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To cite this version:


HAL Id: jpa-00222515

https://hal.archives-ouvertes.fr/jpa-00222515

Submitted on 1 Jan 1982
VISCOUS FAILURE OF GLASS AT HIGH SHEAR RATES

J.H. Simmons, R.K. Mohr and C.J. Montrose

Department of Physics, the Catholic University of America,
Washington D.C. 20064, U.S.A.

Résultat. - La viscosité d'un verre silico-sodo-calcique a été mesurée pour des vitesses de cisaillement élevées; un comportement "pseudo-élastique" a été observé. L'analyse des résultats montre que l'augmentation de la vitesse d'écoulement résulte d'un réarrangement structural. Une contrainte de rupture caractéristique est découverte, elle correspond au passage du comportement ductile au fragile.

Abstract. - The viscosity of a soda-lime-silica glass was measured at high shear rates and "pseudo-plastic" behavior was observed. An analysis of the data shows that the increased flow results from structural rearrangements in the glass. A characteristic failure stress is discovered and is related to a transition from ductile to brittle behavior.

Introduction. - At high temperatures, glasses act as either viscous liquids or rigid solids in response to an applied stress. A stress applied at a rate faster than the relaxation rate of the glass will induce a brittle response, while a slower stress application leads to a ductile response. The relaxation rate of a glass is temperature dependent. Over a limited temperature range, the average relaxation time generally follows the simple Arrhenian behavior:

$$\tau_0 = Ae^{-E/kt}$$  \hspace{1cm} (1)

with $E$ as the activation energy and $A$ a pre-exponential constant. More accurately, the average relaxation time follows the temperature dependence of the viscosity, $\eta$, as:

$$\tau_0(T) = \frac{\eta(T)}{G_\infty}$$  \hspace{1cm} (2)

where $G_\infty$ is the solid or infinite frequency modulus of the glass which has a relatively small temperature dependence.

The theoretical strength of a glass under an applied stress, therefore, depends upon the temperature and the rate of stress application. The measured strength further depends upon surface conditions such as existing cracks or chemical reactions at the surface or at crack tips.
In the experiments reported here, we applied the stress at slow rates and, thus measured the ductile response of the glass. However, when failure occurred, it appeared to be by brittle fracture. The details of the experiment are shown, and the interpretation of the results indicate a mechanism for a ductile/brittle transition.

Experiment. - Soda-lime-silica glasses were drawn into thin fibers 0.2 to 2 mm diameter and were stretched at a constant strain rate, \( \dot{\varepsilon} \), in an Instron test machine. A small furnace heated 10 cm of the fiber length and limited the stretching to that region (see Fig. 1). The shear viscosity of each fiber was calculated by measuring the resulting uniaxial stress, \( \sigma \):

\[
\eta = \frac{\sigma}{3\dot{\varepsilon}}
\]

The constant reduction in diameter of the fiber during stretching was calculated as in Ref. 2.

![Experimental Setup Diagram]

Fig. 1 - Schematic of furnace with 2 end heaters showing the position of the fiber. The temperature was constant \( \pm 2^\circ C \) inside the furnace.

Measurements were conducted from \( 10^{11} \) Pa to \( 10^{14} \) Pa. At low strain rates, the viscosity was observed to be independent of strain rate (Newtonian viscosity). However, as the strain rate was increased, the measured viscosity decreased (pseudo-plastic behavior) as shown in Fig. 2.

![Viscosity vs Strain Rate Graph]

Fig. 2 - Non-linear dependence of viscosity, \( \eta \) as a function of strain rate, \( \dot{\varepsilon} \). The normalization constants are \( \eta_0 \), the Newtonian viscosity and \( \tau_0 \), the glass relaxation time.
When strain rates were applied which caused pseudo-plastic behavior, the measured stress increased with time to a maximum (stress overshoot), then decreased to a time-independent (steady-state) value. The stress overshoot was more pronounced and occurred more rapidly at higher strain rates. The steady-state stress, \( \sigma_s \), increased with increasing strain rate, \( \dot{\varepsilon} \), however, it approached a limiting stress, \( \sigma(\text{limit}) \), asymptotically as shown in Fig. 3 following the equation:

\[
\sigma_s = \frac{3\dot{\varepsilon}\eta_0}{[\sigma(\text{limit}) + \dot{\varepsilon}\eta_0]^3}
\]

where \( \eta_0 \) is the Newtonian viscosity of the glass. The value of \( \sigma(\text{limit}) \) is therefore interpreted as the stress for which the material cannot sustain a finite strain rate and it appears to be the cohesive strength of the glass. A value of uniaxial limiting stress was calculated at \( 4.12 \times 10^8 \) Pa for the glass near 560°C with a viscosity of \( 10^{11} \) to \( 10^{12} \) poise, and \( 5.2 \times 10^8 \) Pa at 535°C where the viscosity is \( 6 \times 10^{13} \) P.

During the tests, the fibers failed by a localized necking in the furnace followed by brittle fracture of the glass. It appears that as the fiber is stretched in the furnace, its diameter decreases uniformly over its hot length. At failure, an instability is formed which causes a localized part of the fiber to thin down more than the rest. This causes an increase in local stress which increases the strain rate and induces a greater deviation from Newtonian behavior. The effect is a runaway reduction in diameter with an accompanying increase in the local stress. When the stress reaches the value of \( \sigma(\text{limit}) \) the fiber then breaks by brittle fracture. This result was confirmed by measuring the diameter of a broken fiber in the necked-down region and calculating the breaking stress at 535°C to be approximately \( 6 \times 10^8 \) Pa, relatively close to the calculated value of \( \sigma(\text{limit}) \).
Discussion. - Calculations of stress-strain rate relationships in a simple, computer-model "glass" by molecular dynamics (MD) show the same viscosity behavior as the soda-lime-silica glass with the existence of a cohesive strength, $\sigma_{\text{limit}}$ which the measured stress approaches asymptotically. In the computer modeling work, it was possible to determine the glass structure and it was found that both the stress overshoot and the pseudo-plastic viscosity were due to a rearrangement of the glass structure under the applied deformation. It appears, therefore, that for a given temperature and viscosity, a glass stretched at high strain rates will rearrange its structure to ease the stretching and will respond in a ductile manner to the applied stress. However, if the applied stress becomes larger than the cohesive strength of the glass for this particular temperature and structure, the glass response changes and brittle fracture occurs.

References