TIE-40 Optical glass for precision molding

1. Precision molding

Hot processing of coarse annealed glass (also called reheat pressing) is the preferred process 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 polished ball, a fire-polished rod, a precision gob (a firepolished preform produced directly from the melt without any additional surface processing) or any other polished lens preform (disc or near shape generated out of raw glass by conventional hot forming or grinding and polishing steps). During the 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 help to lengthen the operating lifetime of the mold material.

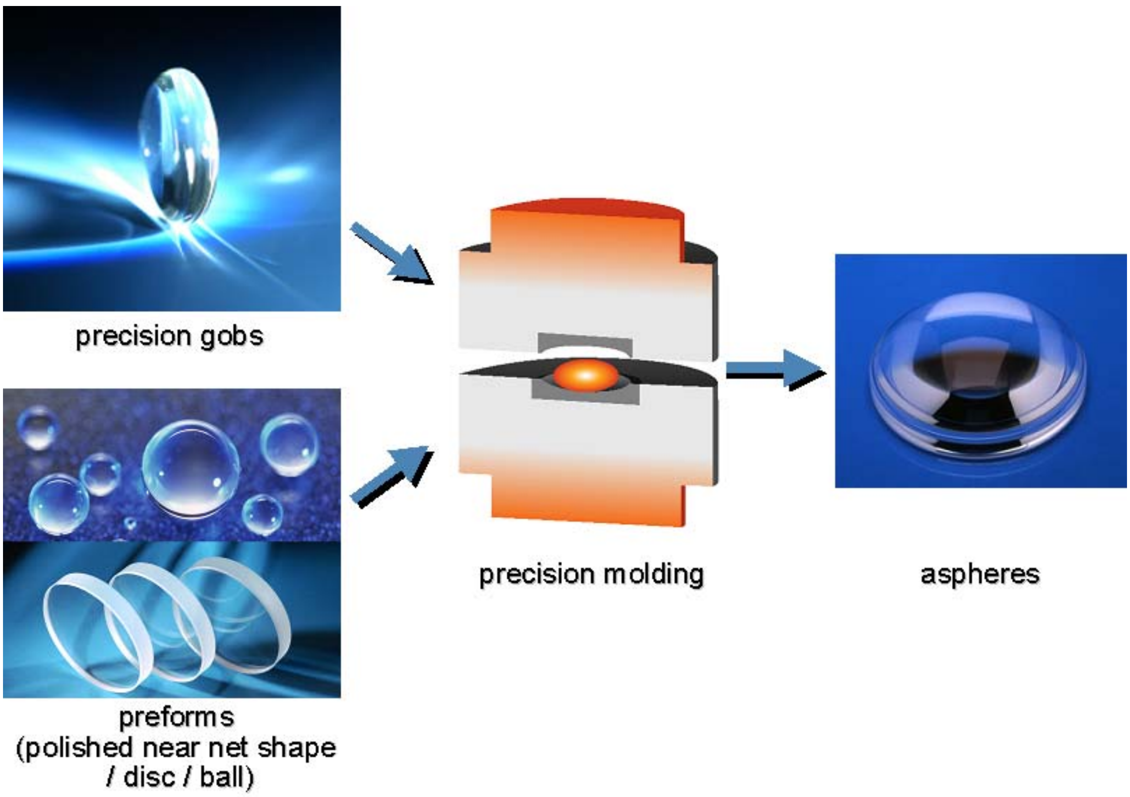

Figure 1: Overview on the precision molding process

2. Optical Glasses for Precision Molding

Precision molding is a state-of-the-art technology for the volume production of complex lenses. Most mold materials of precision molding processes exhibit a thermal stability of up to 700°C. Therefore, a variety of so-called low transformation temperature glasses (low Tg glasses) is required for the precision molding process.

	Optical Properties			Thermal Properties		Chemical Resistance		Physical Properties			
Glass Type	n_d *1	ν_d *1	Color code	Tg [°C]	AT [°C]	SR-J*3	WR-J*3	CTE*4 [10^{-6}/K]	Hardness HK (0.1/20)	Abrasion*3 Aa	Density [g/cm³]
N-FK51A	1.48656	84.47	34/28	464	503	3	1	14.8	345	528	3.68
N-FK5	1.48749	70.41	30/27	466	557	5	4	10.0	520	109	2.45
N-PK52A	1.49700	81.61	34/28	467	520	4	1	15.0	355	526	3.70
P-BK7	1.51640	64.06	33/30	498	546	1	4	7.3	627	66	2.43
N-PK51	1.52855	76.98	34/29	487	528	3	1	14.1	415	592	3.86
N-KZFS2	1.55836	54.01	34/30	491	533	6	6	5.4	490	70	2.54
P-SK57Q1	1.58600	59.50	34/31	493	522	4	1	8.9	535	124	3.01
P-SK57	1.58700	59.60	34/31	493	522	4	1	8.9	535	124	3.01
P-SK58A	1.58913	61.15	35/31	510	551	4	2	8.4	662	102	2.97
P-SK60	1.61035	57.90	33/29	507	547	4	3	8.9	601	86	3.08
N-KZFS4	1.61336	44.49	36/32	536	597	6	4	8.2	520	130	3.00
N-KZFS11	1.63775	42.41	36/30	551	-	-	-	7.6	530	74	3.20
N-KZFS5	1.65412	39.70	37/32	584	648	1	1	7.4	555	122	3.04
P-SF8	1.68893	31.25	40/36	524	580	1	1	11.1	533	200	2.90
P-LAK35	1.69350	53.20	36/29	508	544	4	3	9.7	616	119	3.85
N-KZFS8	1.72047	34.70	38/33	509	561	1	1	9.4	570	152	3.20
P-SF69	1.72250	29.23	40/36	508	547	1	1	11.1	612	142	2.93
P-LAF37	1.75550	45.66	37/31	506	546	4	1	7.8	697	67	3.99
N-LAF33	1.78582	44.05	39/32	600	628	6	1	6.7	730	67	4.36
P-LASF47	1.80610	40.90	39/33	530	580	3	1	7.3	620	70	4.54
P-LASF50	1.80860	40.46	39/32	527	571	3*2	1*2	7.3	655	62	4.54
P-LASF51	1.81000	40.93	39/33	526	570	3	1	7.4	722	66	4.58
SF57	1.84666	23.83	40/37*	414	449	6	1	9.2	350	344	5.51
P-SF68	2.00520	21.00	49/41*	428	468	4-5	1	9.7	404	298	6.19

* wavelength for transmittance 0.7 and 0.05 instead of 0.8 and 0.05
*1 catalog value (reference annealing rate: 2K/h)
*2 preliminary data
*3 SR-J = acid resistance, WR-J = water resistance and Abrasion Aa according to JOGIS
*4 temperature range: 20°C-300°C

Table 1: Optical glasses for precision molding. The detailed technical datasheets are available at:
http://www.schott.com/advanced_optics/downloads/optical_glass

Table 1 gives an overview of the Schott product range of established Low Tg glasses. By using low Tg glasses the press process can be performed at lower temperatures leading to a longer lifetime for the mold. At the same time, the process time is significantly shortened.

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

The letter "P" indicates that these glasses are developed especially for precision molding and that they are free of lead and arsenic. "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 with tighter optical specifications.
The refractive index and Abbe number data given in the SCHOTT glass data sheets represent optical values of fine annealed optical glass. It is necessary to take into account that the cooling rate of the 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 catalog values of the glass, which are annealed at a rate of -2 K/hour. This effect is called index drop and it is explained in more detail 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).
- For all P-type glasses these specifications will be automatically fulfilled.
  For N-FK5, N-FK51A, N-PK52A, N-PK51, N-KZFS2, N-KZFS4, N-KZFS5, N-KZFS8, N-LAF33 and SF57 "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 at the customers side. The dependence of index drop is explained in more detail in chapter 5.

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

4. Precision molding glass preforms

The Schott low Tg glasses are available in various forms of supply, like polished balls, (near net shape and disc shaped) preforms, rods, pressings and cut blanks. However, the most prominent one is currently the polished ball preform. Table 2 summarizes the properties of four different polished preform types, which can be chosen according to the final geometry of the pressed optical element.

Preform types	**Polished ball**	**Polished near net shape**	**Polished disc**	**Fire polished rod**
Diameter in mm	0.8-14	> 3	> 3	< 7
Volume in mm³	> 1	> 50	> 50	any
Glass types	all glass types	all glass types	all glass types	most of the glass types

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

Table 3 displays an overview of the glass type availability in the various preform formats. All glass types are also available as rods, pressings and cut blanks.

	Polished **ball**	Polished **near net shape**	Polished **disc**	Fire polished **rod**
P-BK7	✔	✔	✔	✔
P-LAF37	✔	✔	✔	✔
P-LAK35	✔	✔	✔	✔
P-LASF47	✔	✔	✔	✔
P-LASF50	✔	✔	✔	✔
P-LASF51	✔	✔	✔	✔
P-SK57	✔	✔	✔	✔
P-SK57 Q1	✔	✔	✔	✔
P-SK58A	✔	✔	✔	✔
P-SK60	✔	✔	✔	✔
P-SF8	✔	✔	✔	✔
P-SF68	✔	✔	✔	x
P-SF69	✔	✔	✔	✔
N-FK51A	✔	✔	✔	✔
N-FK5	✔	✔	✔	✔
N-PK51	✔	✔	✔	✔
N-PK52A	✔	✔	✔	x
N-KZFS2	✔	✔	✔	x
N-KZFS4	✔	✔	✔	✔
N-KZFS5	✔	✔	✔	✔
N-KZFS8	✔	✔	✔	✔
N-KZFS11	✔	✔	✔	x
N-LAF33	✔	✔	✔	✔
SF57	✔	✔	✔	✔

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

4.1 Polished ball preforms

Ball lens preforms are available in diameters bigger than 0.8 mm. Their main application can be in 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/dig (MIL –O-13830-A)

- Surface roughness: < 3 nm rms (smaller tolerances are possible on request)

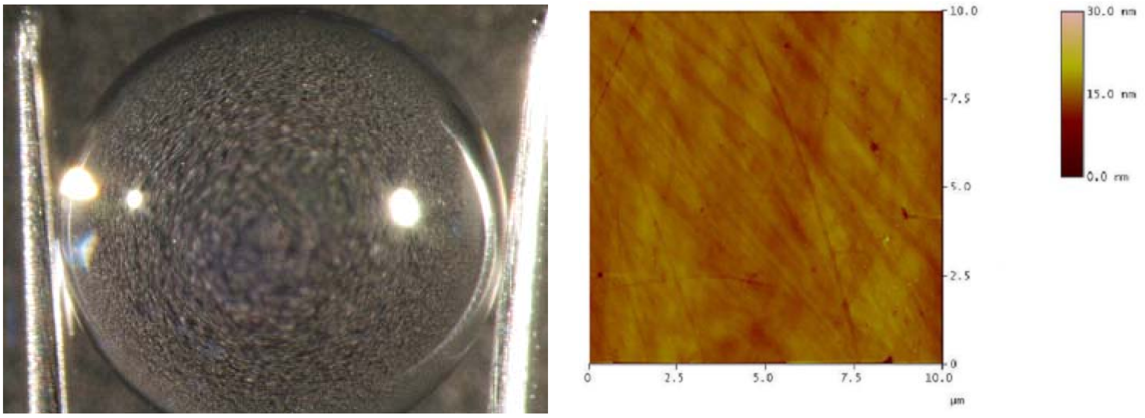

Figure 2: A polished ball preform with diameter = 2 mm (left) and AFM roughness measurement (right)

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

4.2 Polished near net shape and polished disc preforms

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/dig 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 Fire-polished rods

Most of the glasses for precision molding can be delivered in the form of cylindrical rods as well. These rods have a fire polished surface and the diameter is well defined. The length of the rods is customer specific.

Our rods can not only be supplied with high quality polish surface, instead a satin finished surfcace may be provided as well, see figure 3.

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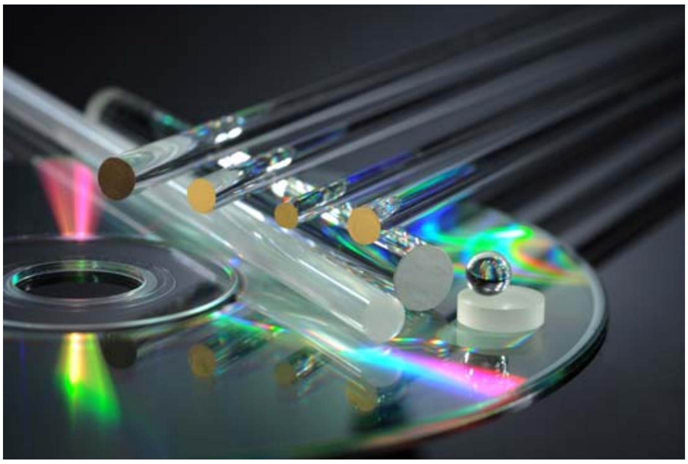

Figure 3: Fire-polished rods with different diameters. A polished ball perform, a cylindrical disc and a precision rod with a satin finish are shown as well.

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 formulas have shown to be reliable, even for annealing rates up to 300°C/h (see [3]):

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

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

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. This is the reason for the change of refractive index after a molding process, which have a high annealing rate. 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 lear 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 catalog 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 section).

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 3 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 catalog value is located in the center of these boxes. The red rhomb shaped dot within the green box depicts the refractive index and the Abbe number of a glass sample which is annealed at 2 K/h (This is the reference annealing rate).

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 the annealing slope is the same, but the location within the diagram will be different. 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 delivered glass lies somewhere between 50 K/h and 100 K/h on the annealing line. (This is the refractive index and Abbe number of the glass which is delivered to the customer. Keep in mind that these optical values will change during the subsequent precision molding process).

Usual fine annealing rates for standard optical glasses range from 0.5 to 2 K/h. For low precision pressings, annealing rates between 2 and 10 K/h are used. For standard optical glasses, the annealing rate is adjusted to achieve a specific refractive index range. At the same time, a low stress birefringence and a good homogeneity is achieved by this slow annealing process.

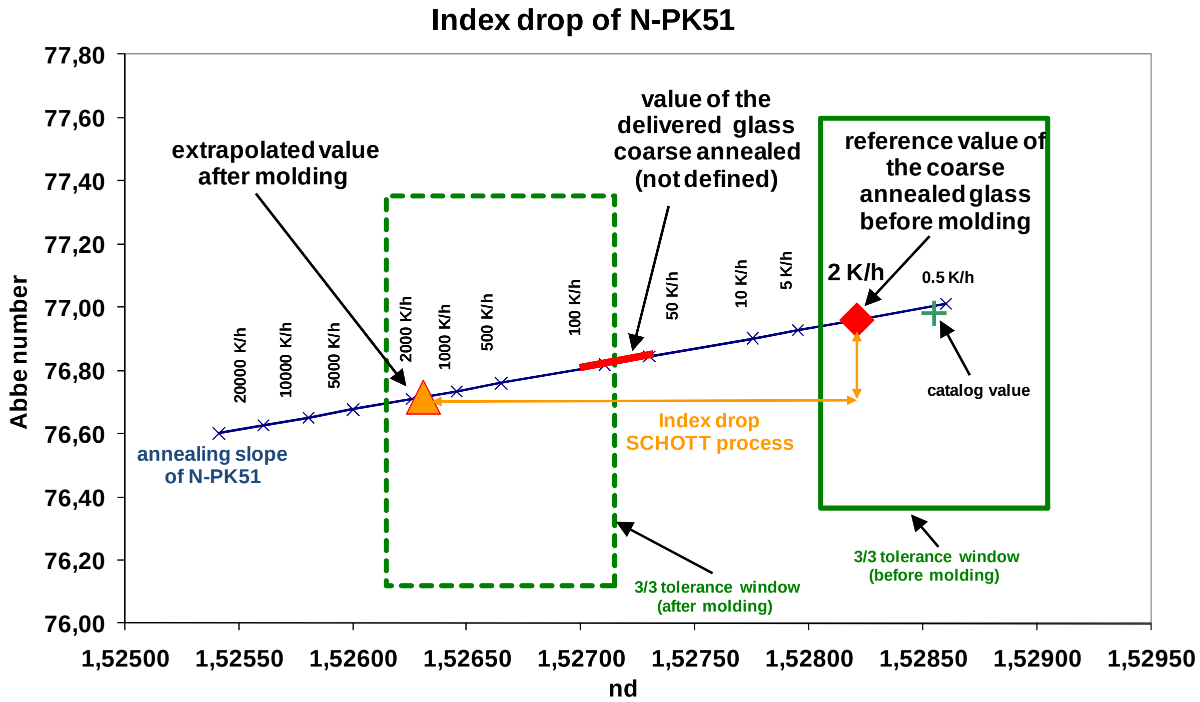

Figure 3: Annealing line and index drop behavior of N-PK51.

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 component. Therefore, the rate is not known in most cases but fixed and reproducible for the process of a given component. In general, there is no additional annealing process to adjust the refractive index after precision molding because another fine (or post) annealing process will cause a change in the shape of the pressed component.

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. 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 our example in figure 3 the values after precision molding are marked by an orange triangle.

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

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

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

The amount of index and Abbe number drop for N-PK51 is indicated with orange arrows in figure 3.

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Index drop for different precision molding glasses with reference to 2 K/h

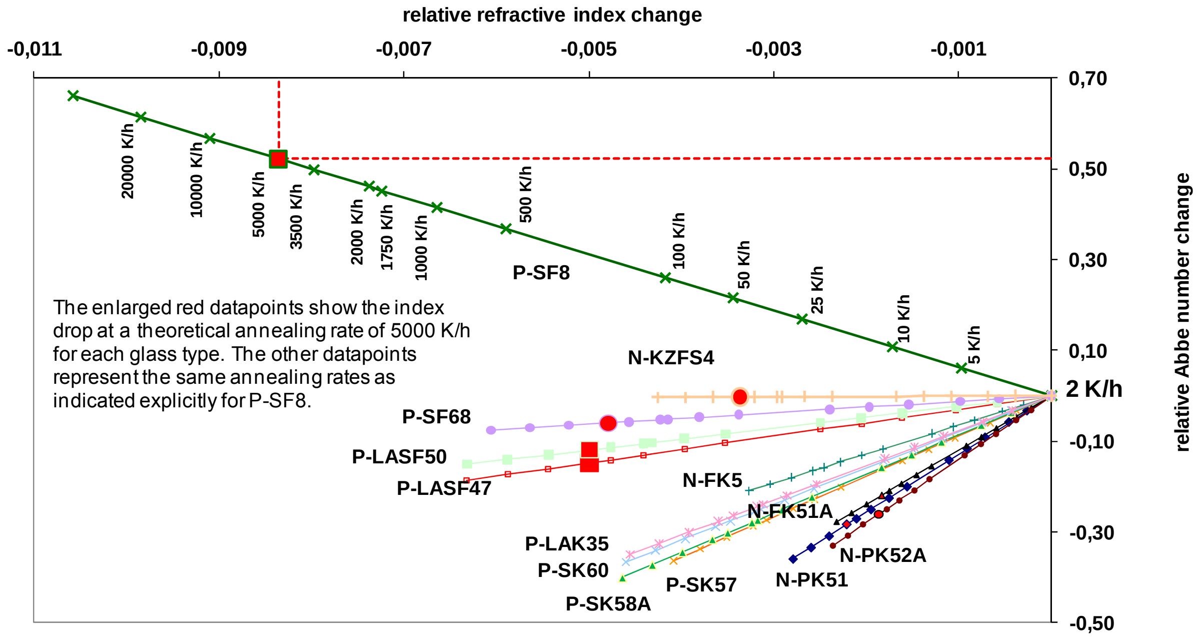

Figure 4: Theoretical index drop for different precision molding glasses assuming an average annealing rate of 5000 K/h (big red dots) and identical geometry.

The index drop is the same for all batches of N-PK51 glasses (using the same molding process). Therefore, the scattering in optical position between the molded glasses of different batches also remain the same under the assumption that the precision molding process is highly reproducible. The tolerance window (solid green rectangle) simply shifts to a new central position (doted green rectangle).

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 result in errors caused by not defined 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 4 shows for some glasses the relative change in refractive index and Abbe number based on the annealing slopes for the precision molding glasses
In the given simplified example it can be seen that the index change for an average annealing rate of 5000 K/h ranges, depending on the glass type, from –0.0017 to –0.0079 for the refractive index n_d. The Abbe number changes in the range of +0.47 to –0.27. P-SF8 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.

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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.

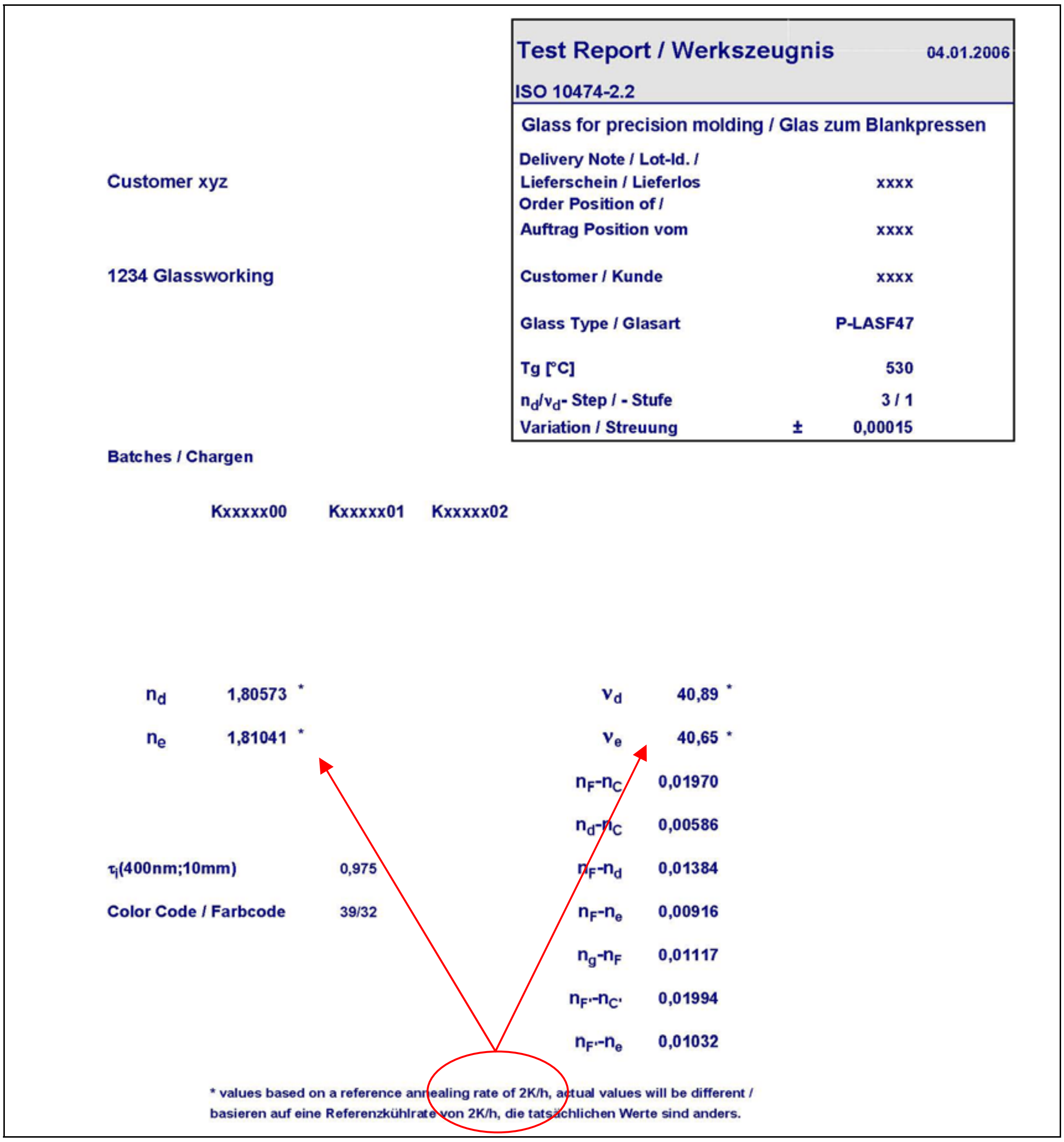
	Before molding 2 K/h reference catalog values				After SCHOTT molding process			
	n_d	n_e	ν_d	ν_e	n_d	n_e	ν_d	ν_e
P-PB7	1,51640		64,06		1,5144		63,9	
P-PK53	1,52690	1,52880	66,22	65,92	1,5232	1,5251	66,0	65,7
P-SK57	1,58700	1,58935	59,60	59,36	1,5843	1,5867	59,4	59,1
P-SK58A	1,58913		61,15		1,5860		60,8	
P-SK60	1,61035		57,90		1,6068		57,7	
P-SF8	1,68893	1,69414	31,25	31,01	1,6814	1,6865	31,7	31,4
P-LAK35	1,69350		53,20		1,6904		53,0	
P-SF69	1,72250		29,23		1,7155		29,7	
P-LAF37	1,75550		45,66		1,7508		45,5	
P-LASF47	1,80610	1,81078	40,90	40,66	1,8016	1,8062	40,8	40,5
P-LASF50	1,80860		40,46		1,8036		40,3	
P-LASF51	1,81000		40,93		1,8056		40,8	
P-SF68	2,00520		21,00		1,9958		20,9	
N-FK51A	1,48656	1,48794	84,47	84,07	1,4847	1,4861	84,2	83,8
N-FK5	1,48749	1,48914	70,41	70,23	1,4850	1,4866	70,2	70,0
N-PK52A	1,49700	1,49845	81,61	81,21	1,4952	1,4966	81,3	80,9
N-PK51	1,52855	1,53019	76,98	76,58	1,5267	1,5283	76,7	76,3
N-KZFS2	1,55836		54,01		1,5534		53,7	
N-KZFS4	1,61336		44,49		1,6098		44,7	
N-KZFS11	1,63775		42,41		1,6341		42,3	
N-KZFS5	1,65412		39,70		1,6493		40,2	
N-KZFS8	1,72047		34,70		1,7145		35,1	
N-LAF33	1,78582		44,05		1,7811		43,9	
N-LASF46B	1,90366		31,32		1,8977		31,4	
SF57	1,84666		23,83		1,8447		23,6	

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.



Test Report / Werkszeugnis 04.01.2006

ISO 10474-2.2

Glass for precision molding / Glas zum Blankpressen

Customer xyz

1234 Glassworking

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

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.

Figure 7: Example of a test report for precision molding glass. The optical values are measured using samples which were taken from the batch and annealed at a reference annealing rate. The delivered glass batch is annealed at a higher rate.

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. The report contains as well the spectral internal transmittance at a wavelength of 400 nm and a sample thickness of 10 mm and the color code.

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7. 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

[3] U. Fotheringham, A. Baltes, P. Fischer, P. Höhn, R. Jedamzik, C. Schenk, C. Stolz and G. Westenberger; "Refractive Index Drop Observed After Precision Molding of Optical Elements: A Quantitative Understanding Based on the Tool-Narayanaswamy-Moynihan Model; J. Am. Ceram. Soc., 91 [3] 780–783 (2008)
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