TIE-40 Optical glass for precision molding

1. Precision molding

Hot processing of coarse annealed glass (also called reheat pressing) is the preferred processing step for small lenses of standard quality at high volumes. The disadvantage of this process is that the surface of these pressings is still rough and the pressings therefore need additional grinding and polishing.

To overcome such restrictions and to reduce the processing expense, precision molding technologies for direct pressing of aspherical lenses have been developed in the past years worldwide. The process of precise molding (figure 1) starts from a polished or firepolished preform. The surface of such a preform must be of very good quality with respect to surface roughness and defects. Such a preform can be a precision gob (a firepolished preform produced directly from the melt without any additional surface processing) or any other polished lens preform (ball, disc or near shape generated out of raw glass by conventional hotforming or grinding and polishing steps). During a precision molding process, the preform is shaped into its final (often aspherical) geometry, while conserving the surface quality of the preform. The molding process is a low temperature molding process with typical temperatures between 500°C and 700°C. Low temperature processes helps to lengthen the operating lifetime of the mold material.

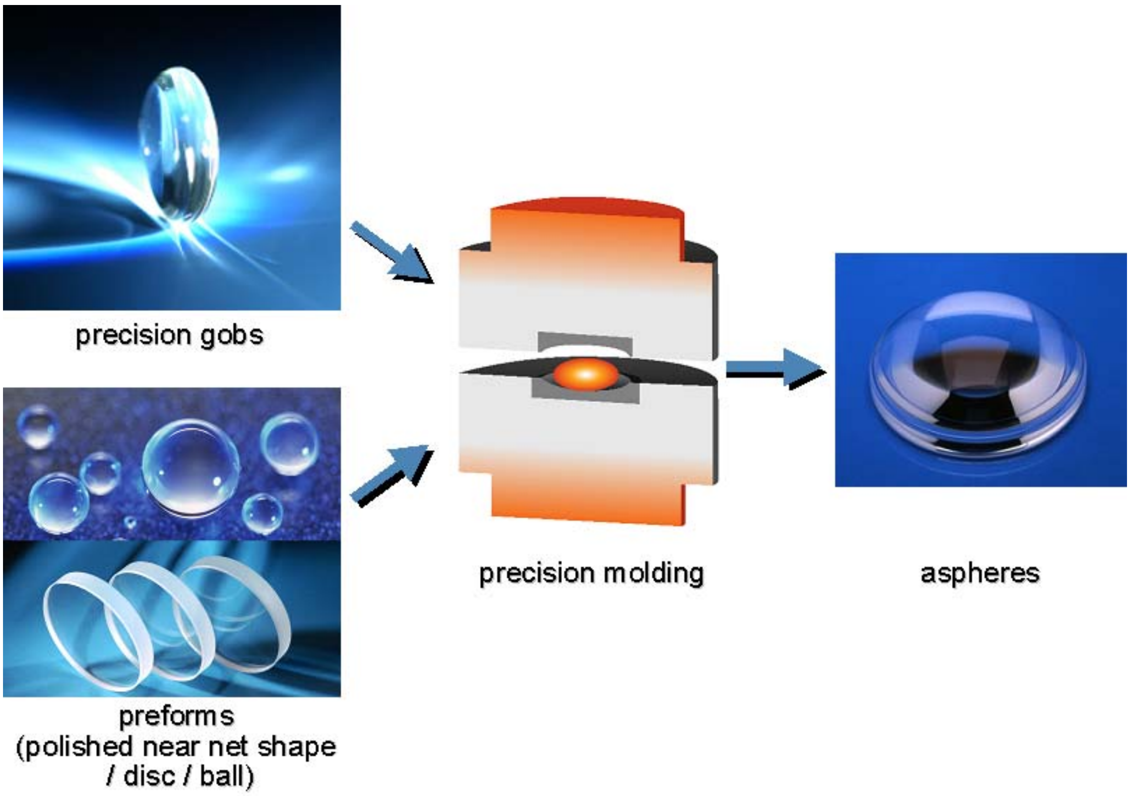

Figure 1: Overview on the precision molding process

2. Optical Glasses for Precision Molding

Precision molding is a state-of-the-art technology for the volume production of complex lenses. Generally used mold materials in the molding process exhibit a thermal stability of up to 650°C. However, a variety of so-called low transformation temperature glasses (low Tg glasses) is required for the precision molding process. Low Tg glasses have a Tg not higher than 550°C. Table 1 shows an overview of such glasses.

	n_d *2	ν_d *2	Internal trans-mit-tance*3	Color code 80/5	Tg [°C]	AT [°C]	CTE [$10^{-6}K^{-1}$] *4	AR *5	WR *6	Density [g/cm³]
P-PK53[*1]	1.52690	66.22	0.994	36/31	383	418	16.0	3	1	2.83
P-SK57[*1]	1.58700	59.60	0.994	34/31	493	522	8.9	4	1	3.01
P-LASF47[*1]	1.80610	40.90	0.967	39/33	530	580	7.3	3	1	4.54
P-SF67	1.90680	21.40	0.276	48/39	539	583	7.4	1	1	4.24
N-FK51A	1.48656	84.47	0.997	34/28	464	490	14.8	3	1	3.68
N-FK5	1.48749	70.41	0.998	30/27	466	557	10.0	5	4	2.45
N-PK52A	1.49700	81.61	0.997	34/28	467	495	15.0	4	1	3.75
N-PK51	1.52855	76.98	0.994	34/29	487	517	14.1	3	1	3.86

*1 new developed glasses, *2 fine annealed = catalog value, *3 at 10mm thickness and 400 nm, *4 value between 20-300°C
*5 AR = acid resistance according JOGIS, *6 WR = water resistance according JOGIS,

Table 1: Optical glasses for precision molding.

The advantage of using low Tg glasses is that the press process can take place at lower temperatures hence leading to a longer lifetime for the mold. At the same time, the press process time can also be shortened.

Low Tg glasses in general are glasses with a glass transformation temperature below 550°C. Furthermore, Low Tg glass compositions have been developed to have low tendencies for devitrification and reduced reactions with mold materials at the molding temperature range.

P-SK57, P-LASF47, P-PK53 and P-SF67 are newly developed low Tg glasses especially for use in precision molding (see table 1). The letter “P” indicates that these glasses are produced for precision molding and are exclusively available as polished preform or precision gob. They are lead and arsenic free. “P-“ type glasses, in general, are coarse annealed glasses with tighter optical specifications (referred to as “P-quality” grade in the following sections.)

The shown N-type optical glasses can be used for precision molding mainly due to their low glass transformation temperature. These glasses are also available in “P-quality” grade. N-type glass in P-Quality grade are also available only as polished perform or precision gob.

The refractive index and Abbe number data given in the SCHOTT glass datasheets represent optical values of fine annealed glasses. It is necessary to take into account that the cooling rate of a precision molding process is much higher than common fine annealing rates. Therefore, the refractive index of any precision molded lens will be significantly lower than the catalogue values of the glass being used. Detailed explanations can be found in chapter 5.

3. Specification of precision molding glass quality (“P-quality”).

Precision molding glasses (P-type glasses) and traditional N-glasses that are available in “P-quality” fulfill the following standard specifications:

- Optical glasses for precision molding are selected based on the refractive index value and Abbe number at a reference annealing rate of 2 K/h.
- Tolerances for refractive index are ± 0.0005 and for the Abbe number are ± 0.5% (step 3/3 according to the catalog based on a 2 K/h reference annealing rate).
- Customers will receive preforms with a test certificate certifying the refractive index and Abbe number of the batch based on a reference annealing of 2 K/h. **The actual refractive index of the glass within the delivery batch will differ from this value but this causes no problem during molding**.
- For all P-type glasses (e.g. P-SK57, P-PK53, P-LASF47 and P-SF67) these specifications will be automatically fulfilled.
- For N-FK5, N-FK51A, N-PK52A and N-PK51 “P-quality” grade preforms shall be ordered.

In contrary to standard optical glass specifications, the refractive index and Abbe number tolerance steps are related to a reference annealing rate. This is necessary for precision molding glass to achieve a reproducible process dependent index drop. The reason is explained in chapter 5.

For internal quality, striae and other specifications, please refer to the standard optical glass catalogue or contact your local sales representative.

4. Precision molding glass preforms

Low Tg glasses (P-type or P-quality glasses) will be delivered as (fire-) polished preforms. Several different preform types are available. Table 2 summarizes the properties of the four different preform types, which can be chosen according to the final geometry of the pressed optical element.

Preform types	Precision gob	Polished near net shape	Polished disc	Polished ball
Diameter in mm	4 to 40	> 3	> 3	> 0.8
Volume in mm^3	33 to 5000	> 50	> 50	> 1
Glass types	not all glass types	all glass types	all glass types	all glass types

Table 2: Typical preform types and their properties suitable for precise molding

Table 3 displays an overview of the glass type availability in the various preform formats.

	Precision gob	Polished near net shape	Polished disc	Polished ball
P-PK53*1	✔	✔	✔	✔
P-SK57*1	✔	✔	✔	✔
P-LASF47*1	✔	✔	✔	✔
P-SF67	x	✔	✔	✔
N-FK51A	x	✔	✔	✔
N-FK5	x	✔	✔	✔
N-PK52A	x	✔	✔	✔
N-PK51	x	✔	✔	✔

Table 3: Available preform types for the different low Tg glasses (x = not available)

4.1 Precision gobs

For many years, SCHOTT has been a reliable supplier for precision gobs made of B270, which is a technical glass used for molding automotive headlight lenses. Since 2004, SCHOTT has also been a supplier of precision gobs made out of optical glass. Precision gobs are semi-finished preforms with geometries near to the final geometry of the lens and a very smooth fire-polished surface with excellent surface roughness. They are manufactured using a unique continuous glass melting and hot forming process and can be produced in volumes from 33 mm^3 up to 5000 mm^3.

Possible dimensions:

- Convex surface radius from 2.5 to 30 mm
- Minimum thickness around 3.8 mm
- Minimum center thickness/diameter ratio values between 0.5 and 1, the lower the ratio, the more critical the production
- Roundness between 0.5 mm and 0.005 mm depending on size

The exact gob geometry can be calculated by simulation prior to the production.

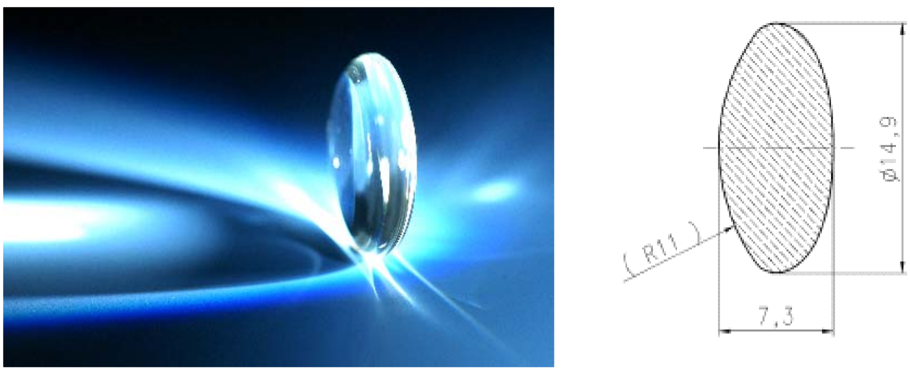

Figure 2: Precision gob (left) and a typical drawing (right)

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Figure 2 shows a typical drawing and picture of a precision gob (drawings can be generated from simulations). The precision gob fabrication is a very economical production process but is not suitable for every precision molding glass. Currently, only the “P-type” glasses can be provided as gob preforms (refer to table 3).

Typical tolerances for a precision gob:

- Diameter tolerance: ± 0.2 mm down to ± 0.005 mm
- Volume tolerance: 0.5% to 2%
- Surface quality: 20/10 scratch and digs (MIL –O-13830-A)
- Surface roughness: < 1 nm rms
- Stress birefringence: < 120 nm/cm (suitable for precision molding)

Precision gobs feature excellent surface quality. Figure 3 shows an example of the result of an AFM (Atomic Force Microscopy) roughness measurement of a precision gob.

Precision gobs are inspected and packed under clean-room conditions, therefore a very good cleanliness level can be achieved. Customer specific cleanliness and packing requirements can also be fulfilled upon request.

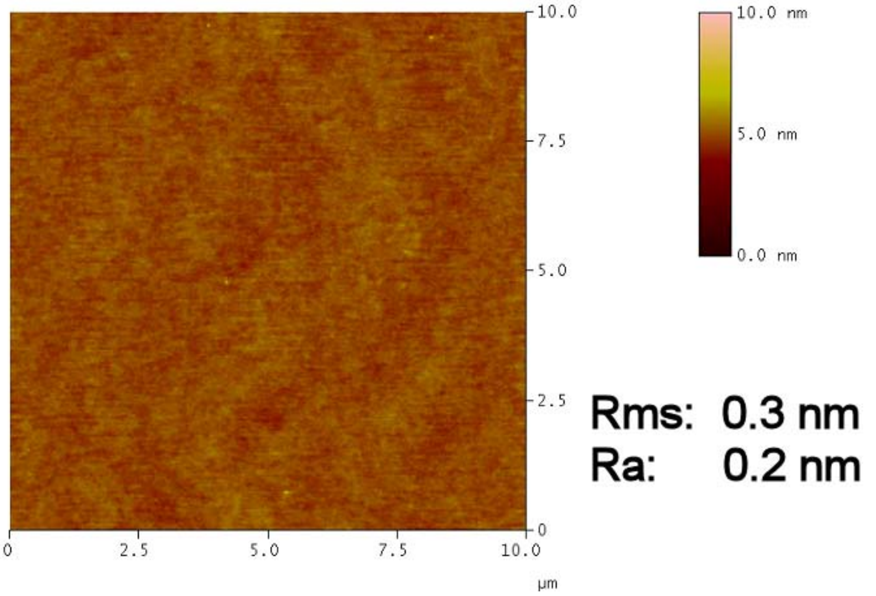

Figure 3: AFM roughness measurement results of a precision gob

4.2 Polished near net shape and polished disc preforms

The precision gob fabrication is a highly economical process for the mass production of preforms. Nevertheless, there are geometries that cannot be produced using the precision gob process. Currently, the precision gob process is restricted to biconvex shaped preforms. The size of the gobs is also restricted to a minimum volume of 120 mm^3.

In addition, SCHOTT offers lens (near net shape) and disc shaped preforms that can be produced based on individual customer designs using classical lens production processes.

The surface quality is equal or better 40/20 scratch and digs and the roughness is less than < 2 nm rms. It is also possible to achieve very tight volume tolerances. Please ask your sales representative for more detailed information.

4.3 Polished ball preforms

Ball lens preforms are available in diameters bigger than 0.8 mm. Their main application can be in small cellular phone camera lenses, for instance.

Typical tolerances for ball preforms are:

- Diameter tolerance ± 5 µm (smaller tolerances are possible on request)
- Surface quality: 40/20 scratch and digs (MIL –O-13830-A)
- Surface roughness: < 2 nm rms (smaller tolerances are possible on request)

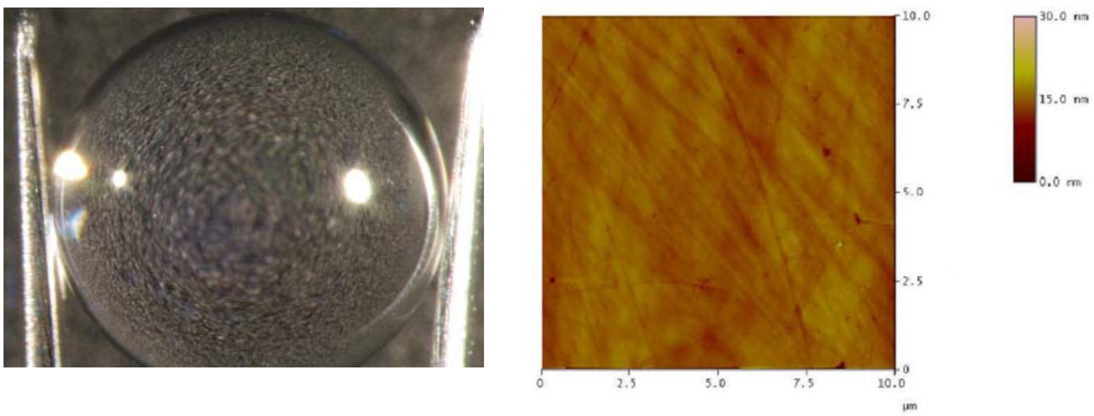

Figure 4: 2 mm size polished ball preform (left) and AFM roughness measurement (right)

Customer specific cleanliness and packing requirements can be fulfilled upon request. Figure 4 shows a typical atomic force microscope roughness evaluation of a 2 mm size ball preform. The roughness is in the range of 0.9 nm rms.

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5. Influence of the molding process on the refractive index and Abbe number

The optical data for a glass type are determined by the chemical composition and thermal treatment of the melt. The annealing rate in the transformation range of the glass can be used to influence the refractive index within certain limits (depending on the glass type and the allowable stress birefringence). Basically, slower annealing rates yield higher refractive indices. In practice, the following formula has shown to be reliable:

$$n_d(h_x) = n_d(h_0) + m_{nd} \cdot \log(h_x / h_0) \quad (1)$$
$$\nu_d(h_x) = \nu_d(h_0) + m_{\nu d} \cdot \log(h_x / h_0) \quad (2)$$

h_0 Original annealing rate
h_x New annealing rate
m_{nd} Annealing coefficient for the refractive index depending on the glass type
$m_{\nu d}$ Annealing coefficient for the Abbe number depending on the glass type

More details can be found in [2]

Values for annealing coefficients of some glasses for precision molding are shown in table 4.

	m_{nd} [10^{-5}]	$m_{\nu d}$
N-FK51A	-55	-0.08346
P-LASF47	-147	-0.04346
P-SK57	-95	-0.08435

Table 4: Annealing coefficients for selected precision molding glasses

The annealing rate influences the refractive index and the Abbe number simultaneously and is the reason for the change of refractive index after molding. This change of refractive index and Abbe number is called “index drop”.

5.1 Coarse annealing of optical glass

After the melting and casting process, the precision molding glass is cooled down in a coarse annealing lehr at a high annealing rate. The annealing rate depends on the dimensions of the strip. Typical values are between 50 and 100 K/h. In order to control the refractive index through the melting and casting process, samples are taken directly from the melt at a given frequency. The refractive index and Abbe number of the samples will be measured based on a special procedure at a reference annealing rate of 2 K/h. Based on this 2 K/h reference, the optical values during production can be controlled in a reliable way.

The glass for precision molding is selected in such a way that the 2 K/h reference value of the glass is within step 3/3 of the catalogue value. The real value of the glass will be different from this value due to the reasons given above. However, this difference is not relevant for the application. (Please refer to the next chapter).

5.2 Influence of the precision molding process on the optical position of the glass: index drop

As mentioned in the beginning of chapter 5, an annealing process influences the refractive index and the Abbe number of an optical glass, simultaneously.

The diagram in figure 5 shows schematically the index drop behavior of N-PK51 based on an exemplary molding process. The diagram displays the Abbe number versus the refractive index (n_d) for N-PK51. The rectangular boxes indicate the tolerance limits of tolerance step 3/3 for the refractive index and the Abbe number of N-PK51. The catalogue value is located in the center of these boxes. The red rhomb shaped dots within the green box are sample 2 K/h reference values of real glasses from different melts.

The straight line in the diagram characterizes the annealing behavior of N-PK51. The slope is characteristic for each glass type. For every N-PK51 glass melt like those indicated with a red rhomb, the annealing slope is the same. The annealing rates printed along the line mark the optical position that will be achieved if this glass would be annealed using the displayed annealing rate. The precision molding glass in general is coarse annealed glass. In the diagram, for example, the big red rhomb has a 2 K/h value within the green tolerance limits whereas the real refractive index of the current glass lies somewhere between 50 K/h and 100 K/h on the annealing line.

Usual fine annealing rates range from 0.5 to 2 K/h. For pressings, annealing rates between 2 and 10 K/h are used. In normal annealing processes, the annealing rate is adjusted to achieve a specific refractive index range with at the same time low stress birefringence and sometimes also a good homogeneity.

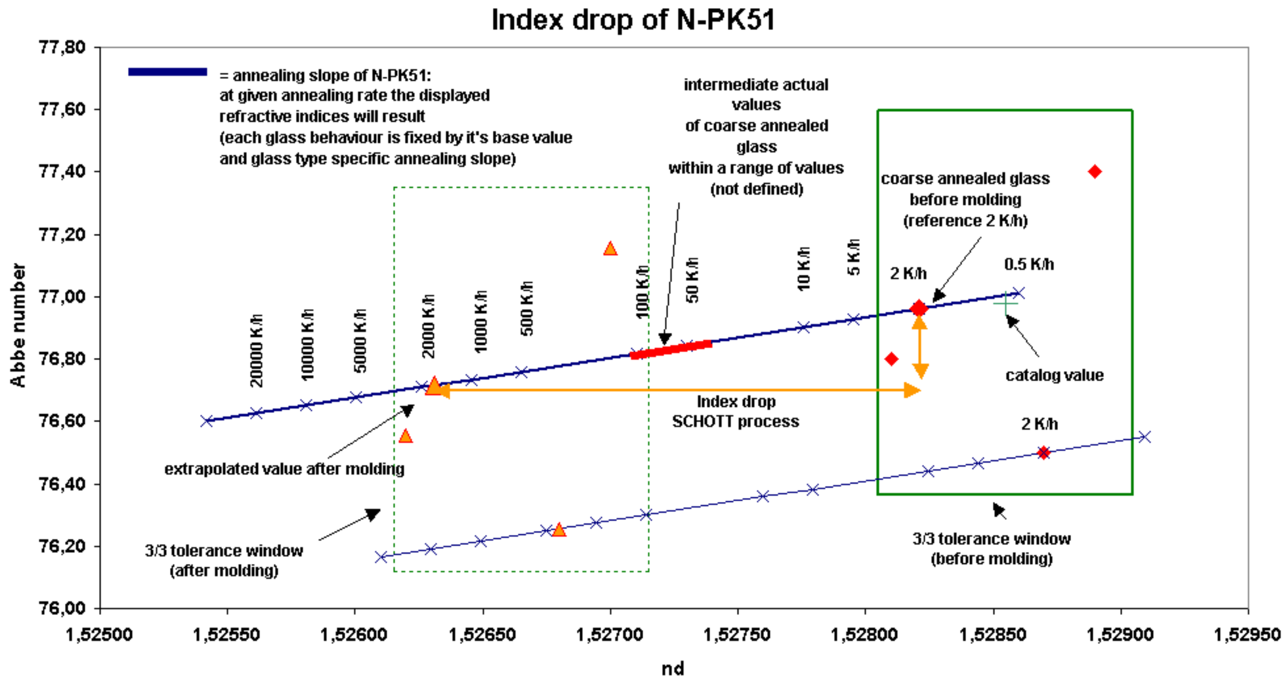

Figure 5: Annealing line and index drop behavior of N-PK51.

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In contrast to these rather low and well defined rates, the annealing in a precision molding process is very fast and it is in most cases individual to the process of the customer and the geometry of the glass part. In general, there is no additional annealing process to adjust the refractive index after molding because of the high risk of decreasing the surface quality. Therefore, the rate is not known in most cases but fixed and reproducible.

Additionally, the annealing rate is not necessarily constant during the cooling process. Nevertheless, by estimating the final optical position of the precision molded glass, an “average” annealing rate can be assigned. Typical “average” annealing rates for precision molding are between 1000 K/h and 10000°K/h (or higher). According to the high annealing rate, the refractive index and Abbe number of N-PK51 is shifted to much lower values. This shift is called index drop. In Figure 5 the values after precision molding are marked by orange triangles.

The index drop is defined as the difference between the final refractive index and Abbe number after molding and the initial refractive index and Abbe number reference values based on a 2 K/h annealing:

$$\Delta n_d = n_d(2K/h) - n_d(after.molding) \quad (3)$$

$$\Delta \nu_d = \nu_d(2K/h) - \nu_d(after.molding) \quad (4)$$

The amount of index and Abbe number drop for N-PK51 is indicated with orange arrows in figure 5.

Figure 5 also shows that the index drop is approximately the same for all N-PK51 glasses within the initial tolerance range (using the same process). Therefore, the scattering in optical position between the molded glasses also remains the same under the assumption that the precision molding process is highly reproducible. The tolerance window simply shifts to a new central position.

It should be noted that it is essential for the reproducibility to always determine the index drop from initial refractive index values based on the same annealing rate. Determination of the refractive index drop based on the actual refractive index values of the coarse annealed glass will lead to errors due to undefined annealing conditions. Therefore, it is recommended to always rely on the values based on one reference annealing rate of 2 K/h.

The index drop differs between glass types because every glass has a different annealing slope. Figure 6 shows the relative change in refractive index and Abbe number based on the annealing slopes for the precision molding glasses P-SF67, P-LASF47, P-SK57, P-PK53, N-FK51A, N-PK51, N-PK52A and N-FK5.

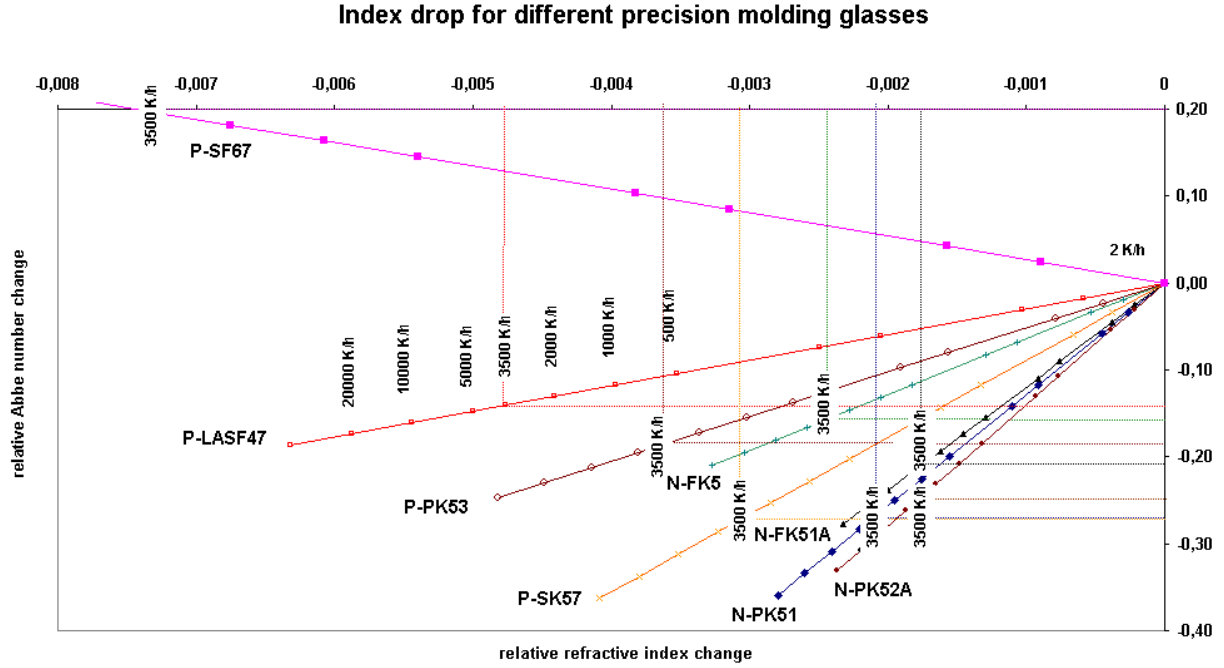

Figure 6: Theoretical index drop for different precision molding glasses assuming an average annealing rate of 3500 K/h and identical geometry.

In the given simplified example it can be seen that the index change for an average annealing rate of 3500 K/h ranges, depending on the glass type, from –0.0017 to –0.0073 for the refractive index n_d. The Abbe number changes in the range of +0.20 to –0.27. P-SF67 behaves different compared to the other glasses, because the Abbe number increases with increasing annealing rate. As mentioned before, this is a simplified view. In reality, there are other factors influencing the real index drop (e.g. geometry, molding process, thermal properties of the glass). Nevertheless, a glass with a steep annealing slope will always lead to a large index drop.

A detailed list of the index drop for SCHOTT precision molding glasses at the d and e wavelength based on our own molding process and part geometries is displayed in table 5.

	Molding temperature range [°C]	Before molding 2 K/h reference catalog values				After molding			
		n_d	n_e	ν_d	ν_e	n_d	n_e	ν_d	ν_e
P-PK53	425 - 445	1,52690	1,52880	66,22	65,92	1,5232	1,5251	66,0	65,7
P-SK57	555 - 580	1,58700	1,58935	59,60	59,36	1,5843	1,5867	59,4	59,1
P-LASF47	595 - 615	1,80610	1,81078	40,90	40,66	1,8016	1,8062	40,8	40,5
P-SF67	610 –630	1,90680	1,91675	21,40	21,23	1,8998	1,9096	21,6	21,4
N-FK51A	505 - 525	1,48656	1,48794	84,47	84,07	1,4847	1,4861	84,2	83,8
N-FK5	600 - 630	1,48749	1,48914	70,41	70,23	1,4850	1,4866	70,2	70,0
N-PK52A	515 - 535	1,49700	1,49845	81,61	81,21	1,4952	1,4966	81,3	80,9
N-PK51	540 - 560	1,52855	1,53019	76,98	76,58	1,5267	1,5283	76,7	76,3

Table 5: List of index drop based on the SCHOTT molding process

The index drop behavior for other wavelengths can be provided on request.

6. Precision molding glass: Test report

The standard test report for precision molding (see example in figure 7) is based on the test report for fine annealed glass with some exceptions.

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Test Report / Werkszeugnis 04.01.2006
ISO 10474-2.2

Glass for precision molding / Glas zum Blankpressen

Delivery Note / Lot-Id. / Lieferschein / Lieferlos	xxxx
Order Position of / Auftrag Position vom	xxxx
Customer / Kunde	xxxx
Glass Type / Glasart	P-LASF47
Tg [°C]	530
n_d/ν_d- Step / - Stufe	3 / 1
Variation / Streuung	± 0,00015

Customer xyz

1234 Glassworking

Batches / Chargen

Kxxxxx00 Kxxxxx01 Kxxxxx02

n_d	1,80573 *	ν_d	40,89 *
n_e	1,81041 *	ν_e	40,65 *
		n_F-n_C	0,01970
		n_d-n_C	0,00586
τ_i(400nm;10mm)	0,975	n_F-n_d	0,01384
Color Code / Farbcode	39/32	n_F-n_e	0,00916
		n_g-n_F	0,01117
		$n_{F'}-n_{C'}$	0,01994
		$n_{F'}-n_e$	0,01032

* values based on a reference annealing rate of 2K/h, actual values will be different / basieren auf eine Referenzkühlrate von 2K/h, die tatsächlichen Werte sind anders.

This test report is printed with EDP. It is valid without signature.
Dieses Werkszeugnis ist per EDV ausgedruckt und ohne Unterschrift gültig

Optics for Devices
SCHOTT AG
Mainz, Germany

QFQ001DA

Figure 7: Example of a test report for precision molding glass

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In addition, the test report contains the glass transformation temperature. The refractive index values given are reference values based on a reference annealing rate of 2 K/h. The actual refractive index of the precision molding glass batches will be different. For the application it is necessary to always refer to the reference values. It also contains the spectral internal transmission at a wavelength of 400 nm and a sample thickness of 10 mm (central value between maximum and minimum) and the color code.

6. Literature

[1] R. Jaschek, C. Klein, C. Schenk, K. Schneider, J. Freund, S. Ritter, "Development of a new process for manufacturing precision gobs out of new developed low Tg optical glasses for precise pressing of aspherical lenses", Proc. SPIE Vol. TD03, pp. 50-52, 2005.

[2] Technical Information "TIE-29 Refractive Index and Dispersion"
http://www.schott.com/optics_devices/english/download/index.html

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