New strain standards for glassware stress photoelastic evaluation

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Strain viewers are used for residual strain evaluation and assessment of glassware. Most viewers are the crossed-nicol type photoelastic apparatus with tint plates, in which the tint colour in the field of view changes with the insertion of strained glassware. Strain standards, which give known or predetermined optical path differences, are necessary for qualitative evaluation of residual internal stress in glassware. Two types of new strain standards, namely rotary-plate type and film-array type, are proposed and presented in detail.

KEYWORDS: optics, residual stress, glassware

Introduction

In glassware manufacturing processes, annealing is an important operation. Annealing suppresses internal mechanical stress in the glassware to a low level, both during and after cooling. This prevents spontaneous or delayed fracturing and improves resistance against mechanical and thermal shocks.

Residual internal stresses are controlled by photoelastic strain viewers. Internal stress F gives a photoelastic optical path difference (retardation) R between two linearly polarized component waves, with the relation

$$R = CFL$$

where R is measured in nm, F in kg cm^{-2}, and L is the light propagation path length in glass, measured in cm, and C is the glass photoelastic constant 2.5 - 3.5 (nm cm^{-1}) (kg cm^{-2})$^{-1}$

Strain viewer

One of the most popular strain viewers is composed of a crossed-nicols arrangement with a sensitive tint plate (Figs 1 and 2). It consists of a white light source (incandescent or fluorescent lamp), a polarizer with a polarization axis P at an angle 0°, an analyser with a polarization axis A which is at 90° to P (crossed nicols), and a tint plate with optical axes (T_1, T_2) in azimuth 45° with P and A. The tint plate is a birefringent plate which gives about 565 nm retardation.

Theoretical bases for quantitative stress evaluation

As long as residual stresses are present and glassware has small wall thicknesses in relation to its total size, the following assumptions are approximately valid:

1. Stress in a direction perpendicular to a glass surface is zero,
2. Two of the three principal stress axes lie in directions parallel with the surface; the last one is perpendicular to the surface,
3. The directions of the former two principal axes are uniform throughout the wall thickness at each point in the glassware.

The directions of the former two axes are easily identified by observing isoclinic lines represented in the glassware between the crossed nicols.

For quantitative stress or retardation evaluation, the glassware must be placed so that the principal stress axes at the test point are in azimuth 45° with P and A.

The role of strain standards

Photoelastic retardation in glassware superposes in an algebraic manner on that of the tint plate and modifies the tint colour. The tint colour changes with decreased or increased retardation in the order of: tint colour → red → orange → yellow → white, or tint colour → indigo → blue → bluish green → white, respectively. The colour change is so sensitive that 3 nm of photoelastic retardation is easily detected.

The relation between photoelastic retardation and the colour is not unique, because tint plate retardations are different from one viewer to another by more than 30 nm, and tint colours scatter from a bluish to a reddish colour between viewers. Therefore, the colour caused by photoelastic retardation cannot be taken as a unique and definite retardation value.

Quantitative determination requires an additional means, such as a strain standard, with precisely predetermined retardations. By putting both the glassware and the standard adjacent to each other in the field of view, photoelastic retardation is evaluated by colour

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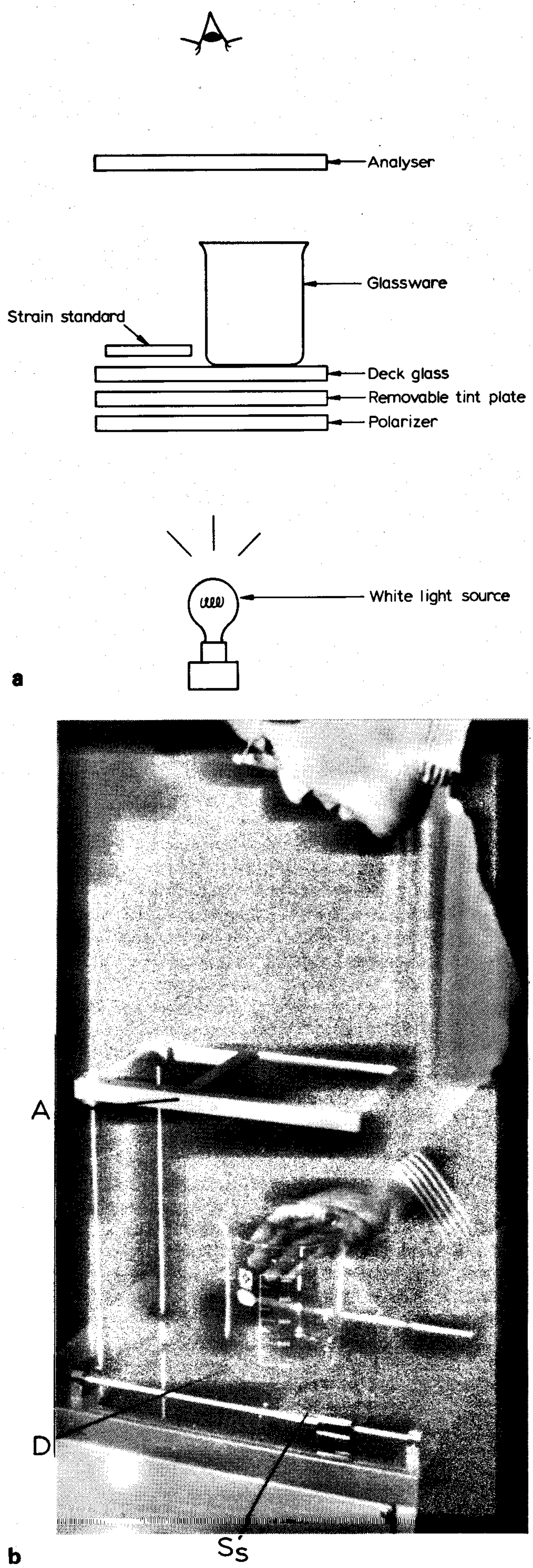

Fig. 1 a and b Stress evaluation in glassware by a cross nicols arrangement with a tint plate. A – analyser; D – deck glass; S_s – strain standard

comparison in a semi-quantitative manner. The British Glass Industry Research Association supplies strain-disc standards for use for this purpose[1]. The standards are composed of glass plates with a 22.8 nm retardation. A combination of the plates gives retardation values $N \times 22.8$ nm ($N = 0, 1, 2, \ldots$).

This paper reports new kinds of strain standards, which are simple in structure and easy to apply.

Rotary plate strain standard

The standard is based on the following evidence (Fig. 2): assume that a birefringent plate with R nm retardation (abbreviated Rnm plate) is placed between crossed nicols. When R is small, the following approximation is valid:

The optical effect of the Rnm plate at an angle of $\theta°$ is equivalent to that of an $R \sin 2\theta°$ plate at an angle of 45° (see Appendix).

Experimental observations indicated that $|R|$ must be in the region of 0 – 130 nm, and that this approximation is especially valid for $\theta°$ near 0°, 45°, 90°, 135°, . . .

Figure 3 shows a rotary plate standard. The rotary plate is an Rnm plate ($R < 130$) and has a multiplication factor of $\times$ (R/10) nm. The frame carries angular graduations 0, 1, 2, . . . , 10; which correspond to $\theta°$s for the plate with $\sin 2\theta° = 0.0, 0.1, 0.2, \ldots, 1.0$, respectively.

The standard is applied in the following manner: put the glassware piece to be tested in the field of view of the strain viewer. The glassware is adjusted so that the principal stress axes at the point to be examined, are at an angle of 45°. Any colour tint change at the point should be simulated and matched by rotating the rotary plate. The graduations are read by a pointer on the plate and the glassware light retardation r(nm) at the examination point is given by

$$r = \text{Graduation} \times \text{multiplication factor} \qquad (1)$$

This relation is verified by the following consideration: colour matching indicates that

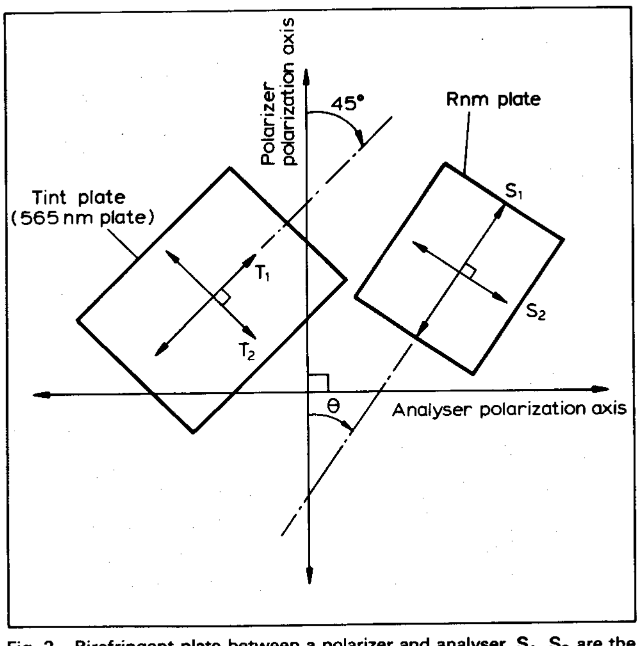

Fig. 2 Birefringent plate between a polarizer and analyser. S_1, S_2 are the optical axes for birefringent Rnm plate in azimuth $\theta°$, and T_1, T_2 are the optical axes for the tint plate

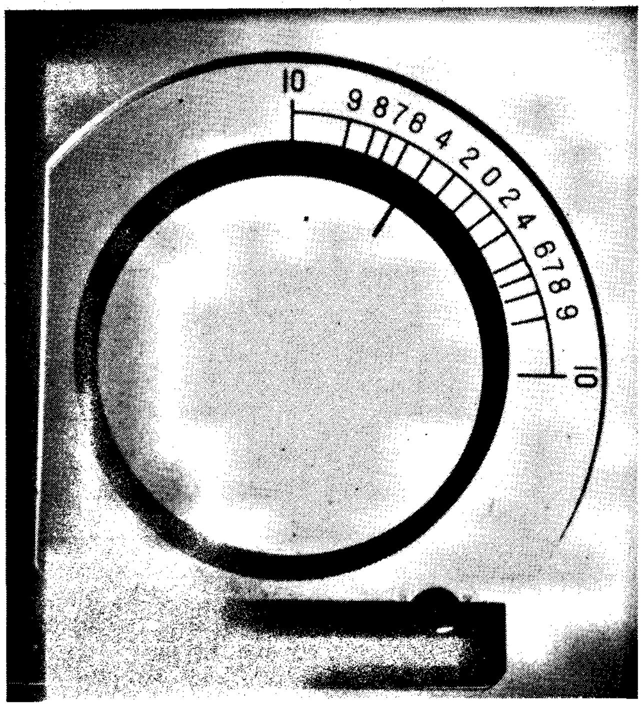

Fig. 3 Rotary plate strain standard

$$r \sin(2 \times 45^\circ) = r = R \sin 2\theta^\circ$$

$$= (10 \times \sin 2\theta^\circ) \times \frac{R}{10}$$

$$\equiv \text{Graduation} \times \text{multiplication factor}$$

A single disc can cover a 0 - 130 nm retardation range. For higher retardation ranges, a stack of additional discs is necessary, for example,

A The combination of 130 nm plate at 45° and a rotary 75 nm plate covers the −205 nm - −55 nm and +55 nm - +205 nm ranges.

B The combination of two 165 nm plates at 45° and a rotary 90 nm plate covers the −420 nm - −240 nm and +240 nm - +420 nm ranges.

For coloured glassware pieces, colour matching is impossible. However, the standard can be used as a compensator for coloured glassware. The procedure for this is as follows: remove the tint plate from a viewer, and the field of view will turn dark. A coloured glassware piece with principal axes at 45° should be placed in series with the standard, and the standard should be adjusted to compensate for the retardation. Compensation is identified by a dark fringe superimposition at the examination point.

The retardation represented by the standard can be calculated and this value is equal to the absolute glassware retardation value.

Film-array strain standard

The principle of the rotary plate strain standard is applicable to form another kind of standard composed of an array of birefringent films with retardations $N \times M_0$ nm ($N = 0, 1, 2, \ldots$,; M_0 = for example, 22.8, 25, 50 etc) (Fig. 4). Each array component is a film or stack of films which represent $N \times M_0$ nm effective retardation. The components are so arranged that they give a pre-specified retardation value when the standard is placed at 45° in a strain viewer.

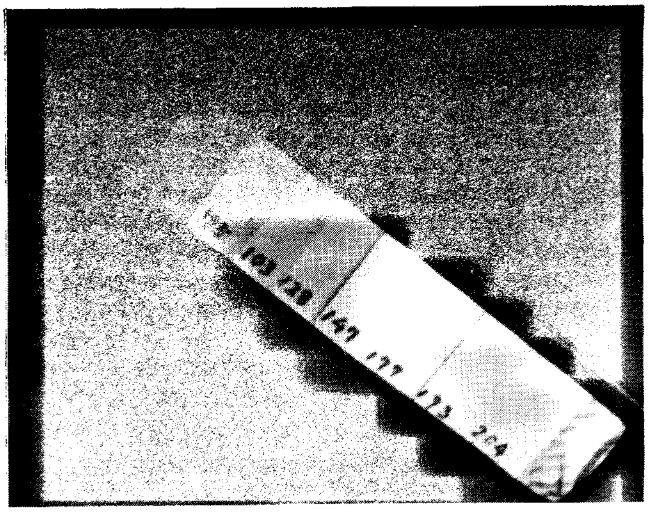
Fig. 4 Film-array strain standard: numerals indicate retardations in nm

The standard is used both as a colour standard for colourless glassware and as a compensator for coloured glassware. It must be used at 45°, together with glassware at 45°, otherwise, it gives false results.

Strain viewer with a strain standard

Figure 1b shows a strain viewer with a rotary plate standard. It has a removable tint plate.

The viewer makes the following measurement possible:

1. The linearly polarized light method to determine the directions of the principal stress axes (isoclinic lines).
2. The linearly polarized light method with a sensitive tint plate to detect small retardations.
3. The linearly polarized light method with a sensitive tint plate and a strain standard for quantitative retardation evaluation (present paper).

These techniques, other than those which use strain standards, are popular in photoelasticity and, therefore, the details are omitted.

Moreover, the rotary plate standard principle is useful to fine-adjust the tint plate retardation to obtain a colour tint which the observer prefers.

Appendix (Fig. 2)

Assume that a monochromatic light wave (with a wavelength of λ nm) passes through a polarizer, a retardation plate and an analyser in a crossed nicols arrangement in succession.

Emergent light intensity

When the retardation plate is an Rnm plate at an angle of θ°, the emergent light intensity is given by (see any text book)

$$J_1 = \sin^2 2\theta \sin^2 \frac{R}{\lambda} \tag{I.1}$$

On the other hand, for an ($R \sin 2\theta$) nm plate at an angle of 45°, the intensity is;

$$J_2 = \sin^2\left(\frac{R \sin 2\theta}{\lambda}\right) \tag{I.2}$$

For small (R/λ),

$$J_1 \simeq J_2 \tag{I.3}$$

holds. This approximation is especially valid for $\sin 2\theta = 0$ and 1.

Effective retardation

The analysis simultaneously indicates that, for the light propagating along the path between the Rnm plate at $\theta°$ and the analyser, the following approximations hold.

(II.1) Amplitudes of component waves vibrating in two directions, at ±45° to the polarizer axis P, are equal to each other;

(II.2) the optical path difference between the component waves is $R \sin 2\theta$.

The relations (I.3), (II.1) and (II.2) indicate that the Rnm plate at an angle $\theta°$ is equivalent to an ($R \sin 2\theta°$) nm plate at an angle of 45° for both the emergent light intensity and for the optical path difference between component waves in the region between the plate and the analyser. Therefore, the algebraic summation between the effective retardations of an Rnm plate at $\theta°$ and another birefringent optical component (for example, a tint plate, a quarter wave plate, any retardation plate or sample glassware) at 45° is possible.

References

1 **Sugarman, B.** *Glass* July (1961)