Shear deformation under pyramidal indentations in soda-lime glass

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The nature of the flow lines that occur in the deformed zone in soda-lime glass under pyramidal indentations has been investigated. A close examination of the deformed zone shows that the spiral flow lines meet at 110°, instead of the 90° required by the ideal rigid–plastic behaviour. The flow lines are indeed shear faults (of negligible thickness) produced by genuine shear displacements which are apparent at the intersection points of some of the flow lines. Evidence of void or crack formation at the intersection points or along the flow lines is also presented, along with a possible hardening effect from the suppression of slip at the intersection points of the flow lines.

1. Introduction

Although soda-lime glass is isotropic in most of its properties, examination of the subsurface deformation under Vickers indentations at high loads reveals that the deformed zone is made up of a series of intersecting flow lines [1–5]. The plastic strains appear to be concentrated on these flow lines while the material between them is strained only elastically [6]. It has been suggested that these inhomogeneous flow lines in the subsurface regions are responsible for the median, radial and lateral cracks that develop around plastic indentations and ultimately lead to strength degradation and erosion of brittle solids in most contact situations [3]. Hagan and Swain have attributed the formation of the median cracks to the need to accommodate strains at the intersection of two flow lines just like crack nucleation from dislocations on two intersecting slip planes [7–9]. The lateral cracks, however, are initiated at nuclei at the elastic/plastic boundary or along the flow lines, and they are propagated by the unloading residual stresses.

These ideas about crack nucleation from flow line interaction have been extended to estimate the critical loads for the nucleation of the median crack and the critical flaw size that could be nucleated by this process [10].

There is, however, an uncertainty about the nature of these deformation flow lines. The problem is that in a material as brittle, homogeneous and amorphous as soda-lime glass, it is difficult to envisage how any shear displacements could be sustained without cracking; and it is not clear whether these flow lines are genuine shear displacements or shear cracks as observed around oblate voids in soda-lime glass under compression [11, 12]. Ernsberger [11] has used the stress at which these lines occur as a measure of the pristine strength of glass. Results will be presented in this paper to show that the flow lines are genuine shear displacements and not shear cracks. The shear cracks around oblate voids probably start as genuine shear displacements and it is only in the later stages of the deformation that they degenerate into shear cracks; and the load at which these flow lines first occur is a measure of the basic flow properties of the glass. There is also evidence for crack nucleation along the flow lines and at the intersection point of the flow lines. A possible hardening effect from the kinking and suppression of slip along some of the flow lines and the subsequent possible lowering of the hardness values are reported.

2. Experiment

The experiment consisted of cross-sectioning Vickers indentations produced at different loads.

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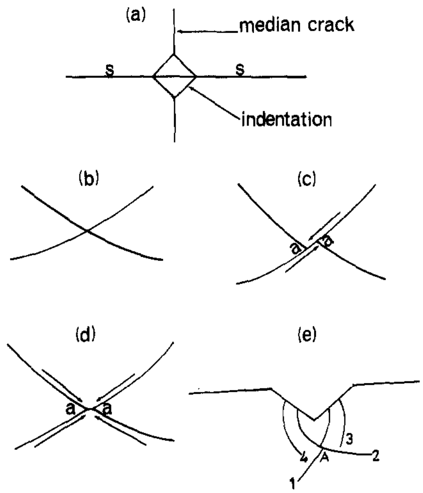


Figure 1 (a) Schematic diagram of the indentation on the sectioning crack, ss. (b), (c) and (d) illustrate the three types of flow line intersections and (e) is a schematic diagram of kink formation at A and the suppression of slip on kinked flow lines.

The sectioning was done by indenting on and near the tip of a pre-existing crack; this technique was used by Peter [1] and in a slightly modified form by Samuel and Mulhearn [13]. The heavy-duty Vickers hardness tester, capable of applying loads of up to 1000 N, was used to make indentations at 100 and 250 N loads. The indentations were sectioned along the diagonal of the indentation as shown in Fig. 1a; the other orthogonal crack coincides with the sectioning crack. In previous work [2, 4] the indentations were sectioned along a median plane; but since the median and radial cracks form along the indentation diagonal it was decided a diagonal section would provide more information on the deformation and cracking processes. Again, there was no distortion of the indentations which were made very close to the crack tip. Both optical and scanning electron microscopy were used to examine the subsurface deformation.

3. Results

The observations are illustrated with Figs. 2 to 6. The subsurface region of a 100 N load indentation is illustrated in Fig. 2a. It shows the spiral flow lines within the deformed zone, dz, and the characteristic median and lateral cracks (mc and lc respectively). Fig. 2b and c are the matching pairs of the same region at a higher magnification. They illustrate more clearly the spiral nature of the flow lines which, according to plasticity theory, should intersect one another at 90°. The intersection is, however, at $\sim 110°$ as in regions marked A. That this angle is different to 90° is perhaps not surprising since densification and compaction in the silicate structure would be expected to modify the ideal plastic behaviour [17]).

At higher indenter loads (250 N), the damage is more extensive as can be seen in Fig. 3a; radial cracks, rc, develop in the bulk (from similarly interacting flow lines) but away from the median crack, mc; these cracks appear to initiate near the elastic–plastic boundary from intersecting flow lines. Sometimes several radial cracks appear in the bulk as in Fig. 3b but the deformed zone directly beneath the indenter is broken up and chipped away. There are also short secondary cracks (src) which occur at the intersection points of some of the flow lines within the deformed zone (see Fig. 3d). When the flow lines intersect, a kink may be produced in the flow line that formed first; these kinks are marked, k, in Fig. 3c which is a higher magnification of a region in Fig. 3a. In general, the flow lines produce three effects at their intersection points as illustrated in Fig. 4. The flow lines either produce: (a) no distortion at the intersection point such as regions a, (b) a kink, b, in one of the flow lines or (c) a short kink, c, in both flow lines. The intersection of the flow lines and the subsequent kink formation are illustrated schematically in Fig. 1b, c and d. The kinks aa, represent the magnitude of the different shear displacements. Often, one flow line may produce kinks of different magnitudes in several flow lines that intersect it and this arises because the shear displacement either varies along the flow line or more probably the strains in the intersecting lines are different. It is obvious from the kink formation, that all the flow lines do not form at the same time.

It appears from the micrographs so far that the actual shear distortion occurs in a layer of finite thickness $\sim 2\,\mu$m. However, higher magnification scanning electron micrographs reveal that the flow lines are faults – very sharp lines – of negligible thickness. These fault lines occur either in the plane or normal to the surface of the pre-existing crack; in the latter case material displaced normal to the surface will give rise to steps in the surface. This is not a feature of the deformation process and it only arises because of the presence of the free surface of the pre-existing crack which allows

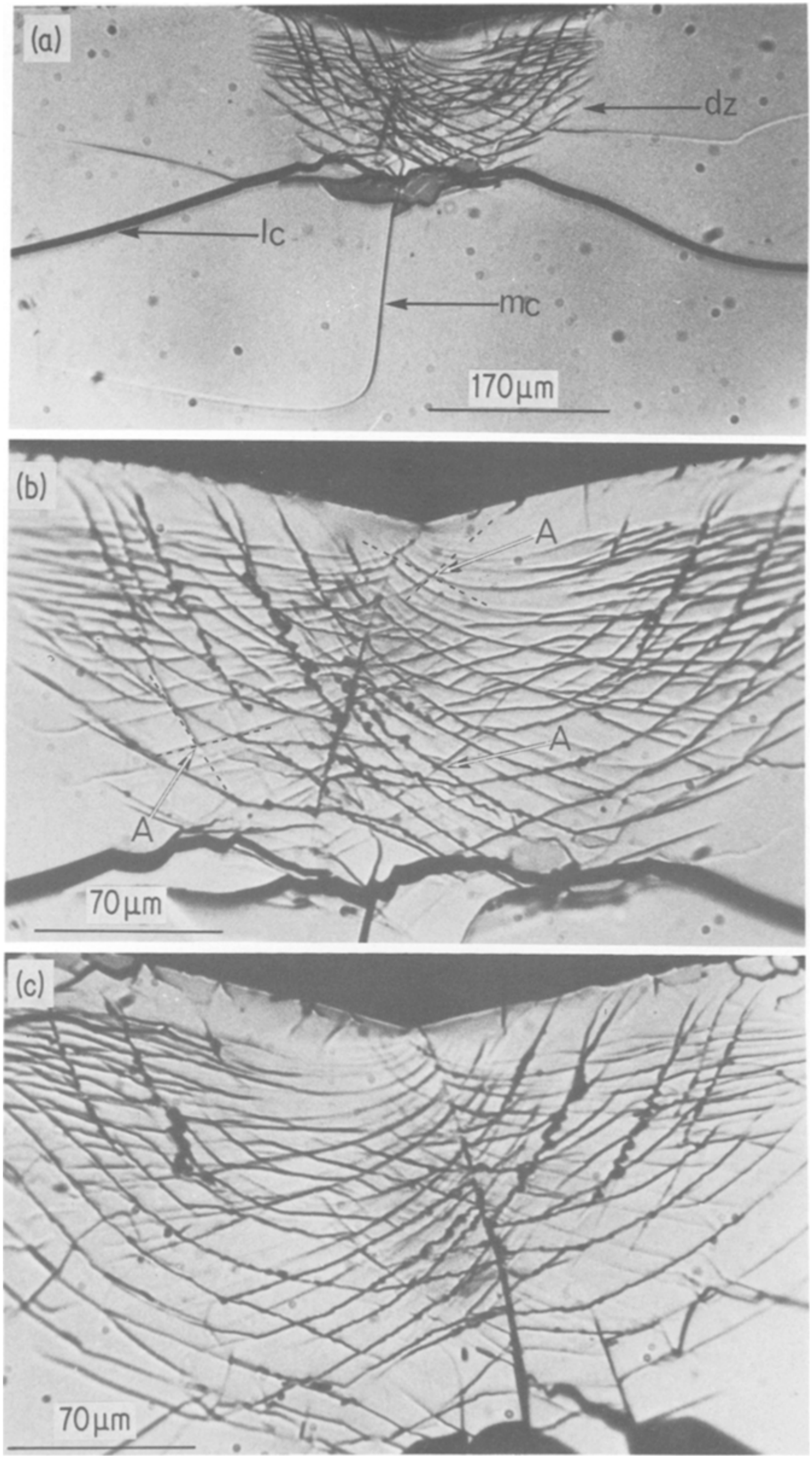


Figure 2 The subsurface damage of 100 N indentation. It reveals the flow lines in the deformed zone, dz, and the characteristic median and lateral cracks (mc and lc, respectively); the sideways curvature of the median crack near its tip is almost certainly formed during the unloading stage.

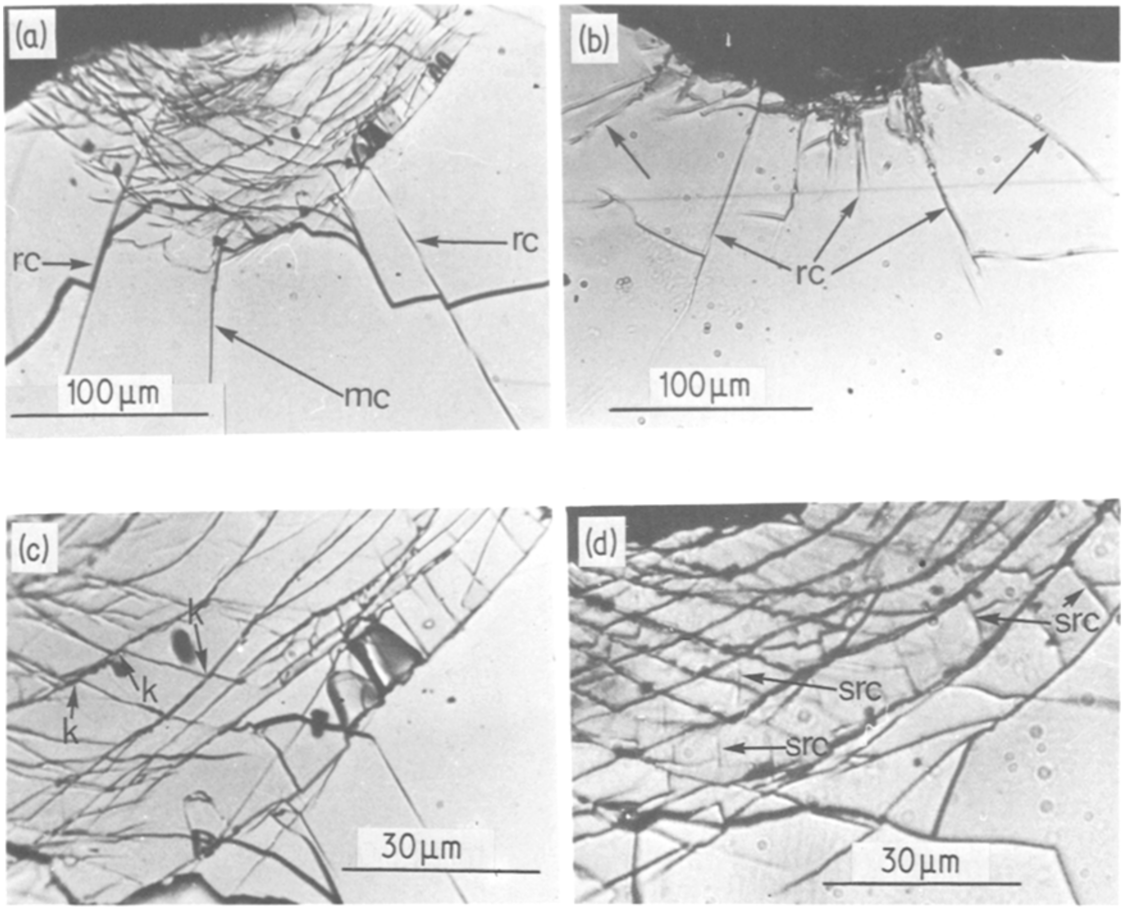


Figure 3 (a) and (b) The formation of radial cracks in the bulk. (c) The kinks, k, at the intersection points of flow lines in the subsurface region in (a). (d) The formation of secondary radial cracks (src) that form within the deformed zone.

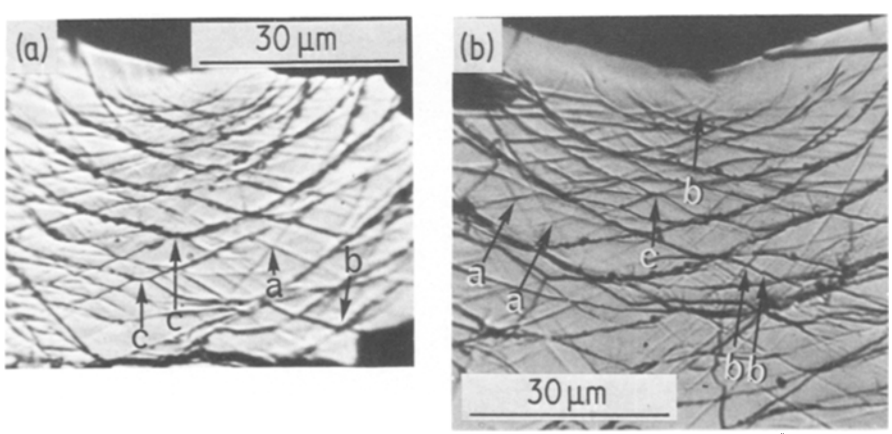


Figure 4 Micrographs of the three types of flow line intersection points. The intersections, a, are for no distortion, b, a kink in one flow line, and c, short kinks in both intersecting flow lines.

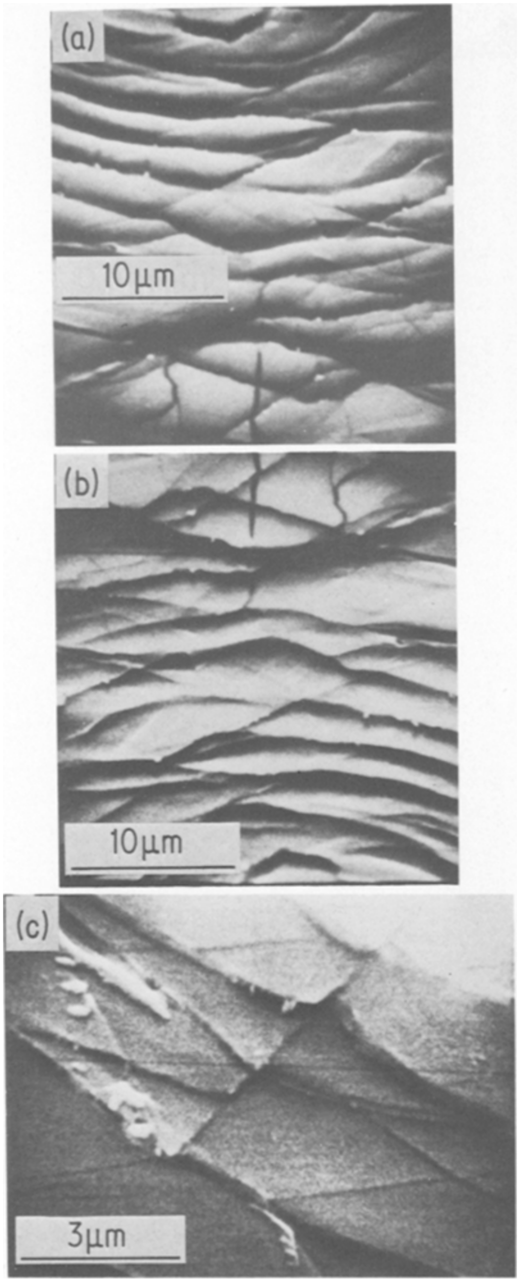
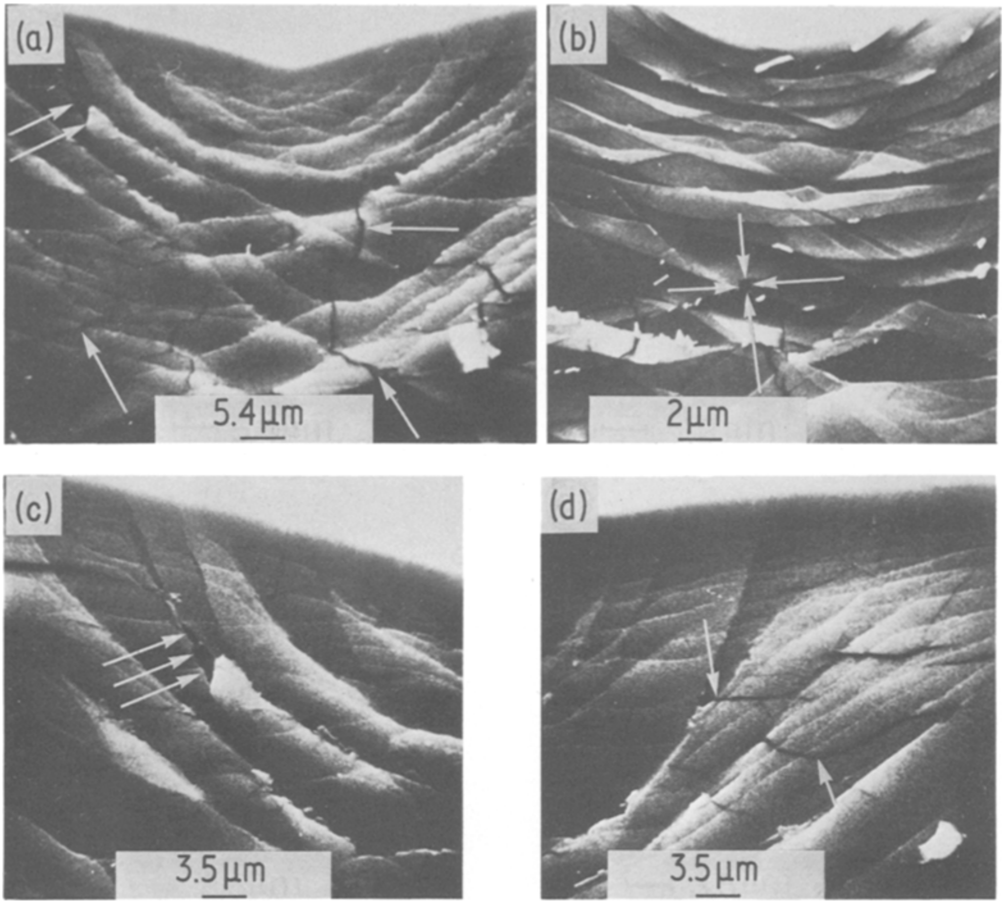


Figure 5 Scanning electron micrographs of subsurface flow lines; (b) as (c) but with the specimen rotated through 180° to reveal the stepped nature of the surface. The steps only serve to illustrate the very narrow nature of the flow lines.

material to be displaced onto it. These micrographs only serve to illustrate the highly localized and fault-like nature of the slip steps and to show that the flow lines are not cracks. The steps on the free surface are illustrated in the scanning micrograph of Fig. 5, which shows a region in the subsurface deformed zone for an indenter load of 150 N. The electron beam was incident normally on the specimen which was rotated through 180° for the two micrographs. Fig. 5 reveals the stepped spiral flow lines; the steps are hardly noticeable in Fig. 5a but are clearly visible in Fig. 5b. The height of the steps lies between 0 and 0.3 μm depending on whether the shearing is in the plane of the free surface or material is being displaced onto the fracture surface. The steps are quite clear in Fig. 5(c) which is a region of another 150 N indentation. In the absence of the free surface (i.e. the pre-existing crack), continued slip would result in void formation or cracking as illustrated in Fig. 6. In fact, voids and cracks develop along the flow lines (Fig. 6e) or at the intersection points of the flow lines as in Fig. 6b. The void along the flow lines in Fig. 6e is probably facilitated by the presence of the slipping along the flow lines ee and ff. The flow line, ee, has been displaced by an amount, aa, arrowed in Fig. 6e, by slip along the flow line aa. There are some random cracks (arrowed in Fig. 6a, b and d) which appear confined initially to the shear faults but may wander across other flow lines. They are probably driven by the unloading residual stress around the indentation.

4. Discussion

The results show the spiral flow lines characteristic of a material yielding radially and the development of the side radial cracks in the bulk and near the elastic–plastic boundary at higher indenter loads. There are also the short cracks (src) that form at the intersection points of flow lines within the deformed zone and these may help to break up material within the deformed zone. The most interesting observation is the kink formation on some of the flow lines that intersect each other. The nature of the kinks indicate that they are genuine shear displacements and not shear cracks with free surfaces. The cracks when they occur in the subsurface deformed zone are readily resolvable (Fig. 6). It is known that when a crack runs into the free surface of another crack, it is often difficult to predict the subsequent propagation of the crack without detailed knowledge of the existing stresses. In fact, the subsequent propagation of the crack may not bear any similarity or relationship to the original crack since the crack will always stop at the free surface and it will have to be nucleated anew on the other free surface and



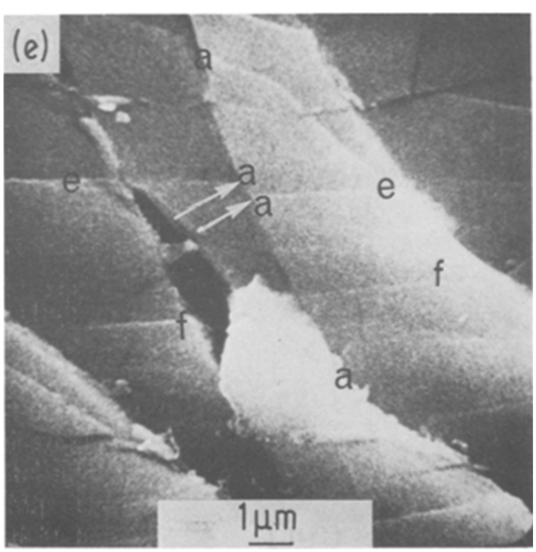


Figure 6 Scanning electron micrographs of the flow lines in soda-lime glass and showing the void formation along flow lines in (a) and (c) and (e) and at the intersection point in (b). They also illustrate the network of cracks (arrowed) and the displacement kink formation that occurs is more pronounced at aa and ee.

across the physical discontinuity. The flow lines, in these observations, maintain their curvature before and after the kinks. In fact, the shear displacements or kinks on the flow lines are similar to kink or jog formation from intersecting dislocations; in such intersections, the kink on one dislocation represents the magnitude or strength of the Burgers vector of the second dislocation. Displacements of 0.5 μm have been measured at some of the kinks (see intersection of flow lines ee and ff in Fig. 6e).

From these observations, it appears that the shear cracks seen around oblate voids in soda-lime glass under compression probably start as genuine shear displacements and it is only in the later stages of deformation that they develop into shear cracks as the strains along the flow lines increase. Thus the use of the stress at which these flow lines appear to measure the intrinsic and virgin strength of glass is not strictly accurate; this stress, however, does represent the onset of irreversible deformation in the glass.

The kinking of the flow lines at some of the intersection points may lead to void or crack formation as observed in Fig. 6. The voids in Fig. 6b are 0.6 μm. It is interesting to compare this void size with the value calculated from the recent analysis by Hagan [10] for the largest flaw sizes that could be nucleated by the intersecting flow lines. Hagan's analysis predicts a flaw of size of

$$c = 29.5 \left(\frac{K_{IC}}{H}\right)^2,$$

where K_{IC} and H are the critical stress intensity factor and hardness, respectively. For values of $K_{IC} = 0.7 \text{ MN m}^{-3/2}$ and $H = 5.6$ GPa, the largest flaw size is 0.5 μm and this agrees very well with the void size of 0.6 μm in Fig. 6b though such excellent agreement is probably fortuitous. It is known that in highly elastic solids the hardness, H, and the yield stress, Y, are related by $H = cY$, where c is much less than 3, the value required by ideal rigid plastic behaviour [14–16]; this is because the elastic strains are comparable with the plastic strains and can no longer be ignored. For soda-lime glass, $c = 1.3$ to 1.6, so that the average axial yield stress is $Y = H/1.4 = 3.9$ GPa. This value is very close to the peak axial stress of 4.2 GPa reported by Ernsberger [11] for the onset of the "shear" cracks observed around oblate voids in soda-lime glass under compression and this agreement points to a basic shear deformation process in the two experiments.

The intersection and kinking of the flow lines has interesting implications because the mutual kinking of the flow lines will make continued slip on the kinked flow line more difficult (akin to hardening) and is compensated by a possible lowering in the hardness value when the intersection and kinking occurs in a favourable place. Attempts at continued slip past such a kink can lead to void or crack formation as evident in Fig. 6. In the absence of void or crack formation, it is possible to activate another slip in the neighbourhood of the kinked flow line to accommodate the strain or slip that was not possible on the kinked flow line; this may lead to a larger contact area for the same load. This effect may be illustrated with Fig. 1e which shows the possible sequence of events occurring in the subsurface deformed zone. The slip occurs first on the flow lines marked (1). This is then intersected by slip on (2) and produces a kink at A and supresses any further slip on (1). To accommodate the extra slip suppressed on (1), it is possible to activate flow line (3) adjacent to flow line (1). This, therefore, leads to a slightly larger contact area for the same load and a possible lowering of the hardness. Thus the kinking of the flow lines, if it causes suppression of free slip, may result in the lowering of the hardness. The softening effect from suppressed free slip probably accounts for only a slight increase in contact area when the load comes to rest. Normally under increasing load and contact area, new flow lines will develop at the new contact area and will intersect the flow lines already present without suppressing any slip.

5. Conclusion

The observations presented here throw more light on the deformation processes in soda-lime glass. It shows that apart from the initial compaction of the silicate network genuine flow does occur. The slip appears like shear faults with slip occurring in atomically sharp boundaries. There is a departure from ideal plastic behaviour which requires the spiral flow lines should at 90°; however, because of compaction and densification, these flow lines meet at about 110° in the bulk and intersect the specimen surface at 50° instead of 45°. The fact that flow lines appear to develop sequentially has rather interesting implications in that it provides a mechanism for a possible hardening effect in soda-lime glass. A recent analysis by Imaoka and Yasui [17] on the indentation in glasses has considered the possibility of hardening effect on the hardness measurements, although its existence is not definite and its overall effects may be negligible.

Following an earlier suggestion by Hagan and Swain [3] it has been shown that continued slip on the kinked flow line can lead to crack or void formation at the intersection points or along the flow lines; what is not clear is the actual process that leads to the formation of these flow lines. It may well be that it is similar to what happens in metallic glasses where shear deformation is by dilation of the already compact structure [18–20]; and the actual nucleation may be due to local structural (density) or chemical (network modifiers) variation in the glass. In inorganic silicate glasses, because of the porous structure of the network, the network is compacted to as near the maximum density as possible. Shear flow is initiated at some local weakness (provided by the network modifiers) and the subsequent flow is by dilation of the structure in the immediate vicinity of the initiation site.

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