical indentations [19]. In soda-lime glass, Hagan and Swain [10] have suggested that the nucleation of the median and lateral cracks is a consequence of the inhomogeneous nature of the deformation.

In fused silica, apart from the initial compaction, the deformation is dominated by the elastic stresses; Hirst and Howes [20] have shown that for indentations in highly elastic material (for example PMMA) the pressure distribution along the interface is very similar to the elastic distribution. However, the expansion of the boundary of the compacted zone with increasing indenter load may lead to median crack formation during loading as suggested by Lawn and Evans [9]. The mismatch of strain at the boundary of the compacted zone during unloading can give rise to the lateral cracks [17]. The unloading residual stresses can also make the tips of the median cracks turn and propagate towards the specimen surface (see Fig. 2b to d). The dominant cracks, the cone cracks, arise from the elastic stresses during the indentation. In the elastic loading of conical and spherical indenters, the surface displacements are such that the radial surface stresses are tensile at or outside the contact [2, 21, 22]. Johnson *et al.* [23] have shown that frictional effects from the mismatch of the elastic properties of a spherical indenter and specimen can influence the magnitude and the position of the maximum tensile stresses. At high enough stresses the tensile stresses will initiate shallow surface flaws, cz, (Figs. 1a and 2a) at the contact area during loading. As the load is increased these shallow cracks are absorbed into the increased contact area and new cracks formed at the new contact. Propagation of these cracks into the bulk is inhibited because they run into the compacted zone which is under hydrostatic pressure. It is only those surface ring cracks initiating outside the contact area that develop outside this deformed zone and therefore develop into the fully grown cone cracks shown in Fig. 2b, to d.

5. Conclusions

The surface and subsurface deformation and cracking around the Vickers indentations in fused silica have been studied. Densification (compaction) was observed beneath the indenter, but no inhomogeneous shear flow occurred as with soda-lime glass. These differences in the irreversible deformation apparently modify the elastic stress fields around the indentations since significant differences were found in the crack patterns for the two materials. The dominant cracks in fused silica are the cone cracks which do not form in soda-lime glass of similar surface finish. The expansion of the boundary of the compacted zone in fused silica, can cause median cracks during loading, while the mismatch of strain at this boundary can lead to lateral crack formation during unloading. It is clear that small changes in material properties can affect the details of the failure processes beneath an indenter. These, in turn, will have important effects on the wear, abrasion and erosion of these solids.

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