Version August 2023

TIE-26 Homogeneity of optical glass

Introduction

SCHOTT offers machined optical glasses with homogeneities up to H5 quality. I-Line glasses can even be offered in higher homogeneities. The achievable homogeneity depends mainly on the glass type and dimension. A range of glasses has been defined that can be delivered from stock in homogeneities H4 or better.

The glass SCHOTT N-BK7® is an example of a high homogenous glass that can be produced in high quantities with dimensions larger than 200 mm in homogeneities of H4 and better.

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1. Definition of Homogeneity

One of the most important properties of optical glass is the excellent spatial homogeneity of the refractive index of the material. In general it can be distinguished between the global or long-range homogeneity of refractive index in the material and short-range deviations from glass homogeneity. Striae are spatially short-range variations of the homogeneity in a glass. Short-range variations are variations over a distance of about 0,1 mm up to 2 mm (see TIE-25 for more information on striae), whereas the spatially long range global homogeneity of refractive index covers the complete glass piece.

2. Generation of global inhomogeneities

There are three main reasons for the generation of global inhomogeneities:

- The melting process: Optical glass is mainly produced in a continuous melting process. Inhomogeneities of refractive index can be caused by gradients of the chemical composition during the melting process. This gradient is generated by surface evaporation of specific components and/or by reaction of the part of the melt that is in contact with the mold wall material. For process control during a continuous melting and casting process the refractive index is observed as a function of time. Glasses with highest homogeneities are extracted from castings in time frames were the refractive index was nearly constant over time.

- Variations of the density due to thermal equilibrium: The density variations depend on the thermal history of the glass. At higher temperatures the equilibrium density is reached in a shorter time than at lower temperatures. The equilibrium density reached is different for different temperatures around the transformation temperature Tg. The refractive index homogeneity is a function of the density distribution in the glass. Uncontrolled cooling of the glass around temperatures near Tg will generate spatial refractive index inhomogeneities. During production of optical glass subsequent fine annealing of the glass prevents such inhomogeneities.

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Glass has to be cooled down slowly from temperatures slightly above Tg in order to prevent thermal gradients. The fine annealing of optical glasses with large dimensions to achieve high homogeneities is a very time consuming process.

- Permanent stresses due to temperature gradients during cooling.

SCHOTT homogeneity class	ISO 10110 part 4 homogeneity class	Maximum variation of refractive index according ISO 10110 part 4	Maximim variation of refractive index according ISO 12123 and SCHOTT optical glass catalog	Availability
S0	0	$\pm 50 \cdot 10^{-6}$		variation tolerance, homogeneity of individual cut blanks is always better
S1	1	$\pm 20 \cdot 10^{-6}$		variation tolerance for individual cut blanks
H1		$\pm 20 \cdot 10^{-6}$	$40 \cdot 10^{-6}$	for individual cut blanks
H2	2	$\pm 5 \cdot 10^{-6}$	$10 \cdot 10^{-6}$	for individual cut blanks
H3	3	$\pm 2 \cdot 10^{-6}$	$4 \cdot 10^{-6}$	for individual cut blanks
H4	4	$\pm 1 \cdot 10^{-6}$	$2 \cdot 10^{-6}$	for individual cut blanks not in all dimensions not for all glass types
H5	5	$\pm 0{,}5 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	for individual cut blanks not in all dimensions not for all glass types

Tab. 1: Homogeneity classes.

3. Homogeneity grades

The availability of glasses with increased requirements for refractive index homogeneity comprises 5 classes in accordance with ISO standard 10110 part 4 [5]. The SCHOTT homogeneity grade H1 to H5 for single parts comprises ISO class 1 to 5. SCHOTT uses class 0 and also 1 of the ISO standard to describe the variation tolerances.
The variation tolerance is the refractive index variation from piece to piece [4]. The ISO 12123 expresses the maximum deviation of refractive index in peak to valley values. This definition is used in the current optical glass catalog [6].
The required homogeneity of optical glass should be specified with respect to the application and the final dimensions of the optical component. It is defined as the maximum refractive index deviation within the required measurement aperture (e.g. 95 % of the physical dimension).

Depending on the volume of the optical element, the glass type and size of the raw glass, the measurement is done on individual cut blanks. Glass parts of up to 500 mm in diameter can be tested with the existing Fizeau-interferometer. Glass parts with dimeters up to 1500 mm are measured in sub-apertures of up to 500 mm in diameter. Subsequently the individual measurements are combined using a stitching software. Interferograms can be provided for individual cut blanks.

Table 1 gives an overview on the available homogeneity classes.

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A refractive index variation within an optical component leads to a deformation of the wavefront passing through the glass piece, according to the following formula:

$$\Delta s = d \cdot \Delta n$$

Δs is the wavefront deviation, d is the thickness of the glass and Δn is the peak to valley refractive index variation in the glass. For example: a plane wave passing once through a 50 mm thick plane glass part with H2 quality will be deformed by a maximum of $50\ \text{mm} \cdot 10 \cdot 10^{-6} = 500\ \text{nm}$. A H5 glass part of the same thickness leads to a wavefront deformation of 50 nm maximum.

4. Measurement equipment

The integrating method by interferometry, preferably phase-measuring interferometry is the preferred measurement method for homogeneity evaluation since the deformation of the entering wavefront is directly measured. The homogeneity is evaluated by integrating over the light path in the glass sample. Therefore a linear gradient of refractive index in the direction of the beam cannot be detected. In order to suppress surface irregularities the glass sample is either positioned between two oil-on-plates sandwiches, which are contacted by immersion oil or polished and measured in different orientations to eliminate the surface influence. Both methods are used by SCHOTT.

SCHOTT in Mainz uses two DIRECT100 Fizeau Interferometer from ZEISS for homogeneity measurement with a maximum aperture of 508 mm (20 inch) and 300 mm (12 inch) Measurements with an aperture up to 600 mm are possible with a Zygo Interferometer at SCHOTT North America in Duryea. A schematic overview of the DIRECT100 setup is shown in figure 1.

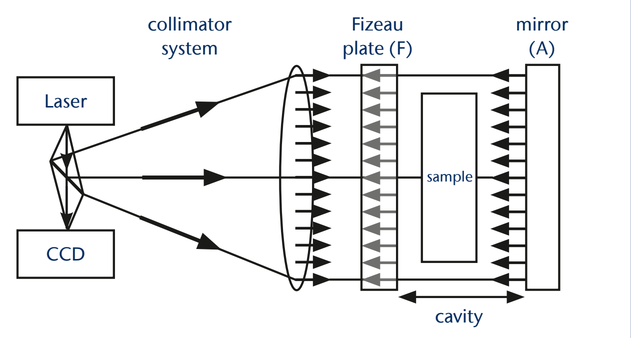

Fig. 1: Schematic of the Interferometer setup.

The setup consists of a He-Ne Laser light source and a large collimator that transforms the laser beam to the full aperture. The collimated, parallel beam travels through a partially reflecting Fizeau plate. Part of the light is reflected back by the Fizeau plate. The remaining light enters the cavity and travels through the sample for the first time. After passing the sample the light is reflected back by a plane mirror and passes the sample and the Fizeau plate and the collimator a second time before it interferes with the reflected light from the Fizeau plate on the CCD array where the interference fringes are recorded.

The Fizeau plate (F) and the autocollimation mirror (A) are made from ZERODUR®. The interferometer employs the direct measuring interferometry method of Carl Zeiss [1]. This method is capable of providing interferograms and calculated wavefronts from the fringes in real time. The data for a single interferogram are taken within 2 ms. The complete wavefront data set is available after 40 ms. Thereby it is possible to average 4000 wavefront data sets in less than 3 minutes.

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The refractive index variation of the glass depends on the temperature due to the thermo-optical coefficient. Therefore temperature gradients within the glass will impact the measurement accuracy. Special measures have to be taken to reduce the temperature variations within the samples. The interferometer room is air-conditioned. The interferometer cavity is separated from the interferometer room by a special cabin (see figure 2). The temperature stability of this cabin is ±0,05 °C, the temperature stability in the room surrounding the cabin is ±0,25 °C. A special transfer system is used to move the prepared samples into the interferometer cavity.

Fig. 2: 12 inch DIRECT100 with robot for placing the sample inside the cavity.

5. Homogeneity measurement methods

The influence of the sample surfaces must be eliminated for homogeneity measurement. SCHOTT uses two methods for homogeneity measurement: The “oil-on-plates sandwich” method and the “polished sample” method.

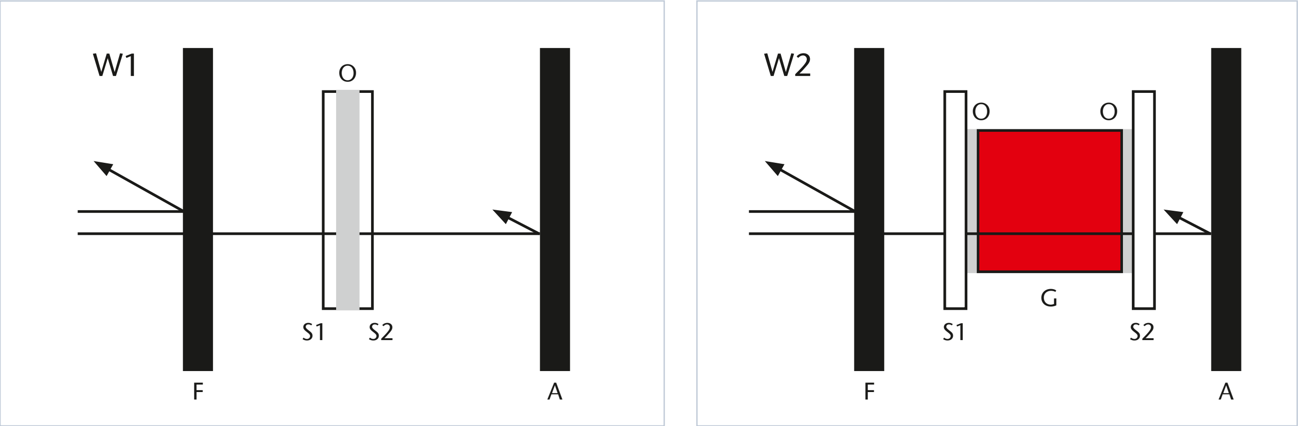

Fig. 3: Oil on plate measurement setup.

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For the “oil-on-plates sandwich” method the sample is placed between two glass plates (S1 and S2 in figure 3). These glass plates exhibit accurate polished surfaces. The glass plates are connected with the samples using an immersion oil liquid (O) that has the same refractive index as the sample. For this method the sample (G) does not need to be polished for the measurement. Only lapped surfaces with a flatness of about 2 µm are required. The measurement starts by measuring the oil-on-plates sandwich alone without sample (W1) and subtracting a measurement of the oil-on-plates with the sample (W2).

The result is a homogeneity plot of the sample. For the accuracy of this method it is very important that the immersion oil matches the refractive index of the sample very accurate (Δn should be less than $1 \cdot 10^{-4}$). To measure a wide variety of optical glasses with varying refractive indices mixtures of three immersion oils are used. Optical glasses with refractive indices from 1.473 to 1.651 can be measured using the “oil-on-plates sandwich” method.

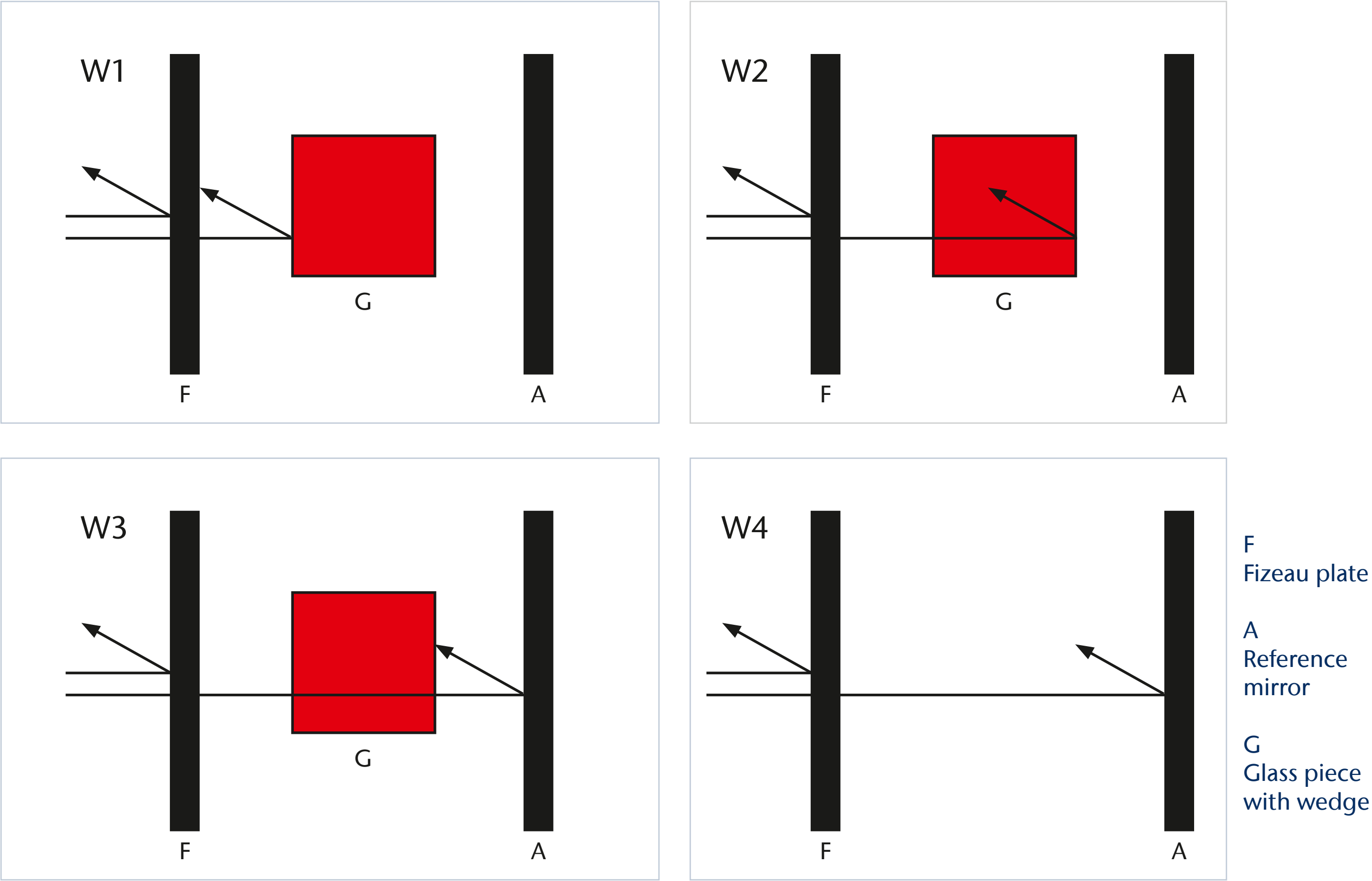

Fig. 4: Polished sample measurement method.

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For optical glasses that cannot be measured using the "oil-on-plates sandwich" method the "polished sample" method must be used [3]. For this method the sample must be polished on both surfaces to moderate optical quality. Additionally a small wedge of a few minutes angle must be introduced between front and back surface. The homogeneity measurement consists of a sequence of 4 individual measurements (see figure 4). First a measurement of the empty cavity is necessary. Then 3 measurements of the sample are performed. The sample will be measured in transmission, in reflection from the back surface and in reflection from the front surface. These 4 measurements are combined subsequently and the homogeneity distribution is evaluated.

6. Measurement accuracy

As mentioned before the homogeneity of optical glass is measured by evaluating wavefront deviations using interferometric techniques. Therefore the measurement accuracy of the interferometer is given in nm wavefront deviation (peak to valley).

The accuracy of the interferometer can be evaluated by repeatability measurements of the empty cavity. The repeatability lies in the range of 3–4 nm peak to valley, which is the so called "noise" of the interferometer.

The overall accuracy of the wavefront measurement is influenced by the temperature homogeneity, the matching accuracy of the immersion oil liquid and the handling (oil-on-plate measurement setup, preparation of the samples for the polished method).

For the oil-on-plate measurement the standard deviation lies in the range of ± 10 nm wavefront deviation (peak to valley).

The practical meaning of ± 10 nm wavefront accuracy is, that for measuring homogeneity grade H5 ($\pm 5 \cdot 10^{-7}$) the sample needs to be at least 10–20 mm thick. The sensitivity of the measurement increases with increasing sample thickness.

7. Inspection certificate and interpretation of measurement results

For each homogeneity measurement the customer can obtain a homogeneity inspection certificate. For the measurement with the DIRECT100 the inspection certificate contains a homogeneity map of the measured sample. This color-coded homogeneity map displays the refractive index variations within the measurement aperture. Different colors express different refractive index values. Color changes therefore express refractive index variations, in other words: in-homogeneities. The homogeneity is given as the peak to valley variation within this homogeneity map. Figure 5 shows a typical homogeneity distribution color map and a 1D "height" profile along the direction of the arrow in the color map.

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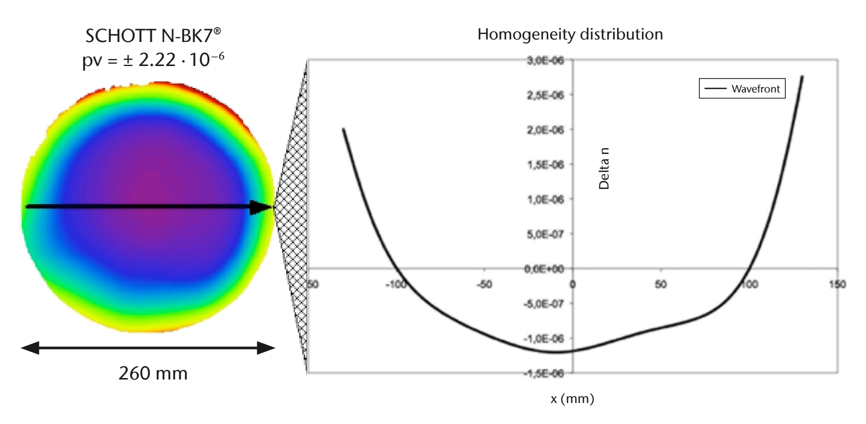

Fig. 5: 2D homogeneity color map and 1D profile along arrow.

The shape of the wavefront deformation (and therefore the homogeneity distribution) can be mathematically described as a polynomial function being a summation of independent aberration terms. These terms contain coefficients expressing the amount of focus, astigmatism, coma and spherical aberration within a wavefront. Piston and tilt deviations are subtracted from the wavefront in advance. SCHOTT uses for the decomposition of the wavefront the Zernike polynomial expansion [2].

The Zernike polynomial expansion of a given wavefront is only valid if the wavefront exhibits a circular aperture.

For certain applications it is important to know the Zernike coefficients to simulate the wavefront deformation due to the component in an optical setup, therefore the SCHOTT homogeneity testing certificate for circular apertures contains information on the Zernike coefficients.

Figure 6 shows the 1D homogeneity distribution with the appropriate main aberration polynoms. The picture on the right shows the 3D homogeneity distribution.

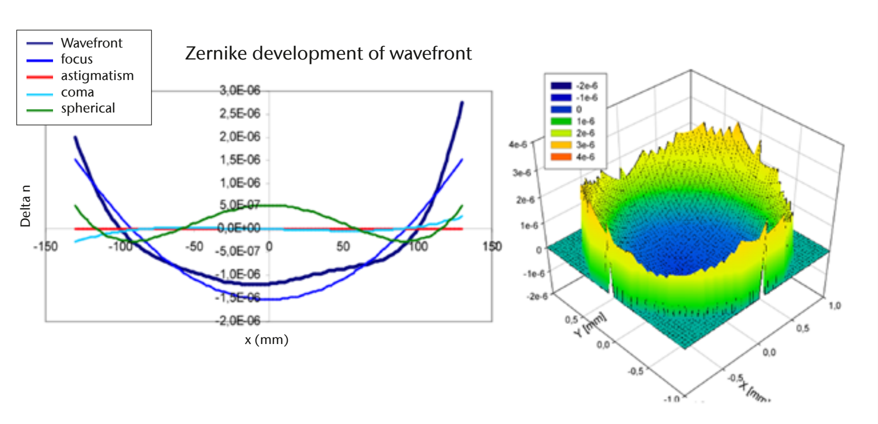

Fig. 6: Example of the Zernike polynomial expansion.

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For most applications of optical glass the focus term can be compensated in lens design by refocusing by the adjustment of lens distances. The peak to valley homogeneity after subtracting the focal term from the complete wavefront is in most cases much lower than the initial value (see figure 7).

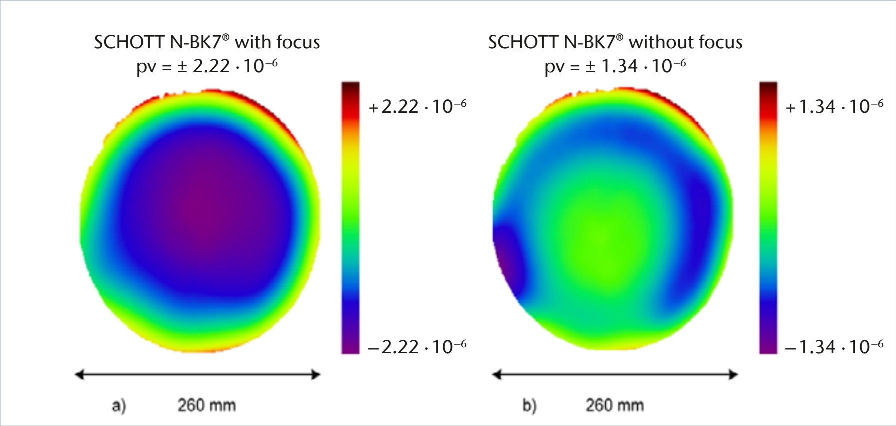

Fig. 7: SCHOTT N-BK7® blank with and without focal aberration.

8. Material selection/Implications

There are several criteria for the selection of homogeneous material from a melt campaign. The plot of the refractive index versus time during a melting process is used to evaluate if glass was produced in higher homogeneities. The best results are achieved if the refractive index remains constant with time, which means that for high homogeneities glass should be taken from areas where the slope of the plot is close to zero.

Another criteria for selecting the glass with higher homogeneity is striae inspection. As a rule glass with a very good global homogeneity does not exhibit striae. Figure 8a shows the homogeneity measurement of a N-BAK1 glass block without striae, figure 8b shows the homogeneity measurement of a N-BAK1 glass block from the same melt with striae. The homogeneity of the striae free block is two times better than the block exhibiting striae. The spatial resolution of the DIRECT100 interferometer is not high enough to make the striae itself visible.

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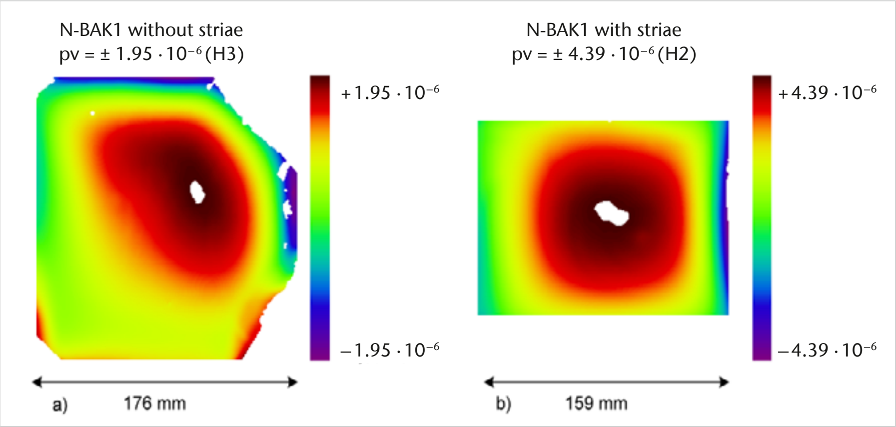

Fig. 8: Striae content as selection criteria for homogeneous glasses.

Either if the glass format is circular or block shaped, most homogeneity distributions exhibit a rotational symmetry. Therefore if the diameter of a large casting is reduced by cutting and grinding the homogeneity increases.

Figure 9 shows the homogeneity of a disc shaped SCHOTT N-BK7® part (with starting diameter 260 mm) as a function of the diameter of the part. At 260 mm diameter the disc exhibits H2 quality, at 250 mm H3, at 210 mm H4 and at 170 mm H5 quality. In general, it can be observed that the homogeneity increases with decreasing diameter.

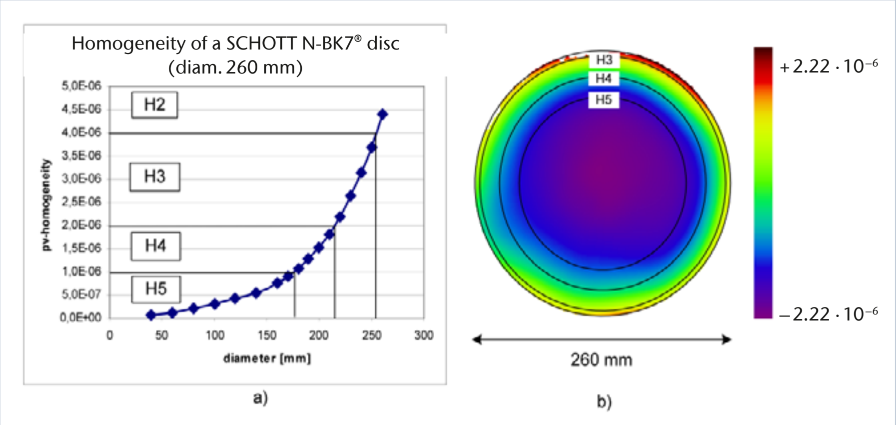

Fig. 9: Homogeneity as a function of diameter.

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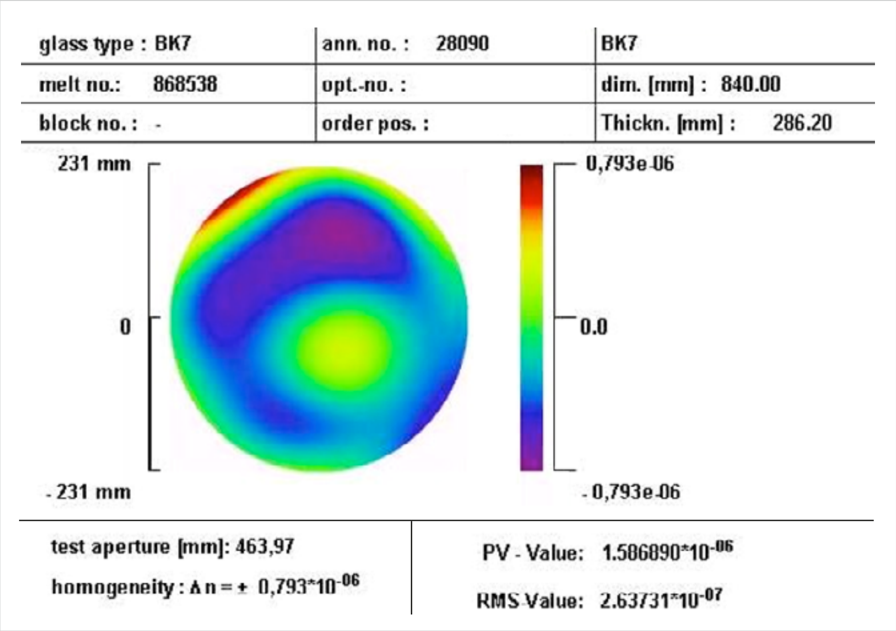
The strongest deviations from homogeneity can be found near the edge of the glass disc. The reason for the decrease in homogeneity towards the mold wall can be found in the casting process. The glass flow during casting forms specific convection patterns. The crucible is filled from the bottom to the top and from the center to the outer areas. Slight changes in the refractive index during time needed to fill up the crucible will be reflected in the refractive index distribution lateron.

This phenomenom will especially have an influence during production of large blanks. Additional reactions with the refractory wall materials of the crucible can worsen the homogeneity at the outer area of the glass.

Figure 10 shows the homogeneity measurement result of an 840 mm diameter SCHOTT N-BK7® disc. Within an aperture of 464 mm H4 quality was achieved.



glass type : BK7	ann. no. : 28090	BK7
melt no.: 868538	opt.-no. :	dim. [mm] : 840.00
block no. : -	order pos. :	Thickn. [mm] : 286.20

test aperture [mm]: 463,97

homogeneity : $\Delta n = \pm\ 0{,}793{*}10^{-06}$

PV - Value: $1.586890{*}10^{-06}$

RMS-Value: $2.63731{*}10^{-07}$

Fig. 10: Homogeneity of an 840 mm diameter SCHOTT N-BK7® disc

The slight differences in the refractive index of the melt during casting time will be more prominent in homogeneity measurement in edge/edge direction than in top/bottom direction. Figure 11 shows the homogeneity distribution of a SCHOTT N-BK7® glass block in top/bottom and edge/edge direction. The homogeneity in edge/edge direction is lower than in top/bottom direction. This observation may be important for the selection of material for extreme quality prism applications.

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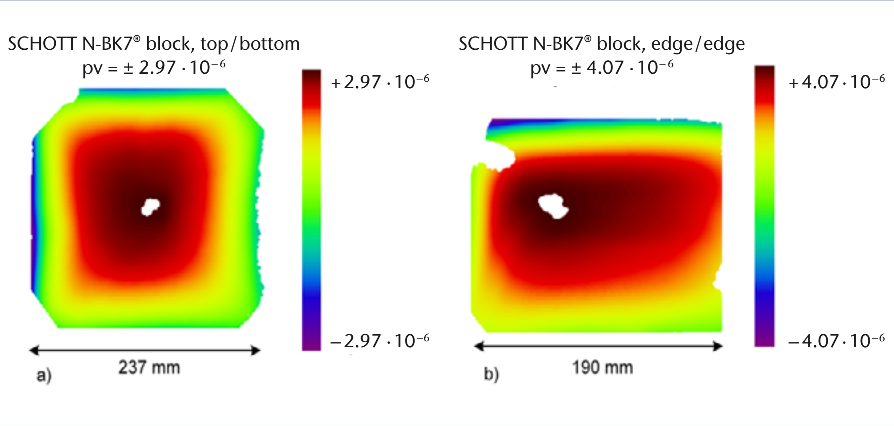

Fig. 11: Homogeneity depending on view direction.

The achievable homogeneity also strongly depends on the glass type and production process. SCHOTT offers a selection of optical glasses as fine annealed cut blanks in high homogeneities from stock.

Table 2 provides an overview on available glass types, dimensions and homogeneity levels. The homogeneity specified is always achieved for at least 90 % of the diameter. On smaller diameters also higher homogeneities are available on request.

SCHOTT N-BK7® and F2 can be delivered for prism applications with homogeneity inspection in two directions perpendicular to each other.

Glass Type*	Supply Form*	Maximum available dimensions*	Homogeneity level
F2	discs	Ø 290 mm, thickness: 100 mm	H4
LF5	discs	Ø 220 mm, thickness: 45 mm	H4
LLF1	discs	Ø 220 mm, thickness: 45 mm	H4
SCHOTT N-BK7®	blocks	400 mm x 400 mm x 70 mm	H4
	blocks	250 mm x 250 mm x 100 mm	H4
N-FK5	discs	Ø 240 mm, thickness: 50 mm	H4
N-FK51A	discs	Ø 200 mm, thickness: 40 mm	H4
N-KZFS11	discs	Ø 170 mm, thickness: 40 mm	H4
N-LAK22	discs	Ø 200 mm, thickness: 50 mm	H4
SF5	blocks	150 mm x 150 mm x 60 mm	H4

*Other types of glass, supply forms and dimensions are available upon request (the dimensions depend on the glass type).

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9. Conclusion

In general the global refractive index homogeneity of optical glasses is better than $40 \cdot 10^{-6}$ (comprising ISO 10110 part 4 homogeneity grade 1).

Most machined optical glasses can be delivered in homogeneities H2 or better. SCHOTT can supply optical glasses with homogeneities up to H5 quality. The achievable homogeneity depends on the glass type and the size. For special applications SCHOTT also offers high homogeneity in two perpendicular directions.

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10. Literature

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[2] **Interferogram analysis for optical testing, Malacara, D., Servin, M.; Malacara, Z.: Marcel Dekker Inc., 1998**

[3] **Homogeneity testing by phase sampling interferometry, Schwider, J., , Appl. Opt. 24, pp. 3059–3061, 1985**

[4] **SCHOTT Optical Glass Pocket Catalogue**

[5] **ISO/DIS 10110 – part 4; Preparation of drawings for optical elements and systems; Material imperfections – Inhomogeneity and striae, 1994**

[6] **ISO 12123 Specification of raw optical glass, 2010**

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