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Digital photoelasticity of glass: A comprehensive review

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ABSTRACT

The recent advances in digital photoelasticity have made it possible to use it conveniently for the stress analysis of articles and components made of glass. Depending on the application, the retardation levels to be measured range from a few nanometres to several thousand nanometres, which necessitates different techniques and associated equipments. This paper reviews the recent advances in the photoelasticity of glass with a focus on the techniques/methods developed in the last decade. A brief introduction to the residual stress in glass is provided initially to bring out its tensorial nature. The subsequent sections are organised thematically rather than chronologically, for better readability and easy access of information.

1. Introduction

Glass is one of the oldest man made materials and history of glass making can be traced back to third century B.C. Over the last decade, there has been an explosion in the use of glass ranging from structural applications to bio-medical engineering. One of the main concerns in the applicability of glass is its brittle nature and failure under tensile stress. Over the years, researchers have understood that the structural behaviour of glass can be regulated to a large extent by controlling the residual stress in them [1–4]. Residual stresses are introduced in glass articles during manufacturing when they are cooled from the glass transition temperature to the room temperature. The residual stresses affect the bending strength and fragmentation properties of glass. Hence, their measurement and control are very important in glass industries.

Photoelasticity is based on the phenomenon of stress/strain-induced birefringence and basically provides principal stress difference and their orientations. This technique has been in use for stress measurement in glass since it exhibits stress-induced birefringence. Though birefringence in glass was first observed by Arago [5] in 1811, it was Seebeck [6] who first performed systematic studies on the birefringence in glass specimens of different shapes with different thermal treatments. Initial significant contributions were made by Brewster [7,8], who independently performed thorough investigation on the photoelastic effect in glass. The roles of Arago, Seebeck and Brewster on the discovery of photoelastic effect in glass is detailed in Ref. [9]. Over the years, a number of photoelasticity based measurement techniques and commercial equipments have been developed for residual stress measurements and on-line quality inspection of glass. One of the earliest monographs [1] on the topic appeared in 1993, which gives an exhaustive discussion on the various techniques adopted till then.

In 1999, Mckenzie and Hand [10] surveyed the available optical methods for glass stress analysis, which is relevant for the users of photoelastic analysis in glass industries. The use of digital computers for photoelastic analysis was still in its infancy during that period. The advent of affordable high quality digital image acquisition and processing systems led to the emergence of digital photoelasticity [11–14]. The recent reviews [15,16] focussed on specific issues in the use of 2D transmission photoelasticity for retardation measurements in glass. In 2008, Aben et al. [17] have briefly reviewed the use of modern photoelastic technology for the residual stress measurement in glass articles.

The last decade has seen rapid advancements in glass stress analysis using photoelasticity. A range of photoelastic techniques are available that can be used for either quick approximate estimation or to carry out detailed studies in cases that demand accuracy of the evaluated parameters. A comprehensive review of the techniques/methods will enable users to make an informed choice and may also aid them to develop newer techniques leading to the advancements in the topic. The review is organised thematically rather than chronologically, to facilitate easy access of information to the user. Glass literature is aplenty with domain specific terminologies, which usually deters a generic stress

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analyst. A brief introduction to the residual stress in glass is provided initially to bring out its tensorial nature.

2. Residual stress in glass

Usually, the residual stresses are introduced in glass plates either by thermal or chemical means. The thermal residual stresses are created during their manufacturing process when they are cooled from the glass transition temperature to the room temperature. These residual stresses affect the structural as well as the optical properties of glass. Usually for structural applications, presence of compressive residual stresses on the surface of glass is beneficial as it improves the strength and fragmentation characteristics. Whereas, for optical applications, this is detrimental as it alters the refractive index. Hence, the measurement of residual stresses in glass articles is important. For structural applications, the minimum residual stress requirements are prescribed by ASTM [18,19]. The residual stress in glass vary from 0 to 1 MPa in moulded glass lens, 70–120 MPa in thermally tempered glass plates to as high as 1000 MPa in chemically tempered glass plates. Generally, the problems involving stress analysis of glass can be classified into three – flat glass, axi-symmetric and generic three-dimensional problems.

The glass literature generally labels the residual stresses in a manner that could be understood in a processing unit as thickness, membrane and edge stresses. Stress is a tensor of Rank 2 and it is desirable that these stresses are also identified as suitable tensorial components. The subsequent sections provide an overview of the nature of residual stress in various glass articles.

2.1. Flat glass

Thermal residual stresses in plate glass are generally divided into two – thickness and membrane stresses [1,2]. The thickness stresses are the stresses induced due to the thermal gradients across the thickness of the glass plates. Membrane stresses are introduced due to the thermal gradients along the surface of the plate. Membrane stresses near the edge of the glass plate is termed as edge stress. In glass literature [1,20], one would also find a term surface stress which denotes the combined effect of the thickness and membrane stresses on the glass surface. Nomenclature of residual stress as thickness, membrane and edge stress is convenient as the reason for their formation can be identified and controlled separately. Further, in measurement, the optical methods lend themselves to measure these separately.

Fig. 1 illustrates the nature of residual stresses in a heat treated glass plate in typical blocks taken at selected locations. For a block at A which is taken away from the edges, the variation of thickness stress components on x and y planes are shown. Tensorially these are σ_y and σ_x components for the coordinate system shown in Fig. 1. Variation of σ_x and σ_y across the thickness of the plate is parabolic in nature with compression near the surface and tension in the central region. The maximum tensile stress is usually half the magnitude of the surface compressive stress [21]. The compressive stress near the surface increases the bending strength of glass, whereas the tension in the mid-plane affects its fragmentation properties. The magnitude of thickness stress is found to depend on the cooling process [22–24] and the dimensions of the glass plate [25]. It is reported that the stress state is hydrostatic ($\sigma_x \approx \sigma_y$) at zones away from the edges and cut-outs [1,2].

Membrane stresses are created due to the non-uniformity in cooling across the surface of the glass plate. They are constant throughout the thickness of the plate [1]. Among the membrane stresses, the stresses near the edge are of interest to the glass manufacturers [21]. Block B (Fig. 1) is taken along the edge parallel to the y-direction and the edge stress component for a typical section in the $-x$ plane are illustrated. Tensorially it is σ_y and is compressive in nature. Similarly, block C (Fig. 1) is taken along the edge parallel to the x-direction and σ_x is the edge stress for a typical section in the y-plane. The σ_z component is usually neglected owing to the small thickness.

Edge stresses are created since the edges of the glass plate act as additional cooling surfaces and cool down faster compared to the central region. They are generally compressive in nature and are beneficial to arrest crack growth and improves the glass strength. Recently, Aben et al. [26,27] reported a correlation between edge stress and surface stress in tempered glass plates. This allows one to determine one type of stress when the other is known.

2.1.1. Visualisation and measurement using photoelasticity

In photoelastic measurements, only those stress components in a plane perpendicular to the light path contribute to photoelastic

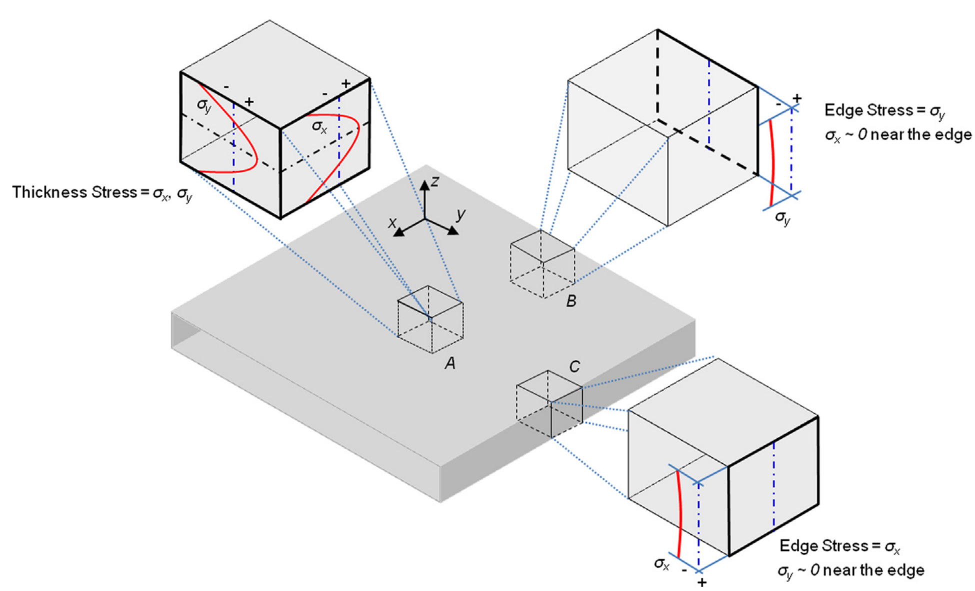

Fig. 1. Schematic illustration of the nature of residual stress in a heat treated glass plate. A rectangular block A is considered at the zone away from the edges to illustrate the nature and variation of thickness stress. Blocks B and C located at the edges illustrate the nature of edge stresses.