PLASTIC PROCESSES IN A RANGE OF SODA-LIME-SILICA GLASSES

J.T. HAGAN * and S. VAN DER ZWAAG **

Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, England

Received 16 May 1983

The effect of composition and indenter angle on the deformation processes in the deformed zone under conical indentations has been investigated for a range of soda-lime-silica glasses. After sectioning the indentations the subsurface deformation was examined using optical and scanning electron microscopy. In high silica glasses ($> 90\%$) the deformed zone contains broad concentric deformation or density contours which are similar to the maximum elastic shear stress trajectories under punch indentations. With increasing cation content ($\sim 85\%$) broad spiral flow lines appear which degenerate into fault-like features at a cation content of $\sim 70\%$. The development of micro phase separation affects the width of the flow lines and produces serrations. At some intermediate compositions the deformed zone exhibits both concentric and spiral flow lines which are characteristic of the initial elastic behaviour and the subsequent plastic deformation respectively. Similar changes in the deformation features for a particular glass composition are also observed as the indenter angle is varied. For 90° and 150° indentations the occurrence of spiral flow lines also depends on the applied load. The reason for the similarities in the deformation pattern for 90° and 150° cone angle indentations is not clear but is possibly due to the fact that the elastic constraints are the same at these indenter angles.

1. Introduction

Recent research into the deformation of oxide glasses has established that part of the deformation in these materials involves the shearing displacement of one region with respect to another. The mechanism of slip is however not understood although it may be similar to that of slip in metallic glasses. Since inorganic glasses are brittle, plastic deformation in these materials occurs only after a confining pressure has been established. The effect of the pressure is also to compact the open network and to increase its density. This compaction can be either reversible or irreversible depending on the nature of the confining pressure: permanent compaction is due to shear stresses, while reversible compaction is caused by the hydrostatic part of the stress field [1]. Although the work of Peter [2], Dick [3] and Hagan and Swain [4] has shown that

* Present address: BP Research Centre, Chertsey Road, Sunbury on Thames, Middlesex TW16 7LN, UK.

** Present address: AKZO department CRU, PO Box 60, Arnhem, The Netherlands.

genuine slip occurs in soda–lime–silica glass, the sources of the observed slip lines are not yet known but could be local fluctuations in density and/or chemical composition. These fluctuations in composition may be micro-separated phases which are present in most multicomponent silicates outside the immiscibility regions. The development of phase separation in apparently homogeneous glasses has a profound effect on the electrical [5], optical [6], rheological [7] and mechanical [8] properties of these materials. Of particular interest in the present work is the effect of composition and possible phase separation on the mechanical properties.

Several workers have studied the effect of composition and phase separation on the overall mechanical properties such as Young's modulus, E , critical stress intensity factor, K_{Ic} , and hardness, H , for a range of glasses. For example, Vernaz et al. [9] have shown that in the Na_2O – SiO_2 system the Young's modulus decreases continuously with increasing Na_2O content, while K_{Ic} exhibits a minimum and a maximum at about 20 and 40% Na_2O respectively. These variations in K_{Ic} have been attributed to the development of microscopic internal tensile and compressive stresses respectively, arising from the elastic mismatch between the matrix and the particular phase which separates out at each of these two concentrations. While phase separation may occur, it is not obvious that the compositional dependence of K_{Ic} is due to the development of internal stresses only; these variations could also be related to crack initiation and propagation processes in either the predominantly weaker Na_2O or the stronger SiO_2 matrices. Hertzian fracture experiments on a range of soda-lime glasses under various environmental conditions [10] have shown a similar minimum in the fracture stress at about 20% Na_2O . This minimum was however attributed to an (unspecified) distribution of sodium atoms which would facilitate stress corrosion cracking. In a series of Vickers indentation experiments on a range of glass compositions, Wada et al. [11] have reported that the probability of crack formation increases with the cation content and decreases with increasing density.

The hardness and the nature of the deformation beneath Vickers indentations are also affected by the cation content. Yamane and Mackenzie [12] have shown that by considering the different modes involved in the deformation of glasses (elastic deformation, flow due to shear and compaction) and relating them to the elastic properties and the average bond strength, a relationship between the hardness and the chemical composition may be obtained. The effect of the various metal oxide additives is to progressively weaken the strong SiO_2 network, as was reported by Ainsworth [13] in a series of earlier experiments.

Inorganic glasses can be divided into two groups depending on their behaviour under indentation [4,14,15]: in so-called "normal" glasses [15], such as commercial soda-lime-silica glass, the plastic deformation is inhomogeneous and highly localised. However, in "anomalous" glasses, such as fused silica, the deformation appears homogeneous and elastic. The large differences in deformation and fracture behaviour, which would not be expected from the small

differences in macroscopic mechanical properties, are probably related to structural modifications at an atomic level. The aim of the present work was therefore to study more closely the effect of composition on the indentation plasticity for soda–lime–silica glasses of different compositions (ranging from fused silica to a 70% SiO_2 –15% Na_2O –15% CaO glass) by examining the deformed region under indentations. Since the material response to imposed deformations depends not only on its elasticity factor, E/Y (which for the range of glasses studied is a constant at about 40) but also on the mean indentation pressure, which varies with the indenter angle [16], we have also examined the effect of the indenter geometry on the shape of the deformed zone and on the nature of the deformation processes therein. In order to produce geometrically similar indentations over a wide range of applied loads, conical indenters were used. In the present work we have concentrated on the deformation processes only. The relation between the deformation processes and the various crack systems which can form around indentations has been described in earlier publications [4,14].

2. Experimental

The indentations were sectioned by making the indentations across the tip of an artificially induced macroscopic crack in thin glass plates ($2 \times 25 \times 50 \text{ mm}^3$). The deformed zone was studied using optical and scanning electron microscopy (SEM). Both Vickers and conical diamond indenters with included angles of 90° , 136° and 150° were used. The tip radius of the 90° cone was $20 \mu\text{m}$. Because of the recent awareness of the distortions and artefacts in the deformation and cracking due to stress concentrations at the edges of the Vickers pyramid, most of the indentations were made with the conical indenters. The applied load was varied between 10 and 200 N.

The composition of the glasses studied and their hardness and critical stress intensity factor are given in table 1. The fused silica and soda–lime–silica glass were obtained commercially. The other glasses were supplied by Dr A.C.

Table 1
Composition and properties of soda–lime–silica glasses

Glass	Composition			Hardness (GPa)	K_{Ic} ($\text{MN m}^{-3/2}$)
	SiO_2	CaO	Na_2O		
Fused silica	100	–	–	7.6	0.79
A	85	7	8	5.9	0.82
B	85	5	10	5.8	0.67
C	80	10	10	5.8	0.65
D	75	12	13	5.7	0.71
E	70	15	15	5.8	0.70
Soda–lime	72	7	14	5.7	0.75

Woodward (Pilkington Bros, Latham Labs, Ormskirk). The glasses A and B (both with 85% SiO_2) displayed a marked Tyndall effect: an obvious indication of well-developed phase separation. The other glasses were optically transparent and clear.

3. Results

The results on the subsurface deformation are considered in three parts:

- (i) conical indentations on soda–lime–silica glass and fused silica as a function of load and cone angle,
- (ii) Vickers indentations on different composition glasses,
- (iii) conical indentations on a “transition” glass.

3.1. Conical indentations on soda–lime–silica glass

Examination of the subsurface deformation for a 90° cone angle indentation at 25 N reveals a deformed zone and traces of cone and lateral cracks (fig. 1a). At low loads the indentations are recovered almost completely within a few hours. The deformed zone consists of concentric hemispherical zones directly beneath the contact area; these zones are probably contours of equal compaction or densification. Unlike the inner boundary which is diffuse, the outermost zone is delineated by a sharp boundary between the compacted deformed zone and the elastic matrix. Near the bottom of the deformed zone there are traces of broad flow lines ff, which extend back into the deformed zone.

As the load is increased the flow lines become more localised (fault-like with negligible thickness) and their density increases. Two types of flow lines can be distinguished in the plastic zone: spiral flow lines, such as AA' and BB' (fig. 1b), which are tangential to the boundary of the central compacted zone and semi-circular ones, such as CC (fig. 1c), which are concentric with the apex of the indentation. Some of these circular flow lines are in the form of short segments which terminate at one of the spiral flow lines. Chipping prevented examination of the deformed zone for loads in excess of 75 N.

For 136° conical indentations the deformed zone no longer shows a well-defined central core. Both at low (25 N; fig. 2a) and at high loads (100 N; fig. 2c) spiral flow lines extend from the apex of the indentation. The sharpening of the flow lines (in particular the spiral ones) with increasing load is clearly illustrated in this figure. The density of the flow lines is much higher than for the 90° indentations. For the blunter indenter, cone cracks are much shorter and the recovery of the impression is not as pronounced.

The deformation features for 150° indentations (fig. 3) are similar to those for 90° indentations. At low loads the subsurface damage consists of a well-defined hemispherical zone, in which broad density contours can be distinguished; at higher loads shear faults of negligible thickness develop

Fig. 1. Optical micrographs of conical indentations on soda–lime–silica glass (cone angle: 90°), (a) 25 N, (b) 50 N, (c) 75 N.

Fig. 2. Optical micrographs of conical indentations on soda–lime–silica glass (cone angle: 136°) (a) 25 N, (b) 50 N, (c) 100 N.

Fig. 3. Optical micrographs of conical indentations on soda–lime–silica glass (cone angle: 150°)
(a) 50 N, (b) 150 N, (c) 200 N.

Fig. 4. S.E.M. micrographs of conical indentations (a) indentation at 150 N on soda–lime glass (cone angle 150°), (b) indentation at 75 N on glass C (cone angle 136°), (c) as for (b).

around this zone. It should be pointed out that both the spiral and the semi-circular flow lines develop near the bottom of this zone. In fig. 3c, which shows the subsurface deformation at 200 N, kinks, marked k, can be distinguished at intersection points between spiral and semi-circular flow lines. These kinks indicate that genuine shear displacements occur along the slip lines. This highly localised shearing displacement is shown more clearly in fig. 4a.

3.2. Conical indentations on fused silica

Similar studies of the subsurface damage in fused silica for 90°, 136° and 150° conical indentations at various loads did not reveal any significant changes in the nature of the deformed zone with the indenter angle or the applied load. For all the different indenters used, indentations at low loads produce only a compacted zone directly beneath the contact area and cone cracks which nucleate at the edge or outside the contact area. At higher loads both median and lateral cracks are also nucleated at the bottom of the compacted zone (see fig. 5). No traces of fault-like flow lines occur as in soda-lime glass. However, sometimes faint semi-circular deformation contours are observed in the deformed zone and they seem to follow maximum shear stress contours. Similar results have been obtained previously for Vickers indentations on fused silica [14,15].

It was observed that when the cone cracks nucleate well outside the compacted zone, the angle of the cone crack (to the specimen surface) is about 26° as predicted from the purely elastic stress field for blunt spherical indenters. However, when the ring cracks nucleate within or very close to the compacted zone, the cone crack makes a much steeper angle (up to 50°) with the specimen surface. The secondary cracks which nucleate further away from the compacted zone make progressively shallower angles with the surface as is shown in fig. 5c for a 150°C indentation at 75 N.

3.3. Vickers indentations on different composition glasses

The effect of the glass composition on the nature of the plastic deformation was studied for 75 N Vickers indentations which were sectioned along the diagonal of the indentation. Fig. 6a illustrates the subsurface damage in glass A (85SiO₂–8Na₂O–7CaO) and reveals traces of steep (about 50°) cone cracks as well as median and lateral cracks. The deformed zone shows both spiral and semi-circular flow lines. The spiral flow lines are more pronounced near the bottom. The deformation lines are much broader than those for identical indentations in soda–lime–silica glass. Similar observations were made for glass B (85SiO₂–10Na₂O–5CaO) which has the same silica content as glass A.

As the concentration of the network modifying elements is increased (Glass C; 80SiO₂–10Na₂O–10CaO) the spiral flow lines sharpen into fault-like fea-

Fig. 5. Optical micrographs of conical indentations on fused silica (a) indentation at 50 N (cone angle 136°), (b) same incident as in (a), (c) indentation at 75 N (cone angle 150°).

Fig. 6. Optical micrographs of Vickers indentations at 75 N (a) glass A, (b) glass C, (c) glass E.

Fig. 7. Optical micrographs of conical indentations on glass C (cone angle 90°) (a) 25 N, (b) 50 N, (c) 75 N.

Fig. 8. Optical micrographs of conical indentations on glass C (cone angle 136°) (a) 25 N, (b) 50 N, (c) 75 N.

Fig. 9. Optical micrographs of conical indentations on glass C (cone angle 150°) (a) 25 N, (b) 50 N, (c) 100 N.

tures (fig. 6b). The flow lines are however more irregular than in soda–lime glass.

Fig. 6c shows the deformation for glass E ($70\text{SiO}_2\text{--}15\text{Na}_2\text{O--}15\text{CaO}$). For this glass composition a dense network of flow lines with negligible thickness is observed. The deformation and cracking behaviour of this glass and that of glass D ($75\text{SiO}_2\text{--}13\text{Na}_2\text{O--}12\text{CaO}$) is identical to that for commercial soda–lime glass.

Because the deformation behaviour of glass C appears to be intermediate between that for fused silica and normal glasses, the deformation behaviour for this particular glass composition was studied in more detail for different cone angle indentations at various loads.

3.4. Conical indentations on glass C

The plastic deformation in glass C for a 90° conical indentation is shown in fig. 7. At a load of 25 N the subsurface deformation consists of an almost completely recovered compacted zone and some faint traces of semi-circular flow lines near its boundary. Beyond a certain load the size of the featureless central zone remains approximately constant but the semi-circular flow lines collapse into fault-like features and their density increases (figs. 7b and c).

Also for the 136° conical indentations on glass C (fig. 8) the flow line pattern is similar to that of soda–lime glass. However, the pattern is more irregular. High magnification SEM micrographs show that there are rather large differences between the slip lines in glass C (figs. 4b and c) and those in ordinary soda–lime glass (fig. 4a). The serrations in the path of an individual flow line suggest that there are heterogeneities in the glass structure which influence the path of the flow lines. The occurrence of genuine slip along these rather broad flow lines can be inferred from the kink in the flow line illustrated in fig. 4c.

Finally, the plastic deformation in glass C due to 150° conical indentations is shown in fig. 9. Of particular interest is fig. 9c which shows that the path of the semi-circular slip planes is determined by local compositional or structural variations.

4. Discussion

Studies of conical indentations of inorganic silicate glasses raise several interesting questions about the mechanics of deformation processes in amorphous materials. Unlike deformation in metallic glasses, plastic flow in oxide glasses only occurs under a confining pressure, which in these experiments is provided by the indentation stress field. The deformation behaviour is elastic–plastic: the initial elastic compaction of the network at low shear stresses and hydrostatic pressures is recovered almost completely when the load is removed. At high shear stresses permanent densification and genuine

slip occur. The present observations show that two types of flow line occur within the semi-spherical plastic zone:

(i) concentric semi-circular flow lines which indicate a primarily elastic response since these flow lines follow the maximum elastic shear stress trajectories under punch indentations [17,18] and

(ii) intersecting spiral flow lines which resemble the classical slip line field of rigid plastic materials and are therefore indicative of a more plastic behaviour. The transition from a mainly elastic to a more plastic behaviour depends on the glass composition, the applied load and the indenter geometry and will be discussed in more detail.

4.1. Conical indentations on soda-lime-silica glasses

Indentations at low loads with 90° and 150° cones reveal that the permanent compaction or density contours are broad and follow closely the elastic stress trajectories as under punch indentations. There are also traces of broad spiral flow lines at the bottom of the deformed zone which increase in density and extend to the specimen surface as the load is increased. The density of the flow lines is highest for the 136° cone indentations and the deformed zone does not show the central flow line-free zone associated with the 90° and 150° cone indentations. The similarities in the deformation features for 90° and 150° cone indentations in soda-lime glass may be due to the fact that the constraint factor, P/Y (where P is the mean pressure and Y the yield stress), is approximately the same for the two indenter angles. The variation of the constraint factor with the indenter (wedge) angle has been studied for a range of materials by Hirst and Howse [16] and their results are illustrated in fig. 10.

Fig. 10. Variation of the constraint factor, P/Y , as a function of the indenter wedge angle for different materials (after Hirst and Howse [16]). Lead: $E/Y \approx 828$; beryllium-copper: $E/Y \approx 100$; PTFE: $E/Y \approx 23$; nylon: $E/Y \approx 13$.

By suitable interpolation ($E/Y \approx 40$ for soda–lime–silica glasses) the constraint factor for the glasses studied here is probably given by the dashed curve in fig. 10, indicating that at the two cone angles of 90° and 150° the constraint factors are approximately equal. The maximum in the dashed curve, at about 130° – 140° , marks the closest approach to true plastic behaviour and may explain the high flow line density at this wedge angle. It must be pointed out that the Hirst and Howse data are for wedge-shaped indenters but a similar behaviour is expected for pyramidal indenters [16].

Since no continuous in-situ observations of the development of these density contours were made, it can not be said conclusively that the broad density contours develop into the concentric and spiral fault-like flow lines as the load is increased. However, the similarities between the two patterns suggests that this is indeed the case. The development of well-defined faults appears to represent an inherent mechanical instability in the structure around the prospective flow line during the shearing process.

4.2. Conical indentations in fused silica

In the case of fused silica the deformed zone is devoid of any spiral flow lines and only faint and broad semi-circular contours form. This mainly elastic behaviour is probably due to the fact that fused silica can accommodate a large amount of deformation by (elastically) collapsing its open network structure. In this respect the material response resembles that of cork which has been described in detail by Gibson et al. [19]. The observed contours are very similar to those observed for 150° indentations at low loads on “normal” soda–lime glass. It is therefore not obvious that the absence of any flow or fault like features in the deformed zone for cone angle indentations in fused silica represents a truly “anomalous” behaviour.

Another feature of the indentations in fused silica is the steep angle of the cone cracks that nucleate just within or at the edge of the contact area. Similar steep cone angles have been observed by Knight et al. [20] for the impact of steel balls on pyrex. The steep cone angle has been attributed to a loading rate effect which makes the contact area spread out faster than the crack propagation velocity: ring cracks nucleated on the surface at the moment of first contact are engulfed by the expanding compression region under the ball as the contact area increases rapidly. The cone crack will then grow as if it was formed under the contact area; the Boussiniq stress field predicts for this case the observed steeper cone angle. The steep cone angle observed in the present experiments can not be attributed to such a dynamic effect. However, it is proposed that for the conical indentations in high silica content glasses the shear induced compaction of the region beneath the indenter extends to the contact area so that any ring cracks nucleated within or at the edge of the contact zone are made to propagate along steeper stress trajectories by the shear stresses.

4.3. *Different composition glasses*

The dependence of the shearing process on the composition and the microstructure of the glasses has been demonstrated clearly in these experiments. The indentations on glasses A and B show that both spiral and concentric flow lines are broad even at the highest indenter load before fragmentation occurred. The broad flow lines are obviously influenced by the microstructure of the glasses. This broadening of the flow lines is similar to the differences in flow line patterns for fine and coarse-grained zinc sulphide [21]: the smaller the grain size the more localised the displacements and the sharper the flow lines. From the close similarities in the plastic behaviour of glasses A and B it can be concluded that the flow behaviour depends primarily on the SiO_2 concentration. The effect of the glass microstructure is more apparent for 136° cone indentations on glass C which represents a behaviour intermediate between that for fused silica and ordinary soda-lime glass. The concentric flow lines are ill-defined but sharpen up with increasing load and appear segmented. High magnification scanning electron micrographs show that the flow lines appear serrated by the microstructure as in figs. 4b and c. For 150° cone indentations the density of the flow lines is lower but they appear sharper as large displacements occur along the few flow lines. The behaviour of glasses D, E and commercial soda-lime glass was identical.

4.4. *Deformation processes in oxide glasses*

There are several aspects in the deformation processes in silica glasses which are similar to dislocation mechanics in crystalline materials. One of these is the random and heterogeneous nucleation of structures which appear as loops on prospective slip planes. The existence of these loops was inferred from our in-situ observations of the flow lines in the deformed zone of indentations made near the polished edge of soda-lime glass specimens. The observed segments of flow lines which terminate in the bulk can only be sections of loops.

Recently Spaepen [22] has suggested that shear localisation around microscopic density fluctuations in metallic glasses can lead to features which resemble dislocation loops. The subsequent growth of these loops occurs by uncorrelated and non-cooperative movement of little segments of the boundary between slipped and unslipped regions. The propagation of these nuclei may be regarded as a continuous and successive collapse of the structure at the ends of the original nucleus by the high shear stresses. The ends of the collapsed regions may be regarded as dislocation kinks. A similar model has been proposed by Maeda and Takeuchi [23] for the inhomogeneous deformation bands in metallic glasses.

In the case of fused silica the structure may be regarded as a single giant molecule. The effect of the network modifying elements is to "depolymerise" this molecule by introducing weaknesses in the structure and to produce

segments, some of which are weakly bonded to the rest of the structure and can undergo large local displacements under the applied stress. The more strongly bonded units undergo little or no distortion at all. It is proposed that with increasing cation content the average size of the “rigid” segments decreases; leading to more localised shearing for low silica content glasses. A similar decrease in the size of ordered segments has been calculated from viscosity data for various binary silica systems in the molten state [24].

5. Conclusions

Different cone angle indentation studies on a range of soda–lime–silica glasses (ranging from fused silica to 70% SiO₂–15% CaO–15% Na₂O) have shown that the material deforms in an elastic or elastic/plastic manner depending on the glass composition and the indentation pressure. In fused silica the deformation is primarily elastic for all cone angles but the deformation becomes more plastic as the cation content in the silica-based glasses is increased. Because of the special nature of the glass structure, transition from elastic to plastic behaviour with applied load occurs by a change in mode of accommodation of displaced material. At high loads the deformed zone shows both broad elliptical flow lines associated with an elastic stress field and fault-like features similar to the spiral flow lines around an expanding cavity in a rigid plastic material. The width of the spiral flow lines decreases with increasing cation content. In glasses where phase separation occurs, the glass microstructure modulates the flow line trajectories.

The similarity in the elastic deformation features for 90° and 150° indenters suggests that the constraint factors for the two indenters are probably the same. The more plastic behaviour for 136° conical indenters suggests that in this case the constraint factor is close to that for a rigid plastic material.

No direct evidence has been presented for the mechanism of nucleation and propagation of slip in amorphous silicate systems. However, some of the features of the flow lines suggest that they are similar to those for dislocation loop nucleation and propagation in crystalline solids.

We thank Dr E.H. Yoffe for helpful discussions, Drs J.E. Field, M.M. Chaudhri and P.H. Gaskell for comments on the manuscript and Dr A.C. Woodward from Pilkington Bros for supplying the specimens. This work was supported by the Ministry of Defence (Procurement Executive).

References

- [1] J.D. Mackenzie, *J. Am. Cer. Soc.* 46 (1963) 461.
- [2] K.W. Peter, *J. Non-Crystalline Solids* 5 (1970) 103.
- [3] E. Dick, *Glastechn. Ber.* 43 (1970) 16.

- [4] J.T. Hagan and M.W. Swain, *J. Phys. D*: 11 (1978) 2091.
- [5] R.J. Charles, *J. Am. Cer. Soc.* 49 (1966) 55.
- [6] J.S. Hammel, J. Mickey and H.R. Golob, *J. Coll. Interf. Sci.* 27 (1962) 329.
- [7] J.H. Li and D.R. Uhlmann, *J. Non-Crystalline Solids* 3 (1970) 205.
- [8] R.H. Redwine and M.B. Field, *J. Mat. Sci.* 4 (1969) 380.
- [9] E. Vernaz, F. Larche and J. Zarzycki, *J. Non-Crystalline Solids* 37 (1980) 359.
- [10] A. Chlebick, R. Adams and P.W. McMillan, *Phys. Chem. Glasses* 18 (1977) 59.
- [11] M. Wada, H. Furukawa and K. Fujita, 10th Int. Conf. Glass, Kyoto, Japan (1974) paper 11.
- [12] M. Yamane and J.D. Mackenzie, *J. Non-Crystalline Solids* 15 (1974) 153.
- [13] L. Ainsworth, *J. Soc. Glass Techn.* 38 (1954) 479.
- [14] J.T. Hagan, *J. Mat. Sci.* 14 (1979) 462.
- [15] A. Aora, B.D. Marshall, B.R. Lawn and M.V. Swain, *J. Non-Crystalline Solids* 31 (1979) 415.
- [16] W. Hirst and M.G.J.W. Howse, *Proc. Roy. Soc. Lond.* A311 (1969) 429.
- [17] M.C. Shaw and G.J. DeSalvo, *Trans. ASME: J. Eng.* 92 (1970) 469.
- [18] M.C. Shaw and G.J. DeSalvo, *Trans. ASME: J. Eng.* 92 (1970) 480.
- [19] L.J. Gibson, K.L. Easterling and M.F. Ashby, *Proc. Roy. Soc. Lond.* A377 (1981) 99.
- [20] C.G. Knight, M.V. Swain and M.M. Chaudhri, *J. Mat. Sci.* 12 (1977) 1573.
- [21] S. van der Zwaag, J.T. Hagan and J.E. Field, *J. Mat. Sci.* 15 (1980) 2965.
- [22] F. Spaepen, *Acta Met.* 25 (1977) 407.
- [23] K. Maeda and S. Takeuchi, *Phil. Mag.* A44 (1981) 643.
- [24] P. Balta and E. Balta, *Introduction to the Physical Chemistry of the Vitreous State* (Abacus Press, Tunbridge Wells, 1976) p. 160.