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Plastic yielding of glass in high-pressure torsion apparatus

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Abstract

Hardness measurements performed at room temperature have demonstrated that glass can flow under elevated pressure, whereas the effect of high pressure on glass rheology remains poorly quantified. Here, we applied a high-pressure torsion (HPT) apparatus to deform SCHOTT SF6[®] glass and attempted to quantify the effect of pressure and temperature on the shear deformation of glass subjected to pressures from 0.3 GPa to 7 GPa and temperatures from 25 °C to 496 °C. Results show that the plastic yield deformation was occurring during the HPT experiments on the SF6 glass at elevated temperature from 350 °C to 496 °C. The yield stress of SF6 glass decreases with increasing temperature and decreasing pressure. An extended Arrhenius model with one set of parameters, namely infinite yield stress $Y_0=0.17\pm0.1$ GPa, activation energy $E_a=4.8\pm0.5$ kJ/mol and activation volume $V_a=1.4\pm0.2$ cm³/mol, can explain the experimental results well.

Keywords: Plastic yielding; glass flow; pressure; high-pressure torsion.

1. Introduction

The viscosity of glass at different temperature regions under ambient pressure has been well studied¹, and numerous models for the temperature dependence of viscosity have been developed that fit the experimental data well^{2, 3, 4, 5, 6, 7, 8}. On the other hand, hardness measurements^{9, 10, 11} performed at room temperature have demonstrated that glass can flow at room temperature under elevated pressure. Yet the actual pressure level and its distribution in the glass underneath an indenter and its consequences on the mechanical behavior remain poorly understood^{12, 13}.

The importance of understanding both the temperature and the pressure dependence of the viscosity of the glass is connected to the fact that density strongly relates to the dynamics of the fluid¹⁴. Several experimental and modeling studies focused on the effect of pressure on the viscosity of glass^{15, 16, 17, 18, 19, 20, 21}. In our previous work²², the effect of pressure on density and volume recovery of SCHOTT N-BK7[®] glass has been studied, and a two-internal-parameter relaxation model was developed, that predicts a linear increase of viscosity with pressure. Moreover, uniaxial deformation experiments²³ on SCHOTT N-BK7[®] glass have also been performed in a Paterson press²⁴, which is an argon gas medium hot press with a compression deformation mechanism, are in general agreement with the prediction of the two-internal-parameter relaxation model²² at the pressure range of 0.1 GPa-0.3 GPa.

On the other hand, viscous flow is not the only deformation mechanism for materials under high pressure. A deformation via plastic yield is widely reported in many

deformation experiments on polymers²⁵, alloys²⁶, and metallic glass^{27, 28}. The atomistic origin for the plastic yield criterion for metallic glass under pressure is discussed by Schuh & Lund²⁹, which generally supports the plastic yield behavior in amorphous materials. Amorphous materials, including glass, lack the microstructural defects which facilitate plastic flow in crystalline materials, and thus potentially have a much higher yield stress in a plastic yield deformation, e.g., up to 3 GPa for oxide glass³⁰ and ~0.5 GPa³¹ to 5 GPa³² for metallic glass. However, industrial oxide glass typically has a low fracture toughness, on the order of $1 \text{ MPa}\cdot\text{m}^{0.5}$, and consequently, brittle fractures usually occur much earlier than plastic yielding.

High-pressure torsion (HPT) is a well-known method to induce severe plastic deformation^{33, 34, 35, 36}. For scientific purposes, it is one of the best methods as it allows for the controlled generation of high pressures and large strains at a number of exterior physical parameters such as strain rate and temperature. Thus, HPT is ideal for highly reproducible experiments under rather extreme conditions. To the knowledge of the authors, the HPT deformation experiments have not yet been conducted on an optical glass before. In this work, we applied HPT to deform the SCHOTT SF6[®] optical glass by torsion at very low rotations speeds and at different temperatures to study the flow of glass under high pressure and as a function of temperature.

2. Experimental

2.1 Samples

The alkali-lead-silicate glass SCHOTT SF6[®] (chemical composition³⁷: 27.3 % SiO₂, 1.5 % K₂O, 71 % PbO) is an optical glass widely used as photonic crystal fiber^{38, 39, 40} for efficient spectral broadening at high repetition rates (several GHz). The density of SCHOTT SF6[®] glass at room temperature and ambient pressure is 5.180 ± 0.001 g/cm³. The glass transition temperature T_g of the SCHOTT SF6[®] glass is 417 °C, which is the temperature at which the viscosity is $12 \log_{10}(\text{Pa}\cdot\text{s})$. The SCHOTT SF6[®] glass specimens with diameters of 6.0 ± 0.02 mm and 10.0 ± 0.02 mm and thickness of 0.54 ± 0.02 and 0.62 ± 0.02 mm were used for the HPT experiments. All glass specimens were ground with a 59 μm sandblast grinding apparatus resulting in uniform surfaces and edges. The surface and edge condition of the glass specimens were investigated under the microscope, and one example of SF6[®] glass is shown in Fig.1 (b).

The composition dependence of glass rheology is not the topic we study in this work. We choose SCHOTT SF6[®] glass for these experiments mainly due to its low glass transition temperature combined with the good stability of the material properties. The temperature limit for the present HPT setup is ~ 540 °C due to the softening of the anvil steel Boehler S390 MC around that temperature in combination with the loads applied. The SCHOTT N-BK7[®] glass used in our previous work^{22, 23} with $T_g = 561$ °C is not suitable for the HPT deformation experiments.

Fig.1 (a) Schematic graph of high-pressure torsion apparatus in this work; (b) Microscope image of the glass sample.

2.2 Test equipment and experimental process

The high-pressure torsion (HPT) apparatus used in these experiments is a Klement HTP pre-series machine, with the same basic design as described in Vorhauer et al.³⁴ and Wetscher et al.⁴¹, a sketch of the principle of operation of HPT is shown in Fig.1 (a). Two anvils are pressed against each other with the (glass) sample in between thus applying a hydrostatic pressure. The contact surfaces between sample and anvil can be both flat (unconstrained HPT), both with identical cavities or with asymmetric cavities (quasi-constrained HPT). The unconstrained HPT configuration is most similar to a classical rheometer, whereas the symmetric cavities are most common and correspond closest to a true hydrostatic loading of the sample. During the initial uniaxial compression, a burr forms in the gap between the anvils on the rim of the cavity providing a sealing of the sample as well as preventing the anvils from touching which results in the measurement of the friction of the anvils instead of the load on the samples. In the present case for a proper formation of the burr, the total depth of both cavities was determined to be

approximately 20% smaller than the thickness of the glass sample. With this experimentally determined value, only a small amount of the material freely flows into the burr during the initial part of the experiment.

After the application of pressure, the lower anvil is rotated at nominal 0.01 rounds per minute (RPM), which causes the sample to transmit a torque on the upper anvil and its holder. A self-built torque-sensor consisting of four strain-gauge half-bridges from HBM connected to two full bridges in averaging configuration is used to measure the torque needed to deform the sample. Before each set of experiments, the raw physical value (mV/V) of the strain-gauge signal was calibrated using a standard Gedore torque-wrench at 50 Nm and 100 Nm, with a limiting precision of 2% without any pressure applied. The calibration was also monitored randomly between experiments. The effect of the hydrostatic loading on the torque signal (zero-shift) was also recorded (it is smaller than one percent) and subtracted from the signal before evaluation.

The hydrostatic load was recorded as the pressure in the piston and as the load transmitted via the sample to an HBM C2A load-cell directly in N. The present machine is designed to provide controlled pressure application from 1-10 GPa, depending on the sample diameter.

In this work, firstly, a set of 6 mm diameter glass samples was used to investigate the pressure range from ~ 3 GPa to ~ 7 GPa. A second set, with improved torque-sensor and the cooling system, aimed to achieve lower pressures by using 10 mm samples for pressures from ~ 1 GPa to ~ 3 GPa (by automatic loading). Also using 10 mm samples for

~0.3 GPa pressure were obtained by manual loading, bypassing computer control of the pressure.

An important parameter in the present case is the sample temperature: Heating was performed using a Hüttinger induction heater, symmetrically heating the anvils. The temperature control and monitoring were done by using a Sensortherm pyrometer with a control unit capable of detecting temperatures above 75 °C. The control window of the setup is below 0.5 °C. A reference measurement using a thermocouple in a copper disc in place of the sample showed that the sample lags at most two minutes behind the Pyrometer data (large deviation at low temperatures). The overall uncertainty of the temperature is about ± 5 °C.

The procedure of the current experiment was as follows: firstly, both cavities of the two anvils were sandblasted with 250 microns quartz sand. Then, the glass specimen was placed in the lower anvil and lifted to a bare touch of the upper anvil, and the samples were heating to the initial temperatures ranging from 350 °C to 496 °C. After waiting the experimentally determined two minutes, the pressure from 0.3 GPa to 7 GPa was applied via uniaxial loading. Finally, the deformation was started with the nominal speed of 0.01 RPM, which turned out to be 0.0096 RPM as calculated from the data recorded over several minutes.

To verify the reproducibility of the data, for each sample heating cycles were performed, between the chosen temperatures thus checking the consistency per sample. Additionally, the whole experiment was repeated on another sample.

Furthermore, an experiment at room temperature and a pressure of 3 GPa was also performed. In order to be able to compare with measurements in a rheometer and to judge the effect of the burr, also flat anvils were used for one deformation.

To isolate the effect of the pressure on the torque one experiment at 435°C, 10 mm diameter sample was performed, stepwise increasing the pressure from 0.3 to 5.1 GPa once the torque readout stabilized.

2.3 Data analysis

For a torsional deformation, the glass sample could be deformed as a viscous flow¹ or via a plastic yielding²⁹.

2.3.1 Approach 1: viscous flow

For a viscous flow, the viscosity is constant when the deformation reaches steady state, and the viscous strain rate, stress, and viscosity can be calculated by

$$\dot{\epsilon}(r) = \frac{2\pi r f}{H} \quad (1)$$

$$\tau(r) = \eta \dot{\epsilon}(r) = \eta \frac{2\pi r f}{H} \quad (2)$$

$$M_T = \int_0^R 2\pi r \cdot \tau(r) \cdot r dr = \frac{\eta \pi^2 R^4 f}{H} \quad (3)$$

$$\eta = \frac{M_T H}{\pi^2 R^4 f} \quad (4)$$

where $\dot{\epsilon}(r)$ is the change of strain with time at a radius r , $\tau(r)$ is the shear stress at a radius r , η is the viscosity, M_T is the measured torque, f is the frequency of the rotation (converted to SI-units via RPM/60), H is the thickness of the sample, and R is the outer radius of the sample.

2.3.2 Approach 2: shear yielding

For a yield deformation, the shear yield stress Y is not dependent on the radius, and therefore

$$M_T = \int_0^R 2\pi r \cdot Y \cdot r dr = \frac{2\pi R^3 Y}{3} \quad (5)$$

$$Y = \frac{3M_T}{2\pi R^3} \quad (6)$$

And the friction coefficient can be calculated as

$$\mu = \frac{Y}{P} \quad (7)$$

where P is the uniaxial pressure (normal stress).

3. Results

The experimental conditions and the measured mechanical data are provided in Table 1. The number of the aforementioned repetition stages per experiment and their changes, as well as the resulting deviation of the measured values together with the nominal, identical experimental parameters, are reported in Table 1.

Most importantly, torsional experiments could be performed on SCHOTT SF6® glass under pressures from 0.3 GPa to 7.4 GPa, the work necessary to maintain the deformation could be monitored accurately via the torque measured as shown in Fig.2. The experiments at 435 °C (black curve) show that the torque increases approximately proportional to the pressure from 137 N·m at 1.1 GPa to 307 N·m at 5.1 GPa. However, in another experiment at a pressure of 7.4 GPa, the measured torque at 435 °C increased dramatically high to nearly 776 N·m. Subsequent visual inspection of sample and anvils,

showed that the top and bottom anvils had touched together at this high pressure, and a clear deformation band of approximately 18 mm in place of the rims of the cavities had appeared, as is visible in Fig.2.

Fig.2 Mechanical torque curves of SF6 glass measured at different pressures and setups. The digital photo shows the status of anvils after the experiment at 7.4 GPa (red curve).

The bottom piston of the HPT with anvil diameter of 10 mm could automatically lift and smoothly deform the sample at the pressure above 1 GPa. To obtain a lower pressure, the bottom piston was manually lifted until a load was detected by the upper load sensor, corresponding to 0.3 GPa, and subsequently, the deformation was started. To better judge the torque measurements via HPT in the current context, two anvils were machined to flat

surfaces, allowing an experiment in the HPT equipment with the ideal rheometry configuration. The flat-anvil measurement reported in Fig.2 reaches a similar torque value as the one measured with the quasi-constrained setup (with burrs). However, the curve also shows that the deformation was not as stable as for the higher pressures, most likely connected with some sliding occurring.

The raw torque curves from the HPT deformation measurements are shown in Fig.3. The deformation experiments at a constant torsional speed of 0.0096 RPM and different temperatures, pressures and anvil diameters reach steady state torques from $\sim 50 \text{ N}\cdot\text{m}$ to $\sim 275 \text{ N}\cdot\text{m}$. To determine the pressure dependence, we conducted automatic loading experiments at uniaxial pressures ranging from $\sim 1 \text{ GPa}$ to $\sim 7 \text{ GPa}$. At the same temperature, the torque is approximately increasing linearly with elevated pressure of $\sim 40 \text{ N}\cdot\text{m/GPa}$ using 10 mm samples and $\sim 15 \text{ N}\cdot\text{m/GPa}$ for 6 mm samples.

Fig.3 Original mechanical torque data from the HPT measurements of SF₆ glass. For all curves, 1 data point out of every 600 points is shown for clarity.

An overview of the temperature dependence is well observable in Fig.3. At the same pressure, the temperature reduction from 496 °C to 435 °C is accompanied by a torque increase of around 25 N·m is observed in the setup of 10 mm anvils. The temperature decrease from 435 °C to 350 °C is accompanied by a torque increase of around 27 N·m. However, the significant temperature change yields only slight influence on the torque measurements in 6 mm setup. Besides, the torque does not even change significantly when the glass sample is quenched to room temperature.

The torsional experiment was also done at room temperature at 3 GPa, during which a big cracking noise was heard at the beginning of the deformation. A clear yielding point

in the torque data of approximately 185 N·m is seen in Fig.4. After the yielding point, the torque is gradually decreasing to around 164 N·m and reaches steady state. It must be noted that the torque measured at room temperature at 3 GPa is even ~40 N·m lower than at 496 °C. A pause test was done in this experiment by stopping the rotation of the HPT machine. The torque subsequently decreased gradually, and it recovered to the same level (as before the pause) once the deformation was turned on. After the deformation, a large amount of fine glass powder generated in the anvil (especially the burr area) was observed. A possible explanation of this experiment is discussed in the shear yielding part.

Fig.4 Torque measurement of SF6 glass at room temperature and high temperatures under 3 GPa. For all curves, 1 data point out of every 220 points is shown for clarity.

4. Discussions

4.1 Approach 1: viscous flow

Assuming that viscous flow is the predominant deformation mechanism in the present experiments on SCHOTT SF6[®] glass, the corresponding viscosity was calculated. The 3D plot in Fig.5 gives an overview of the temperature and pressure dependence of the HPT torque evaluated viscosity of SF6 glass. The temperature change from 350 °C to 496 °C is accompanied by a maximal torque evaluated viscosity change from 10.8 Log₁₀(Pa·s) to 11.7 Log₁₀(Pa·s) only, which is entirely different to the black curve at ambient pressure, where the change is from 16.2 Log₁₀(Pa·s) to 8.0 Log₁₀(Pa·s). Indeed, the influence of the pressure on the viscosity is rather small of only approximately 0.1 Log₁₀(Pa·s)/GPa. Specifically, the viscosity of SF6 at 435 °C and 1 GPa is 10.87 Log₁₀(Pa·s), which is even slightly lower than the viscosity at 435 °C at 1-atm of 11.01 Log₁₀(Pa·s).

Fig.5 HPT torque evaluated viscosity-temperature-pressure 3D plotting of SF6 glass samples compared to the viscosity at 1-atm.

To answer the question if the viscous flow dominates the HPT deformation of SF6 glass, as well as to explain the experimental data, consider the following two cases:

4.1.1 Viscous flow induced by dissipative heating

A significant temperature increase can occur during HPT deformation, depending on the rotation speed^{42, 43}. The high pressure (load) may produce viscous heating, and therefore have similar equivalent viscosities, independent of the ambient parameters. If we assume a pure viscous shear heating, the dissipative heating rate is

$$q_{diss} = \int_0^R 2\pi r \cdot \tau(r) \cdot \dot{\epsilon}(r) \cdot dr \cdot H = \frac{2\eta\pi^3 R^4 f^2}{H} = 2\pi f M_T \quad (8)$$

which under stationary thermal conditions has to be equal to the dissipative heat loss rate of

$$q_{loss} = q_{diss} = \kappa A \Delta T_{diss} \quad (9)$$

where κ is the heat transfer coefficient depending on the material and cooling rate of anvils, $W/(m^2K)$, $A=2\pi R^2$ is the heat transfer area (upper and lower sample surfaces), and $\Delta T_{diss} = T_{sample} - T_{measured}$ is the additional temperature difference between the sample the temperature reference point. We assume a κ of 37 $W/(m^2K)$ for all the SF6 glass experiments and calculate the dissipative shear heating induced temperature increase reported in Fig.6. The calculated temperature increase is too low for some of the measurements at 350 °C and too high for some of the measurements at 496 °C. Thus, this simple assumption with a constant κ does not explain all measurement results. We expect that the overall result does not change if we account for the change of material properties at elevated pressure. Therefore, we stay at the simplest calculation with a constant κ .

Fig.6 Calculated dissipative shear heating induced temperature increase of SF6 glass as a function of pressure ($\kappa=37 \text{ W}/(\text{m}^2\text{K})$).

Additionally, the experiments were performed at a nominal deformation speed of 0.01 RPM. Extrapolating the Results from Edalati et al.⁴² and Zhilyaev & Langdon⁴³ to the speed we applied in this work shows only small heating is to be expected. Using the Vickers hardness $HV=3.6 \text{ GPa}$ and $\omega=f=0.0096 \text{ RPM}$ for the present case gives only $2 \text{ }^\circ\text{C}$ heating at 2 GPa and $7 \text{ }^\circ\text{C}$ heating at 6 GPa .

In summary, viscous flow induced by dissipative heating is not the main mechanism for the deformation of SF6 glass via HPT.

4.1.2 Viscous flow induced by elastic energy

The elastic energy which is greatly influenced by pressure might also govern the viscous flow of glass in our work. The elastic energy in HPT consists of the elastic shear stress (deviatoric), and the hydrostatic stress (volumetric). E_1 accounts for the shear stress (deviatoric)

$$\frac{1}{H} E_1 = \int_0^R 2\pi r \cdot \frac{1}{2} \sigma_{xy} \delta_{xy} \cdot dr = \int_0^R 2\pi r \cdot \frac{1}{2G} \left(\eta \frac{2\pi r f}{H} \right)^2 \cdot dr = \frac{M_T^2}{\pi G R^4} \quad (10)$$

where R , H , f , M_T and η are the same as in section 2.3, σ_{xy} is the shear stress, δ_{xy} is the shear strain, G is the shear modulus.

And E_2 accounts for the hydrostatic stress (volumetric). In this work, we assume

$$\frac{1}{V} E_2 = \frac{1}{2} \sigma_{hyd} \varepsilon_{hyd} = \frac{1}{2} \frac{P^2}{K_{ref}} \quad (11)$$

where σ_{hyd} is the hydrostatic stress, ε_{hyd} is the bulk strain, P is the hydrostatic pressure, K_{ref} is the reference bulk modulus at ambient pressure.

Thus, we obtain the total elastic energy:

$$\frac{1}{V} E = \frac{1}{V} E_1 + \frac{1}{V} E_2 = \frac{M_T^2}{\pi^2 G R^6} + \frac{1}{2} \frac{P^2}{K_{ref}} \quad (12)$$

To assess the equivalent temperature increase ΔT_{elas} ,

$$E = \rho C_p \Delta T_{elas} \quad (13)$$

is used, where ρ is the density measured at room temperature and pressure, and C_p is the heat capacity measured at room temperature and pressure. The resulting ΔT_{elas} as a function of pressure shown in Fig.7. The calculated equivalent temperature increase at pressures lower than 3 GPa is smaller than 85 °C which cannot explain the data. Therefore, viscous flow activated by elastically stored energy is thus also not the main mechanism for the deformation of SF6 glass via HPT.

Fig.7 Calculated elastic energy induced temperature increase of SF6 glass as a function of pressure.

4.2 Approach 2: shear yielding

To account for the temperature influence on the yield stress, Raghavan et al.²⁶ used the Arrhenius model

$$Y = Y_0 e^{\frac{E_a}{RT}} \quad (14)$$

In this work, we extend the Arrhenius equation to Eq. (15) by introducing an activation volume as has been reported in other studies^{22, 44} to account for the pressure effect.

$$Y = Y_0 e^{\frac{E_a + PV_a}{RT}} \quad (15)$$

where Y_0 is a hypothetical yield stress at infinite temperature, E_a is the activation energy,

and V_a is the activation volume. To keep the model simple, we apply one set of constant Y_0 , E_a and V_a parameters to fit all the yield stress data.

The experiments were performed at the same constant strain rate for two different sample diameters. Looking at the yield stress results in Table 1, the yield stress at 3 GPa measured by different anvil setups achieved similar values, which indicate that the reproducibility of the results from the two different anvil setups is acceptable. The apparent activation energy E_a can be determined from a linear fit to the plots in Fig.8 (a). The SF6 glass during HPT deformation exhibited very low activation energy of only around 1 kJ/mol compared to the activation energy of 515 kJ/mol at ambient pressure for viscous flow. Similarly, Fig.8 (b) is used to obtain the apparent activation volume V_a . The calculated V_a varies from 1.16 cm³/mol to 2.06 cm³/mol, which is close to the activation energy of SCHOTT N-BK7[®] glass of ~2 cm³/mol reported by Ding et al.^{22, 23}. Moreover, Fig.8 (b) shows that the yield stress increases with increasing pressure.

Fig.8 (a) Yield stress of SF6 glass deformed in HPT as a function of pressure to determine the apparent activation energy; (b) Temperature dependence of the yield stress to determine the apparent activation volume of SF6 glass during HPT deformation; (c) Yield stress calculated from the HPT measurements fitted by an Arrhenius type model.

However, the SF6 glass samples deformed at 435 °C under 0.3 GPa and at room temperature at 3 GPa are not used to determine the fitting parameters of the proposed Arrhenius type model. For the former, the low pressure (by manual loading) might not suppress sliding as well as for the higher pressures. For the latter, we recall the big noise heard from the sample deformed at room temperature under 3GPa. The big noise during the high-pressure loading indicates that a brittle fracture occurred, which opening the bulk glass sample and lower the torque. On the other hand, the cracking of glass generates various fine powders in the sample, which might be another important mechanism for glass flow at room temperature. Indeed, the particle size of glass influences the ability of the glass flow⁴⁵.

To fit the experimental data, we employ a multidimensional unconstrained nonlinear minimization optimization algorithm (using the MATLAB function `fminsearch`⁴⁶), to find the best-fit parameters for the model. Fig.8(c) displays that the Arrhenius type model can coarsely describe the experimental yield stress calculation with the parameters $Y_0 = 0.17 \pm 0.01$ GPa, $E_a = 4.8 \pm 0.5$ kJ/mol and $V_a = 1.4 \pm 0.2$ cm³/mol. The best-fit activation energy is slightly higher than the calculation in Fig.8 (a), and the best-fit activation volume is in agreement with the calculation in Fig.8 (b). The model also extrapolates the yield stress at ambient pressure decreases with increasing temperatures, with ~0.44 GPa at 350 °C, ~0.39 GPa at 435 °C, and 0.37 GPa at 496 °C, respectively. We note that the fitting is only in coarse agreement with the experimental data, and some

slight differences remain in the slope of the experimental data and model, which may result from systematic deviations. Yet the model is better than the other explanations even in its basic version.

4.2.1 Pure friction?

Considering that all the deformation experiments exhibit similar activation energy, one other possible reason could be sliding between the glass samples and anvils. The friction coefficient determined according to Eq. (7) and plotted in Fig.9 apparently decreases with increasing temperature in the 10 mm anvils setup and is thus not a possible explanation for the torques measured. Furthermore, the samples (even for the 0.3 GPa case at least at one sample side) showed well surface characteristics/markings of the anvil, most notably scratches. This is a strong indication that in this area no sliding was present and that thus the overall amount of sliding should not be dominant.

Fig.9 Friction coefficient of SF6 glass as a function of pressure in HPT.

5. Conclusions

Deformation experiments were performed on SCHOTT SF6[®] in an HPT apparatus under high pressure and different temperatures. From several approaches tested, the mechanism of plastic shear yielding during the HPT experiments on SF6 offers the most likely explanation for the measured results. This yield stress of SF6 glass decreases with increasing temperature and decreasing pressure. An extended Arrhenius model was applied and shown that it can explain the experimental results of SF6 glass, with some short-comings.

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Table 1 Experimental conditions and results

Samples	Glass type	Diameter [mm]	Thickness [mm]	Pressure [GPa]	Temperature [°C]	Torque [N·m]	Viscosity Log ₁₀ [Pa·s]	Yield stress [GPa]	Repeat times	Note
S1	SF6	6	0.54±0.02	3.3±0.1	435±5	49±1	11.32±0.02	0.87±0.02	4	
S2	SF6	6	0.54±0.02	5.2±0.1	496±5	80±1	11.53±0.02	1.41±0.02	4	
S3	SF6	6	0.54±0.02	4.9±0.1	435±5	81±1	11.53±0.02	1.43±0.02	4	
S4	SF6	6	0.54±0.02	5.0±0.1	350±5	89±1	11.58±0.02	1.57±0.02	4	
S5	SF6	6	0.54±0.02	7.1±0.1	496±5	121±2	11.71±0.02	2.14±0.04	4	
S6	SF6	6	0.54±0.02	6.8±0.1	435±5	115±1	11.68±0.02	2.03±0.02	4	
S7	SF6	6	0.54±0.02	6.5±0.1	350±5	113±2	11.68±0.02	2.00±0.04	4	
S8	SF6	10	0.54±0.02	0.3±0.0	435±5	57±3	10.49±0.02	0.22±0.01	3	Manual
S9	SF6	10	0.54±0.02	1.3±0.1	496±5	111±5	10.78±0.05	0.42±0.02	3	
S10	SF6	10	0.54±0.02	1.1±0.1	435±5	137±2	10.87±0.01	0.52±0.01	3	
S11	SF6	10	0.54±0.02	1.1±0.1	350±5	164±3	10.95±0.03	0.63±0.01	3	
S12	SF6	10	0.54±0.02	2.1±0.1	496±5	144±4	10.90±0.02	0.55±0.02	3	
S13	SF6	10	0.54±0.02	2.1±0.1	435±5	178±2	10.99±0.01	0.68±0.01	3	
S14	SF6	10	0.54±0.02	2.0±0.1	350±5	201±3	11.04±0.01	0.77±0.01	3	
S15	SF6	10	0.54±0.02	3.2±0.1	496±5	206±4	11.05±0.02	0.79±0.02	3	
S16	SF6	10	0.54±0.02	3.0±0.1	435±5	221±3	11.08±0.01	0.84±0.01	3	
S17	SF6	10	0.54±0.02	3.0±0.1	350±5	251±2	11.14±0.02	0.96±0.01	3	
S18	SF6	10	0.54±0.02	3.0±0.1	25	164±2	10.95±0.01	0.63±0.01	2	Room T

S19	SF6	10	0.54 ± 0.02	3.7 ± 0.1	435 ± 5	250 ± 2	11.14 ± 0.01	0.95 ± 0.01	2	
S20	SF6	10	0.54 ± 0.02	5.1 ± 0.1	435 ± 5	307 ± 3	11.23 ± 0.03	1.17 ± 0.01	2	
S21	SF6	10	0.54 ± 0.02	7.4 ± 0.2	435 ± 5	776 ± 9	11.63 ± 0.02	2.96 ± 0.03	1	Anvils touching
S22	SF6	10	0.62 ± 0.02	0.3 ± 0.0	435 ± 5	50 ± 15	10.50 ± 0.12	0.19 ± 0.06	1	Flat anvils