Optics and Lasers in Engineering 91 (2017) 30–40

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

An iterative approach to remove the influence of light ray bending from micron-scale scattered light tomography

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A R T I C L E I N F O

Keywords:
Non-destructive measurement
Micron-scale stress profile
Ion-exchanged glass
Chemically strengthened glass
Iterative approach
Light ray bending

A B S T A R C T

We present numerical experiments to test an iterative approach which can remove refraction-induced errors form scattered light tomography. Gradient scattered light tomography is the first method capable of direct non-destructive residual stress measurement in chemically strengthened glass. The method is based on an oblique incidence scattered light photoelasticity combined with an iterative approach to remove the influence of light ray bending from the scattered light method. In this article further numerical experiments are performed which demonstrated that the iterative approach grants the removal of the influence of light ray bending from stress profiles that have complicated shapes. Two classical examples of stress profiles in chemically strengthened glass were studied: (1) unusual stress profile, where the outermost layers of the surface are in tension (tensile surface stresses being 300 MPa), rather than compression; (2) relaxed compressive stresses in the outermost surface layer with a depth of 20 μm. We found that the nature and rate of convergence of the iterative process were notably different for compressive and tensile stresses. The analyzed stress profiles were taken from literature and hence are realistic representations of the ones that researchers might come across in glass science. Refraction induced reconstruction error $\Delta\sigma$ as a function of surface stress and incidence angle were simulated.

1. Introduction

Recently a non-destructive gradient scattered light method for micron-scale stress profile measurement in chemically strengthened glass was presented [1]. It was the first study that took into account the influence of light ray bending in the classical oblique incidence scattered light method. In case of strongly refracting media, such as chemically strengthened glass, where the component of the refractive index gradient ∇n is normal to the direction of light ray propagation, straight line inversion may result in a significant reconstruction error. Consequently, inversion schemes which incorporate correction for refraction need to be developed.

Chemically strengthened aluminosilicate glass [2,3], which has high scratch and impact resistance [4], has been used as a protective cover of space solar panels [5], mobile devices [6] and mirror foil for future X-ray telescopes [7]. Varshneya et al. [8–10] have contributed to the development of chemically strengthened lithium aluminosilicate glass, which has found its application as one layer in bulletproof armour plates due to its high compression stress (with a magnitude of ~1000 MPa) and large case-depth (up to 1000 μm). Shim et al. have studied the impact resistance of chemically strengthened borosilicate [11] and soda-lime glasses [12]. They demonstrated that those glasses can be used as lightweight bulletproof materials. Residual stress profiles in all these strengthened glasses can be measured by gradient scattered light method, which emphasizes the importance of further studies on the theme.

In tomography, interferometric data is interpreted assuming that the probing light rays are straight lines within the medium under study. This simplified theory has been extremely useful if the refractive bending of light rays is small but can result in significant reconstruction errors in case of strongly refracting media. Therefore, reconstruction algorithms have been developed which take into account the bending of light rays. Dolovich & Gladwell [13] examined iterative schemes for reconstructing refractive-index fields to establish sufficient conditions for convergence. Lira and Vest [14] reviewed iterative approaches, intended for refractive index reconstruction, for which convergence is not guaranteed. In numerical experiments where these algorithms have been applied to data produced numerically from a known field, iterates have often diverged from the known field after initially approaching the reference solution. Vest [15] showed that for strongly refracting axi-symmetric objects, reconstruction from optical path length data has small errors only near the axis. Acosta et al. [16] presented an iterative tomographic algorithm to reconstruct refractive-index profiles for fibre preforms and GRIN lenses from the measured deflection angles of refracted rays.

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http://dx.doi.org/10.1016/j.optlaseng.2016.11.003
Received 20 September 2016; Received in revised form 25 October 2016; Accepted 5 November 2016
Available online 17 November 2016
0143-8166/

All other previous studies on the influence of light ray bending in residual stress tomography concentrated on transmission photoelasticity. The first studies about the influence of light ray bending in transmission photoelasticity were conducted by Bokshtein [17]. Hecken and Pindera [18] and Aben et al. [19,58] suggested incorporating the experimentally measured deflections of light rays into the photoelastic theory. Dolovich et al. [20] described an iterative approach to remove the influence of light ray bending from transmission photoelasticity. They studied specific cases of a glass beam in pure bending and a diametrically loaded disc.

Pagnotta and Poggialini [21] studied how to compensate the influence of light ray bending in transmission photoelasticity in the case of residual stress measurement in axi-symmetric glass fibre preforms. They used experimentally measured radial refractive index profile by a P104 fibre preform analyzer (Photon Kinetics, USA) [22], rather than Maxwell stress-optic equations [23] that were used by Dolovich et al. [20]. The fibre was scanned with a He-Ne laser, and the deflection of the laser beam was analyzed to determine the radial refractive index profile. It was mentioned that a Mathematica™ program was developed, but neither the actual equations nor the complete simulation parameters were given that would allow recreating the presented simulations. However, experimental and calculation results (optical retardations along the curved ray path and straight ray path) were well described. For comparison, let us point out here that maximum axial stress levels in fibre preforms and fibres are in the range of 10–110 MPa [21,24] and surface compressive stresses for chemically strengthened glass up to −1000 MPa [1,9].

On the one hand, bending of light rays might be a source of errors in photoelastic tomography. On the other hand, refraction-induced optical retardation (integrated gradientphotoelasticity [25]) can be an indicator of the stress profile. Although, this method is limited to stress profiles with known shapes, such as almost parabolic stress profile in thermally tempered glass plate. The precise shape of the stress profile in thermally tempered glass can be described by Indenbom's [26] or Narayanaswamy's [27] theory. Stress profiles in chemically strengthened glass plates can have very complex engineered shapes [28], which are not measurable by integrated gradientphotoelasticity.

The possibility of scattered light method was already predicted by James Clerk Maxwell [23] in 1853 but experimentally discovered by Weller [29] in 1941. The scattered light method for stress profile measurement in tempered glass plates has been further studied by many authors [1,30–37]. Introduction of the laser as a light source for the method was made by Bateson et al. [31]. Cheng contributed to the development of oblique incidence method [32] and added dual observation technique [33]. Oblique incidence method for stress profile measurement in tempered glass plates was automated by Anton [34]. Gradient scattered light method [1] is specifically intended for measurement of micron-scale stress profiles in chemically strengthened glass. It is a new development from Anton's polariscope SCALP by changing the incidence angle of the light beam from 45° to 81.9° and adding an iterative approach to remove the influence of light ray bending, which is the direct result of using such a high incidence angle. Hödemann et al. [35] introduced confocality as a detection method of Rayleigh-scattered light in order to reach ultra-high spatial resolution. Confocal mapping of a line along the laser beam propagation direction, using a micro-translation stage, is equivalent to the observation of a very narrow light ray (with diameter 5 μm) passing through the glass. Reviews on the scattered light method, in general, have been written by many authors [36–38], recent ones by Ramesh et al. [39] and Hemsley [61].

In this article, numerical simulations are performed to test the effectiveness of the iterative approach in the removal of the influence of light ray bending from realistic stress profiles with, e.g., tensile surface stresses or relaxed compressive stresses just under the surface. The aim is to find out whether an iterative approach grants a reconstruction of the stress profiles that have such complex shapes. The analyzed stress profiles were taken from literature and hence are realistic representations of the ones that researchers might come across in glass science.

2. Gradient scattered light method

The main concept of gradient scattered light method [1] incorporates ray tracing into the theory of oblique incidence method [32,34] to obtain the correct stress profile. Straight ray inversion is regarded as a first approximation to the residual stress depth profile. It is used in conjunction with the theory of gradient scattered light method to determine the first estimate of light ray paths and a curved ray inversion may be performed to yield (what is hoped to be) an improved approximation to the stress field. Then this approximation is used, in turn, to recalculate the ray paths which form the basis for the next iteration until a suitable termination criterion is satisfied. This recursive process is the basis of the gradient scattered light method.

2.1. Oblique incidence scattered light method

The method is based on Rayleigh scattering excited by a polarized beam of light passing obliquely through a flat chemically strengthened (or thermally tempered) glass plate (Fig. 1.). Refractive index fluctuations, that are small in comparison to the light wavelength, act as dipoles that scatter the light predominantly in the direction perpendicular to the dipole axis. For the theoretical formulation of the method, we assume that the global x-axis lies in the incident plane and is parallel to the top surface of the glass whereas the global y-axis is perpendicular to the top surface of the glass and points into the glass. The global z-axis is chosen to form a left-handed triad with x and y axes. A local rectangular coordinate system x'-y'-z' is associated with the light ray, such that x' is tangent to the ray, y' is on the incident plane and z' is perpendicular to the incident plane. The clockwise angle between the x' and y axes is denoted θ.

Secondary principal stresses (effective principal stresses) are defined as the stress components that are perpendicular to the propagation direction of the light ray. Those stresses induce Rayleigh scattered light fringe pattern that is observable in the direction OD_1 and OD_2. Principal stress σ_y is fixed in the direction of the optic axis and is independent of the light ray propagation direction. If the light ray propagates through the glass perpendicular to the z-axis, birefringence is caused by secondary principal stresses σ_z and $\sigma_{y'}$, as seen in Fig. 1. The stress field defined in the global set of coordinates can be expressed in the local system via the stress transformation equations:

$$\sigma_{x'} = \sigma_x \sin^2\theta + \sigma_y \sin^2\theta + 2\tau_{xy}\sin\theta\cos\theta, \tag{1a}$$

$$\sigma_{y'} = \sigma_x \cos^2\theta + \sigma_y \sin^2\theta - 2\tau_{xy}\sin\theta\cos\theta, \tag{1b}$$

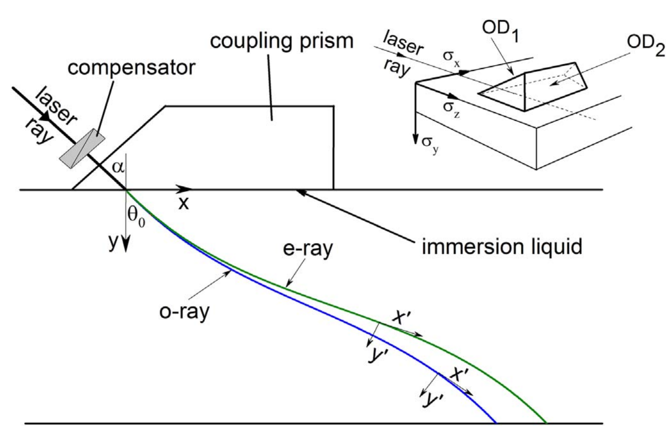

Fig. 1. The experimental set-up for stress profile measurement. A laser beam is passed via a coupling prism obliquely through the strengthened glass plate. Ultrathin layer of immersion liquid is used between the prism and the glass surface to allow unimpeded propagation of light. From the observation directions of OD_1 and OD_2, that are at 45° to the surface of a glass plate, the scattered light intensity distribution along the light path can be recorded.