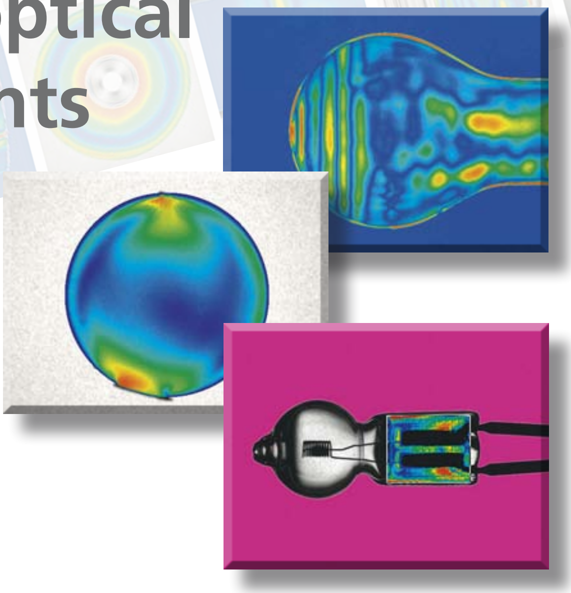
Imaging measurement of stress birefringence in optical materials and components



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Inherent stresses in optical components influence the polarisation of light by stress birefringence, an effect that is undesirable in demanding applications such as microlithography, laser optics and astronomy. Frequently, the requirements on the precise measurement of even low stress birefringence values are correspondingly high. Imaging polarimeters, which here also deliver a statement about the spatial distribution and orientation of the stress birefringence, make this possible.

Optical glasses are optically isotropic in the relaxed condition, i.e. the refractive index is equally large in all spatial directions. However, mechanical stresses induced by material or production lead to deformations in the material structure and thus to different particle densities along axes. As the propagation velocity of light depends, among other things, upon the density of the material, this sort of change in the microstructure leads to different velocities of light in the medium and thus to a direction-dependent change of the refractive index[1]. The medium therefore becomes birefringent under stress; one designates this effect as stress birefringence (SBR).

Apart from optically isotropic materials there are also many naturally occurring optically anisotropic materials, also known as birefringent materials, e.g. crystals such as calcite or quartz. For these materials the ratio of the refractive indices is also seen to change under mechanical stress – these changes can become so large, that the corresponding material stress can cause material damage to the crystal. But even small local variations of the refractive index can negatively influence the imaging properties of optical components and thus their function. In addition, birefringence alters the polarisation state of transmitted light, this being detrimental for applications such as those in metrology. Exact determination of stress birefringence and its spatial distribution is therefore of great importance in the manufacture of optical materials and components.

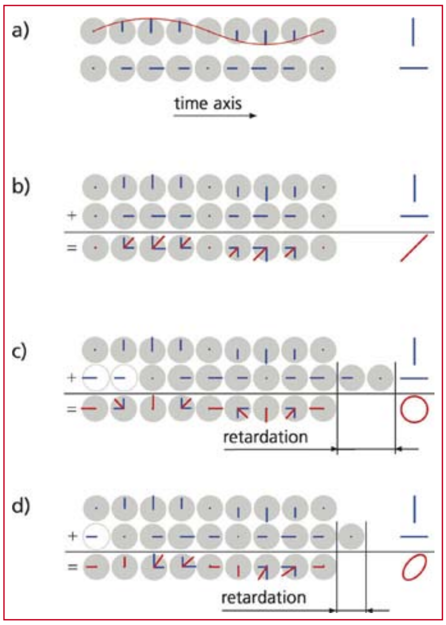

Figure 1: a: Two waves that oscillate vertically or horizontally. The circles show the time development proceeding from the left; b: Superposition of the two waves with the same propagation velocity. The resulting wave is again linearly polarised; c: Superposition of two waves with retardation amounting to exactly one quarter of the wavelength. One obtains circularly polarised light; d: Superposition of two waves with a phase delay of one eighth of the wavelength. One obtains elliptically polarised light

1 The photoelastic effect

In principle one can measure stresses by determining the propagation velocity of light along different axes. The differences occurring in this case are a direct measure of the birefringence and thus of the stresses causing it. However, instead of determining the propagation velocities or the resulting phase difference directly, e.g. by interferometry, one can use the photoelastic effect to directly induce changes in polarised light.

Linearly polarised light, the electrical field of which oscillates only in one plane, can be decomposed graphically as a superposition of two collinear light waves oriented at an angle of 45° to the original light wave, of fixed relative phase and at right angles to one another (**figure 1a**). If these two waves propagate at the same speed, the peaks and valleys of both waves coincide with one another. The addition of the waves produces the original, linearly polarised light wave (figure 1b).

However, if the two light waves are propagated at different velocities within a birefringent material of given length, a delay is induced between the two waves which is designated as optical retardation and is stated in nm or in fractions of the wavelength. If the retardation is exactly one quarter of the wavelength λ, the resulting field vector describes a circle, and

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[1] The refractive index is defined as the ratio of the phase velocity of light in vacuum to its phase velocity in the medium.

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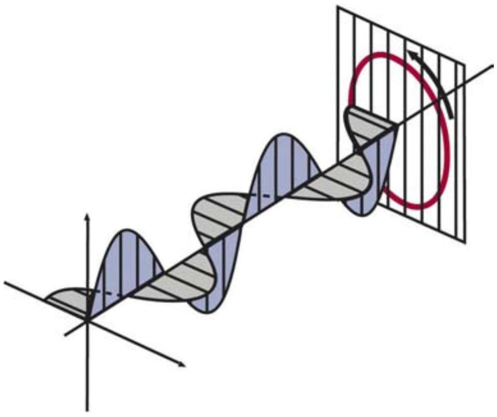

Figure 2: If a wave peak of the horizontal wave coincides with a zero passage of the vertical wave, one speaks of circularly polarised light

one speaks of circularly polarised light (figure 1c and **figure 2**). However, the retardation is generally not equal to λ/4 and elliptically polarised light is the result (figure 1d). Linear and circular polarisation can also be understood as extreme cases of elliptical polarisation.

Linearly polarised light entering a birefringent material therefore leaves this graphically as a superposition of two light waves oriented with polarisations at right angles to one another but now with differing phase, so that in the general case elliptically polarised light will be present. The ellipticity of the emerging light, i.e. the ratio between the ellipse axes, is in this case a measure of the birefringence and thus also of the inherent stresses in the material.

2 Measuring principle

Instead of measuring the shape of the ellipse directly, one can convert the elliptically polarised light back into linearly polarised light with the aid of a quarter-wave plate. The method is designated as the compensation method according to de Sénarmont; the associated measuring setup is shown in **figure 3**. The quarter-wave plate is aligned in this case with its fast axis parallel to the polariser. Strictly speaking, the light after this is not completely linearly polarised, but it is sufficient to consider only the linearly polarised part. This is now changed compared with the original polarisation direction by a certain angle that is proportional to the retardation and thus also represents a measure of the ellipticity as well as of the birefringence. The angle can be determined in a simple manner by rotating a second polariser (named analyser) so long until an intensity minimum is reached for the viewed measuring point.

In the basic position the analyser is arranged at right angles to the polariser. Without a birefringent sample, one therefore obtains a dark image as the light is absorbed completely by the analyser. However, if one introduces a transparent test specimen with, for instance, edge stresses running tangentially, then these lead to local bright regions (**figure 4** on the left), as the material stresses in the diagonals are at 45° to the orientation of the polariser axes and thus a part of the light is let through by the analyser. If one now rotates the analyser, the intensity changes (figure 4 centre and on the right). The minimum intensity is reached when the polarisation direction of the analyser is again at right angles to the polarisation plane of the light. The retardation R in nm as measure of the (stress) birefringence can be determined according to the relationship

$$R = \alpha \cdot \lambda / 180° \qquad \text{(Eq. 1)}$$

Here α is the angle of rotation in degrees and λ the wavelength of the light used in nm. However, only stresses that are oriented at 45° to the polariser and thus to the quarter-wave plate are correct in their absolute magnitude.

3 Automatic measurement

The disadvantages of the above, still largely visual method include the difficulty of determining the position of the intensity minimum with the required accuracy and reproducibility. Additionally, a statement about the spatial distribution is possible only with a large number of measurements and much time. Finally, only stresses that are oriented at 45° to the polarisation direction can be measured with this method. All other orientations appear attenuated, as can be seen on the left in figure 4. The test specimen must therefore be aligned correspondingly before the measurement. In particular for small SBR values (< 10 nm), an objective and sufficiently precise measurement is scarcely possible or involves much time and effort. In addition one would have to first rotate the test specimen into the correct position for each measuring point when measuring anisotropic stress orientations.

In view of the described difficulties, it makes sense to automate the measuring setup and procedure. Solutions have been available for some time now with which the stress birefringence for individual measuring points can be determined automatically with the required accuracy. However, these measuring systems deliver information only for a small measuring area. The test specimen must be scanned in order for larger surfaces to be measured.

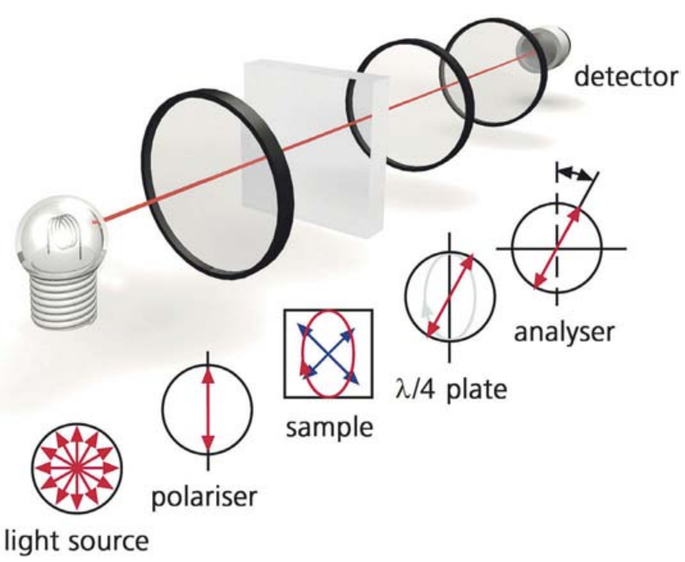

Figure 3: Schematic of a polarimeter for measuring stress birefringence according to the de Sénarmont principle. The polariser lets only the linearly polarised share of the incident light through. Birefringence in the sample leads to elliptically polarised light. Linearly polarised light, the polarisation angle of which can be determined with a rotatable analyser, is obtained from the elliptically polarised light with the aid of a quarter waveplate. The optical retardation can then be calculated

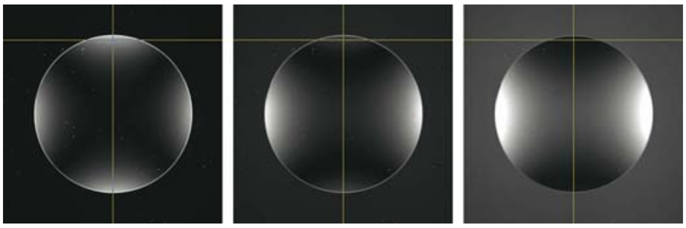

Figure 4: Intensity images of a glass disk with pre-defined edge stresses under different analyser positions. The polarisation plane lies diagonally to the figure axes

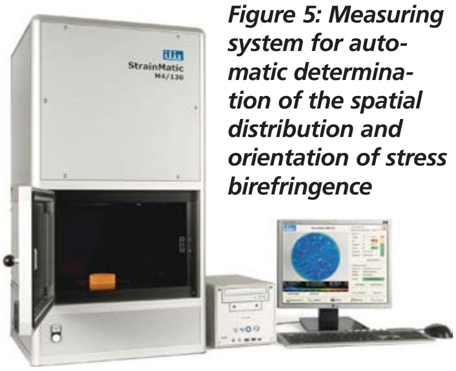

Figure 5: Measuring system for automatic determination of the spatial distribution and orientation of stress birefringence

The spatial resolution achievable in an acceptable measuring time is correspondingly low for large sample dimensions. Furthermore, high requirements are placed on the optical flatness and surface quality of the sample in order to avoid issues with beam deflection and scatter.

4 Imaging measurement

For these reasons an imaging measuring system that facilitates rapid, spatially resolved determination of the magnitude and orientation of stress birefringence with high accuracy has been developed. **Figure 5** shows the implemented measuring system, the functional principle for which essentially corresponds to the setup indicated in figure 3. Through the use of a matrix camera instead of a photo detector, this system can analyse an entire measuring field in a single shot, obviating the need to scan the sample and repeat single point measurements. The lateral resolution is determined in this case by the size of the measuring field and the resolution of the camera.
As already mentioned, only stresses that are oriented at 45° to the polariser axis can be determined with a linear polarimeter. For this reason several measurements are performed under different polariser settings (instead of rotating the measured object, the optical system rotates practically about the sample). The partial results are then combined to an overall result, as shown in **figure 6.**
For instance, a spatial resolution of approx. 0.14 mm (pixel spacing) is obtained when analysing a field size of 100 x 75 mm^2 with an image resolution of 696 x 520 pixels. Reproducibility of the stress birefringence values in the range of ±0.1 nm is achieved in measurement times of less than one minute. The SBR orientation is determined in this case pixel by pixel with angular degree accuracy.

5 Applications

An important application of the measurement of stress birefringence by imaging systems is in testing materials for the manufacture of photolithographic lenses, especially for optical wafer stepper systems. In addition to the so-called i-line glass (365 nm lithography), quartz glass and calcium fluoride crystals are used for shorter wavelengths (248 and 193 nm). In this case the requirements on the optical quality of the starting materials are especially high because of the image quality that needs to be achieved (structure sizes of 40 nm). Apart from the precise measurement of the residual stress level, measurement by imaging systems with high spatial resolution delivers information about the smallest defects in the glass matrix or crystal structure (**figure 7** and **8**).
Further important application areas in optics are, for instance, mirror carriers made of glass ceramic in astronomy as well as quarter-wave plates, compensators (**figure 9**), laser crystals, optical windows, lenses, prisms, etc., in particular those designed for use in laser optics.

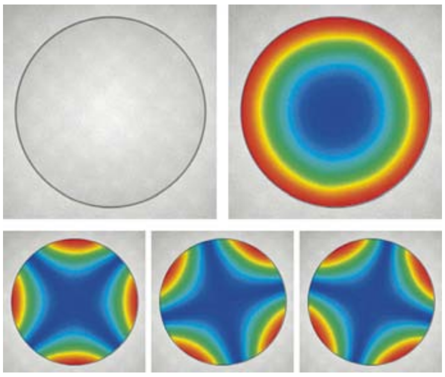

Figure 6: Camera image of the strain disk from figure 4 with measuring result (above right) as well as partial results at 0°, 30° and 60° polariser position (below). In the colour coded diagram, blue stands for low SBR values and red for high SBR values

6 Summary

Imaging polarimeters facilitate fast and accurate determination of stress birefringence and its spatial distribution and orientation. Measurement using imaging systems offers clear advantages over point-by-point measuring methods, not least in applications requiring high spatial resolution, and additionally because of the comparably low requirements on surface quality.

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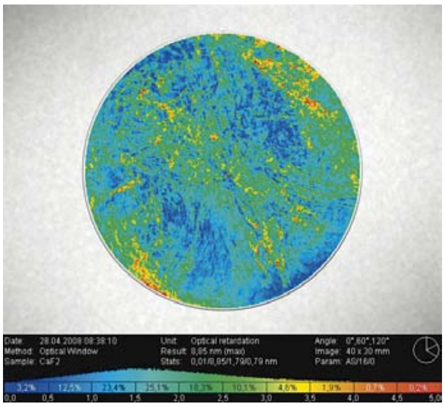
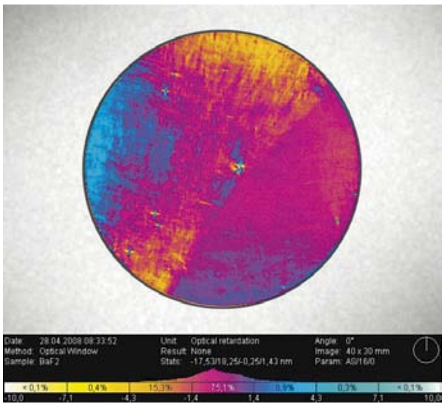


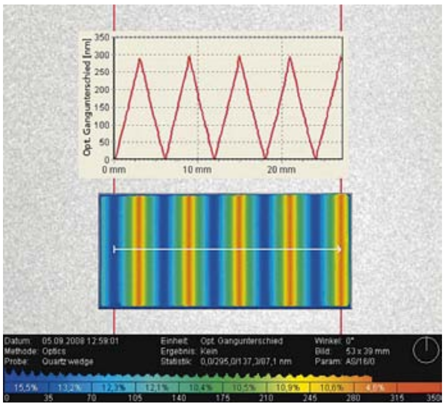
Date: 28.04.2008 08:38:10
Method: Optical Window
Sample: CaF2
Unit: Optical retardation
Result: 8,85 nm (max)
Stats: 0,01/8,85/1,79/0,79 nm
Angle: 0°,60°,120°
Image: 40 x 30 mm
Param: AS/16/0

Figure 7: Measuring result for a CaF_2 single crystal with 25 mm diameter and 4 mm thickness



Date: 28.04.2008 08:33:52
Method: Optical Window
Sample: BaF2
Unit: Optical retardation
Result: None
Stats: -17,53/18,25/-0,25/1,43 nm
Angle: 0°
Image: 40 x 30 mm
Param: AS/16/0

Figure 8: Measuring result for a BaF_2 single crystal (∅ 25 mm). Local faults within the crystal structure can be clearly seen



Datum: 05.09.2008 12:59:01
Methode: Optics
Probe: Quartz wedge
Einheit: Opt. Gangunterschied
Ergebnis: Kein
Statistik: 0,0/295,0/137,3/87,1 nm
Winkel: 0°
Bild: 53 x 39 mm
Param: AS/16/0

Figure 9: Measuring results for a quartz wedge: colour coded distribution presentation and line scan evaluation

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