Integrated photoelasticity for residual stress measurement in glass articles of complicated shape

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The paper gives a review of the application of integrated photoelasticity for residual stress measurement in glass articles of complicated shape. Basic relationships of the method are presented. Measurement of the stresses both in axisymmetric and nonaxisymmetric articles is considered. An automatic polariscope for photoelastic measurements is described. Several examples illustrate practical application of the measurement technology

1. Introduction

Residual stress is one of the most important characteristics of glass articles from the point of view of their strength and resistance[1,2]. In the case of optical glass, birefringence caused by the residual stresses characterizes the optical quality of the article.

During about a century photoelasticity[3] has been the most widely used method for quality control in the glass industry. Two-dimensional photoelasticity permits the determination of the so-called form stresses (which are constant through the thickness in flat glass). As for the thickness stresses (which vary parabolically through the thickness), their distribution can be determined using the scattered light method. Specific methods have been developed for nondestructive determination of the stresses on the surfaces of the flat glass[4].

It is much more complicated to estimate stresses in glass articles of complicated shape: in bottles, drinking glasses, tubes, fibres and fibre preforms, etc. At the same time, development of glass technology demands exact information about the residual stresses in glass articles. Let us mention that while numerical methods are being successfully used for the calculation of stresses in glass caused by external loads (e.g., by internal pressure in bottles[5,6]), their application for the calculation of the residual stresses gives less reliable results due to the lack of exact data about the temperature distribution and physical parameters of the specimen during various phases of the production process[7].

Thus, development of experimental, desirably nondestructive, methods for residual stress measurement in glass articles of complicated shape is of current interest. For this purpose during the last two decades considerable development of integrated photoelasticity has taken place. In this paper, measurement technology and several applications of integrated photoelasticity in glass stress measurement are described.

2. Integrated photoelasticity

In integrated photoelasticity[4,8] the test object is placed in an immersion tank and a beam of polarised light is passed through it (Fig. 1). Transformation of the polarisation of light in the specimen is measured on many rays. Since the values and directions of the principal stresses vary on the light rays, optical phenomena in integrated photoelasticity are complicated and the relationships between the measurement data and parameters of the stress distribution are nonlinear.

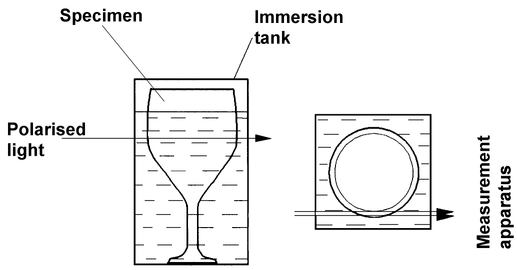

Fig. 1. Experimental set-up in integrated photoelasticity

However, it has been shown[4] that if birefringence is weak or rotation of the principal stress directions on the light rays is weak, a three-dimensional specimen can be investigated in a conventional transmission polariscope similarly to two-dimensional specimens. On every light ray it is possible to determine the parameter of the isoclinic φ and the optical retardation δ. The latter are related to the components of the stress tensor on the ray by simple integral relationships

$$\delta \cos 2\varphi = C\int(\sigma_z - \sigma_x)dy\,, \qquad (1)$$

$$\delta \sin 2\varphi = 2C\int \tau_{zx} dy\,, \qquad (2)$$

where C is the photoelastic constant and σ_x, σ_z, and τ_{zx} are components of the stress tensor in the plane perpendicular to the light ray y. Formulas (1) and (2) express the *integral Wertheim law*.

It has been shown that if the parameter of the isoclinic φ and optical retardation δ have been measured on many light rays in two parallel sections, perpendicular to the axis z of the axisymmetric specimen, then radial distribution of the axial stress σ_z and shear stress τ_{rz} can be determined[4].

If stress gradient in the direction of the z-axis is smooth, the other stress components, σ_r and σ_θ, can be determined using the equilibrium equation

$$\frac{\partial\sigma}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} + \frac{\partial\tau_{rz}}{\partial z} = 0\,, \qquad (3)$$

and the classical sum rule

$$\sigma_r + \sigma_\theta = \sigma_z\ . \qquad (4)$$

If stress gradient in the direction of the z-axis can not be ignored, then instead of (4) the generalized sum rule is to be used[9]

$$\sigma_r + \sigma_\theta = \sigma_z - 2\int_{R_0}^{r} \frac{\partial \tau_{rz}}{\partial z}\,\mathrm{d}r + C\,. \qquad (5)$$

Fig. 2. Automatic polariscope AP-03 SM

For photoelastic measurements a computer-controlled polariscope has been constructed (Fig. 2). As the light source, light diodes have been used. One polariser and one quarter-wave plate are controlled by stepper motors. Specimen in an immersion tank is placed on the platform of a co-ordinate device which enables one to select the part of the specimen to be measured.

The polariscope can be used as a circular polariscope as well as a device to use the phase-stepping method. A specific phase-stepping method has been elaborated that permits also determination of the direction of the first principal stress[10]. A laptop PC, which is supplied with sophisticated software, controls the photoelastic measurements and calculates stresses.

3. Examples

In strongly tempered drinking glasses birefringence is high and often many fringes can be observed in a circular polariscope. In this case the fringe pattern is digitized and using this information the stresses are calculated[11] (Fig. 3).

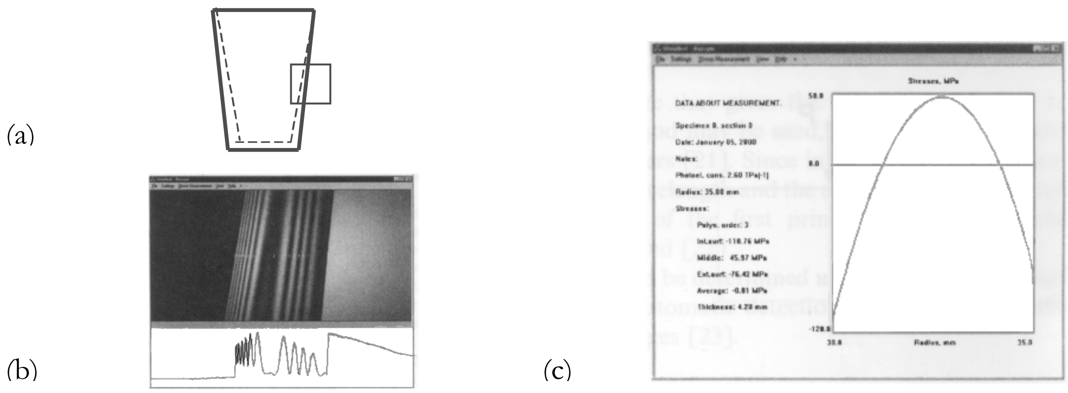

Fig. 3. Geometry of a tempered tumbler (a), physical and digitized fringe patterns (b), and axial stress distribution (c).

Figure 4 shows residual stress distribution in the neck tube of a CRT glass bulb. In this case photoelastic measurements were carried out with the phase-stepping method[10]. Circumferential stress σ_θ was calculated using the generalized sum rule (5).

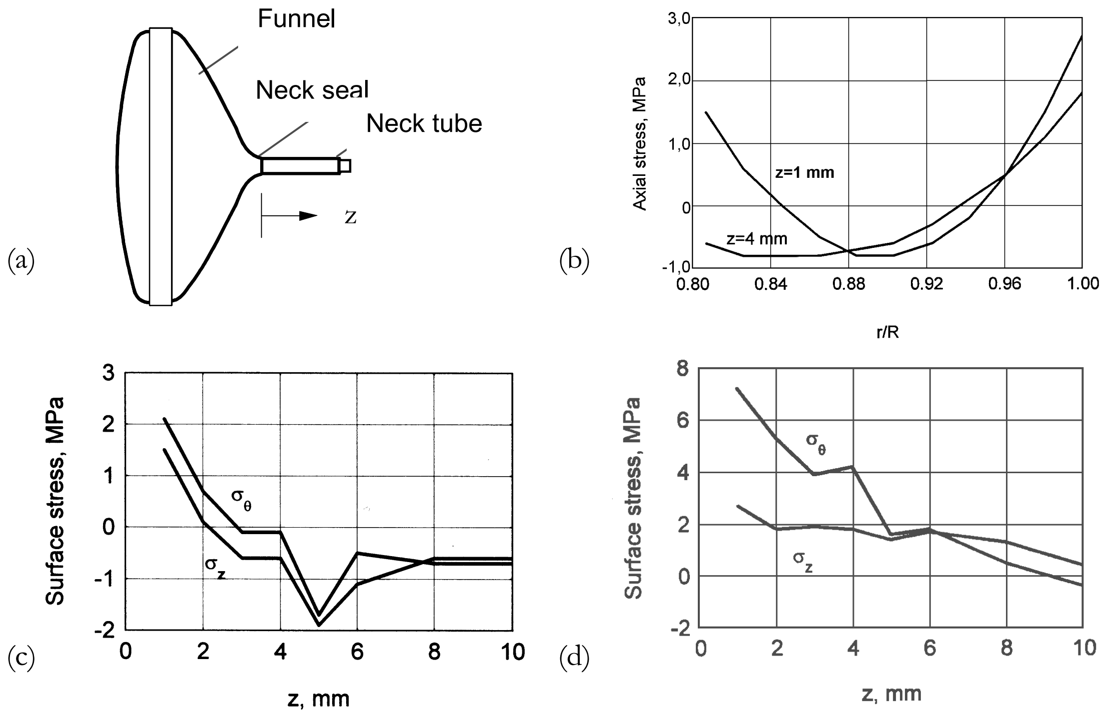

Fig. 4. Geometry of a CRT glass bulb (a), stress distribution in two sections (b), and axial and circumferential stress distribution on the internal (c) and external (d) surface of the neck tube.

In Fig. 5, geometry of the cross-section of a bow-tie-type fibre preform and axial stress distribution are shown. In this case tomographic photoelastic measurements were carried out for 60 azimuths and for every direction of the light beam the birefringence was recorded for 140 points.

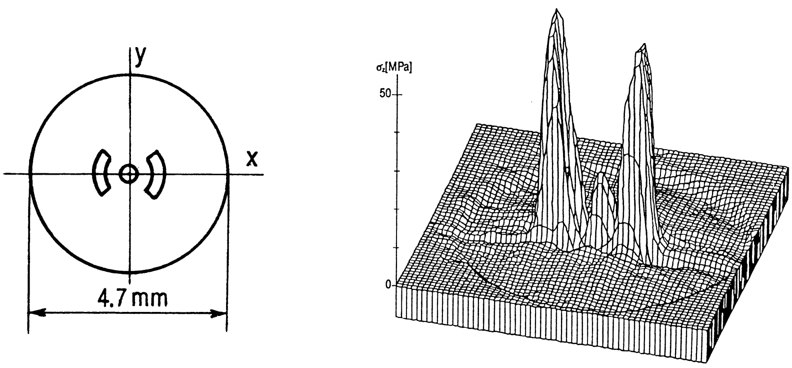

Fig. 5. Geometry of the cross-section of a bow-tie-type optical fibre perform and axial stress distribution.

Figure 6 shows stress distribution in a step-index optical fibre perform[12]

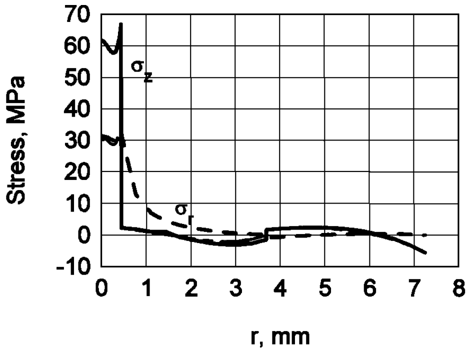

Fig. 6. Distribution of the axial (σ_z) and radial (σ_r) stress in a step-index optical fibre preform.

Acknowledgement

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