Version October 2018

TIE-31 Mechanical and thermal properties of optical glass

Introduction

The mechanical and thermal properties of optical glasses are important to know for e.g. component processing and the performance of lens systems under thermo-mechanical stress. Hardness and grindability influence the process required to achieve a good polishing quality. The mechanical design of the lens system in temperature sensitive applications takes into account the thermal expansion and the thermal conductivity of optical glasses to achieve better performance.
The Young's modulus is a measure for the stiffness and the stresses that can be expected on the optical glass under mechanical loads.
The density has a large influence on the weight of the final component and the lens system in total. With the nowadays large variety of optical glass compositions also the mechanical and thermal properties of optical glass vary over a large range.

1. Density

The density of optical glass varies from 2.39 g/cm³ for N-BK10 to 6.19 g/cm³ for P-SF68. In most cases glasses with higher densities also have higher refractive indices (e.g. SF type glasses). The density is mainly determined by the chemical composition of the glass. To a small amount the density is influenced by the annealing conditions of the glass near the transformation temperature. Due to the thermal expansion of the glass the density decreases with increasing temperature.

2. Elasticity Modulus, Torsion Modulus, Poisson's Ratio

Glass shows an almost perfect brittle-elastic behavior at temperatures lower than the transformation point. The deformation is proportional to the stress according to Hooke's law. If the ends of a rod are exposed to a stress σ, its relative elongation is given by:

$$\frac{\Delta l}{l} = \frac{\sigma}{E} \tag{1}$$

E is called the modulus of elasticity (Young's modulus). The elongation of the rod decreases its cross section. The relation between the relative decrease in the thickness t and the relative elongation is called Poisson's ratio μ, defined as:

$$\frac{\Delta t}{t} \Big/ \frac{\Delta l}{l} = \mu \tag{2}$$

➜

SCHOTT
glass made of ideas

The torsion of a rod is characterized by the modulus of torsion (or shear modulus) G. The properties E, G and μ are characteristic constants of the individual glass type and depend on the chemical composition of the glass.

The Young's modulus E and the torsion modulus G is given in units of N/mm^2 or more commonly in GPa (1 GPa = 10^3 N/mm^2).

The following relationship exists between the elasticity modulus E, torsion modulus G, and Poisson's ratio μ

$$\mu = (E/2G) - 1 \tag{3}$$

The Young's modulus is measured using an ultrasonic measurement method that determines the natural frequency of a transversal resonance (~1 kHz) of a fine annealed rod shaped test body. Using this method the adiabatic elasticity modulus is provided. The measurement accuracy is in the range of ± 1 % to ± 2 %. The torsion modulus is measured by determination of the torsional natural oscillation.

The values listed in the data sheets for the elasticity modulus and the Poisson's ratio are guideline values and were measured at room temperature. Young's modulus of optical glass ranges from 132 GPa (LASF35) to 54 GPa (SF57). In general lead containing glasses exhibit small Young's modulus values. Lanthanum glasses have large Young's modulus values. The elasticity modulus for 3 selected glass types is shown as a function of temperature in figure 1.

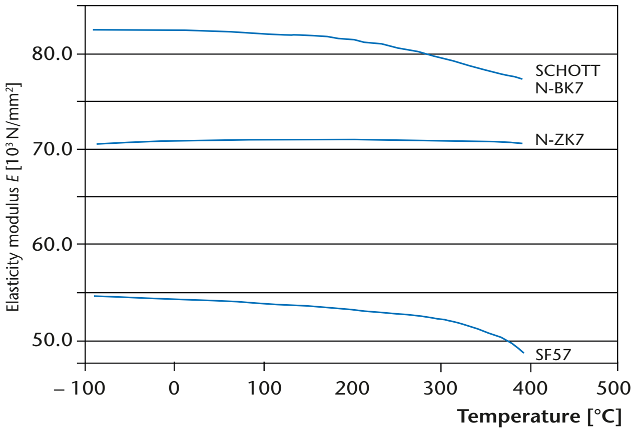

Fig. 1: Elasticity modulus as a function of temperature for several optical glasses.

The longitudinal velocity of sound v_{long} can be derived from the elasticity modulus, Poisson's ratio, and density ρ:

$$v_{long} = \sqrt{\frac{E \cdot (1-\mu)}{\rho \cdot (1+\mu) \cdot (1-2\,\mu)}} \tag{4}$$

The dilatational wave speed v_D for long, thin rods is given by:

$$v_D = \sqrt{\frac{E}{\rho}} \tag{5}$$

3. Knoop Hardness

The resistance of a material to indentation is characterized by the indentation hardness. Several testing methods can be used: scratching, abrasion or penetration; however, the results are not exactly comparable.

In the Knoop hardness test the indentation depth of a rhombus-shaped diamond pressed with a defined force a time on the material is measured. The diamond surfaces have defined intersection angles of 172.5° and 130.0°. During pressing of the diamond into the glass plate an elastic and plastic deformation occurs. The size of the permanent indentation depends on the hardness of the material, which is given by the chemical composition.

The Knoop hardness can be calculated from the diagonal size d of the indentation using the following formula:

$$HK = 1.4233 \cdot \frac{F}{d^2} \tag{6}$$

→ ← Back to index

The standard ISO 9385 [1] describes the measurement procedure for glasses. In accordance with this standard, the values for Knoop hardness *HK* are listed in the data sheets for a test force of 0.9807 N (corresponds to 0.1 kp) and an effective test period of 20 s. The test was performed on polished glass surfaces at room temperature. The data for hardness values are rounded to 10 *HK* 0.1/20. The microhardness is a function of the magnitude of the test force and decreases with increasing test force.

In general glasses with a high content of network formers (silica or boron oxide) have high hardness values. Barium-lanthanum-borate glasses (LaK and LaSF glasses) have the highest hardness. An increasing alkaline and/or lead content decreases the indentation hardness.

---

4. Grindability with Diamond Particles According to ISO 12844

The behavior of a given glass in a grinding process depends on many different conditions. A well-defined physical material property, that could characterize the grinding process, unfortunately does not exist. No useful correlations with material properties, such as Knoop hardness, the elasticity modulus, or combinations of them have been found.

Since the grinding process of glasses is very important for practical planning and control of optical workshops, it is useful to have a measurement size that allows a comparison of different glasses among one another. The standard ISO 12844 [2] defines such a measurement size.

Twenty samples of the glass to be classified are ground for 30 seconds in a standardized diamond pellet tool under predetermined conditions. Then the samples are compared by weighing the samples and considering the density of the removed volume of the glass with that of a reference glass, N-SK16. The following formula is used to calculate the grindability *HG* as a comparison value:

$$HG = \frac{(w_x / \rho_x)}{(w_o / \rho_o)} \cdot 100 \qquad (7)$$

where

w_x	is the average mass removed from five samples of the glass to be classified
w_0	is the average mass removed from five samples of the reference glass
ρ	is the density of the glass to be classified
ρ_0	is the density of the reference glass

The classification will be done according to the following scheme.

Grindability Class	Grindability Limit Value
HG 1	≤ 30
HG 2	> 30 ≤ 60
HG 3	> 60 ≤ 90
HG 4	> 90 ≤ 120
HG 5	> 120 ≤ 150
HG 6	> 150

Tab. 1: Grindability classes according to ISO 12844.

According to this scheme the removal in the lower classes is less and in the higher classes more than in the reference glass N-SK16. The grindability classes of our optical glasses are listed in the data sheets.

→ ← | Back to index

TIE-31 Mechanical and thermal properties of optical glass

5. Strength of Optical Glasses

In some practical applications it sometimes occurs that optical glasses are subjected to mechanical stresses. For example, SCHOTT N-BK7® is often used as a high quality optical material for vacuum windows. Hereby tensile stresses arise on the vacuum side as a result of the atmospheric pressure, with maximum stress in the center of the piece of glass.

If glass parts are subjected to rapid temperature changes, stresses form based on the arising temperature differences and the thermal coefficient of expansion. When laminating glass parts to one another, especially when the thermal expansion coefficients of the bonding materials are different, when unfavorable geometric conditions are involved, or when the cement shrinks or hardens too much, stresses may form in the glass.

The size of the stressed surface, the rate of increase and duration of the tensile stress load, and the surrounding media serve as additional influences.

With equal stress, fast increase rates and short load durations are more favorable than slow increase rates and lengthy loading. Water is the least favorable surrounding medium. In a moist environment glass is weakened much more than in a dry environment.

Glasses such as the boron crowns are rated at 4 – 6 MPa as a guideline value for the strength of ground surfaces under permanent loads. This is a comparatively low value that is insufficient for many applications. In such cases, the tensile stress loading and the strength of the glass parts concerned must be analyzed more closely.

Information on the strength and data for a number of materials with defined surface states is available upon request. Please walso refer to [3].

6. Viscosity

Between melting temperature and room temperature glasses run through a viscosity range of 15 – 20 powers of ten and within this range are subjected to three different thermodynamic states (figure 2).

1. Melting range – above liquidus temperature
2. Supercooled melt range – between liquidus and solidification temperature
3. Solidified melt – below solidification temperature

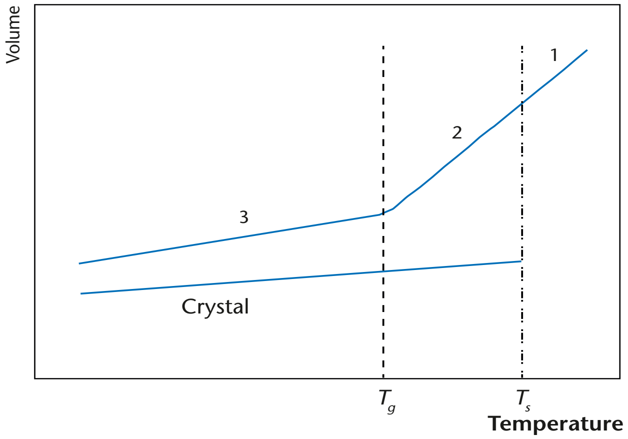

Fig. 2: Volume as a function of temperature during crystallization and glass formation (schematic): T_s = melting temperature of crystals, T_g = transformation temperature.

During cooling of the melt ($1 \cdot 10^0$ – $1 \cdot 10^4$ dPa · s) the viscosity of glass constantly increases (figure 3). Between $1 \cdot 10^4$ and $1 \cdot 10^{13}$ dPa · s a transition from a flowing to a plastic state can be observed. Just above $1 \cdot 10^9$ dPa · s the viscosity becomes increasingly time dependent.

The delay, which is necessary to achieve structural equilibrium becomes so great with further viscosity increase (= temperature decrease) that the glass structure in the range $1 \cdot 10^{13}$ dPa · s can be described as solidified or "frozen" under normal cooling conditions.

TIE-31 Mechanical and thermal properties of optical glass

The low fluidity at this viscosity is just enough to relieve internal stresses within the glass during a waiting time of about 15 minutes. On the other hand dimensional stability is already good enough for numerous purposes and brittleness (susceptibility to cracking) is almost completely formed. In the transformation range the characteristics of glass change. This is indicated by a great change in the temperature coefficient of these properties.

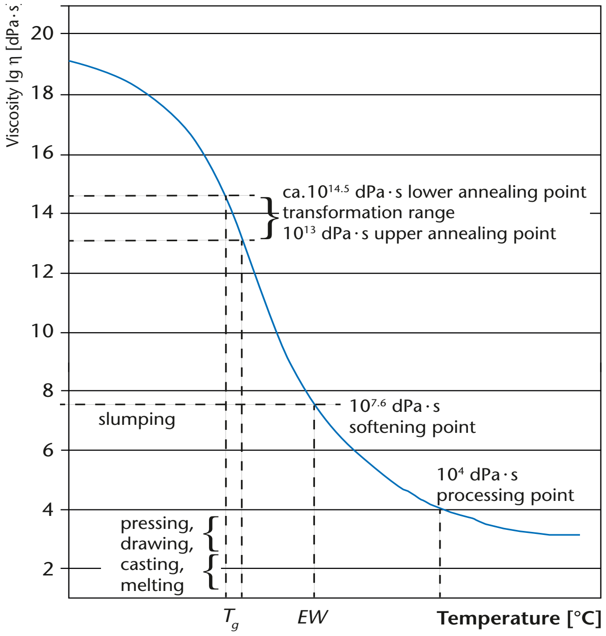

Fig. 3: General course of viscosity as a function of temperature. Viscosity ranges for important finishing operations and fixed points.

Thus the change in slope of the thermal coefficient of expansion with a temperature increase of 5 K/min serves to identify the transformation range through the so-called transformation temperature T_g in accordance with ISO 7884-8 [4].

The annealing point $T_{10}{}^{13}$ is important for the annealing of glass. This is the temperature at which the glass has a viscosity of $1 \cdot 10^{13}$ dPa · s. The so-called upper annealing point as per ISO 7884-4 [4] and the transformation temperature T_g generally lies right at $T_{10}{}^{13}$.

Stresses can be relieved in glass around 5 to 15 K above the upper annealing point within 30 minutes following completely uniform heating [5]. If during heat treatment a temperature of $T_{10}{}^{13} - 200$ K is exceeded, optically precise surfaces may deform, and the refractive index may change.

The so-called softening point *EW* ($T_{10}{}^{7.6}$) is designated to identify the viscosity range in which glass articles deform under their own weight (for example, shaping through slumping, sintering of glass powder). That is the temperature at which the glass has a viscosity of $1 \cdot 10^{7.6}$ dPa · s.

The transformation temperature T_g and the viscometrically determined annealing temperature points $T_{10}{}^{7.6}$ and $T_{10}{}^{13}$ are listed in the data sheets [6].

Viscosity as a function of temperature is listed for several glasses in figure 4

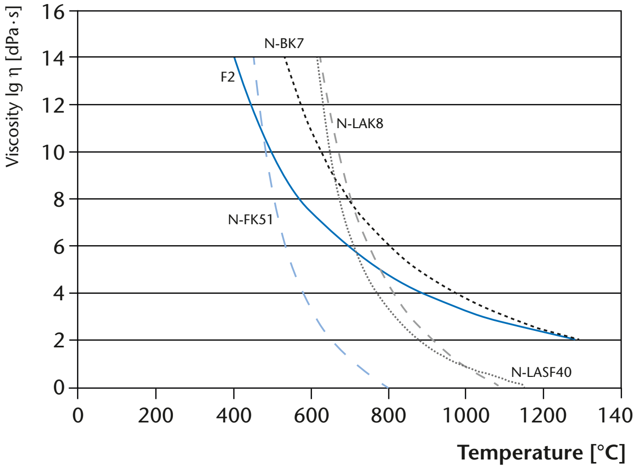

Fig. 4: Viscosity of several glasses as a function of temperature.

TIE-31 Mechanical and thermal properties of optical glass

7. Coefficient of Linear Thermal Expansion

The length and volume of glasses increase with increasing temperature (positive coefficient of linear thermal expansion α).

The typical curve (figure 5) begins with $\alpha = 0$ at the absolute zero point. Then follows a noticeable increase in slope to approximately room temperature (Section A) and a reduced increase in slope to the beginning of experimentally detectable plastic conditions (Section B = nearly linear area). A noticeable bending of the expansion curve as a result of increasing structural movement within the glass is characteristic of the transformation range C. Following this, the expansion again approaches linearity, which has a noticeably greater rate of increase, however.

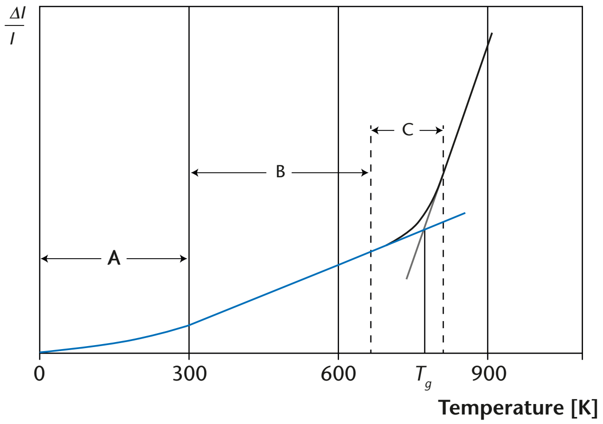

Fig. 5: Typical curve for the coefficient of thermal expansion α, Determination of the transformation temperature T_g.

Due to this dependence of the coefficient of thermal expansion α on temperature, it is advisable to list two average linear expansion coefficients α for the following temperature ranges:

- α(–30 °C; +70 °C) as relevant information for room temperature
- α(20 °C; 300 °C) as an internationally used value for comparison purposes and for orientation in melting processes and temperature change loads.

The expansion coefficients α(20 °C; 300 °C) ranges from 4 to $16 \cdot 10^{-6}$/K.

The internal stress σ generated in a glass piece due to temperature differences ΔT can be estimated in first approximation using the following formula:

$$\sigma = \frac{(E \cdot \alpha)}{(1 - \mu)} \cdot \Delta T \qquad (8)$$

The internal stress is proportional to Young's modulus E and to the coefficient of thermal expansion α. Therefore optical glasses with a large thermal expansion coefficient and Young's modulus value are very sensitive to thermal shock and have to be processed very carefully. Differences in temperature between the cooling liquid and the glass during machining can lead to large tensile stresses in the glass surface. Small hardness values ease the generation of surface defects that can act as crack origins [5].

The optical glasses that are most sensitive to thermal shock are N-FK51, N-PK52A and N-PK51.

TIE-31 Mechanical and thermal properties of optical glass

8. Thermal Conductivity

The range of values for thermal conductivity for glasses at room temperature extends from 1.38 W/(m · K) (pure quartz glass) to about 0.5 W/(m · K) (high lead containing glasses). The most commonly used silicate glasses have values between 0.9 and 1.2 W/(m · K). Figure 6 shows the general dependence on temperatures up to 500 K.

Above 300 °C the radiation component of the transfer of heat in glasses begins to increase noticeably. The dependence on temperature grows, and the absorption of radiated heat of the glasses becomes more significant.

The thermal conductivities shown in the data sheets apply for a glass temperature of 90 °C; the degree of accuracy is ± 5 %.

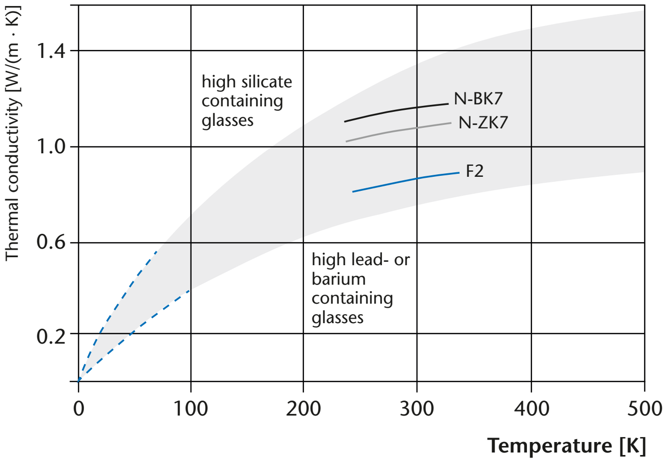

Fig. 6: Range and basic curve of thermal conductivity of glasses at temperatures for 0 K to 50 K.

9. Specific Thermal Capacity

The mean isobaric specific heat capacity c_p (20 °C; 100 °C) is listed for a portion of the glasses as measured from the heat transfer of a hot glass at 100 °C in a liquid calorimeter at 20 °C. The range of values for c_p (20 °C; 100 °C) and also for the true thermal capacity c_p (20 °C) for silicate glasses is between 0.42 and 0.84 J/(g · K). Above the transformation temperature, c_p is essentially temperature independent.

TIE-31 Mechanical and thermal properties of optical glass

10. Summary

In the following table some mechanical and thermal properties of glass are compared to polymers, ZERODUR®, Al_2O_3 ceramic, steel, aluminum and diamond.

	Density [g/cm³]	Young's modulus [GPa]	Thermal conductivity [W/mK]	Thermal expansion coefficient [10^{-6}/K]
Polymers	1 – 2	0.1 – 10	0.1 – 1	20 – 500
Optical glass	2.4 – 6.0	50 – 130	0.5 – 1.4	4 – 16
ZERODUR®	2.53	90.3	1.46	0.02
Al_2O_3 ceramic	4	400	30	8
Steel	8	210	40	13
Aluminum	2.7	70	200	22
Diamond	3.5	1000	800	1.1

Tab. 2: Mechanical and thermal properties of Optical glass in comparison to other materials.

---

11. Literature

[1] ISO 9385: Glass and glass ceramics – Knoop hardness test;
ISO – International Standardization Organization (1990)

[2] ISO 12844: Raw optical glass – Grindability with diamond pellets – Test method and classification;
ISO – International Standardization Organization (1999)

[3] Bending strength of optical glass and ZERODUR®; SCHOTT Technical Information TIE-33

[4] ISO 7884-8: Glass-Viscosity and viscosimetric fixed points – Determination of annealing point; part 1 – 8;
ISO – International Standardization Organization (1986)

[5] Stress in optical glass;
SCHOTT Technical Information TIE-27

[6] Thermal loads on optical glass;
SCHOTT Technical Information TIE-32

Version October 2018 | SCHOTT Advanced Optics reserves the right to make specification changes in this product flyer without notice.

← Back to index

Advanced Optics
SCHOTT North America, Inc.
400 York Avenue
Duryea, PA 18642
USA
Phone +1 570/457-7485
Fax +1 570/457-7330
info.optics@us.schott.com

www.us.schott.com/advanced_optics

SCHOTT
glass made of ideas