Effect of glass composition on plastic deformation and residual stress of oxide glasses using Finite Element Analysis: spherical indentation test

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Understanding indentation-induced stress-fields is of great importance for design of damage-tolerant glass products. In this work, we investigate the deformation behavior and stress development during the indentation process of two archetypical glasses: silica and soda-lime-silicate; a ball indenter was used for the indentation test. Finite Element Analysis (FEA) was used as the main tool to obtain the stress/deformation fields. An elliptical yield surface was used to model the glass plasticity. Raman measurements and geometry of the residual imprints were used for model confirmation. Finally, the effect of glass composition on the simulation results is discussed.

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1. Introduction

Understanding of cracking behavior of glass under indentation is of great importance for designing stronger glass products. Experimental evidence suggests that there is a relationship between plastic deformation ability of glass and susceptibility to radial/median crack initiation under Vickers indentation [1]. Oxide glasses deform mainly by three mechanisms: elastic deformation, densification, and plastic flow. The ratio of each mechanism to the total deformation depends strongly on glass the composition. Having access to quantitative information of each deformation mechanism and stress distributions is very important to predict the types of crack that will be generated during the half load-unloading indentation cycles. FEA has demonstrated to be an effective method to predict stress distribution of microtests such as indentation in silica glass, however, there are no previous work regarding simulation of indentation of glass using ball indenter [2]. Sphere indentation generates stress distributions in the glass that differs much from those observed in sharp indentation. This mechanical test may provide new insights about oxide glass plasticity. In this work, the spherical indentation behavior of silica glass and soda-lime silicate glass were simulated by means of FEA.

2. Experimental

Spherical indentation experiments were performed on silica and SLS glass plates. A spherical diamond indenter with a tip radius of 47 μm, was used. Indentation experiments were performed at different loads from 100gf (0.9087N) up to 700gf (6.864N). The geometry of the imprints was measured using white-light interferometry. Raman experiments were performed in order to measure the densification distribution within the plastic zone. For this purpose the half-integral method was used [3]. A numerical approach to the indentation experiment was made using FEA. Solid models were built for the indenter and sample using an axisymmetric approach. The plasticity of the glass was modeled using an elliptical yield surface, which has been found to reproduce well the plastic deformation of silica glass [2]. The stress-state was monitored for each glass during the simulation (half loading-unloading cycle).

3. Results and discussion

The cross-section depth-profiles (geometry) of silica and SLS glasses and the residual depths at different loads were obtained using white-light interferometry. The residual depth increases with indentation load being larger for the case of SLS glass (at every load). Ring cracks were observed upon unloading depending on applied load. The threshold for ring crack formation was smaller for the case of SLS (300gf) compared to silica glass (600 gf). The measured and calculated (FEA) densification-depth profiles for the two different glasses are shown in **figure 1**. For silica glass, the experimental densification reached a maximum of 10%, while for the SLS glass the densification reached a maximum of 3.5%. The maximum densification values agree well with the Raman results for the case of SLS but are underestimated in case of silica glass. The plasticity model used in this work has shown to reproduce well sharp indentation but it seems to fail to reproduce the spherical indentation test. Our results suggest that the permanent volumetric plastic strain needs to be enhanced in the current plasticity model. The maximum tensile stresses were calculated from FEA for each glass as a function of load. Since tensile stresses might be the origin of cracks, we focused only on the tensile stresses. Radial stress σ_r is associated with ring/cone crack formations, axial stress σ_z is associated with lateral crack formation, and hoop σ_θ stress is associated with radial/median crack formation. Our first observations from the simulation results do not show a clear difference in stress values between both glass systems, although the type of formed cracks (experimentally) can be inferred from the stress distribution. The plasticity models could be further improved. In particular, the densification maximum is underestimated in the case of silica glass. Other options such as non-associative plasticity must be considered in future calculations.

4. Conclusions

Spherical indentation test was performed experimentally and through FEA on silica and SLS glasses. The maximum densification of silica obtained through FEA was underestimated compared to the Raman results but gave a better agreement for the case of SLS. No clear differences in the stress distributions among the glass compositions were observed in the simulations but the most probable cracking type could be inferred from the simulation results.

5. References

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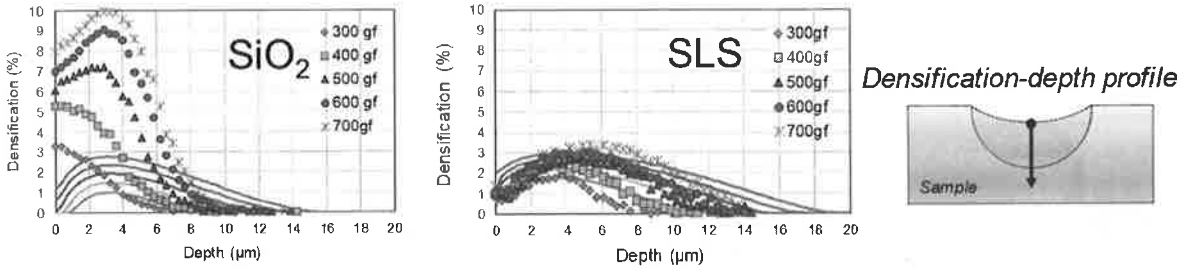

Figure 1. Densification-depth profiles for silica and SLS glasses at different loads. The symbols correspond to experiment (Raman) and the solid lines to the calculations using the elliptical model. [2].