Principles of Photoelasticity

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The strength of glass and plastic products and their ability to be processed is influenced strongly by mechanical stresses that can arise for production reasons (e.g. in injection molding or extruding plastics) or due to problems in the stress-relief process (e.g. annealing glass). Moreover stresses have an influence on optical properties, which is undesirable in certain applications (e.g. glass or plastic lenses for polarization optics). Fast and accurate measurement of residual stresses accompanying production is thus an essential prerequisite for controlling the decisive process parameters and thus an essential factor for optimizing quality. This article provides a graphic introduction to the physical principles of optical stress measurement.

Stresses in solid bodies

Mechanical stresses lead to deformations of the material structure. If one for example pulls an air cushion foil apart with one's hands like an expander, one sees that the distance between the bubbles increases in tensile direction. This effect also occurs in compact bodies of glass or plastic, but at a microscopic level.

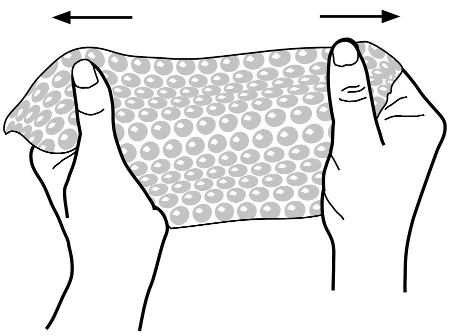

Fig. 1: Deformation of an air cushion foil under tensile stress. The distance between bubbles increases in tensile direction.

What effects do such changes of the microstructure have on the interactions between light and material and thus on the optical properties of the material?

Light propagation

If light strikes an atom, then its electron shell is stimulated to oscillate due to the electromagnetic field of the light. The oscillation leads in turn to radiating light.

This process can be compared with a relay race. One runner reaches the next runner, he passes the baton on to him, who in turn runs on and so on. The speed of the baton would be reduced in a 400 m relay race if one would increase the number of runners for the same distance and assumes that there is a delay at each handover.

In transparent materials a higher number of particles per distance traveled also leads to a reduction of the velocity of light, i.e. the propagation speed of the light depends upon the particle density.

Light refraction

The *refractive index* is a measure of the velocity of light in the relevant medium. The larger the propagation velocity v of the light in relation to the velocity of light c in vacuum, the smaller is the refractive index n:

$$n = c/v$$

Since on expansion the distance between the molecules becomes greater and thus the velocity of light in the medium increases, the refractive index must therefore decrease in tensile direction.

It now becomes clear that the propagation velocity of the light in tensile direction and at right angles to this differs; therefore the refractive index also varies in different directions. One says that a material is *optically birefringent*.

There are materials that are birefringent even without the presence of mechanical stresses, for example many crystals.

Other materials, such as glass, are by contrast *optically isotropic*, i.e. the refractive index is the same in every spatial direction in relaxed condition. However, these materials become birefringent when they are under stress.

One can therefore measure stresses in these materials by determining the propagation velocity of the light for the different directions. The differences occurring in this case are a direct measure of the birefringence and thus of the stress.

In the measurement one makes use of the influence of optical birefringence on *linearly polarized light*. But what exactly is polarized light?

Linearly polarized light

One imagines a lattice of balls that are connected to one another flexibly with springs (Fig. 2).

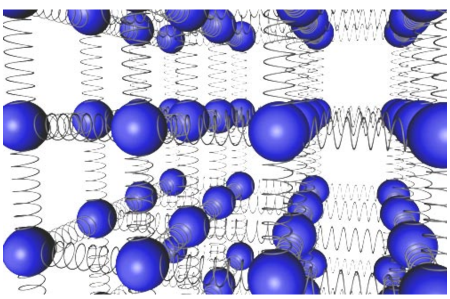

Fig. 2: Graphic model of a solid body.

If one deflects a ball in this lattice to the left and lets it go, this ball oscillates alternately to the right and left. However only briefly; its next neighbors also start to oscillate to the right and left. This oscillation is quickly propagated in the lattice while the originally deflected ball comes to rest. One can observe an analogous behavior for deflections up and down. This is a graphic model of the effect of the electromagnetic field of light on a solid body.

If the electrical field oscillates only in one plane, then one speaks of *linearly polarized light*. In this model this means that the balls oscillate only to the right and left or up and down.

Optical retardation

If one deflects a ball diagonally, then one can view this as superimposition of a horizontally and a vertically polarized light wave, i.e. one obtains a wave with vertical deflection (Fig. 3) and a second wave at right angles to this (Fig. 4).

If these two waves propagate with equal speed, a wave peak of the vertical wave always meets a wave peak of the horizontal wave. The addition of the deflections results in the original diagonal wave (Fig. 5).

If the distance between the balls in the ball model in the vertical direction is different from that in the horizontal direction, as is the case in birefringent materials, the light propagates in the horizontal direction with a velocity differing from that in the vertical direction. Thus there is a delay between the two waves. This delay is designated *optical retardation* and it is measured in the unit of nanometers.

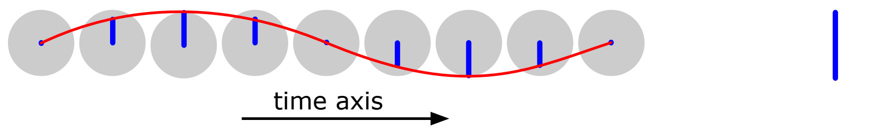

Fig. 3: A wave the deflection of which changes between up and down. The circles show the time development proceeding from the left.

Fig. 4: A wave the deflection of which changes between to the right and to the left.

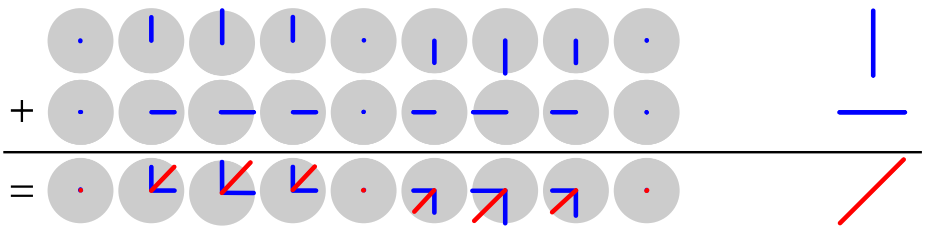

Fig. 5: Wave peaks of the vertical wave meet a wave peak of the horizontal wave. The addition of the deflections results in a diagonal wave (red). The deflections therefore lie in the diagonal plane; one still has linear polarization.

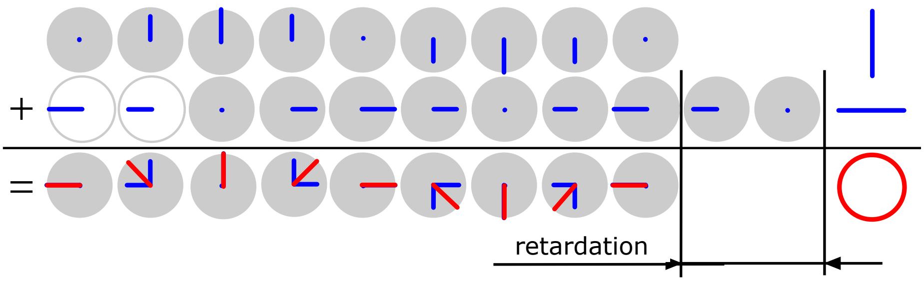

Fig. 6: If a wave peak of the vertical wave meets a zero passage of the horizontal wave, one speaks of circularly polarized light.

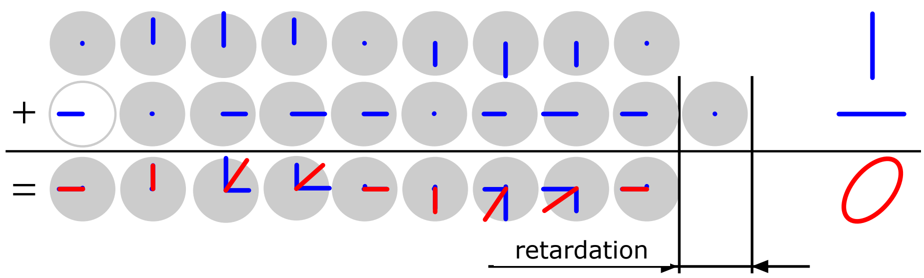

Fig. 7: If the shift is smaller than one quarter of the wavelength, then one does not obtain a circle but an ellipse. One then speaks of elliptically polarized light.

Circularly and elliptically polarized light

If the retardation is just large enough so that a wave peak of the vertical wave meets a zero passage of the horizontal wave, then one has a special case: When the light wave is viewed in the propagation direction it describes a circle. The retardation is then exactly one quarter of the wave length λ and one speaks of *circularly polarized light* (Figures 6 and 8).

However in the general case the retardation is not equal to a quarter of the wavelength and one does not obtain a circle but an ellipse. One then speaks of *elliptically polarized light* (Fig. 7).

Linearly polarized light therefore leaves a birefringent material as superimposition of two light waves standing at right angles to one another with different phase relation and is therefore in the general case elliptically polarized.

The ellipticity of the emerging light, therefore the ratio between short and long half axis of the ellipse, is here a measure of the optical birefringence and thus also of the stress in the material.

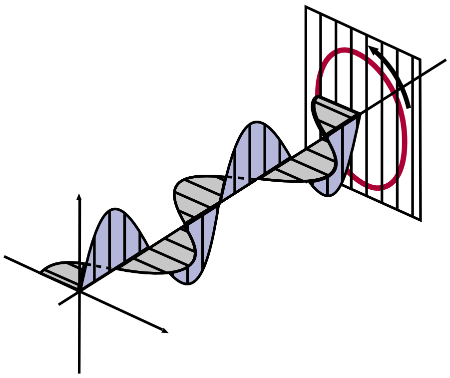

Fig. 8: If a wave peak of the horizontal wave meets a zero passage of the vertical wave, one speaks of circularly polarized light.

If one views a birefringent sample through a polarizer the polarization plane of which is arranged at an angle of 90° to the original polarization direction, one sees bright areas in the otherwise black field of view, and the intensity of these areas is proportional to the ellipticity of the light.

The degree of stress birefringence can therefore already be concluded from the intensity of the brightness. However, it is expedient for the quantitative determination of the birefringence to convert the elliptically polarized light back into linearly polarized light with the aid of a quarter-wave plate.

Quarter-wave plate

A *quarter-wave plate* consists of birefringent material, e.g. quartz crystal. The difference between the refractive indices is just large enough so that the horizontally polarized wave is delayed by a quarter wavelength compared with the vertically polarized wave. The retardation of the two waves is therefore λ/4, for which reason the quarter-wave plate is also named λ/4 plate.

In the case of quarter-wave plates one speaks of a fast and a slow axis. Light that is polarized parallel to the fast axis moves faster than the light with polarization oriented at right angles to this. Linearly polarized light the polarization direction of which lies at an angle of 45° between the fast and the slow axis is converted by the quarter-wave plate into circularly polarized light and vice versa.

Strain measurement

Figure 9 shows the basic construction of a *polarimeter* for measuring stress birefringence according to Sénarmont. The quarter-wave plate is arranged here so that its optical axes are oriented parallel to the polarization direction of the incident light.

Elliptically polarized light that issues from the sample is therefore converted back into linearly polarized light, but with a different polarization direction. The difference between this and the original polarization direction is named the *polarization angle*. The polarization angle describes the ellipticity of the light emerging from the sample and is therefore a measure of the birefringence and thus of the stress in the material.

The polarization angle is determined with an *analyzer*, a second, rotating polarizer which in its initial position is at right angles to the first polarizer.

Regions of the sample under stress appear as bright areas in the otherwise black field of view. The analyzer is now rotated until an intensity minimum is reached at the place viewed. The angle of rotation of the analyzer is then the same as the polarization angle.

The optical retardation R in nm, which is a measure of the stress, can be calculated from the polarization angle α according to the equation:

$$R = \alpha \cdot \lambda / 180°$$

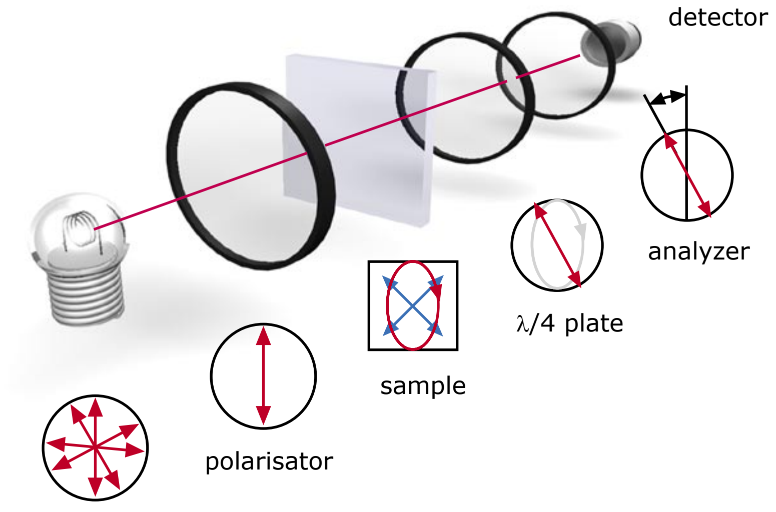

Fig. 9: Construction of a polarimeter for measuring optical birefringence. The polarizer lets only the linearly polarized component of the incident light through. Birefringence in the sample leads to elliptically polarized light. Linearly polarized light is obtained from the elliptically polarized light with the aid of a quarter-wave plate. The polarization angle can be determined with a rotating analyzer and the optical retardation can be calculated from this.

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