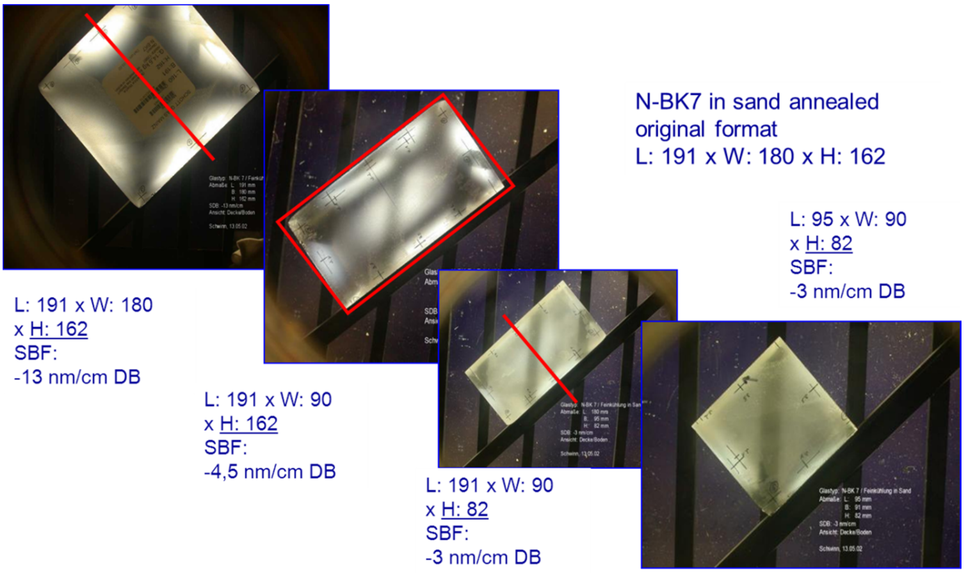


Figure 4.17 A block of N-BK7 shows stress birefringence reduction due to cutting it down to smaller-sized pieces.

4.14 Transient Stress Birefringence

Stress birefringence as discussed in Chapter 3 is called permanent stress birefringence because it is introduced during the production process and cannot be changed unless the glass item is subjected to another annealing process.

Another type of stress birefringence called temporal or transient stress birefringence is caused by stress resulting from thermal gradients occurring in application. This could be from, for example, switching on a strong lamp in a digital projector, which imposes a sharp temperature rise in the color-combining prism cube.

Birefringence in such cases depends on three factors. First is the tendency to reduce thermal gradients to restore equilibrium, which can be described by the relaxation time t_r, formed by the ratio of thickness d squared to thermal diffusivity κ:

$$t_{\mathrm{r}} = \frac{d^2}{\kappa}. \tag{4.6}$$

κ contains the material-dependent quantities thermal conductivity λ, specific heat c_p and density ρ as follows:

$$\kappa = \frac{\lambda}{\rho \cdot c_{\mathrm{p}}}. \tag{4.7}$$

The second factor is the reaction of the glass items to thermal gradients with stress and is ruled by the geometrical factor f, the thermal stress coefficient φ, and the temperature difference ΔT:

$$\sigma = f \cdot \varphi \cdot \Delta T. \tag{4.8}$$

The thermal stress coefficient φ is another material-specific quantity governed by the coefficient of thermal expansion α, Young's modulus E, and Poisson's ratio μ:

$$\varphi = \frac{\alpha \cdot E}{1-\mu}. \tag{4.9}$$

The third factor determines how strongly a glass reacts to stress with birefringence. This is the stress-optical coefficient K.

Combining the three factors allows one to define a figure of merit $K_{\Delta T}$ that is useful for ranking optical glasses based on their sensitivity with respect to birefringence against thermally induced transient stress:

$$K_{\Delta T} = \frac{c_{\mathrm{p}}\rho}{\lambda} \cdot \frac{\alpha \cdot E}{1-\mu} \cdot K. \tag{4.10}$$

Figure 4.18 shows a ranking of glass types according to the figure of merit. The selection was made to demonstrate the variation and thus enhances the extreme regions. Most glasses by far lie within the range of 4000 to 6000. The exceptional position of SF57 is clearly noticeable. Its lead- and arsenic-free variant N-SF57 has a $K_{\Delta T}$ value that is about 200 times higher.

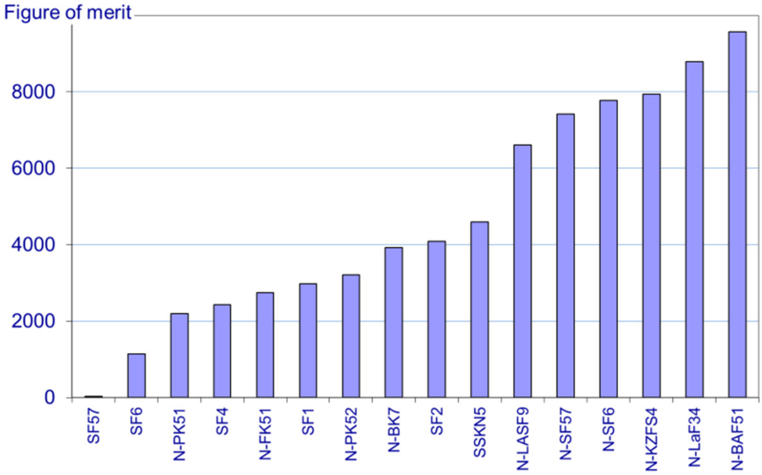


Figure 4.18 Glass type ranking according to their reaction on temperature differences with birefringence using the figure of merit quantity $K_{\Delta T}$.

Large optical glass disks sometimes are specified with high-refractive-index homogeneity. In such cases, it is not only the contribution of the refractive index that must be taken into account. Thermally induced stress birefringence can also introduce high wavefront distortion values. Consider a disk with 100-mm thickness. H4 homogeneity grade limits wavefront distortion to $2 \times 10^{-6} \times 100$ mm = 200 nm. Such wavefront distortion also results from thermally induced stress birefringence if the disk's center temperature differs from the edge temperature by only 1 °C. Many glasses react to temperature differences with 15–20 nm/cm·K^{-1} stress birefringence. For the highest-quality imaging performance, large lenses must be temperature stabilized to the best possible degree. For very critical applications, mirror optics should be considered as a preference over large lenses.[13]

4.15 Birefringence Measurement

The commonly used method for measuring stress birefringence is the de Sénarmont and Friedel[14] method (Fig. 4.19). A detailed description can be found in standard ISO 11455 Raw Optical Glass–Determination of Birefringence. Light with wavelength λ and polarization angle of 45 deg with respect to the stress direction is elliptically polarized after travelling through the glass sample of thickness d. The quarter-wave plate converts the elliptical polarization back to a linear one but rotated with respect to the polarization of the incident light. The rotation angle α is proportional to birefringence and is determined with the analyzer. Stress is calculated from the rotation angle employing the stress-optical coefficient of the glass being measured with the formula

$$\sigma = \frac{\alpha \cdot \lambda}{180} \cdot \frac{1}{K \cdot d}. \tag{4.11}$$

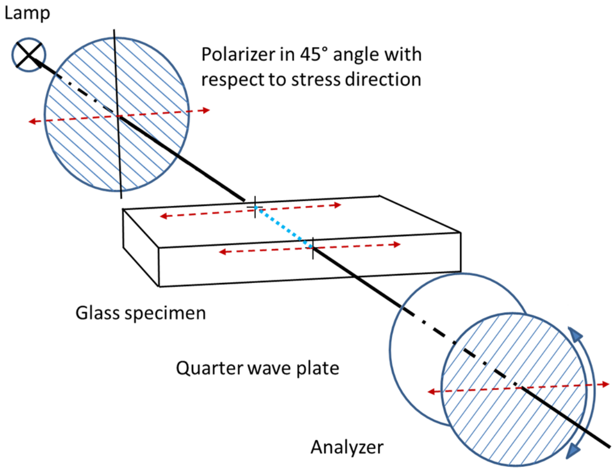
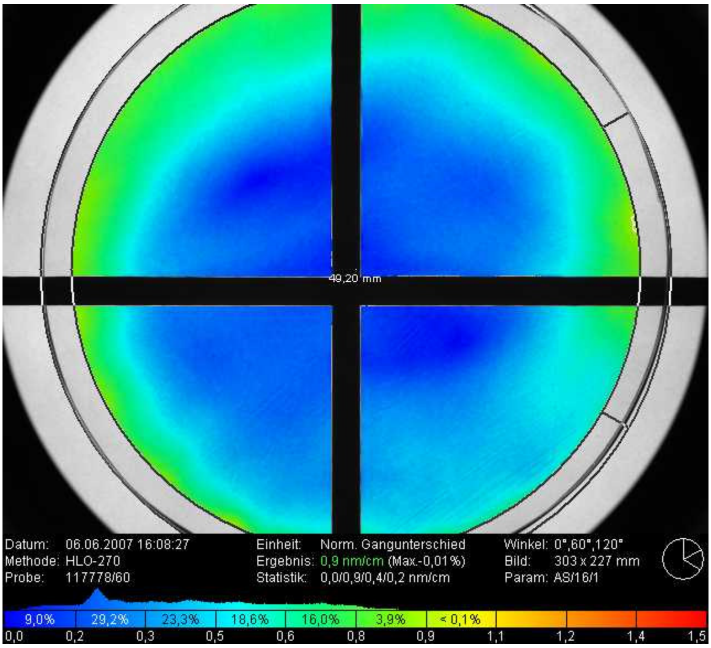


Figure 4.19 Birefringence measurement method of de Sénarmont and Friedel.

In order to simplify interpretation, measurements are usually taken at positions close to the edges, where the radial component of the stress tensor approaches zero and only the tangential component is effective. In the past, such measurements were quite tedious and could be made only at selected positions of the disks. Today, setups are commercially available that measure the total cross-section of the disk in one short measurement process, rendering high spatial resolution and high birefringence accuracy. Figure 4.20 shows such a measurement report with a color-coded scale. The measurement principle is the same as was explained earlier in this section. The field of view covers 300 mm × 225 mm with a spatial resolution of approximately 1–1.5 mm. Wavefront retardation accuracy is about ±1 nm absolute. The complete areal distribution of birefringence can be seen in a single view.



Datum: 06.06.2007 16:08:27
Methode: HLO-270
Probe: 117778/60
Einheit: Norm. Gangunterschied
Ergebnis: 0,9 nm/cm (Max.-0,01 %)
Statistik: 0,0/0,9/0,4/0,2 nm/cm
Winkel: 0°,60°,120°
Bild: 303 x 227 mm
Param: AS/16/1

Figure 4.20 Birefringence report for a highly homogeneous glass disk used in i-line microlithography. The measurement principle used was that of de Sénarmont and Friedel. Field of view covers 303 mm x 227 mm, and maximum birefringence is 0.9 nm/cm.

4.16 Bubbles and other Inclusions

In general, the term *inclusion* comprises all localized material imperfections in optical glass. Bubbles, small spherical gas-filled voids, are the most common type of inclusion. Their cause is imperfect refining of glass melts. Solid inclusions coming from nonmolten raw material are scarce. The present-day quality of glass with respect to numbers of bubbles and inclusions has reached a high level; even in large items, only a very small number will occur.

For optical imaging quality, bubbles are only of little importance. They reduce transmitted light and contribute to stray light. The resulting contrast reduction will be negligible.[15] Since this effect is roughly proportional to their cross-section, bubble quality is traditionally specified by using their total cross-section within a reference volume. However, bubble quality in delivered glass is important not for technical reasons, but for esthetics. Bubbles can easily be seen in an optical system. Depending on their position, they can appear to be larger than they are due to magnification by curved surfaces. All technical arguments supporting individual test results for the very system are worthless if the customer is irritated by clearly visible inclusions in the glass. This holds especially if the optical system is very expensive. Customers expect glass without any visible imperfections. In the end, this results in a bubble quality level much higher than is technically needed.

4.17 Bubbles and Inclusions: Inspection

The setup for bubble and inclusion inspection is very simple (Fig. 4.21). The glass sample is located on a black cloth and illuminated from the side. An inspector determines the number and sizes of the bubbles in the volume by visual comparison with reference samples. If necessary, a microscope with long working distance can be used to increase accuracy (Fig. 4.22).

This setup is very sensitive. Inclusions with sizes of only few micrometers can be seen clearly. If the illumination is too strong, such tiny inclusions will be overestimated in size, which can result in discarding glass samples that would have worked perfectly well under the actual light conditions of its application. In order to specify the bubble and inclusion quality of optical glass, one uses the sum of the cross-sections of all inclusions (in millimeters squared) within a reference volume of 100 mm^3.

Cross-sections of nonspherical inclusions are calculated by multiplying their maximum length and width. All inclusions that are smaller than 0.03 mm will be disregarded. Smaller bubbles and inclusions are scarcely observed. From a technical point of view, this specification would be sufficient. However, esthetics requires the introduction of another characteristic: the number of bubbles per reference volume.

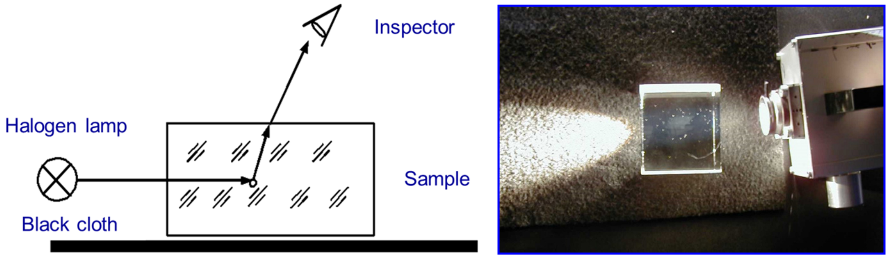


Figure 4.21 (left) Bubble and inclusion inspection setup using (right) lateral illumination with black background.