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By

H.- L. Tardy

Translated from
Revue d'Optique,
8, 59 - 69 (1929)

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A PRACTICAL METHOD FOR INVESTIGATING AND MEASURING THE BIREFRINGENCE OF OPTICAL GLASS

By H.-L. Tardy

Revue d'Optique, Vol 8, 1929, pp 59--69

SUMMARY. -- A practical method for studying the annealing of optical glass should make it possible: 1. to survey at one glance the general distribution of the birefringence; 2. to determine quickly (in a few seconds) the value of the birefringence in arbitrarily selected points; 3. to trace, if this be deemed useful, the contour lines of the birefringence on the glass under examination.

A method is presented that satisfies these conditions and a suitable instrumental arrangement is described.

An example of an application is given.

Builders of optical instruments are much concerned with the annealing of the different types of glass that they use, and they set specifications to glassmakers in this respect that may seem excessive if one considers to what minute changes in index they correspond. But experience has taught the optician how hard it is to cut a satisfactory optical workpiece from a glass that has either a bad distribution, or more than a certain grade of annealing; this depends also on each special case: e.g., a disc with birefringence that is not centrally symmetric is not suitable for a component of a good objective.

How does annealing affect the quality of an optical piece? By splitting the index? By changing the mean index, or by causing hardness? All these questions should be studied. In any case the annealing to the optician is the manifestation of an undesirable state of the glass, making it difficult to work with, more sensitive to outside influences, in other words a sort of in-born flaw that should be eliminated as much as possible.

It is interesting that the problem of measuring such a practically important phenomenon has found no industrial solution and that glassmakers and opticians have to be satisfied with qualitative tests that are undoubtedly valuable, but not sufficient.

Yet there is no scarcity of methods for measuring birefringnece: some have been described in this journal.* But all these methods have a serious disadvantage: they are slow and this alone would make them unsuitable for industrial application and in addition it makes any tracing of birefringence contour lines dubious. The latter is extremely sensitive to temperature variations and, unless special precautions are taken, it is probable that these will occur in an extended experiment. Even if these temperature changes did not cause large errors in birefringence, they would cause a change in its distribution, a property that often has great importance: thus one might get a distorted or even incoherent picture of the bottom of a bay, if one would use the raw data of the soundings without introducing tidal corrections.

A practical method for studying the annealing of optical glass should permit: 1. to obtain an instantaneous overall view of the distribution of birefringence; 2. to determine its value swiftly (in a few seconds) in points selected at will on the piece under examination; 3. to make it easy to trace the contour lines of birefringence, if this is thought to be useful. Moreover, these various operations should be carried out without a necessity to manipulate the glass under study, or even to come near it.

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*See Revue d'Optique, March 1929: "Measurement of the Birefringence of Optical Glass," by Henri Boissier.

We shall give a review of essential concepts and properties of birefringence before describing the method devised at the Optics Laboratory of the Geographical Service of the Army, intended to meet the above requirements.

The characteristic property of a birefringent medium is that inside it, starting from a point O, only the light vibrations directed along two lines at right angles to each other (called the neutral lines of the medium in O) can be propagated without modification, i.e., without ceasing to follow straight lines parallel to their original directions; but they will have different velocities. A monochromatic linear vibration of wavelength λ, arriving at O on a birefringent plate of thickness e, is generally transformed, upon leaving it, into an elliptic vibration; its components lying along the neutral lines have a path difference Δ, expressed in the same length units as λ and e, or a phase difference ψ expressed in radians. When n' and n'' stand for the indices of the plate we have:

$$\Delta = (n' - n'')\, e \quad \text{and} \quad \frac{\Delta}{\lambda} = \frac{\psi}{2\pi} = b$$

b is characteristic of the birefringence of the plate at the point under consideration and $n' - n''$ of the birefringence of the material it is made of. The directions of the neutral lines and the value of $n' - n''$ are independent of the position of the point chosen in a regular crystalline plate; the birefringence of a glass slab is, however, variable from point to point in magnitude and direction; it can thus only be completely described by a map, just like a topographic surface.

Description of the method. -- A pencil of circularly polarized light passes through the piece V under examination, illuminating it uniformly. It then converges in the eye of the observer after passing a fixed "quarter-wave plate" L', and then an analyzer Nicol A that can be rotated around the axis of the pencil.

Let us select as origin of the angles the direction Ox, making an angle of 45° with the neutral lines of the "quarter-wave plate" L', and let us consider the beam passing through the glass V at a point where the birefringence is characterized by the phase difference 2φ and the angle α between Ox and one of the neutral lines. Finally, let θ be the angle with the reference direction of the light vibration passed by the analyzer A. The intensity of this beam when it reaches the eye of the observer is proportional to the factor:

$$K = \sin^2(\varphi - \theta) + \sin 2\varphi \sin 2\theta \sin^2 \alpha.$$

1. Let us first assume $\theta = 0$.

The piece V is situated under the usual conditions of inspection in circularly polarized light. The illumination at any point is independent of α, i.e., the orientation of the neutral lines, and it is proportional to $\sin^2 \varphi$, or in other words it is exclusively a function of the absolute value of the birefringence. The birefringence will thus appear in relief: the most strongly lighted areas are those where the annealing is maximal, assuming that the birefringence does nowhere exceed one half wave length, and this is always true in optical glass.

A disc, for example, of 100 mm diameter and 12 mm thickness, and an axially symmetrical anneal that increases regularly from the center to the edge looks like a dish, as shown in Figure 1.*

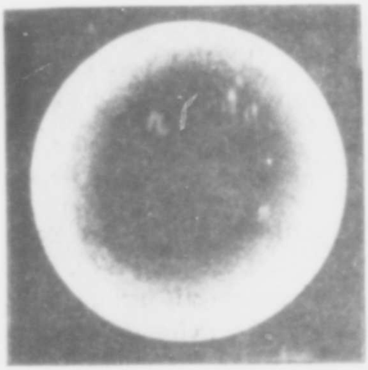

Fig. 1.

Fig. 2.

A same level of illumination corresponds to the same value of birefringence, and thus, on a photograph of the piece V taken under these conditions all points of equal darkness belong to the same contour line of birefringence. For evaluating the birefringence one observes that the expression K is symmetrical in φ and θ, and thus the illumination in a point with birefringence 2φ when $\theta = 0$ is equal to that in a point

*This photographic picture, as well as all those that will follow, gives only an imperfect idea of the phenomena: they are clearer and in greater relief when observed visually.

of zero birefringence when $0 = \varphi$. It is thus possible by making a number of photographs with identical exposure time and different angles θ to see how the blackening of the plate depends on θ in one of the points of the piece where the birefringence is zero (if such a point exists) and then to give a quantitative evaluation to the contour line drawn previously. This method, however, is rather time-consuming because it requires microphotometric density measurements, and in general the much faster visual observation is preferred.

2. Let us now assume that θ has an arbitrary value θ_1, differing from zero.

It is readily seen that the factor K can become zero only when one of the following sets of two conditions is fulfilled:

$$\text{either} \quad \varphi = \theta_1 \text{ and } \alpha = 0,$$

$$\text{or} \quad \varphi = -\theta_1 \text{ and } \alpha = \frac{\pi}{2}.$$

This means that darkness occurs only at points where simultaneously the birefringence has a certain value, $2\theta_1$, and where the neutral lines have also a certain orientation, at 45^o to those of the quarter-wave plate L'.

Such points are in general isolated on the piece. Figure 2 shows, for instance, the appearance of the disc of Figure 1 for $\theta = 3^o45'$. The value of the birefringence in the center of the two diametrically opposed dark spots is:

$$b = \frac{7^o 30'}{360^o} = 0{,}021.$$

By turning the complete system quarter-wave plate plus analyzer A, maintaining θ at the value $3^o45'$, one will make the centers of the dark spots move in such a way as to describe on the stationary piece V the locus of points where the birefringence has the value 0.021; this will be a circle concentric with the disc if the anneal is axially symmetrical.

It is thus possible to trace the contour lines of the birefringence cinematographically.

If measurement of the birefringence is intended at a point B, marked on V, the first step will be to position the neutral lines of the quarter-wave plate at an angle of 45^o to those of V at point B -- how this is done will be shown below -- and then the center of one of the dark spots appearing on V is brought to coincide with B by increasing the angle θ.

Among the points chosen for this determination one will usually find the maxima of birefringence N revealed by inspection in circularly polarized light. These points are quite often located on the edge of V; this is the case for the disc of Figures 1 and 2 and also for the slab studied below.

The measurements made in these boundary points are less easy than others because the shadows do not have the symmetry that makes it possible to find its center. On the other hand, the conditions are favorable for determining whether the illumination in N is the same as the background illumination, i.e., that part of the pencil that did not pass through the piece V, because the two brightnesses to be compared are adjacent to each other. This equality occurs, as shown by the expression K, when $\theta' = \frac{\varphi}{2}$, i.e., at a value of θ half the value that will bring the center of a shadow to the same point, and the birefringence of N has the value $b = \frac{4\theta'}{2\pi}$. The latter equation is only an approximation because losses from reflection and absorption due to passage through V are neglected. The error, however, will exceed 0.01 b only if b is larger than 0.25.

Instrumental arrangement.* An autocollimation assembly with spherical mirror was chosen, resulting in an apparatus that is easier to build and to run, possessing in addition two important advantages: any passage through glass except for that of the samples studied is avoided, and besides, the sample under study is passed twice by the light and consequently the measured birefringence is doubled. The two passes admittedly do not occur at exactly the same point and they are slightly oblique; the resulting errors, however, are negligible in the case of optical glass.

*Built by Jobin and Yvon Co.

The arrangement is schematically represented in its entirety in Figure 3; Figure 4 is a photograph of the whole back part, including: the light source, the polarizer and analyzer systems with their "quarter-wave plates," and finally the observer's telescope, all mounted on a carriage.

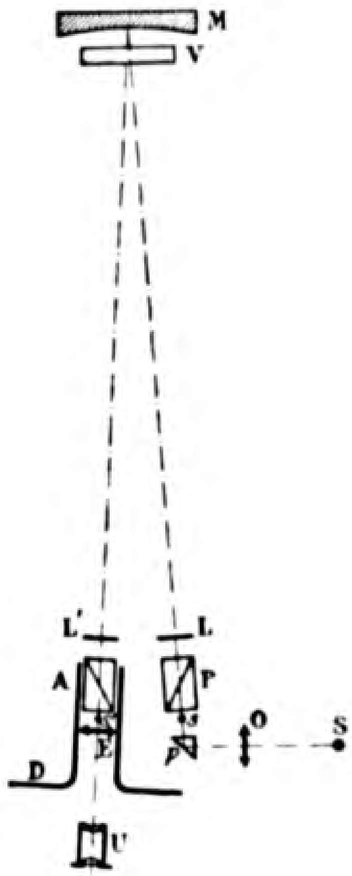

Fig. 3.

The objective O and the prism with total reflection p form an image of the light source S,* projected to the side of the apparatus, near the center of curvature of the concave spherical mirror M. The divergent pencil s passes through a polarizer P, then a quarter-wave plate L (for $\lambda = 0.546\ \mu$); subsequently it passes the glass slab V under test, placed against the silvered mirror M. The pencil is reflected in this mirror, passes again through V and converges in s', symmetrical with s relative to the center of curvature of M.

*This light source may be a small Dunoyer mercury vapor lamp, the green radiation of which is isolated with a suitable filter, or, in case the measured birefringence is weak, and not too great a precision is demanded, an incandescent lamp, in which case a green screen on the diaphragm B (Fig. 4) passes only the radiation in the vicinity of $0.55\ \mu$.

Before reaching s' the light meets the quarter-wave plate L' and the analyzer A. A viewer consisting of an objective E in the plane of the image s' and an eyepiece U finally enables the observer to focus on the sample V. Where V is absent the observer thus views the uniformly lighted surface of the mirror M.

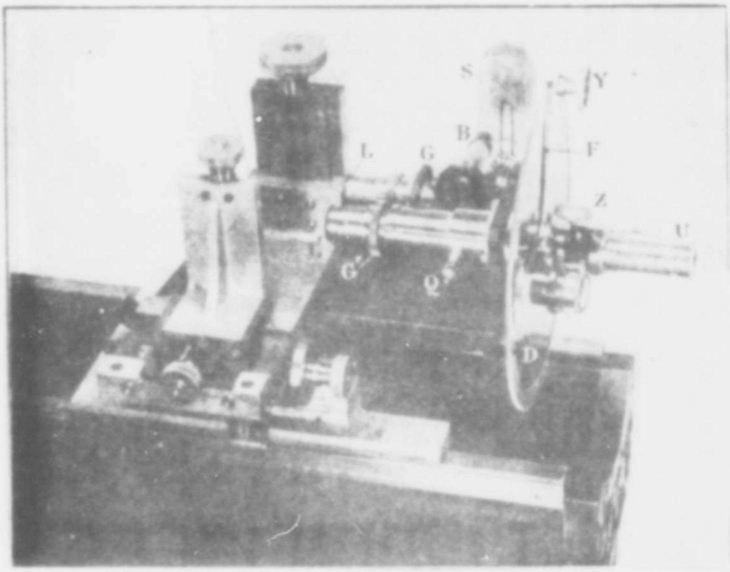

Fig. 4.

The optical parts P, L, A, L' are capable of undergoing the following rotational movements around their axes sM, s'M:

a) the Nicol prism A can turn in relation to the quarter-wave plate L' with angles measured by the shift of an indicator over a dial divided into 200 equal parts: the birefringence b is therefore read directly with a precision of 0.005. When the indicator is at zero, the Nicol A should be exactly crossed with the polarizer P; a zero set knob Z (Fig. 4) that slowly moves the Nicol A without turning the indicator makes it easy to carry this out. The indicator is moved by an arm F with which it forms one part. The arm has at its end a pinion engaging the teeth of the rim of D and it is manipulated by the knob Y.

b) The "quarter-wave plates" L and L' can turn by 45° on their own axes, so as to have their neutral lines oriented either at 45° to the principal sections of P and A (this is at the zero of the dial D) or parallel to them.

These two positions are for each quarter-wave plate marked by a stopping block. In the first case the assemblies P L and A L' form a circular polarizer and analyzer: these stopping blocks are marked C (circular).

In the second case the plates L and L' play no part: everything happens as if they did not exist and the piece V is examined in linearly polarized light: the corresponding stopping blocks are marked R (linear).

c) System P L and system A L' can turn in the same direction simultaneously with equal angles around their axes sM and Ms'.

The equal rotations are made sure by two identical tooth-edged rings G G' (Fig. 4) mounted one on P L, the other on A L', each engaging a planet gear, loose on its axis.

Thus when the two Nicols A and P are originally crossed they will remain so during the whole movement.

A locking knob Q (Fig. 4) on the side can lock this movement.

The polarizer-analyzer assembly, together with the objective O, the prism p and the viewer are mounted on a carriage that can move in three directions at right angles to each other.

The concave mirror M, with a radius of 1.50 m and an opening of 150 mm, is mounted on a support that is adjustable in height and direction. All these parts are located on an optical bench.

Application. -- Let us, as an example, undertake the complete study of the birefringence of an end mirror of a range finder, a glass slab with the dimensions 76 x 72 mm and 13 mm in thickness.

1. Bringing out the birefringence in relief. Bring the quarter-wave plates to their stopping blocks C and keep the indicator at zero: the slab then appears as shown in Figure 5.*

*This photograph clearly shows the "threads" present in the slab under study.

Fig. 5.

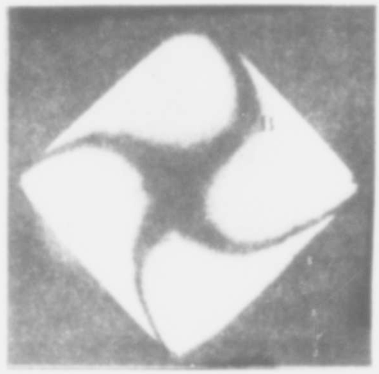

Fig. 6.

Fig. 7.

2. Determining the value of the birefringence at a point B chosen on the piece. The quarter-wave plates are brought up against their stopping blocks R while the indicator stays at zero; the assembly P L, A L' (motion c) is then turned in such a way that one of the dark lines (isoclines) that appear on the slab (Fig. 6) goes through B.

The neutral directions B are thus at a 45° angle with the neutral directions of the quarter-wave plate L' when it is in position C. The motion c is now locked with knob Q.

The plates L and L' are now set at their stopping blocks C; the indicator is turned, and the Nicol A with it (motion a) until one of the dark spots seen on the piece (Fig. 7) appears on point B. This is sure to happen, because the rotation of the Nicol A makes the dark spots follow the isoclines of the previous examination.

The value b of the birefringence in B is now read on the circle: in this case b = 0.030. From this we conclude:

$$n' - n'' = b\frac{\lambda}{e} = 0{,}03\,\frac{0{,}55}{13 \times 10^3} = 13 \times 10^{-7}.$$

Figure 7 shows that the birefringence is also 0.03 in three other points: H, I, J. By referring to Figure 5 one confirms that the darkening is the same in these four points.

The complete determination described above of the birefringence at one point requires 15 seconds and it is made with a precision of 0.005 in b.

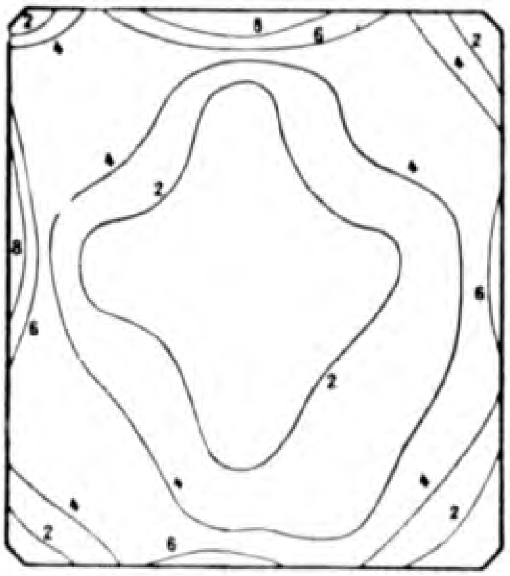

Fig. 8.

3. Tracing the contour lines that correspond to round values of birefringence. -- The quarter-wave plates are in the positions C and the indicator is set at the selected value on the dial D, e.g., 0.02. The knob Q is unlocked and the assembly P L, A L' is rotated (motion c). One follows on the piece the movement of the dark spots that mark the different sectors of the contour line 0.02. The final result is the map of birefringence (Fig. 8).

Remarks

1. The autocollimation method described here makes it impossible to exceed birefringence b of 0.50, or path differences Δ of $\frac{\lambda}{2}$ by the direct method. These high values are quite exceptional in optical glass, but they can be measured nevertheless with the above equipment. One only has to note that the path difference Δ produced by any birefringence may be put in the form:

$$\Delta = (K + \epsilon) \frac{\lambda}{2}$$

where K is an integer and ϵ a fraction less than 1. Observation of the piece in circularly polarized white light reveals the value of K by the color and the fraction ϵ is determined by the method described above.

2. The glass to be examined for annealing is usually in the form of a slab with roughly plane parallel faces; in this case it is placed in its entirety against the mirror M. One may, however, have to determine the birefringence of an optical system, e.g., an objective. The spherical mirror M is then replaced by a plane mirror and the objective is then positioned to make the points s and s' (Fig. 3) fall in its focal plane, symmetrically to the main focus.

This arrangement is identical with that for investigating the objective by the Foucault method. It is easy to shift from observing the shadows to observing the annealing, and thus it is possible to find out whether a local flaw shown up by the method of the knife corresponds to a peculiarity of the birefringence, or, in other words, to specify the relation between the annealing and the quality of an optical system.

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