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On the machining of glass

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A study to examine the feasibility of cutting glass in the same manner as ductile metals was carried out on three types of glass (soda-lime microscope slides, carefully polished specimens of lead-doped flint and fused silica). No success was obtained with fused silica while soda-lime glass showed clear evidence of cutting in a manner similar to ductile metals, but provided variable results with different specimens. The most encouraging results were obtained with the lead-doped flint glass. Using a diamond tool with a semi-circular face at a rake angle of $-34°$, crackfree cuts were produced with widths and depths up to about 100 and 1.6 μm, respectively. The "chips" produced during this machining are tightly curled with a serrated concave side. The results of this preliminary investigation suggest many aspects for further study. However, the essential conclusion is that certain glasses may be machined in a manner similar to ductile metals if the "size" of the cut is small enough.

1. Introduction

Recently, the machining of metallic surfaces with single-point diamond tools has given very successful results. Aspherical surfaces with high quality finish can be produced which are directly useful in optical systems [1]. These encouraging experiments have raised the question of whether a similar technique could be applied to the shaping of glass lenses. At first sight, the idea might seem impractical, as glass at room temperature is known to behave, essentially, in a brittle manner. A machining process, similar to that used on metals and capable of giving adequate surface finish, would inevitably involve a chip forming mechanism. However, such machining of silicate glass, if feasible, would present enormous advantages. It would open up the possibility for producing aspherical lenses in an inexpensive manner, thus reducing cost and weight of optical components and it could also replace the tedious, time consuming and expensive polishing operation.

In the present paper a short term, mainly experimental study, is reported, undertaken to demonstrate the feasibility of matching glass in a manner similar to ductile metals. Experiments showing the continuous machining of glass will be presented together with observations pertaining to the mechanisms of brittle chipping.

2. Continuous machining of glass: statement of the problem

Although the controversy about the nature of the "flow" that may precede fracture in glass has not yet been settled, the literature abounds with evidence suggesting that some permanent deformation process can take place. Besides the now classical pin cushion patterns observed upon indentation, the piling up of material at the intersection of two furrows has been noted [2]. In addition, Peters [3], and Dick [4] have obtained very convincing photographs of material extrusions and pile-ups in glass as well as of deformation markings similar to slip-line in metals. In a recent paper, Schmidt and Hopfe [5] show a photograph of a deformed strip at the tip of a crack in a thin sheet of soda-lime glass. Applying the Dugdale model for the plastic zone size in metals they were able to deduce a value of the flow stress.

Ernsberger [6] has given a review of possible mechanisms involved in the so-called plastic deformation of glass. The debate mainly centres around the relative importance of compaction with respect to shear deformation. Leaving that question open for the moment, we can state the problem of producing flow in glass in terms of limit stresses. In a macroscopic strength test, glass will fail in a brittle manner at a stress σ_f,

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determined by the distribution of surface flaws on the specimen. Because the broken specimen displays no signs of permanent deformation, it can be contended that the failure strength σ_f is lower than a hypothetical flow stress σ_y. On the other hand, we know that σ_f is very much smaller than the ideal strength of the glass so we have the relationship

$$\sigma_f < \sigma_y < \sigma_{\text{ideal}}. \quad (1)$$

In order to produce flow before brittle fracture occurs, the left part of the Inequality 1 must be reversed so that

$$\sigma_y < \sigma_f < \sigma_{\text{ideal}}. \quad (2)$$

The success of a machining operation on glass depends on how well Inequality 2 can be achieved on a local scale, at the tip of the tool. The reversal of the inequality $\sigma_f < \sigma_y$ will depend on a great number of factors. In Fig. 1 we have tried to summarize schematically their interaction.

Because of the statistical distribution of the strength impairing flaws in glass, there will be a size effect on the value of σ_f. This phenomenon has been evidenced in erosion experiments by Sheldon and Finnie [7] where a transition from behaviour typical of a brittle solid to that typical of a ductile material was observed when the eroding particle size was decreased. The work by Bridgman [8] and Bridgman and Simon [9] has demonstrated how a high hydrostatic stress favours flow even in glass. Peter [3] claims that only glasses with an appreciable amount of network modifier will display ductile type behaviour, whereas fused silica would only be compacted and fail in a brittle manner. It is clear that the tool geometry will play a decisive role. This is also suggested by identation experiments by Dick [4]. It was found that "pile ups" around the impression would only form when the angle between the intender face and the work piece was greater than a critical value, estimated around 45°. The other factors shown in Fig. 1 will probably be of less importance although static fatigue in conjunction with residual stresses due to compaction might have a very disruptive effect.

3. Experimental procedure

First a series of screening tests on microscope slides were run, using a Vickers indenter and a scratching tool mounted in a Leitz micro-hardness tester. The Vickers intender had a rake angle of −68° (measured from the normal to the surface to the face of the tool) and an included angle between the lateral faces of 126°. On the scratching tool these angles were 0° and 120°, respectively. The reason for starting with pointed tools was the considerable amount of data and results concerning indentation and scratching problems published in the literature (see for example, Lawn and Wilshaw [10], Swain [11] and Veldkamp *et al.* [12]) and the fact that some experience of the scribing of silicon wafers had already been acquired [13].

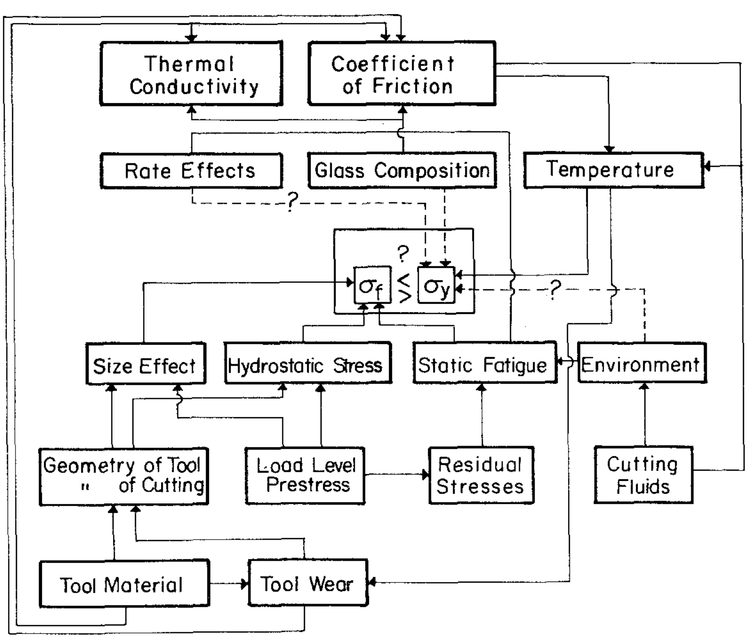

Figure 1 Summary of the factors which may help to induce flow in glass.

The preliminary tests clearly demonstrated the influence of the rake angle and confirmed Dick's results. With the Vickers indenter the material was merely compacted, whereas the scratching tool with zero rake definitely cut material. Separate tests performed at the Lawrence Livermore Laboratory [14] led us to the conclusion that $-35°$ was close to an optimum rake angle. It was also found that the limiting load for a pointed tool would be very low (around 15 g for the scratching tool on microscope slides).

The remainder of the experiments were carried out on a Karl Süss scribing machine, commonly used in the production of semiconductor chips or liquid–crystal displays. This was more versatile and more precise than the hardness tester. In particular, the machine allowed adjustment of the rake angle, the load and variation of the feed rate. Although the cutting speed could be imposed automatically, it was preferable to move the table and work piece by hand to prevent shock on the diamond tools.

In addition to soda-lime microscope slides two more materials were investigated: a lead-doped flint glass (Schott SF-6) and fused silica (Corning). The SF-6 and fused silica samples received an optical polish and were checked for flatness and parallelism before testing. The microscope slides were used as bought.

In addition to the scratching tool, a semicircular diamond tool (Fig. 2a) of the type used for the turning of metals was also adapted to the Süss machine. The circular tool is a much more realistic geometry than a pointed indenter for machining purposes. It is expected to reduce the amount and likelihood of cracking and will produce a finished surface with decreased roughness when the grooves are partly overlapping (Fig. 2b).

All the experiments were performed without cutting fluids. After a direct observation with a light microscope mounted on the scribing machine the samples were transferred to a sputter-unit and gold-plated for further observation under the SEM.

4. Results

A pointed indenter certainly does not represent the best geometry for cutting purposes because of the stress state at its sharp tip which is likely to induce cracking. Nevertheless, encouraging results were obtained on microscope slides. Fig. 3* shows a groove cut with the scratching tool and Fig. 4 typical "debris" or "chip" nearby. Note, in particular, the serrations at regular intervals occurring along the chip. It is evident from Fig. 3 that the cracking is occurring transverse to the scribing direction, probably due to tensile stresses behind the tool. Also, the sides of the scratch are not very regular. It was noticed that the performance of the tool is very sensitive to its sharpness. A slightly worn tip will reduce the cracking as is evident in

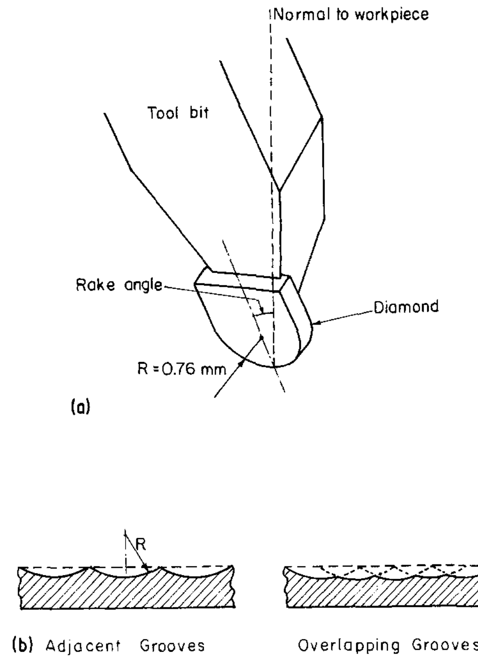

Figure 2 Schematic view of (a) the circular cutting tool used for most of the tests and (b) the shape of the surface produced.

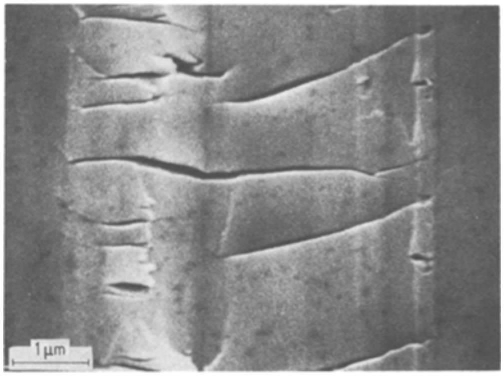

Figure 3 Single cut on a microscope slide using the scratching tool with a load of 15 g and a rake angle of $-20°$.

*In all the pictures presented here, the relative movement of the tool is from bottom to top.

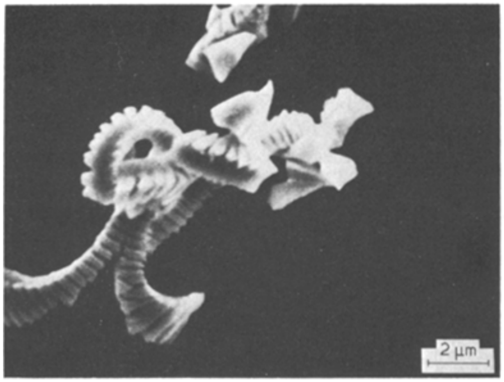

Figure 4 Chip produced under the cutting conditions of Fig. 3.

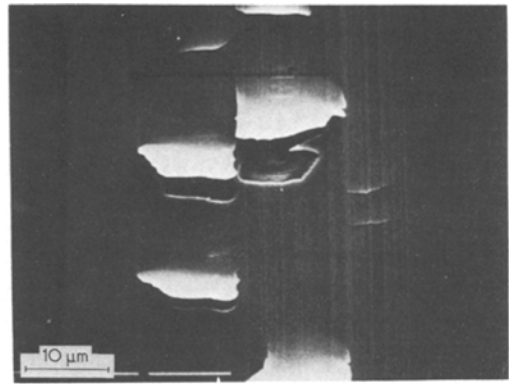

Figure 6 Single pass on a microscope slide using the tool of Fig. 2 with a load of 70 g and a rake angle of – 35°.

Fig. 5 showing a groove cut with a blunted tool. Again a serrated chip was observed, lying in a now smooth groove together with smaller curled chips. The fin-like features sticking out from the right side are caused by a misalignment of the tool which was slightly tilted to the right. Similar features are presented by Dick [4].

The first tests with the rounded diamond on microscope slides proved a little disappointing. It seemed that only compaction and brittle chipping were occurring. Fig. 6 gives an example of the damage caused. The vertical lines indicate the area swept by the diamonds. Remarkable features besides the tranverse cracks are the tongues of material curling up out of the surface, which must be formed *behind* the tool as can be deduced from the scribing direction.

Further trials with the rounded tool finally gave good results under similar conditions as for the unsuccessful runs. It was possible to cut regular grooves of circular profile at vertical loads ranging from 50 to 80 g. Fig. 7 shows an area of microscope slide on which adjacent grooves have been cut and covered with abundant debris. In Fig. 8 a close-up view of the end of one groove with a pile up of chips is seen. Worth noticing again is the discontinuous nature of the chips and their width. A close look at the bottom of a groove revealed the presence of some tranverse curved cracks similar to the horseshoe cracks formed behind a sliding spherical indenter [15].

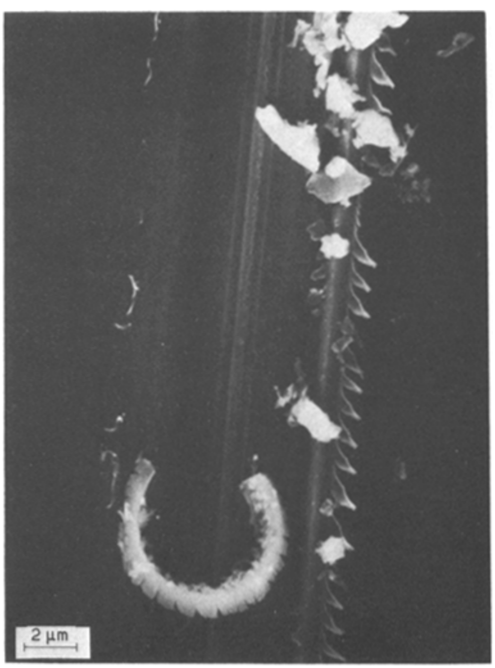

Figure 5 Single cut on a microscope slide using a blunted scratching tool with a load of 15 g and a rake angle of – 10°.

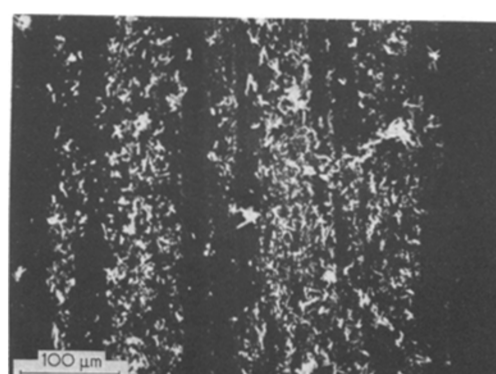

Figure 7 Multiple cuts on a microscope slide using the tool of Fig. 2 with a load of 50 g and a rake angle of – 35°. The light material is chips removed from the surface.

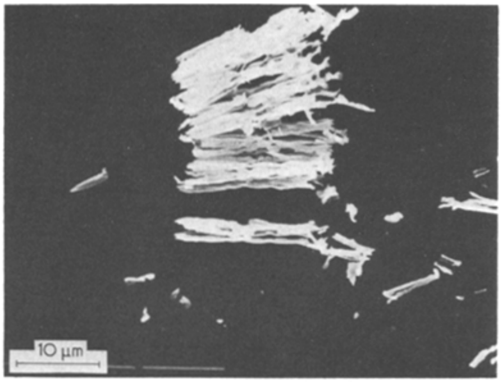

Figure 8 Detail at the end of a cut performed under the same conditions as Fig. 7.

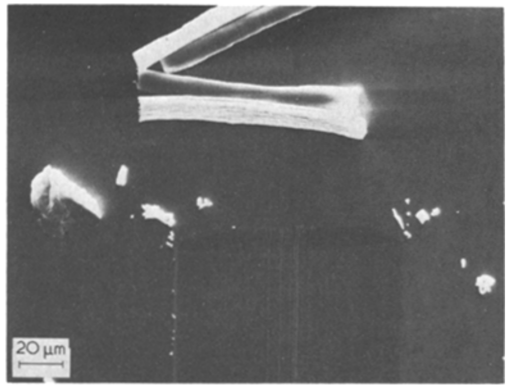

Figure 10 Detail at the end of a cut performed under the same conditions as Fig. 9.

It was concluded that the variability in behaviour observed in microscope slides was due to the poor quality of the glass, which certainly shows great differences from one sample to the other.

This difficulty was not encountered in testing the SF-6 samples. Cuts at a $-35°$ rake angle and with the load increasing from 80 to 400 g all gave excellent results. The grooves were smoothly formed but showed light longitudinal markings caused by the surface roughness of the diamond. Their width was significant, typically of the order of 100 μm for 400 g load which corresponds to a depth of cut of 1.6 μm. Two of these grooves can be seen in Fig. 9 together with chips, whereas Fig. 10 shows the end of a cut. Under the quoted conditions it was also possible to machine adjacent cuts, Fig. 11. Only when the 600 g load range was reached did some cracking start to occur as, for instance, in Fig. 12.

Close observation of the chips revealed very interesting features. In Fig. 9 they are seen to be curved; serrated on the concave side and smooth on the convex side (see also Fig. 12). An enlarged view of the serrated face is given in Fig. 13 which suggests that the serration is due to the sliding of successive layers under a shear deformation. A slight waviness at the bottom of the larger grooves, with the wave length corresponding to the serration spacing tends to support this idea (Fig. 12).

In contrast to the work on SF-6, efforts to cut smooth grooves on fused silica were totally unsuccessful. Whatever the combination of the cutting paramenters tried, only compaction, brittle failure or both simultaneously was achieved.

5. Comments and conclusions

The experiments on microscope slides and SF-6 glass, which represent extremes in specimen preparation, demonstrate that silicate glasses with some amount of additive can be cut in a manner similar to the ductile cutting of metals.

The study of the chip morphologies reveals that

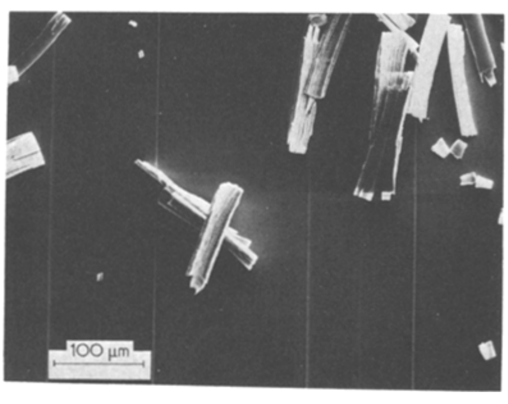

Figure 9 Two cut on SF-6 glass using the tool of Fig. 2 with a load of 400 g and a rake angle of $-35°$.

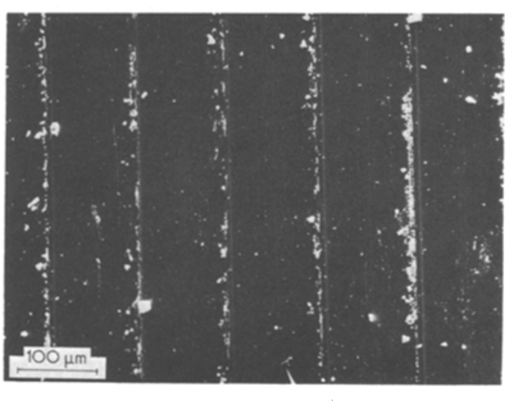

Figure 11 Multiple cuts on SF-6 glass using the tool of Fig. 2 with a load of 400 g and a rake angle of $-35°$.

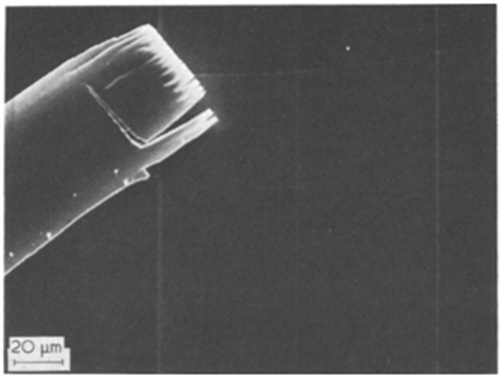

Figure 12 A single cut under the same conditions as Fig. 11 except that the load has been increased to 650 g.

independent of the tool geometry or the material cut, the chips present a common feature, i.e. their serration (Figs. 5, 8, 9 and 13). This observation allows some conclusions to be drawn about the mechanism of chip formation. It appears that the material is removed by successive concentrated shearing on parallel and equally spaced planes (see in particular Fig. 13). Such behaviour has been reported in the literature before [3, 4]. It is believed that only the weaker links produced by the modifiers shear, whereas the siloxane network remains intact because of its strong covalent bonding. This would explain the failure to obtain satisfactory results with fused silica.

The shear mode of deformation and compaction are probably two competing processes, the contributions of which would be mainly controlled by the rake angle, as is indicated by the preliminary screening tests.

At this point, further work is needed to clarify the mechanism of cutting glass. Quantitative observation under the SEM, together with measurements of the horizontal forces, should be of value in constructing and verifying a simple model. Also, a better understanding of compaction and of the residual stresses it induces would certainly be welcome because of the role these stresses play in triggering brittle chipping.

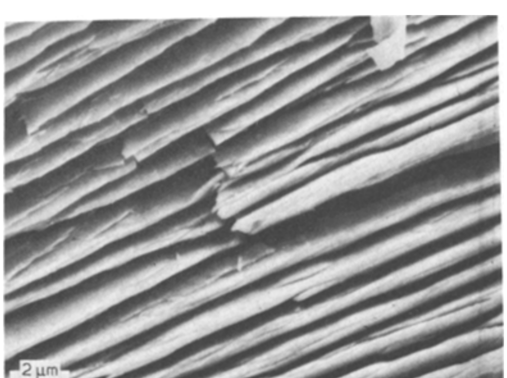

Figure 13 Enlarged view of the concave side of one of the chips in Fig. 9.

This study provides additional information about the development of brittle failure. The tongues of Fig. 6 appear to be formed in the following way: as the tool moves it compacts the material under it and causes subsurface cracking. If one simulates the rounded tool with a spherical indenter, this can be interpreted using the Hamilton and Goodman solution for an indenter with sliding friction [16]. The solution further predicts tensile stresses behind the tool so that when the tool advances horseshoe cracks will form in its wake. These cracks link up with the subsurface damage, thus allowing a relaxation of residual stresses in the compacted layer, which causes the curling up of the tongues in Fig. 6. This is not the only mechanism of brittle chipping, but it is an important one in so far as it emphasizes the role of the frictional forces in forming the horseshoe cracks.

As already mentioned, a lot of work remains to be done in order to fully understand the cutting process and improve it. It would be interesting to test different materials and find which ones are amenable to machining and to what extent. Also, it is hoped that cutting fluids will improve performance. If the technique is to be used in the production of optical components, a thorough characterization of the roughness and quality of the machined surface will be required. This implies detection of any possible subsurface damage and inhomogeneous structural changes. Finally, tool wear will play a crucial role on which the applicability and economy of the procces will very much depend. It is known that the diamond tool wears, but very little can be said about how it wears and how the wear affects the cutting process.

6. Summary

Dry experiments show that the diamond turning of modified silicate glasses is feasible whereas trials with fused silica were completely unsuccessfull. Evidence is given to support a deformation mechanism by inhomogeneous shear. Further, the rake angle is found to play an essential role in promoting either cutting or compaction with an intermediate value of $-30°$ to $-40°$ being optimum.

7. Acknowledgements

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