TIE-25: Striae in optical glass

0. Introduction

Optical glasses from SCHOTT are well-known for their very low striae content. Even in raw production formats, such as blocks or strips, requirements for the most demanding optical systems are met. Striae intensity is thickness dependent. Hence, in finished lenses or prisms with short optical path lengths, the striae effects will decrease to levels where they can be neglected completely, i.e. they become much smaller than 10 nm optical path distortion.

Striae with intensities equal and below 30 nm do not have any significant negative influence on the image quality as Modulation Transfer Function (MTF) and Point Spread Function (PSF) analyses have shown (refer to Chapter 7).

In addition, questions such as how to specify raw glass or blanks for optical elements frequently arise, especially with reference to the regulations of ISO 10110 Part 4 “Inhomogeneities and Striae”. Based on the progress that has been made in the last years regarding measurement, classification and assessment of striae, this technical information shall help the customer 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 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 the 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 smoothens out the in-homogeneities further.

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

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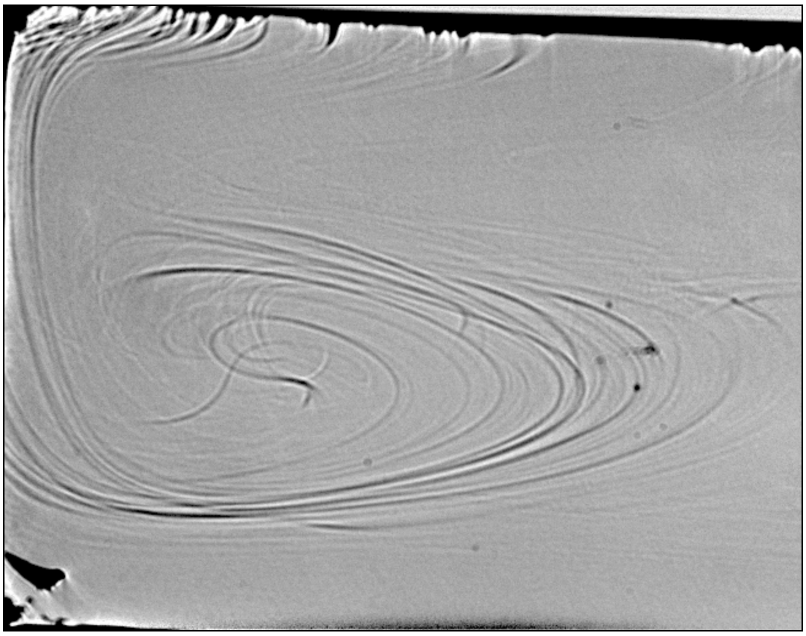

Figure 1: Shadowgraph picture of striae within N-LAK8 exhibiting a frozen convection pattern

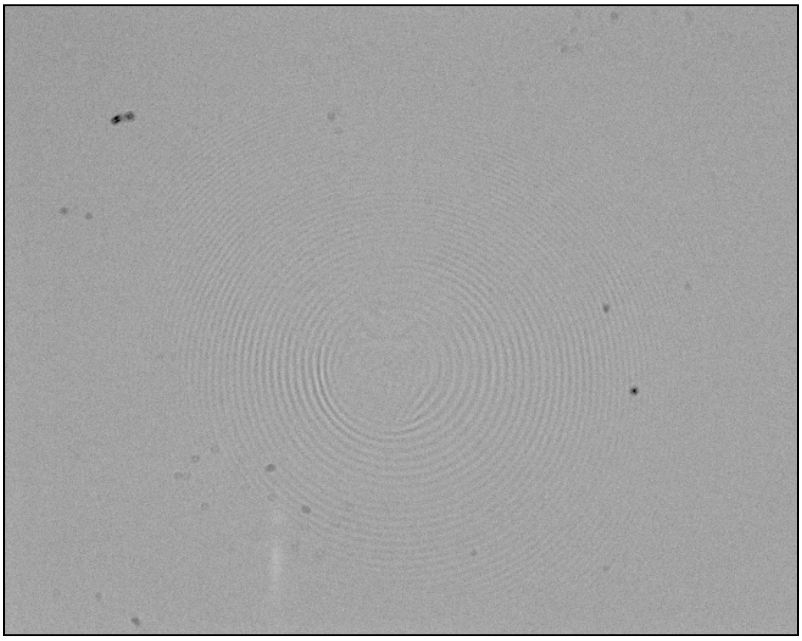

Figure 2: Whirl shaped band-like striae from the tank melting process. Sophisticated casting control helps to prevent such striae.

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3. The shadowgraph method

The shadowgraph method is suitable for striae detection due to its high sensitivity and ease of set up and handling [1].

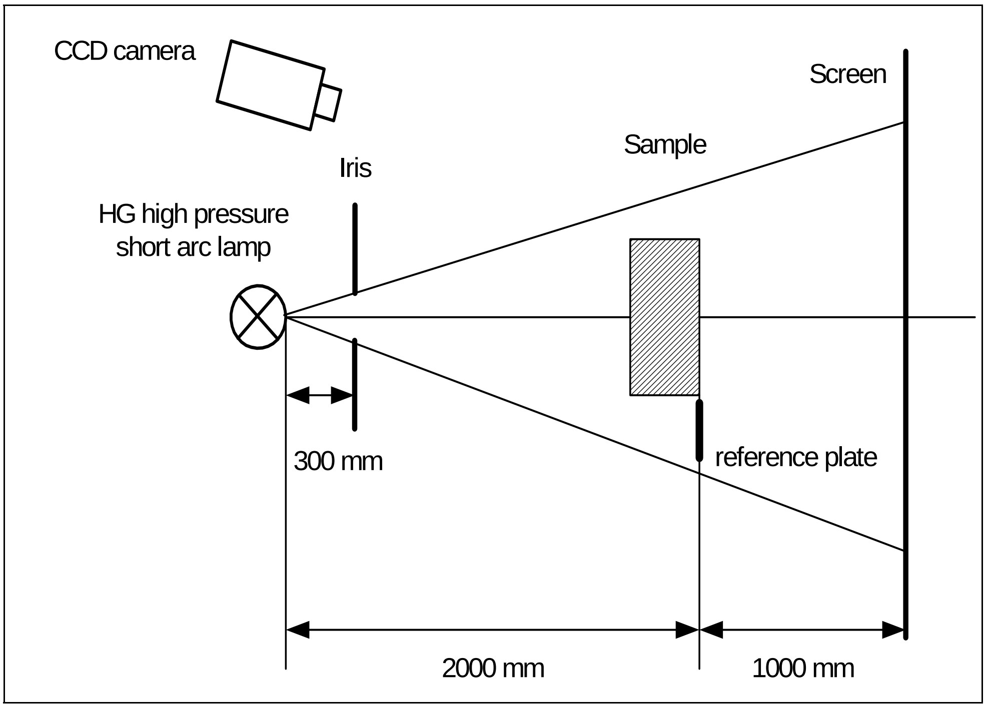

Figure 3: Shadowgraph setup.

The setup for the shadowgraph consists of the following elements: a 100 W Mercury high pressure short arc lamp (as a source) with a pinhole aperture without any imaging optics, a sample holder on a turn table and a white non-transparent projection screen (Figure 3). 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. By placing a sample with striae into the beam, the striae will become visible on the screen as gray or dark areas (in generally straight or curved line patterns).

As the refractive index of the striae is different from that of the matrix material, the light traveling through the sample is refracted slightly by the striae. The position of the striae hence, becomes visible on the screen as a darker area.

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

The glass must be inspected in a room with subdued light. The glass sample is polished for inspection on both sides (Figure 4). These two opposite sides should be flat and almost parallel; otherwise, the interpretation of the results will be difficult due to imaging effects. This method is quite insensitive towards large-scale homogeneity changes, which would be introduced by slightly wedged or unparallel samples.

Figure 4: Striae testing using the shadowgraph method.

Striae samples cut from standard strip glass have a defined optical path length of 50 mm in application direction. Block glass will be inspected at ~200 mm optical path length.

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

To further improve the contrast and the uniformity of the projection screen, the screen is also rotated during measurement. In addition, a CCD camera is installed for purpose of documentation.

4. Shape and appearance of striae

Striae can appear in the form of sharp, cord-like regions. This kind of striae can be found mainly in glasses produced by the clay-pot melting process. Cord-like striae have a clear straight geometrical shape with sharp edges and can therefore be accurately localized (Figure 5 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 and 5 right). The MIL specification categorizes the striae in four different grades from low striae intensity grade A to high striae intensity grade D (please refer to chapter 5).

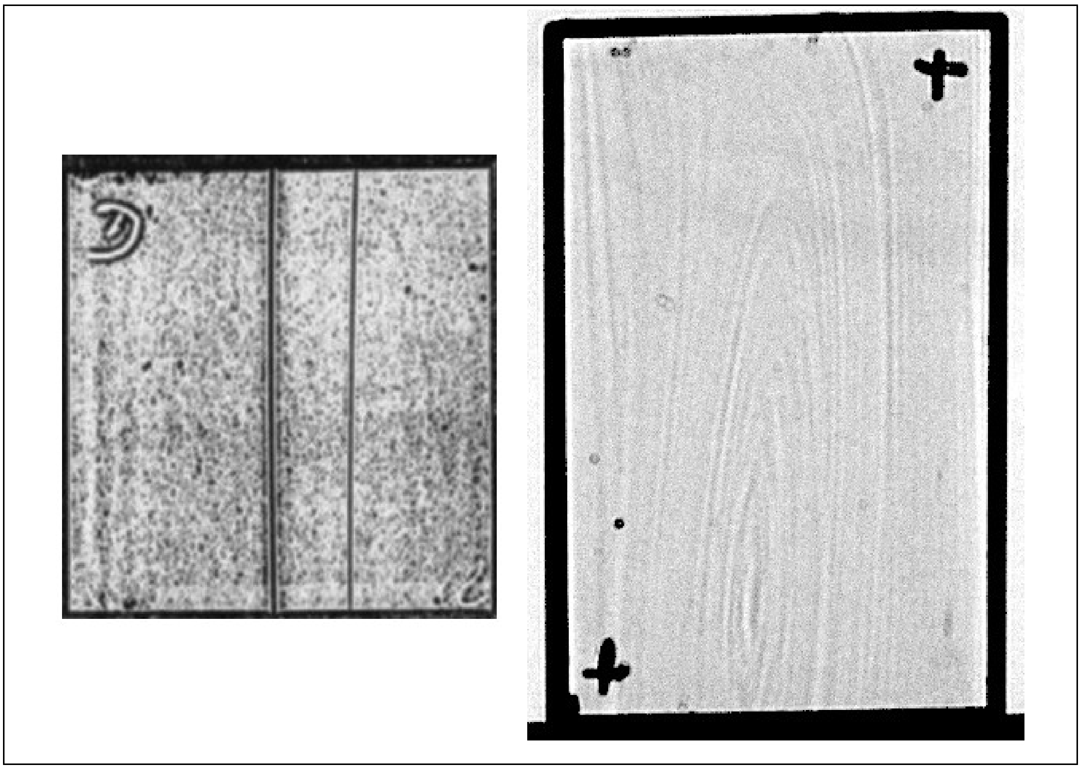

Figure 5: Cord-like striae according to MIL grade D (left) and Band-like striae grade D (right).

Band-like striae may affect large volumes of the glass parts. If the striae are spread through the viewing direction of the glass, the effect of striae decreases with decreasing optical path length (glass dimension in viewing direction). Figure 6 shows a comparison of the striae intensity inside glasses of various thickness and their respective optical path lengths.

In the given example, the striae intensity decreases from grade C at 50 mm optical path length to grade B at 10 mm optical path length. This is an important observation. The standard measurement thickness for striae testing is 50 mm whereas the final lens thickness in consumer applications is often not larger than 10 mm. This suggests that standard grade C striae within the glass will be almost unidentifiable in the final lens.

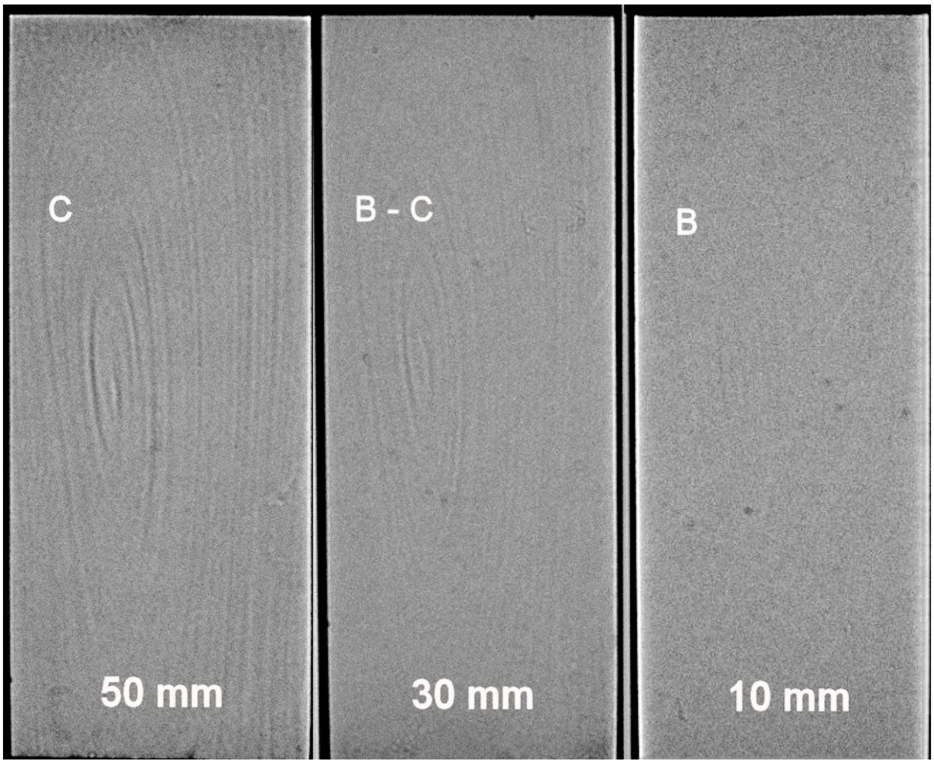

Figure 6: Striae intensity as a function of the thickness of the glass.

Striae are also highly directional dependent. In the striae example below (Figure 7), the striae visibility in the shadowgraph setup almost disappears when the samples are rotated ±5° around the vertical axis.

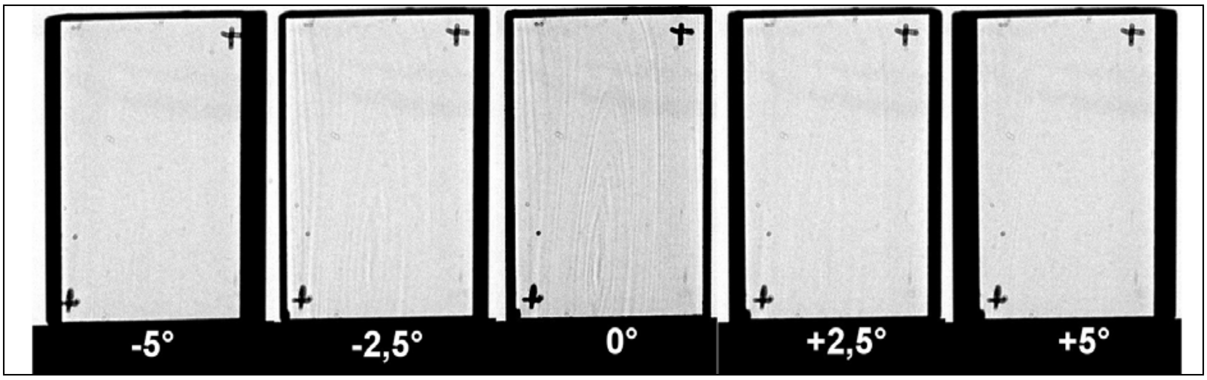

Figure 7: Influence of the viewing angle on the striae visibility.

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Figure 8 shows the shadowgraphs of a rectangular glass sample in three perpendicular directions. The striae intensity in the first direction is C grade whereas the striae intensity in the remaining two directions ranges between A and B grades.

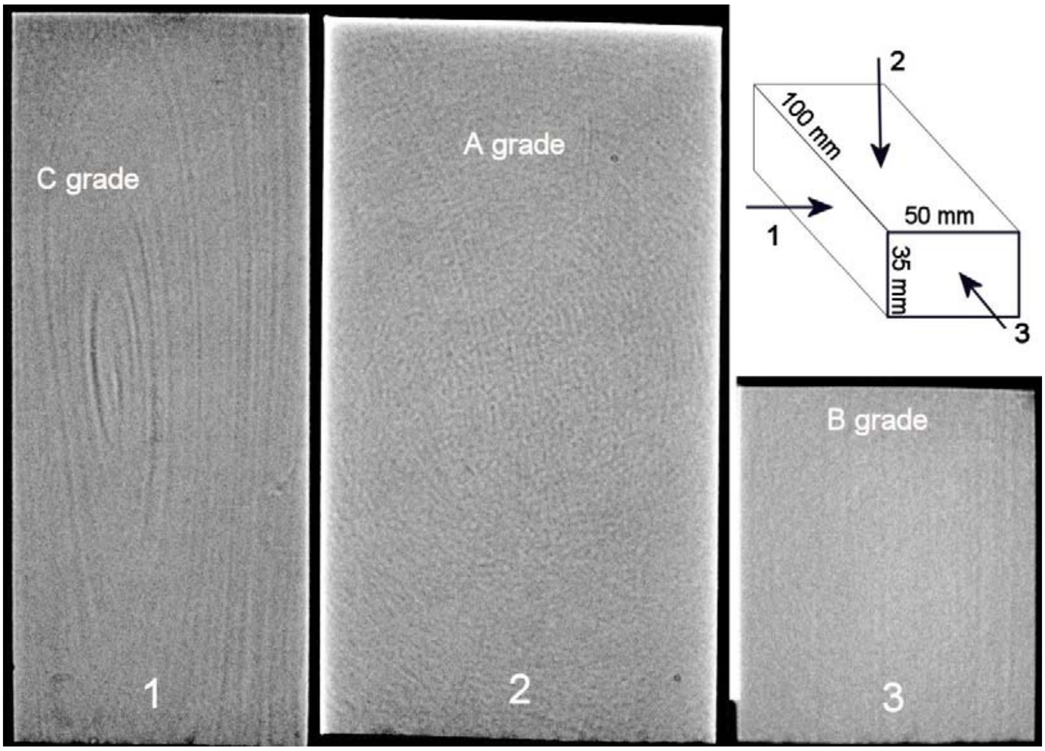

Figure 8: Striae intensity in three perpendicular directions.

5. Specification of Striae: Comparison of different standards

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

Striae are characterized by two main properties: Their intensity or wave front deviation and the geometrical area of the striae. For striae that are not localized, such as cord-like striae, the thickness of the sample has an important influence on the intensity of the striae. As a rule of thumb, reducing the thickness will reduce the intensity of striae, if its shape is band-like and extends through parts of the glass volume.

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

The intensities of the MIL reference striae have been measured externally using an interferometer with a very high spatial resolution. From this a wave front, deviation can be assigned for each class. The old SCHOTT striae specification uses this definition (Figure 9).

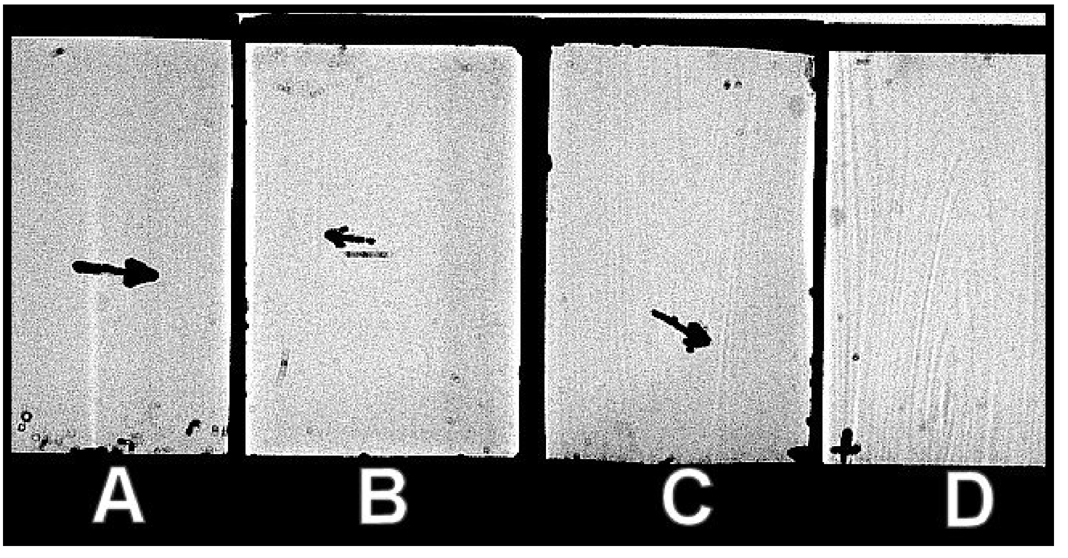

Figure 9: Striae grade A to D according to the old SCHOTT specification (based on MIL –G-174B).

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 as compared to the complete area of the part. Striae with intensities less than 30 nm are categorized in class 5. The main problem with this standard is that it is defined only for finished optical parts.

The previous SCHOTT specification used internally adhered to 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 therefore does not depend on thickness. 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 catalogue [6], in general, excludes striae with grades higher than C. This is because such striae is prevented during the production process , with the exception of a thin layer (< 3 mm) lying directly below the fire polished surfaces which originates from the evaporation of constituents during casting. These layers are eliminated in the subsequent machining process steps. SCHOTT's normal quality is always class C or better per 50 mm path length, corresponding to about 30 nm optical path difference. Therefore, SCHOTT standard optical glass fulfills the requirements of the ISO 10110 class 1-4.

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 parts. The glass parts are tested over a thickness that is often much higher than the thickness of the finished parts. Hence, the standard quality of the finished parts, which have a reduced thickness, is equal or better grade B (corresponding to about 15 nm optical path difference).

By taking into account the thickness of the finished parts, 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 more stringent 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 must be visible with the shadowgraph method. Schott also offers VS2 quality. Such glass meets the requirements of step VS1 in two directions perpendicular to one another. For pressings using VS quality glass, we use pre-inspected raw glass since inspections of the pressings themselves is not possible.

The main implications of the SCHOTT specifications 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 exhibits 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 be even suitable for finished parts with grade A striae quality, if the thickness of the raw block in the 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)	
Striae grades	**D** (no quantification)	≥ 30 nm **1:** ≤ 10% **2:** ≤ 5% **3:** ≤ 2% **4:** ≤ 1%	**D:** ~ 60 nm	
	C (no quantification)		**C:** ~ 30 nm	< 30 nm: **normal** quality of raw glass
	B (no quantification)	**5**: extreme low striae content Further details have to be marked in the drawings	**B:** ~ 15 nm	~ < 15 nm: finished glass
	A (no quantification)		**A:** < 10 nm	
			VS: no striae visible	**VS1/VS2:** No striae visible in one/two directions

Table 1: MIL and ISO standards for striae as compared to the SCHOTT specification

6. A simple striae model

The influence of striae on optical imaging depends on their size, shape and the difference between the refractive indices of glass and the 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 striae with the shape of a straight half sheet paper introduced into a glass block (see Figure 10). 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 $\sim 3 \cdot 10^{-7}$. Therefore, a plane wave front passing through the glass block in different directions will be distorted in different ways.

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A wave front in view direction 1 will pass half of the striae length and therefore 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 striae in thickness direction is very low (n2-n1)*2 mm. Striae of intensities less than 10 nm cannot be observed with the shadowgraph. Hence, 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 appears very dark. In addition, the shadowgraph screen displays the projection of the striae shape. According to the overview, the striae appears to be a 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. In reality, striae are of more complicated shapes, especially band-like striae are difficult to determine. Nevertheless, there are some points that can be learnt from this simple model:

1) Striae can generally be characterized by their intensity, in terms of wave front deformation and their area. The visibility of striae depends on the view direction.

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

In the next chapter, simulations of the effects of sinusoidal model-shaped striae inside a lens will be discussed.

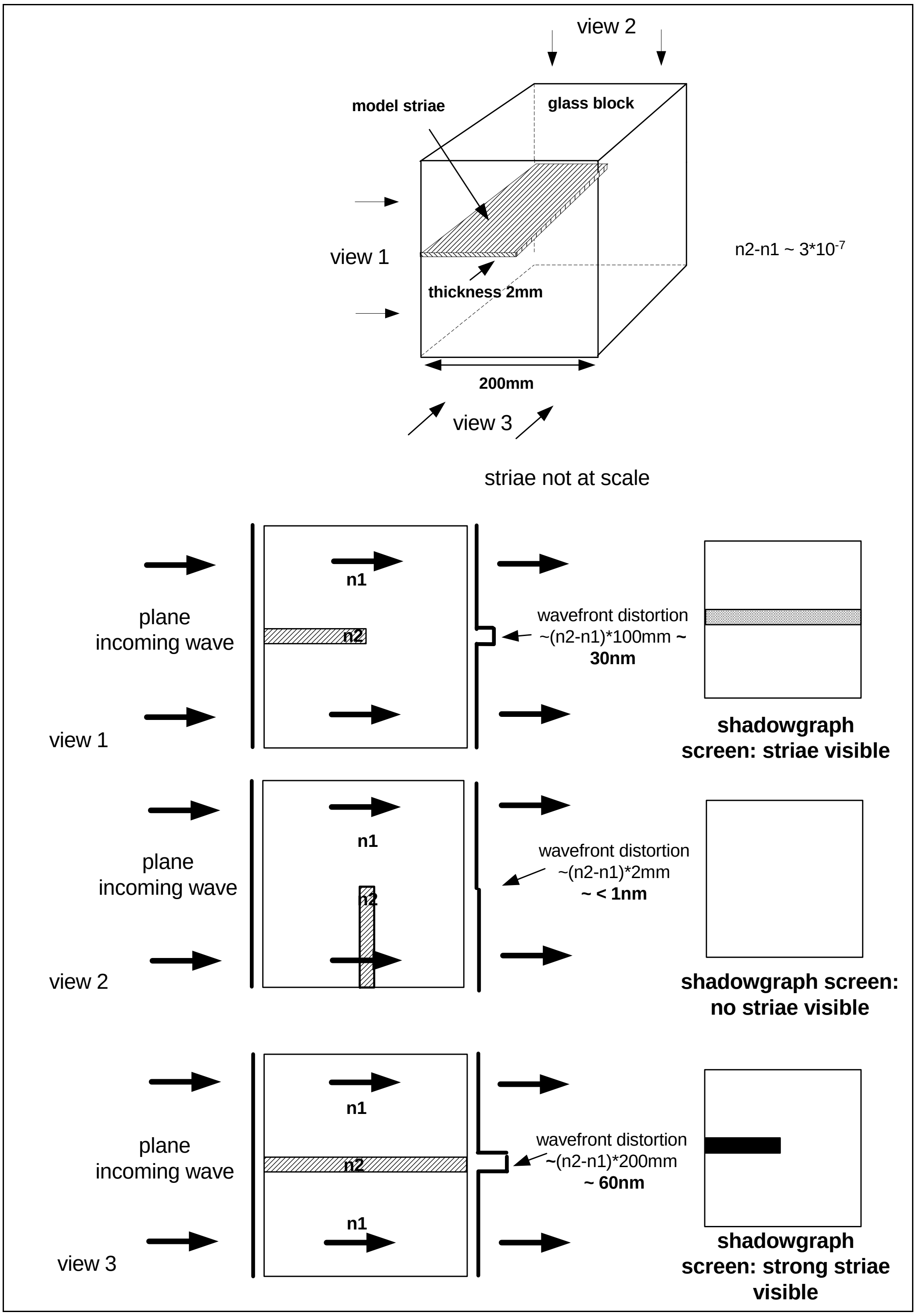

Figure 10: Influence of different view directions on the shadowgraph of model striae.

7. 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. Depending on their position, striae introduce aberrations 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 the striae broadens the intensity distribution of a picture from an ideal point source (see Figure 11). It has been shown that striae intensities below $\lambda/10$ has no significant effect on the image quality (taking λ=535 nm this would compare to striae intensity less than 54 nm (better than D quality)) (refer to [4]).

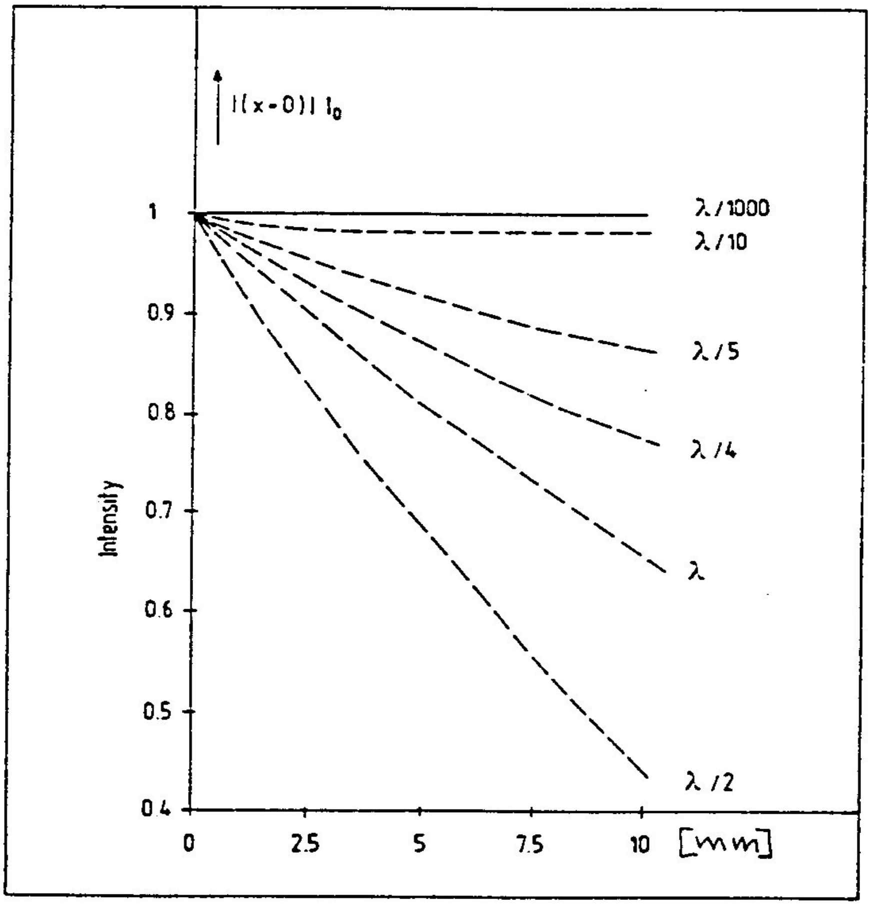

Figure 11: Central intensity of a picture of an ideal point source dependent on striae size and wave front deviation (intensity of the striae) [4].

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In the following sections, the results of the striae simulation using Zemax optical design software are discussed. Artificial striae with different intensities have been built into an ideal optical setup and in a real double Gauss lens system to analyze the influence on the image quality.

7.1. Influence of striae on the point spread function (PSF) and modulation transfer function (MTF) in an ideal aberration free optical system

For the simulation of the effect of striae on an ideal aberration free imaging system, a simple setup has been used. The setup consists of a lens with a focal length of 500 mm and an aperture of 50 mm diameter (f/10). In front of this lens, a plane plate with sinusoidal structures in one direction is placed. This sinusoidal structure introduces a phase modulation with a spatial frequency of 0.2 mm^{-1} and a variable peak to valley (pv) amplitude (60 nm, 30 nm, 15 nm, 8 nm). This structure is a worst case model of striae in an ideal system. Figure 12 shows the setup of the model. The calculations are carried out for a wavelength of 500 nm.

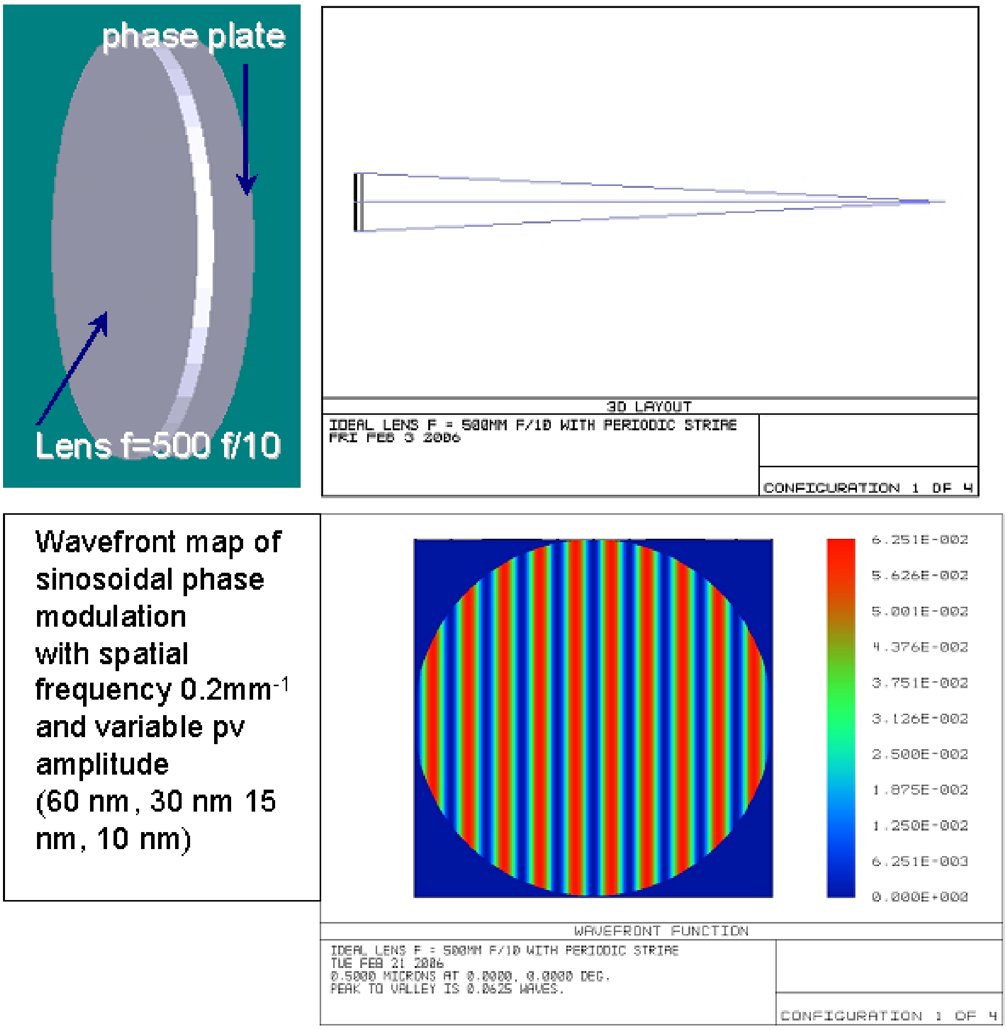

Figure 12: Setup of a Zemax model for the simulation of the effect of striae on an ideal optical system

The following figures show the influence of the model striae on the PSF of the system. An ideal aberration free system would show a diffraction limited point image with no side intensity maxima.

The striae in the system generates side maxima in the PSF. The intensity of the side maxima depends on the striae intensity.

Figure 13 shows the log-scaled area plot of the intensity distribution and figure 14 shows the log-scaled intensity distribution along the x-axis.

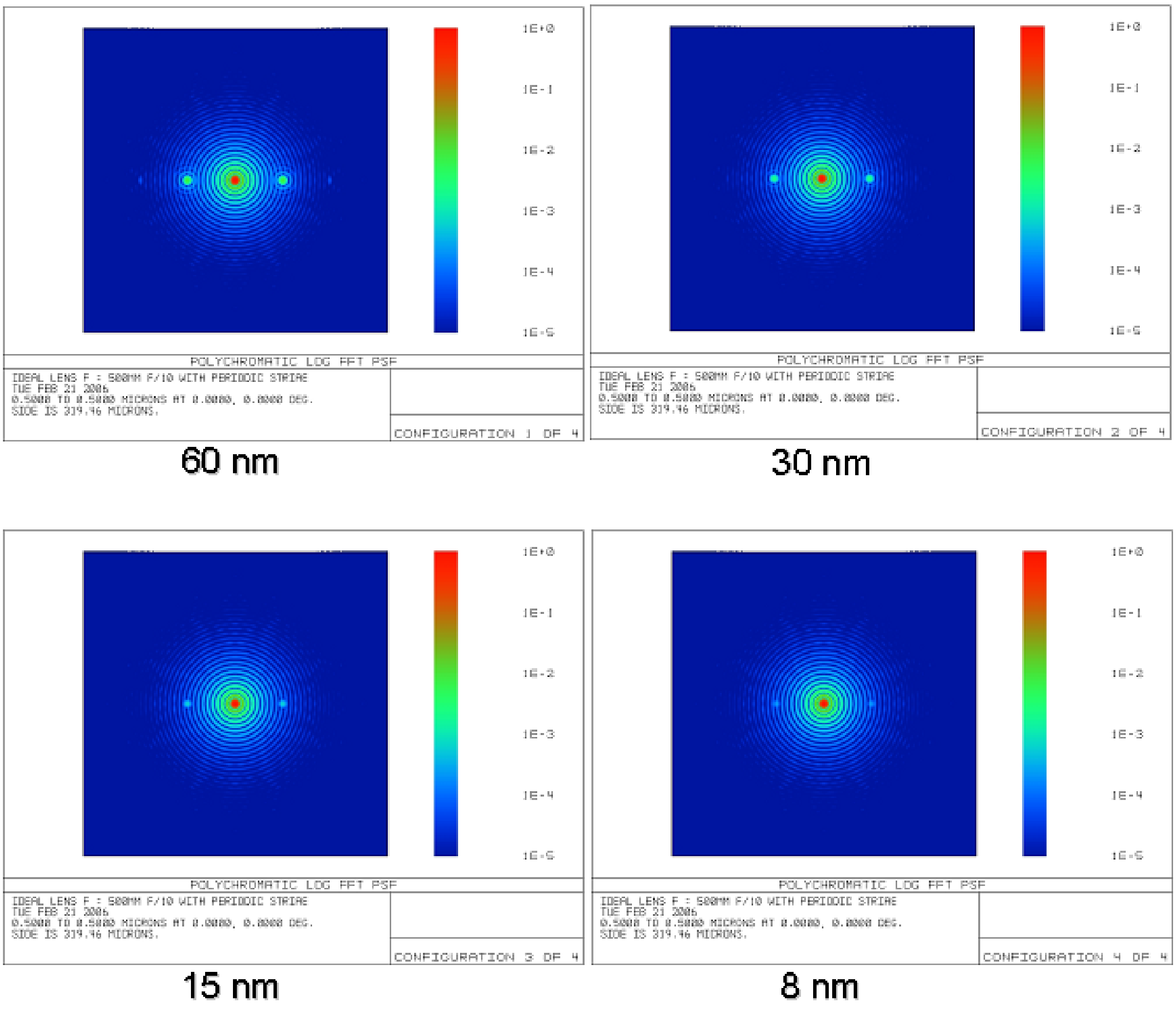

Figure 13: PSF of an ideal system with striae grade D (60nm) to A (8nm)

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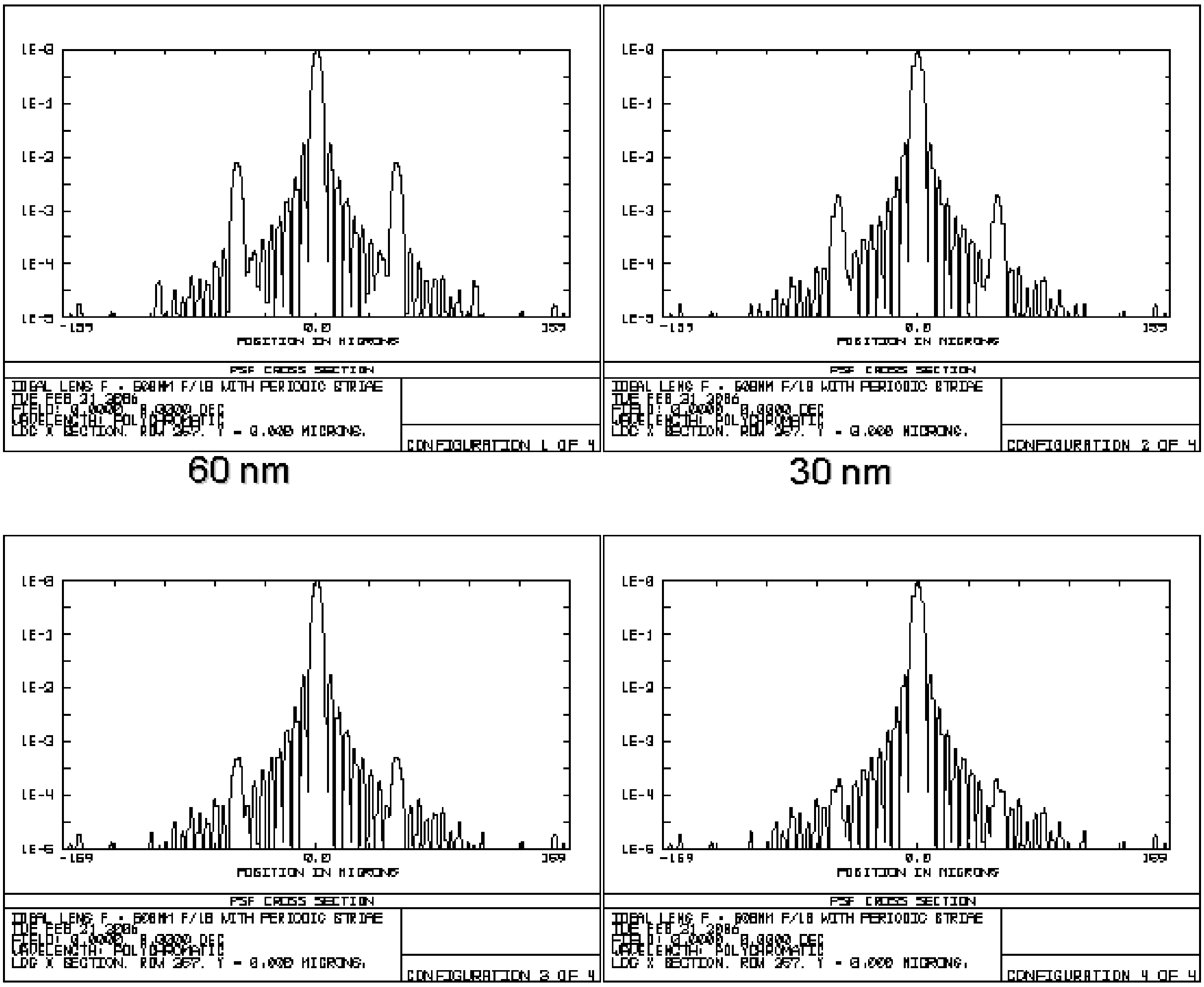

60 nm 30 nm

15 nm 8 nm

Figure 14: Two dimensional plot of the PSF of an ideal system with striae grade D (60nm) to A (8nm)

The side maxima intensity generated by a 60 nm striae is about 1/100 of the intensity of the main peak. For standard C grade striae with 30 nm optical path difference, the side maxima intensity is less than ~1/500 of the intensity of the main peak. For B grade striae with 15 nm, this fraction goes down to less then ~ 1/1000 and for A grade striae, the effect is nearly a magnitude smaller in the range of ~1/10000.

Taking into account that the displayed striae represents a worst case scenario, the PSF deviations visible are negligible for standard applications.

This becomes even more apparent if we display the corresponding MTF for the striae grades A to D (Figure 15). A 60 nm striae results in clearly visible effects in the MTF curve of the ideal system. Below 30 nm striae intensity, the effects are nearly invisible and hence negligible.

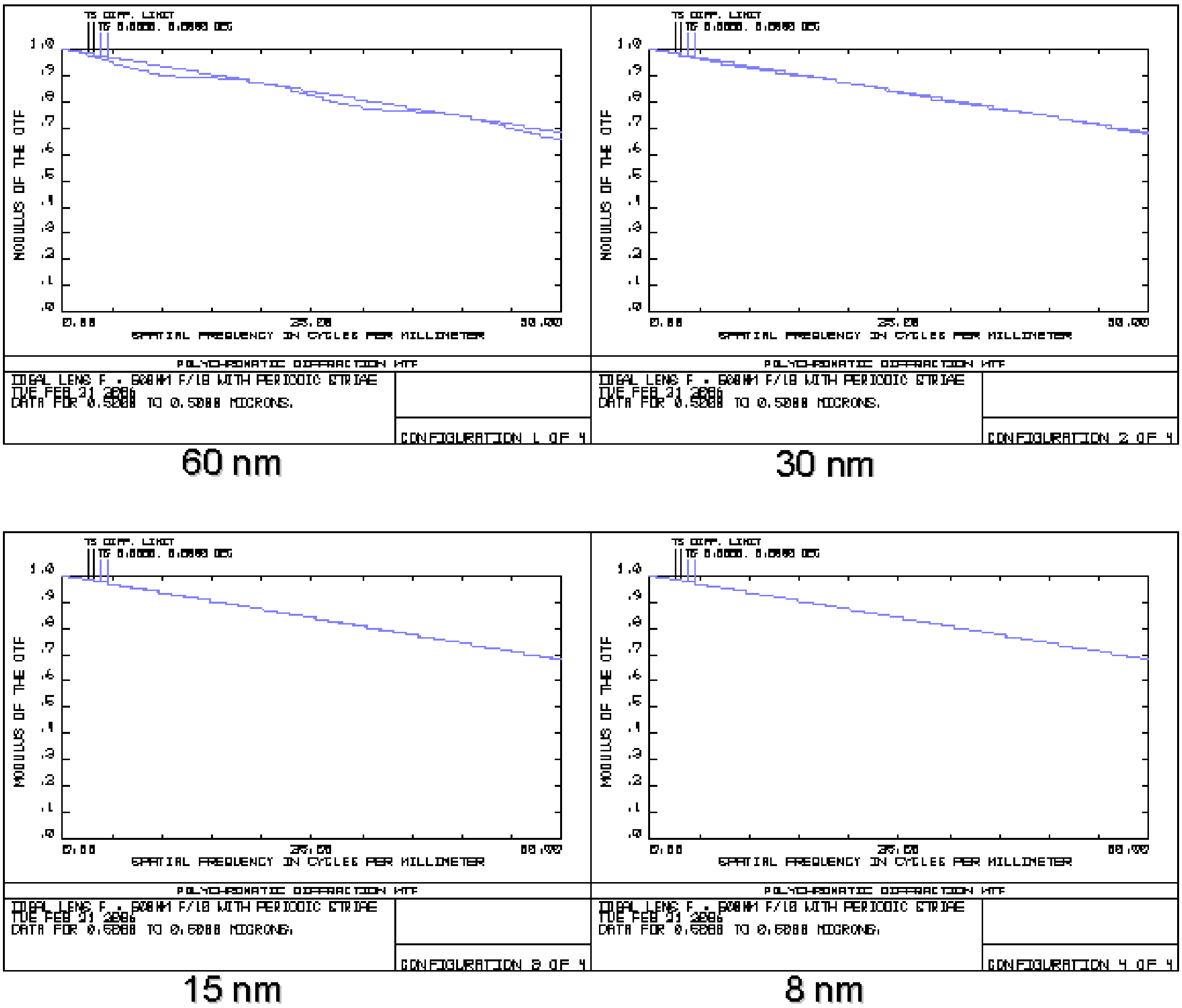

Figure 15: MTF of an ideal system with striae grade D (60nm) to A (8nm)

In general, it can be concluded that the standard grade striae equal or below 30 nm shows now recognizable degradation of the image quality of an ideal system.

7.2. Influence of striae on the point spread function (PSF) and modulation transfer function of a double Gauss lens

The influence of the striae on an ideal optical system is shown in the last chapter. In this chapter, the striae is built into a real optical lens system. The double Gauss system has been chosen as a model system. The double-Gauss design form has dominated the class of photographic lenses for many years. There are literally thousands of adaptations of this form, which has an apt combination of aperture, field, and design complexity. They are most commonly used in the 50mm lens with wide apertures. The double-Gauss is a 6-element design.

Figure 16 shows the used double Gauss system. The focal length is 100 mm at f/4. The striae plate was introduced between the second and the third element. The striae plate consists of sinusoidal phase modulations with a spatial frequency of 0.5 mm^{-1} and D grade striae intensity of 60 nm peak to valley. The wave front map shows that the double Gauss system is dominated by zonal errors with a maximum of 500 nm at a field angle of 0°. The striae plate structures are not visible in this plot due to the large-scale. All calculations are based on a wavelength of 500 nm.

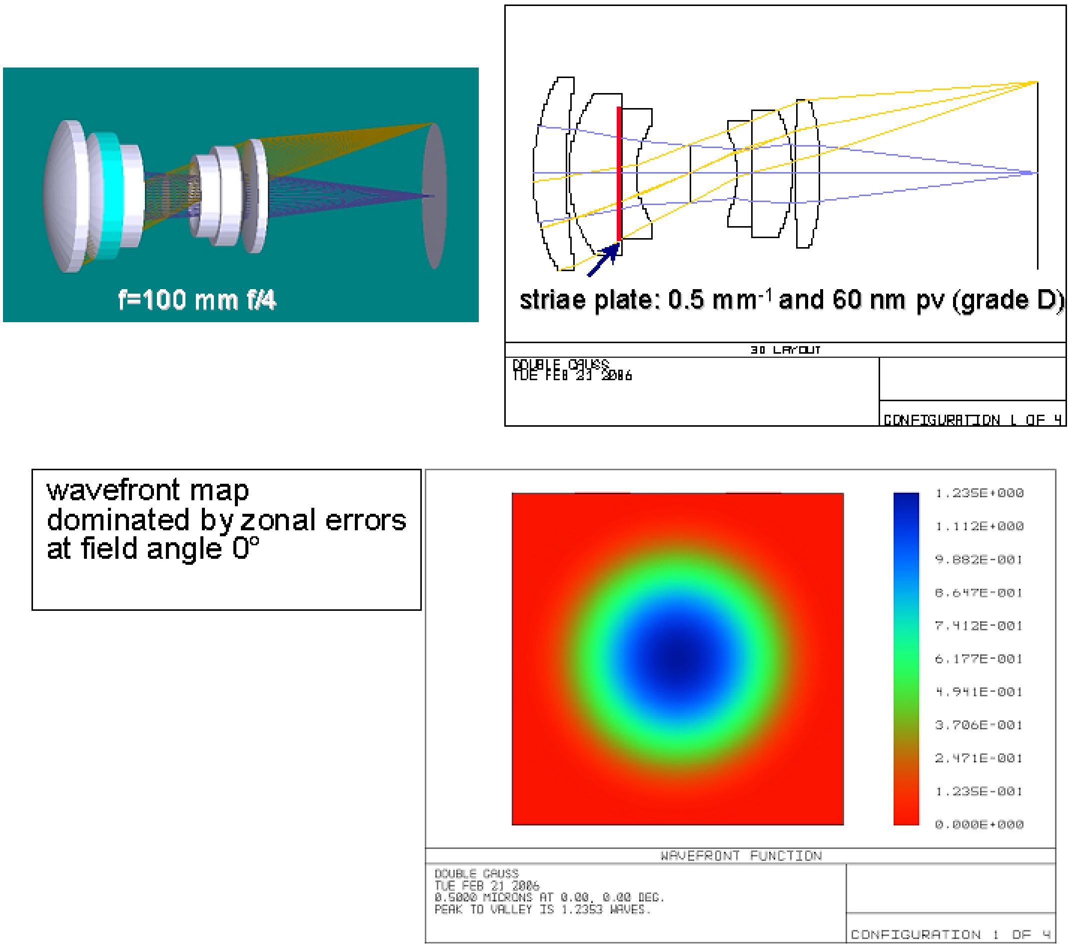

Figure 16: Setup of a Zemax model for the simulation of the effect of striae on a double Gauss system.

Figure 17 shows the results of the PSF for this system. The two dimensional intensity plot shows that the peak is broadened due to the aberration of the double Gauss system. No side maxima introduced by striae are visible. The aberrations of the double Gauss system dominate the influence of the striae.

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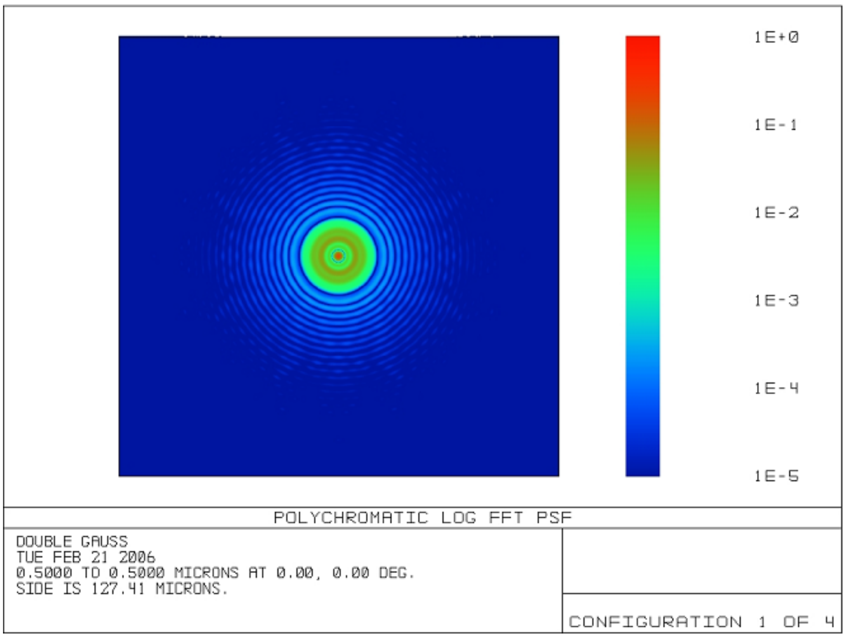

Figure 17: PSF of the double Gauss system with D grade striae (60nm).

The domination of aberration effects becomes even more apparent in the MTF given in figure 18 for parallel beams. The aberrations lead to a strong decrease of the curve at higher spatial frequencies. The striae have no recognizable influence on the shape of the MTF curve.

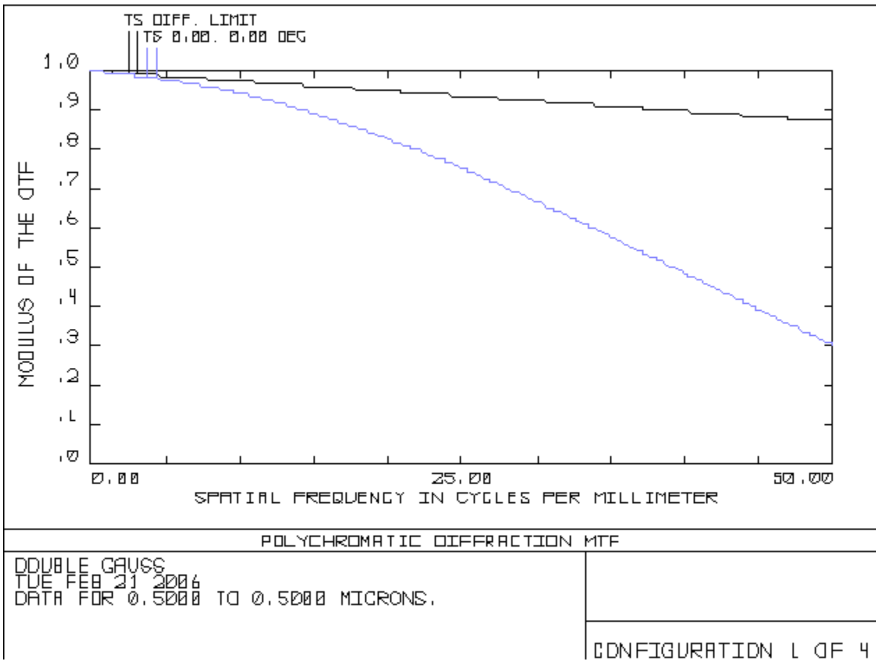

Figure 18: MTF of an ideal system with striae grade D (60 nm)

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7.3 Conclusions

The calculations of the PSF and MTF curve clearly show that striae with intensities less then 60 nm have no effect on the image quality of a standard double Gauss lens system as it is used in many photographic systems. The aberrations of the system override the effect that striae have on the image quality.

As shown in chapter 7.1, striae intensity below 30 nm shows no significant influence on the image quality of an ideal diffraction limited system.

Standard C grade striae quality (30 nm optical path difference) inspected with samples with 50 mm thickness is adequate for consumer optics, and even many industrial grade applications. For prisms with longer optical path lengths, C grade quality is also recommended when verified with an inspected path of 200 mm at minimum.

In optical systems with the highest demands on image quality, especially in the microscopy and lithography industries, Schott offers VS1 quality with less than 10 nm intensity as shown in chapter 5.

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

8. Literature

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