

TIE-32: Thermal loads on optical glass

1. Introduction

In some applications optical glasses have to endure thermal loads:

- ∅ Finishing procedures for optical elements like lenses, prisms, beam splitters and so on involve thermal processes as coating of the surfaces.
- ∅ Glass pieces may be used at high or low temperatures for long terms.
- ∅ The environmental temperatures of a glass piece may vary with time slowly or according to a program.
- ∅ The environmental temperatures may rise or fall sharply, acting as a thermal shock.

In such cases questions arise:

- ∅ Will a given piece of glass endure the expected thermal load?
- ∅ Which type of glass has to be chosen for an application with a given thermal load?
- ∅ Which possibilities exist to increase the endurance of a given piece of glass to thermal loads?

This document does not intend to cover the topic in detail. The physical processes are too complicated to do so. The following comments shall introduce the reader into the theme, give him some essential facts and enable him to perform rough calculations. The results of the calculations may serve as conservative limit values. They form bases for estimations, in order to get a "feeling" of what goes on in a piece of glass when it is subjected to temperature changes.

2. General physical aspects of thermal loads on glass

2.1 Thermal stresses

Glass has a thermal conductivity, which is very low compared with metals (see table 2-1). The heat capacity is in the same region as for metals partly even a little higher.

	Cu	Steel	Pb	N-BK7	Optical glasses (range)
Thermal conductivity [W/(mK)]	395	13-17	35	1.1	0.50 – 1.28
Heat capacity [J/(gK)]	0.38	0.45	0.13	0.86	0.30 – 0.89

Table 2-1: Thermal conductivity and heat capacity: Some data for comparison

Because of the low thermal conductivity the temperatures within the volume of a glass piece cannot follow changing environmental temperatures quickly and therefore significant temperature differences arise between different volume regions.

The high values of the Young's modulus (40 - 132 GPa) and the coefficients of thermal expansion ($3.7 - 14.6 \cdot 10^{-6}/K$; -30 to +70°C) for the optical glasses lead to thermally induced stresses in glass volume consequently.

This is e.g. very important for the processing of glass with high thermal expansion coefficient like N-PK52a or N-FK51, in which the glass is subjected to cooling liquids during cutting, grinding or polishing. To prevent thermal stresses during processing it is therefore important to keep the temperature difference between glass part and cooling liquid as low as possible.

2.2 Upper limit of thermal stresses

The thermally induced stresses σ_w can be calculated with the following formula:

$$\sigma_w = f \cdot \frac{\alpha \cdot E}{1 - \mu} \cdot \Delta T \quad (2-1)$$

f: specific factor (see below and chapter 5.2)

α : coefficient of thermal expansion, $\alpha(-30,70^\circ\text{C})$ e.g.

E: Young's modulus

μ : Poisson's ratio

ΔT : temperature difference

The material dependent part of the formula is called the thermal stress factor

$$\phi_w = \frac{\alpha \cdot E}{1 - \mu} \quad (2-2)$$

For some selected glasses it is given in table 2-2. The thermal stress factor gives the stress, which is induced within a glass volume by a temperature difference of 1 K. It is a measure to compare glass types with respect to their sensitivity against thermal loads.

The specific factor f depends on the given physical arrangement i.e. the geometry of the glass piece, its frame or support, the environmental media and the temperature change rates or in other words it depends on the heat flow to or from the glass piece developing in time. The maximum value of f is 1.

Formula 2-1 above can serve for the calculation which maximum stress may arise in a glass subjected to a temperature difference of ΔT .

Thermal loads material data							
Material	Coefficient of thermal expansion $\alpha(-30,+70^{\circ}\text{C})$ [$10^{-6}/\text{K}$]	Young's modulus E [GPa]	Poisson-ratio ν [-]	Thermal-stress factor ϕ_w [Mpa/K]	Thermal conductivity λ [W/mK]	Heat capacity c_p [J/gK]	Transform. temperature T_g [$^{\circ}\text{C}$]
N-ZK7	4.5	70	0.21	0.40	1.04	0.77	539
N-SK2	6	78	0.26	0.64	0.78	0.60	659
SF11	6.1	66	0.24	0.53	0.74	0.43	503
N-KZFS11	6.56	79	0.25	0.69	0.81	0.69	551
N-BAK4	6.99	77	0.24	0.71	0.88	0.68	581
N-BK7	7.1	82	0.21	0.73	1.11	0.86	557
N-KZFS4	7.3	78	0.24	0.75	0.84	0.76	547
F2	8.2	57	0.22	0.60	0.78	0.56	432
SF57	8.3	54	0.25	0.60	0.62	0.36	414
N-SF6	9.03	93	0.26	1.14	0.96	0.69	594
N-PK52A	12.93	71	0.30	1.31	0.73	0.67	453
N-FK51	13.3	81	0.29	1.52	0.91	0.64	420
Zerodur	0.05	90	0.24	0.006	1.46	0.80	-
Floatglass	9.0**	73	0.23	0.85**	1.06	0.80	535
Duran	3.25*	63	0.20	0.26**	1.16	0.83	525
* for (-20, 200 $^{\circ}\text{C}$)		** for(20, 300 $^{\circ}\text{C}$)					

Table 2-2: Thermal stress data of selected glasses

2.3 Directions and types of thermal stresses

2.3.1 Directions of the thermal stresses

The directions of the thermally induced stresses depend on the direction of the temperature change. When a warm piece of glass will be cooled down the outer volume parts try to shrink. Since they are hindered to do so by the still warm internal region they will develop tensile stresses. The internal region will develop compressive stresses as mechanical reaction. For a cold piece being warmed up all directions will be reversed.

From the applications point of view one can distinguish between two types of thermal stresses.

2.3.2 Stresses relaxing by bending reactions

In some cases the arising thermal stresses can be reduced by the glass part itself when it is able to react mechanically on the stresses.

A temperature gradient across the thickness of a glass plate will lead to a bending reaction of the plate, which reduces the arising stresses significantly. Heating or cooling a window glass from one side ideally will not result in higher stresses when the clamping of the plate is not too tight, so that it is free to bend. Since the clamping arrangement has to employ soft casketing material in any way to prevent damages of the glass, it will allow the bending reaction in any case.

2.3.3 Stresses non-relaxing because of self-restraint

Other geometrical shapes or arrangements do not allow bending reactions. Here the full stresses for the actual temperature differences arise. Plunging a thoroughly warmed piece of glass into a water bath is an example for such a case.

2.3.4 Intermediate cases

The window glass plate mentioned above is an example for an intermediate case. Bending can reduce part of the stresses. Other stresses have to be taken into account, which arise because the clamping frame covers parts of the plate. Temperature differences between the internal zone and the rim zone lead to stresses that cannot be reduced because the glass part restrains itself.

If thermally induced stresses occur in the rim zone of a glass piece with sharp corners they may be enhanced there until the corners break off. Glasses to be used with thermal loads should have round edges therefore.

3. Strength of glass, admissible stresses

The strength of glass and glass-ceramics is not a material property like the Young's modulus e.g. It is dependent on

- ∅ the microstructure of the surface which is tension stressed by the load applied,
- ∅ the area of the surface exposed to tensile stress,
- ∅ the rate of stress increase and
- ∅ the environmental media.

Conservative strength values for long-term applications of optical glass and Zerodur are 8 MPa and 10 MPa respectively [1].

In many cases these values are too restrictive. In order to obtain more appropriate values calculations have to be performed. An outline of the calculation procedure and a data collection is given in [2,3].

Dealing with temperature loads on glass parts one has to take the chamfers and side faces into account discussing the strength of the parts. Since their surfaces are normally only in a ground state they have a lower strength than the polished faces.

4. Possibilities to increase the thermal load endurance

There are several possibilities to meet increased thermal load requirements.

- ∅ Slowing down the temperature change rates, especially for cooling processes, which induce tensile stresses at the surfaces.
- ∅ Increasing the strength by improving the surface conditions: Polishing or etching of ground faces. Disadvantage: A scratch will reduce the strength again, most probably even below the preceding value.
- ∅ Pre-stressing may increase the strength significantly. Disadvantage: Permanent stress birefringence is introduced which may be disturbing for the application of polarized light. SCHOTT offers pre-stressing for filter glasses.
- ∅ Application of Zerodur, the SCHOTT glass ceramic material with almost zero thermal expansion and hence a negligible thermal stress factor.

5. Application limitations

5.1 Temperature limits

To low temperatures there is no application limit for glasses in principle, to the high temperatures there are several limits depending on the application requirements:

- ∅ For not pre-stressed glasses used for less demanding optical requirements the upper temperature limit is 0.6 to 0.7 T_g. T_g is the transformation temperature which is characteristic for each glass type (see the enclosed data sheet).
- ∅ For pre-stressed glasses or for glasses to be used with high optical requirements 0.5 T_g must not be surpassed.

5.2 Limits for the temperature change rates

In principle limits for the temperature change rates can only be given for a well-defined physical arrangement including all components that influence the heat flow to or from the glass part. This presupposes the solution of the differential heat conduction equation combined with the stress tensor field within the glass volume. This is very complicated, time consuming and still not really exact, because several quantities that enter into the calculation usually are not known to a sufficient accuracy (e.g. heat transfer resistances).

Therefore in most cases formula 2-1 is used to estimate the stresses caused by a given temperature difference. When the design strength of the glass part will be surpassed by tensile stresses at the glass part's surface one has to take one of the measures of chapter 4 to fulfill the application requirements.

To employ formula 2-1 there is still one quantity, which has to be given, the specific factor f .

- ∅ For temperature shocks, i.e. passing through the total temperature difference within seconds or shorter, the full thermal stresses arise since the thermal conduction in the glass volume has not started yet. Therefore $f = 1$.
- ∅ For moderately changing temperatures the thermal conduction is already able to reduce temperature differences in the glass volume. The specific admissible change rates strongly depend on the shape and volume of the glass. When the thermal conduction may be assumed to be effective $f = 0.5$ to 0.7
- ∅ For temperatures changing very slowly one may assume that the thermal conduction prevents larger temperature differences to arise. Therefore it is justified to take $f < 0.5$.

5.3 Combination of a thermal load with a pressure load

When a thermal load acts on a glass part in combination with a pressure load the necessary total strength of the glass needs not to be high enough to endure the sum of the arising stresses in any way. In many cases the maximum stresses for each load occur at different locations, so that the strength has only to be sufficient for the higher individual load.

5.4 High optical requirements combined with thermal loads

When a glass part with high quality polished surfaces is designed to endure a thermal load it can be pre-stressed (as mentioned before SCHOTT offers pre-stressed filter glass) but only before the optical finishing process. Pre-stressing after polishing would deteriorate the surface quality because the glass has to be heated up to a temperature where its viscosity is low enough that slight deformations may occur.

The polishing of pre-stressed glass parts is a somewhat delicate process. Only thin layers of material can be taken off in order not to change the surface figures by bending reactions as a result of the rearrangement of the stress mechanical equilibrium. The process is time consuming since the part has to be polished several times at both faces alternating. We recommend performing this by an optical workshop that has experience with the process.

For applications with very high requirements on the optical resolution the stress induced birefringence may be disturbing because it gives rise to a faint aberration.

6. Recommendations for maintaining the thermal endurance of glass parts

It is essential not to deteriorate the strength of the glass part.

Cleaning procedures should use liquids in abundance and soft clothes. Avoid rubbing. Check the glass part on scratches, chips, flaws or other damages. Such damages will make the design strength become invalid.

A glass part exhibiting damages must not be used any more. Frames must not exert forces on glass parts, especially point like forces. Avoid direct metal contact.

Use flexible or at least ductile gasketing material. Adhesive joints shall be made using soft glues with layers not too thin, so that they can compensate shear stresses.

Do not surpass the thermal design limits. A thermal shock higher than designed for will destroy a glass part with high probability.

Exposing a glass part to higher temperatures than allowed in chapter 5.1 will lead to irreversible changes of its properties. The surface quality may be deteriorated, other pre-stressing if existent may relax, so that at the next thermal loading it may be destroyed.

7. Literature

[1] SCHOTT TI-33 "Design strength of optical glasses and Zerodur"

[2] R.J.Roark: "Formulas for stress and strain" McGraw-Hill, New York 1954 p. 334 to 340

[3] D.R. Uhlmann, N.J.Kreidl (eds.) "Glass: Science and technology", vol. 5 "Elasticity and strength in glass"

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