TIE-25: Striae in optical glass

0. Introduction

Optical glasses from SCHOTT are well known for their very low striae content. Even in the raw production formats like blocks or strips requirements for most demanding optical systems are met. In the finished lenses or prisms which are normally by far smaller the striae effects decrease to levels where they can be neglected completely, i.e. they become much smaller than 10 nm optical path distortion. On the other hand frequently questions arise how to specify raw glass or blanks for optical elements especially with reference to the regulations of ISO 10110 Part 4 “Inhomogeneities and Striae”. Basing on the progress that has been made in the last years in measurement, classification and assessment of striae this technical information shall help the customer to find the right specification.

1. Definition of Striae

An important property of processed optical glass is the excellent spatial homogeneity of the refractive index of the material. In general one can distinguish 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. Whereas the spatially long range global homogeneity of refractive index ranges covers the complete glass piece (see TIE-26/2003 for more information on homogeneity).

2. Generation of striae

Striae are mainly generated due to the unfinished homogenization of the raw materials during melting and by detached tank wall material. Homogenization during the melting process takes place due to convection processes in the tank and in the refining chamber. The mixing process within the mixing chamber further smoothens in-homogeneities out.

Striae can also be generated by detached old glass within the casting nozzle and by material dropping on the cast surface during the cutting process necessary to cut the glass melt from the cast glass.

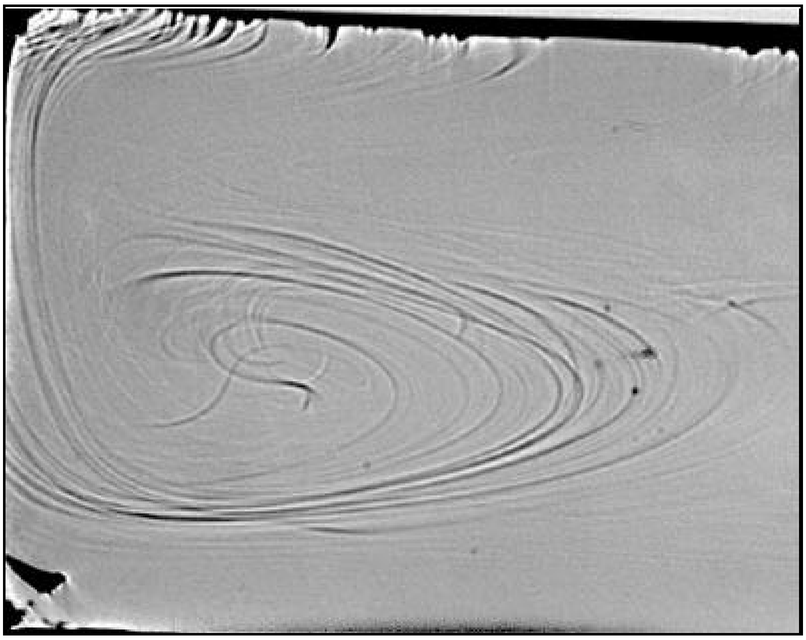

Figure 1: Striae within N-LAK8 exhibiting a frozen convection pattern

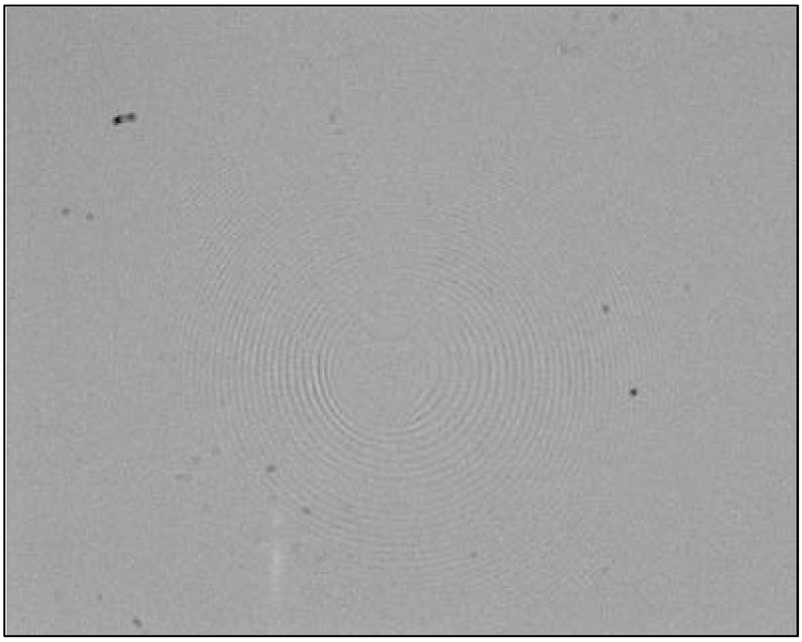

Figure 2: Whirl shaped band like striae from the tank melting process. Such striae are prevented by sophisticated casting control.

3. Shape of striae

Striae can appear in the form of sharp, cordlike regions. This kind of striae can mainly be found in glasses produced by the clay pot melting process. Cordlike striae have a clear straight geometrical shape with sharp edges and can therefore be localized very accurate (figure 3 left).

The well-known but now invalid MIL specification for striae is based on reference samples made from the clay pot melting process. More common today are band like striae structures produced by the tank melting process. These striae do not exhibit sharp edges and their shape is similar to a frozen convection pattern (figure 1+2, 3 right).

Band like striae may affect large volumes of the glass part. This also implies that the effect of the striae may decrease with decreasing glass thickness in view direction if the striae are spread through the thickness of the glass.

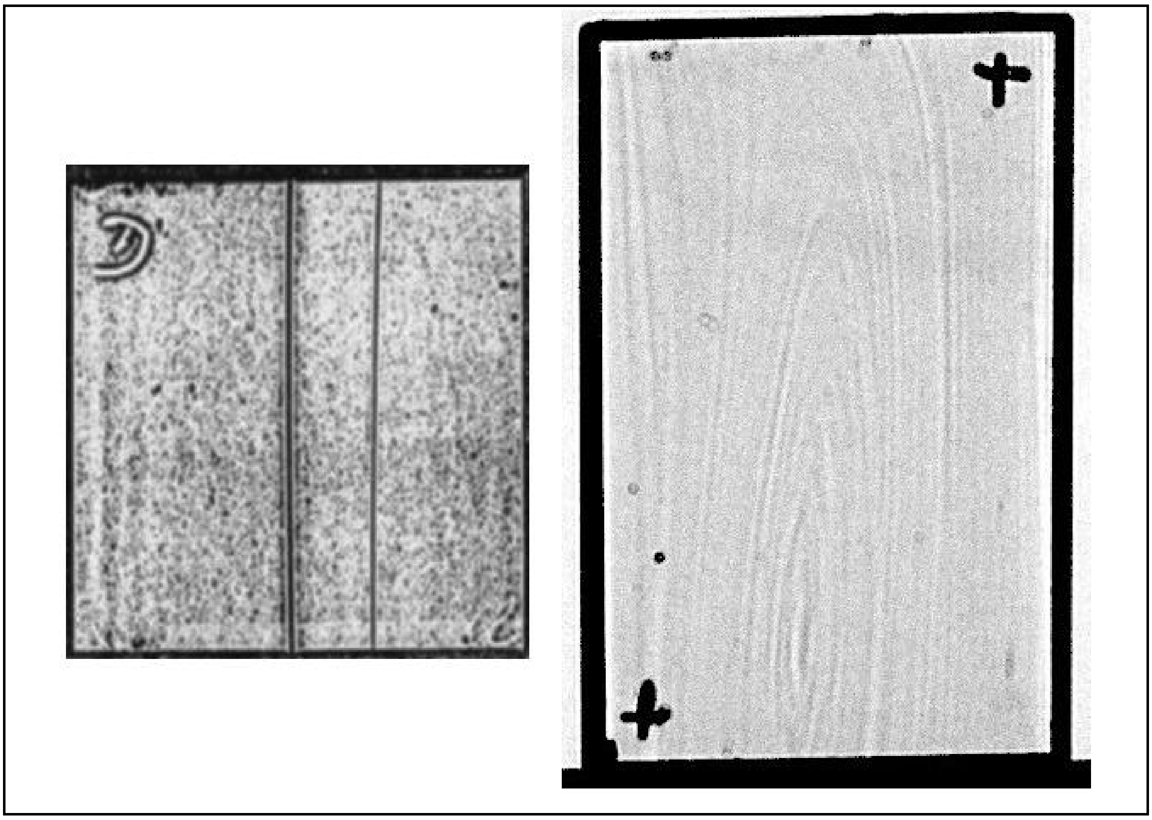

Figure 3: Left: cordlike striae according to MIL grade D, right: band like striae grade D.

4. The shadowgraph method

The shadowgraph method is very well suited for striae detection due to its very high sensitivity simple setup and ease of handling [1].

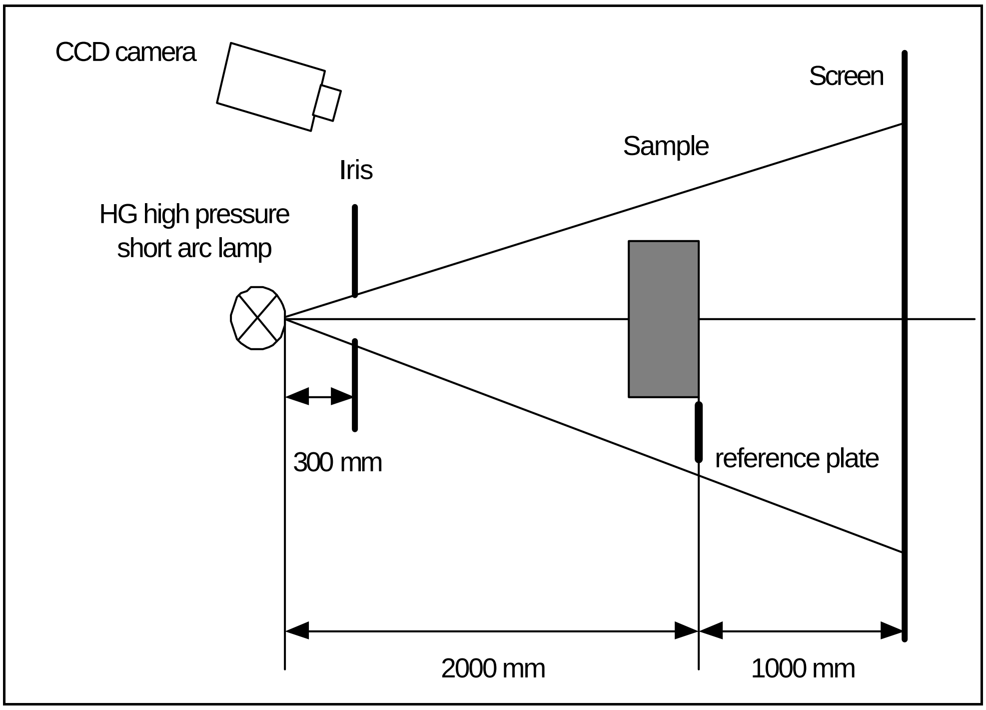

Figure 4: Shadowgraph setup.

The setup for the shadowgraph consists of the following elements: a 100 W Mercury high pressure short arc lamp as a source with pinhole aperture without any imaging optics, a sample holder on a turn table and a white non transparent projection screen (figure 4). The light emitted from the lamp is divergent and partly coherent. Without a sample the illumination pattern on the projection screen will show a constant bright area. Putting a sample with striae into the beam the striae will be visible on the screen as gray or dark areas (in general straight or curved line patterns).

The reason for these areas is that striae have a different refractive index than the matrix material. The light traveling through the sample will be refracted slightly by the striae. The position of the striae becomes visible on the screen as a darker area.

The sensitivity of this method depends on the geometrical setup only. The highest sensitivity of about 10 nm optical path difference, can be achieved by placing the sample in the middle between lamp and projection screen and by maximizing the lamp-screen distance [2]. Due to the influence of diffraction the projected striae becomes slightly diffuse with increasing sensitivity of the setup. SCHOTT uses an optimized geometrical setup with a lamp-screen distance of about 3 m. The sample is placed in 1 m distance of the projection screen.

The inspection of glass has to be done in a room with subdued light. The glass sample is polished for inspection on two opposite sides (figure 5). These two opposite sides should be flat and almost parallel otherwise the interpretation of the results will be difficult due to imaging effects. However, the method is quite insensitive towards large-scale homogeneity changes which would be introduced by slightly wedged / unparallel samples.

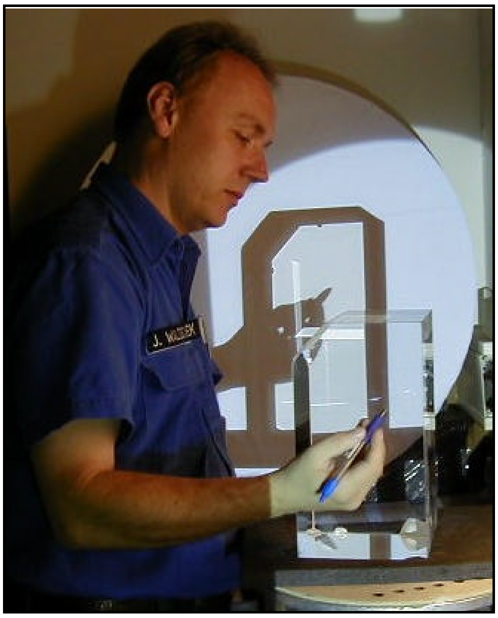

Figure 5: Striae testing using the shadowgraph method.

The sample must be rotated by ±45° with respect to the incident beam until the striae are most prominent (figure 6). Furthermore this rotation allows discrimination between surface flaws and internal striae. The surface flaw position would change by rotating the sample whereas the position of the striae would be almost constant.

To further improve the contrast and the uniformity of the projection screen the screen will be rotated during measurement. Additionally a CCD camera is installed for documentation.

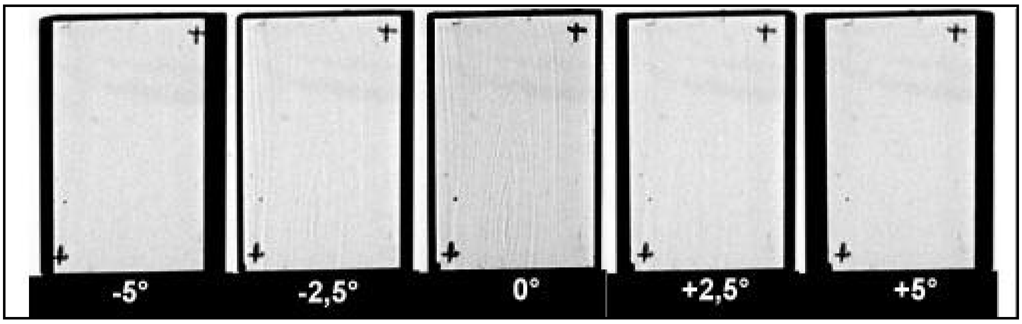

Figure 6: Influence of the viewing angle on the striae visibility.

5. Characterization of striae

The influence of striae on optical imaging depends on their size, shape and the difference between the refractive indices of glass and striae area.

The difference in refractive index generates a wave front deviation. The amount of wave front deviation is proportional to the length of the striae in the direction of observation. For a better understanding imagine a striae with the shape of a straight half sheet of paper introduced into a glass block (see figure 7). The striae have a different refractive index (n2) than the rest of the material (n1). For this theoretical review it is assumed that the difference in refractive index between the striae and the remaining material is $\sim 3*10^{-7}$. Therefore a plane wave front passing through the glass block in different direction will be distorted in different ways.

A wave front in view direction 1 will pass half of the striae length and therefore will be distorted by $(n2-n1)*100\ mm=3*10^{-7}*100\ mm=30\ nm$. The wave front distortion can be observed using the shadowgraph method. On the shadowgraph screen a projection of the striae will become visible. The striae will appear as a medium dark solid line. The darker the striae appears the higher the wave front deviation. The term intensity is often used to express the wave front deviation.

A wave front traveling in view direction 2 will be distorted only by the thickness of the striae. As mentioned before striae are very localized homogeneity deviations therefore the wave front deviation introduced into a plane wave passing a striae in thickness direction is very low $(n2-n1)*2\ mm$. With the shadowgraph striae with intensities $< 10\ nm$ can not be observed any more, therefore no striae would be observed in view direction 2.

In view direction 3 the plane wave front passes the striae over the complete length of 200 mm. Therefore the wave front deviation and the intensity of the striae on the shadowgraph screen is very high. The striae appear very dark. Additionally the shadowgraph screen displays the projection of the striae shape. According to the overview the striae appears to be solid half line reaching to the middle of the screen.

It is important to keep in mind that the striae assumed here is only a model striae. In reality striae are of more complicated shape. Especially band like striae are difficult to determine.

Nevertheless there are some points that can be learned from the simple model

In general striae can be characterized by their intensity in terms of wave front deformation and their area

The visibility of a striae depends on the view direction. The intensity of a striae depends on the length of the striae in view direction, therefore striae viewed in thickness direction are invisible and do not affect any optical application.

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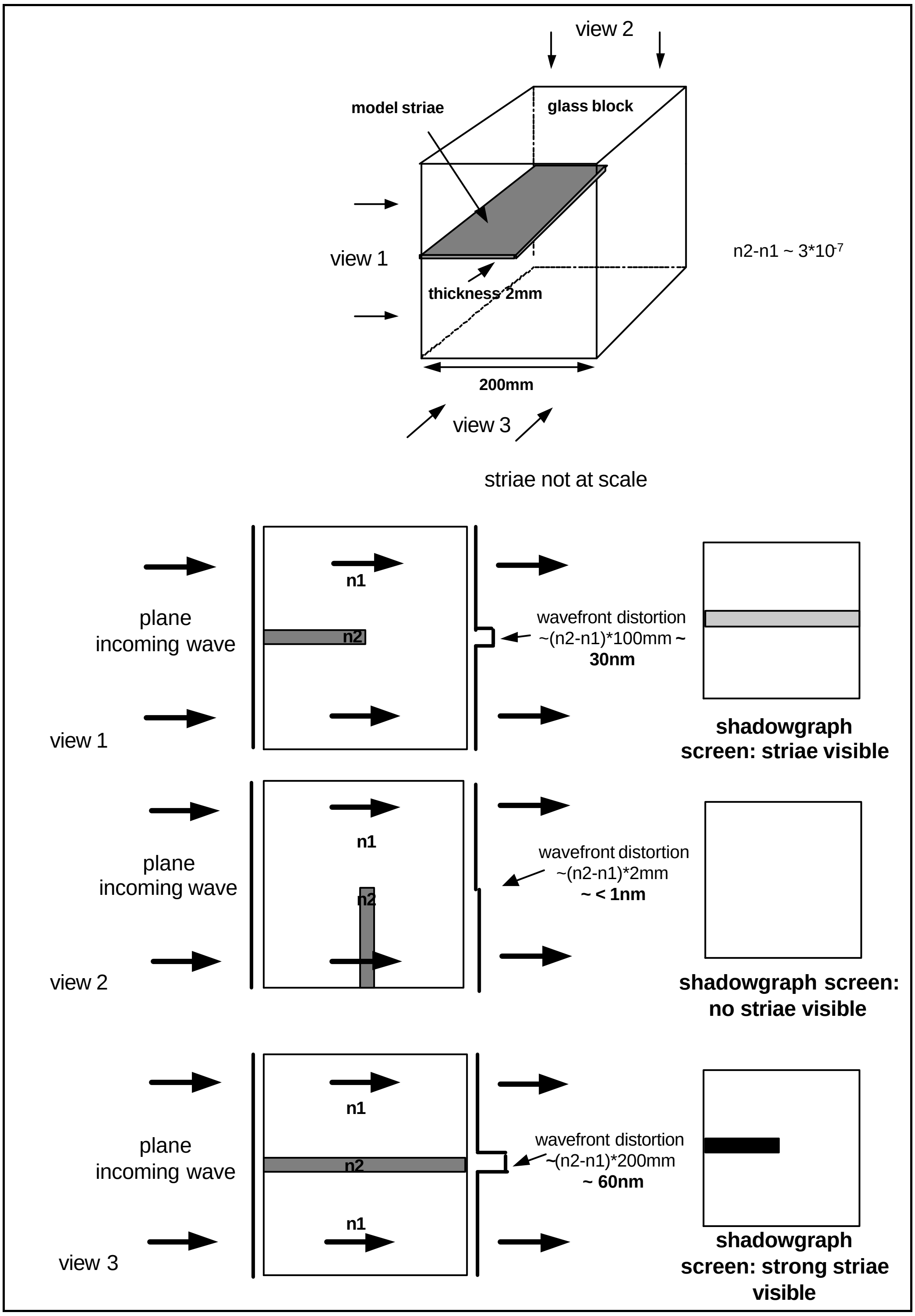

Figure 7: Influence of different view directions on the shadowgraph of a model striae.

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6. Influence of striae in application

An ideal optical system is defined by its ability to focus a point like object without any aberrations to a point like image. Normal optical systems are in general not aberration free. Striae introduce aberrations depending on their position within the optical systems. In the wave optical theory the point like object emits waves with ideal constant spherical wave fronts and phases.

The aperture of an optical system is given by the element in the system that limits the beam diameter and therefore the amount of light exiting the system. This can be a separate iris or the lens itself. The image of the aperture is called entrance and exit pupil.

Striae near pupils introduce a phase shift and therefore change the shape of the wave front. In practice this means that a cordlike striae broadens the intensity distribution of a picture from an ideal point source (see figure 8).

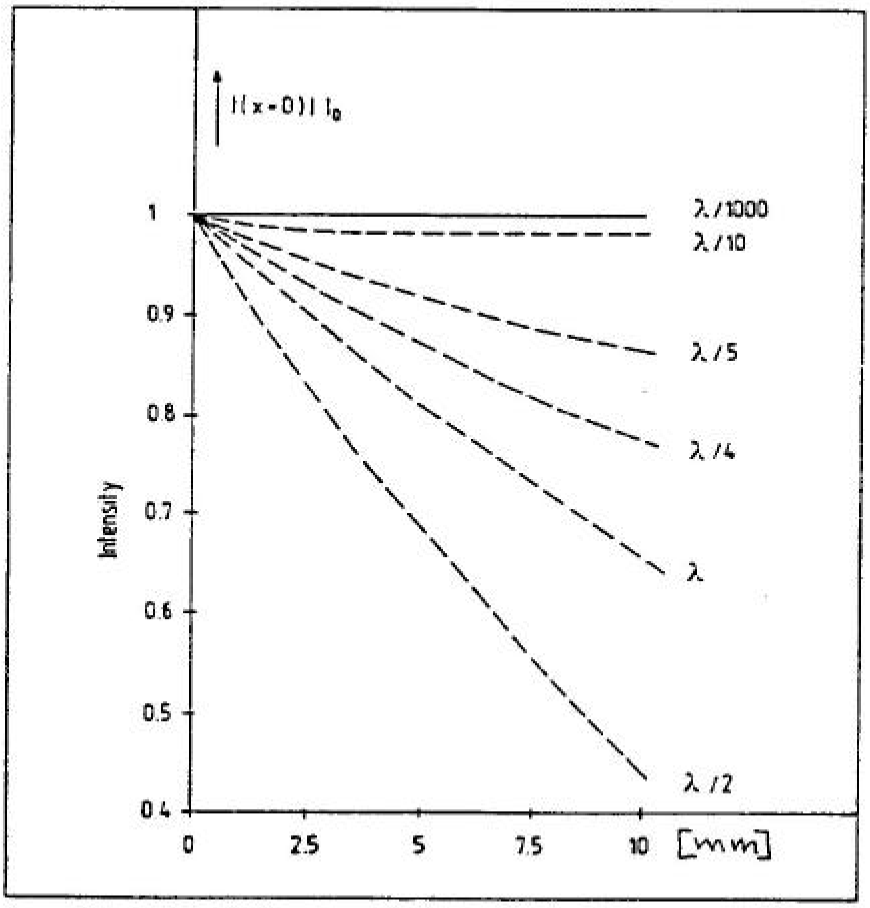

Figure 8: Central intensity of the picture of an ideal point source in dependence on striae size and wave front deviation (intensity of the striae) [4].

Striae within the lens plane disturb the imaging geometry and therefore lead to local aberrations in the picture. The light beam passing a striae in the lens plane will be refracted slightly. These effects are most prominent for large cordlike striae with high intensities.

It was shown that striae with intensities of $\lambda/10$ (~60 nm) wave front deviation have no significant effect on the image quality. This border is only valid if surface irregularities due to the lens polishing process can be prevented because such defects have similar effects as striae.

Another problem is that an optical system consists of many parts and therefore the summation of small striae in single lenses over the complete system could lead to large unwanted aberrations.

More information on the influence of striae in optical systems can be found in [3], [4] and [5].

7. ISO/Standards for striae compared to the SCHOTT standard

The most prominent standards for striae are the ISO 10110 part 4 and the expired MIL-G-174 B. This chapter explains the difference between these standards and the interpretation of the SCHOTT catalogue definition with respect to these standards:

In the previous chapters it was stated that striae are characterized by 2 main properties:

Their intensity or wave front deviation. For striae that are not localized like cord like striae the thickness of the sample becomes important. As a rule reducing the thickness will reduce the intensity of a striae if its shape is band like and extending through parts of the glass volume.
The geometrical area of the striae.

The MIL-G-174 B [8] categorizes the striae in a raw piece of glass according to its intensity but without any reference to the striae area and sample thickness. The striae will be categorized by 4 reference samples of cordlike striae into four classes A-D. These reference samples are older than 25 years.

The intensity of the reference striae has been measured externally with an interferometer with a very high spatial resolution. From this a wave front deviation could be assigned for each class. The old SCHOTT striae specification uses this definition (figure 9).

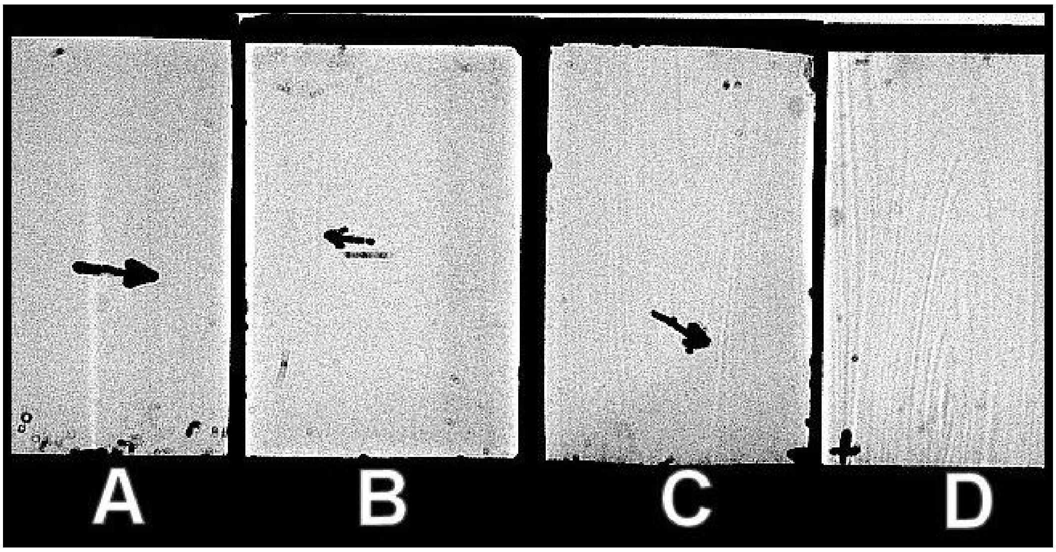

Figure 9: Striae grade A to D according to the old SCHOTT specification (based on MIL –G-174B).

The ISO 10110 part 4 [7] introduces 5 classes of striae grades for finished optical parts. In grades 1-4 only striae with intensities greater than 30 nm optical path difference are categorized. The grades 1-4 differ by the area of the striae compared to the complete area of the part. Striae with intensities less than 30 nm are categorized in class 5. The main difficulty of this standard is that it is defined for finished optical parts.

The old SCHOTT specification internally used the nomenclature of the MIL specification. The reference samples are characterized according to their wave front deviation. The MIL specification characterizes only cord like striae and does therefore not depend on thickness whereas the new SCHOTT specification introduces a reference thickness of 50 mm to take into account the behavior of band like striae that are most common in the glass production process.

The specification in the current SCHOTT catalog [6] excludes striae with grades higher than C in general because due to the production process such striae are prevented except for a thin layer (< 3 mm) directly below the fire polished surfaces which originate from evaporation of constituents during casting. These layers vanish in the subsequent machining process steps. SCHOTT's normal quality is always class C per 50 mm path length or better corresponding to about 30 nm optical path difference. Therefore SCHOTT standard optical glass fulfills the requirements of the ISO 10110 class 1-4 in general.

As mentioned before striae in optical glass are mainly band like striae due to the production process. The intensity of band like striae depends on the thickness of the glass part. The glass parts are tested over a thickness that is often much higher than the thickness of the finished parts. Therefore the standard quality of finished parts that have a reduced thickness is equal or better grade B (corresponding to about 15 nm optical path difference).

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By taking into account the thickness of the finished part it is even possible to fulfill the need of grade A striae within a finished glass part from a glass block exhibiting a higher striae grade. This depends on the geometry of the striae and the thickness difference of the raw glass block and the finished part.

For highest requirements Schott offers VS1 quality with less than 10 nm optical path difference due to striae. VS1 quality for fine annealed pre-shaped glasses is valid only with respect to the inspection direction. In this category no striae visible with the shadowgraph method are allowed. Schott offers also VS2 quality. Such glass meet the requirement of step VS1 in two directions perpendicular to one another. For VS for pressings we use pre-inspected raw glass since inspections of the pressings themselves is not possible any more.

The main implications of the SCHOTT specification for the customer are summarized as follows:

- SCHOTT optical raw glass blocks always fulfill MIL-G-174B grade C (< 30 nm wave front deviation) and ISO 10110 part 4, class 1-4. Striae in optical glass if present are band like striae. The intensity (wave front deviation/class) depends on the thickness of the glass.
- Raw optical glass blocks exhibit greater thickness compared to finished parts therefore finished parts exhibit striae class B (according MIL-G-174B) or better.
- Raw optical glass blocks of normal quality might even be suitable for finished parts with grade A striae quality if the thickness of the raw block in application direction is much larger than the finished part.
- VS quality is only valid for fine annealed glass with respect to the inspection direction.

	MIL-G-174B	**ISO 10110**	**SCHOTT old (Only internal use)**	**SCHOTT new**
valid for:	Raw glass	Finished glass	Raw glass	
Characterized by:	Intensity without sample thickness	Area of striae (density)	Intensity with sample thickness (50 mm)	

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<table>
<tr><th></th><th>MIL-G-174B</th><th>ISO 10110</th><th>SCHOTT old (Only internal use)</th><th>SCHOTT new</th></tr>
<tr><td rowspan="5">Striae grades</td><td>D (no quantification)</td><td rowspan="2">$\geq$ 30 nm
1: $\leq$ 10%
2: $\leq$ 5%
3: $\leq$ 2%
4: $\leq$ 1%</td><td>D: ~ 60 nm</td><td></td></tr>
<tr><td>C (no quantification)</td><td>C: ~ 30 nm</td><td>$<$ 30 nm: normal quality of raw glass</td></tr>
<tr><td>B (no quantification)</td><td rowspan="3">5: extreme low striae content Further details have to be marked in the drawings</td><td>B: ~ 15 nm</td><td rowspan="2">~ $<$ 15 nm: finished glass</td></tr>
<tr><td>A (no quantification)</td><td>A: $<$ 10 nm</td></tr>
<tr><td></td><td>VS: no striae visible</td><td>VS1/VS2: No striae visible in one/two directions</td></tr>
</table>

8. Literature

[1] Kerkhof, F.: Optische Verfahren zur Erfassung von Schlieren; Glastechnische Fabrikationsfehler, dritte Auflage, Editors: Jebsen-Marwedel, H.; Brückner, R.; page 89, 1980
[2] Schardin, H.: Glastechnische Interferenz- und Schlierenaufnahmen, Glastechnische Berichte 27, page 1, 1954
[3] Hild, R.; Kessler, S.; Nitzsche, G., Influence of schlieren on imaging properties of an optical system: I. Point spread Function, Optik 85, page 123, 1990
[4] Hild, R.; Kessler, S.; Nitzsche, G., Influence of schlieren on imaging properties of an optical system: II. Modulation Transfer Function (MTF), Optik 85, page 177, 1990
[5] Hild, R.; Kessler, S.; Nitzsche, G., Influence of schlieren on imaging properties of an optical system: III. Isoplanatic and nonisoplanatic imaging, Optik 86, page 1, 1990
[6] SCHOTT Optical Glass Pocket Catalogue
[7] ISO/DIS 10110 - part 4; Preparation of drawings for optical elements and systems; Material imperfections – Inhomogeneity and striae, 1994
[8] MIL G 174 A, (invalid)

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