High strain rates at high temperatures: new perspectives on the microplasticity of fused silica

Remo N. Widmer[1a], Alexander Groetsch[2], Guillaume Kermouche[3], Ana Diaz[4], Manish Jain[2], Rajaprakash Ramachandramoorthy[5], Laszlo Pethö[2], and Johann Michler[2]

[1] Alemnis AG, 3602 Thun, Switzerland.
[2] Empa - Swiss Federal Laboratories for Materials Science and Technology, 3602 Thun, Switzerland.
[3] Mines Saint-Etienne, CNRS, F-42023 Saint Etienne, France.
[4] Paul Scherrer Institute, 5232 Villigen PSI, Switzerland.
[5] Max-Planck-Institut für Eisenforschung GmbH, 40237 Düsseldorf, Germany.

[a]remo.widmer@alemnis.ch

Abstract. The ability to predict the micro-scale strength and plasticity of fused-silica micro-components is crucial as their miniaturization and applications in harsh environments advance. This study focusses on the micro-mechanical behaviour of fused silica micropillars at high temperatures and variable strain rates. Recent progress in additive manufacturing and laser-based lithography is now enabling the efficient and precise fabrication of complex micrometer-sized glass components [1], [2]. The tailorable functional properties of such glasses in combination with their excellent chemical and thermal stability led to myriad technological applications, including in sensors, micro-fluidics, medical technology, data storage, and photonics. As the miniaturization of glass components progresses, one begins to encounter important size-effects. Below a certain length scale, the mechanical behavior of microscopic glass parts is no longer predictable based on classical knowledge of bulk-mechanical properties. This is because the probability of occurrence and the size of structural and mechanical flaws decrease together with the tested volume. As a result, the material can now be loaded up to its intrinsic yield strength while averting brittle failure.

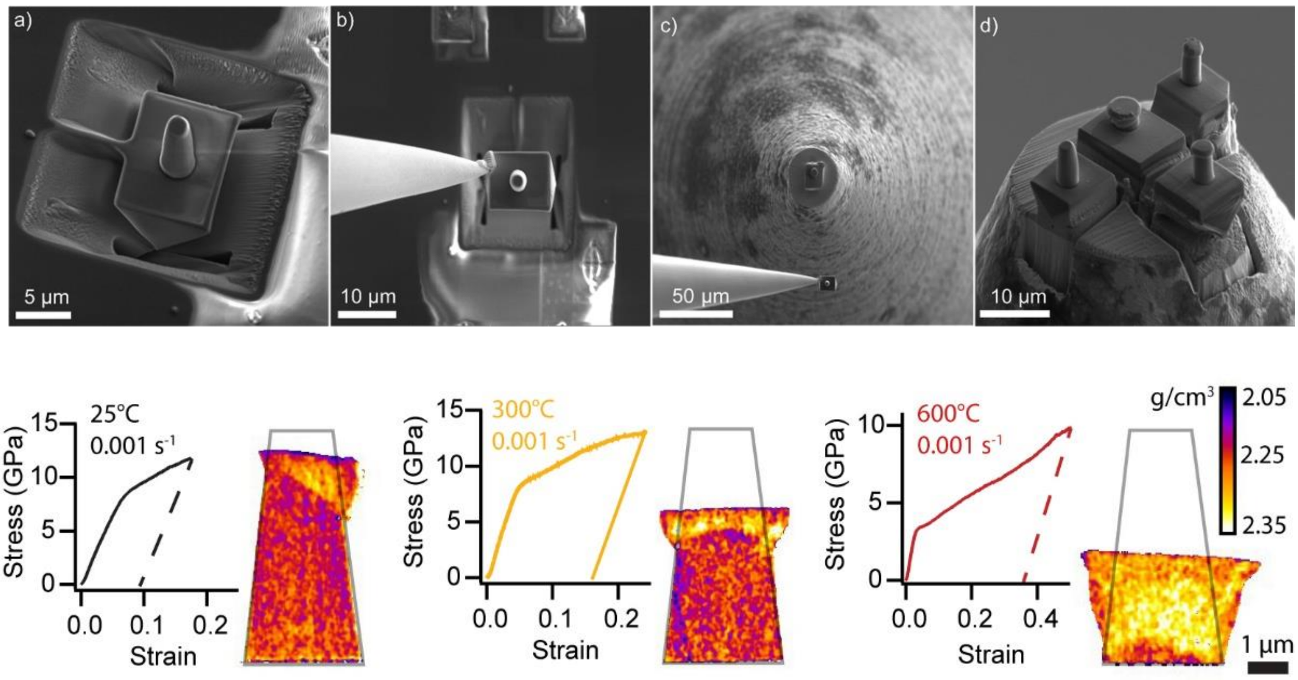

Fig. 1: Top: Lift-out procedure and sample preparation for nano-tomography measurements of deformed fused silica micropillars. Bottom: Stress-strain curves and nano-tomographic density reconstructions of fused silica micropillars deformed at variable temperatures.

One consequence is that glass under this condition can be plastically deformed, and intrinsic deformation mechanisms can be observed, based on the atomic interaction only. The three fundamental deformation mechanisms that accommodate plasticity under such conditions are: (1) volume-conservative homogeneous shear flow (2) volume-conservative localized shear banding, and (3) non-volume-conservative structural densification. All three deformation mechanisms can occur either isolated or combined. The relative contributions depend on external parameters such as the shape of the stress-field, the temperature, or the strain rate. Despite the technological relevance, the interplay of these mechanisms remains poorly understood and has still unexpected outcomes. [3], [4], [5], [6]

Motivated by the lack of understanding of (1) fundamental properties at high temperatures and (2) the potential adverse effects of operating temperatures and loading conditions on the mechanical performance in applications, we have tested 160 micro-pillars with a diameter of 1.6 µm at temperatures between -120°C and 600°C and strain rates between 10^{-3} s^{-1} and 1 s^{-1}. Moreover, we have carried out post-compression synchrotron-based ptychographic X-ray computed tomography (PXCT) on a subset of these plastically deformed micro-pillars. Finally, we simulated the mechanical behavior at ambient temperatures by FEM.

We found a non-linear temperature dependence for both the absolute yield strength and the strain rate sensitivity of the yield strength. Between -120 °C and 300 °C, the yield strength (6–8 GPa) and strain-rate sensitivity (≤ 0.03) varied only marginally. However, at 600 °C, we observed a significant decrease in yield strength (2.5–4.5 GPa), accompanied by an increase in strain-rate sensitivity to 0.09. The corresponding deformation mechanisms appear to transition as follows: shear-banding and shear-promoted densification at 25 °C; constrained densification and homogeneous shear-flow at 300 °C; and extensive densification and unconstrained shear-flow at 600 °C. The FEM calculations suggest that the strain localizations at 25°C and 300°C is due to taper.

These results suggest that the classification of fused silica as a glass that deforms predominantly through densification [2] should be challenged, at least under unconstrained compression. The degree of densification does not significantly vary as a function of strain, pointing at a significant contribution of shear flow. The results provide a new perspective on the interplay of deformation mechanisms that accommodate plasticity in glasses at high temperatures. Importantly we also introduce the use of a novel X-ray nano-tomography technique that now matches the required contrast and spatial resolution to investigate plasticity enabling mechanisms in amorphous materials.

References

[1] F. Kotz, et al. *Three-dimensional printing of transparent fused silica glass,* Nature, Vol. 544 (2017) p 37-339.

[2] D. G. Moore et al.: *Three-dimensional printing of multicomponent glasses using phase-separating resins,* Nature materials, Vol 19 (2020) p 212-217.

[3] S. Bruns, et al.: *Indentation densification of fused silica assessed by Raman spectroscopy and constitutive finite element analysis,* Journal of the American Ceramic Society, Vol. 103 (2020) p 3076-3088.

[4] T. Vo, et al.: *Effect of domain size, boundary, and loading conditions on mechanical properties of amorphous silica: A reactive molecular dynamics study,* Nanomaterials Vol. 10 (2019) p 54.

[5] O. Benzine, et al*.: Local deformation of glasses is mediated by rigidity fluctuation on nanometer scale,* Advanced Science Vol 5 (2018) p 1800916.

[6] C. Martinet, et al. *Highlighting the impact of shear strain on the SiO2 glass structure: From experiments to atomistic simulations*, Journal of Non-Crystalline Solids Vol. 533 (2020) p.119898.