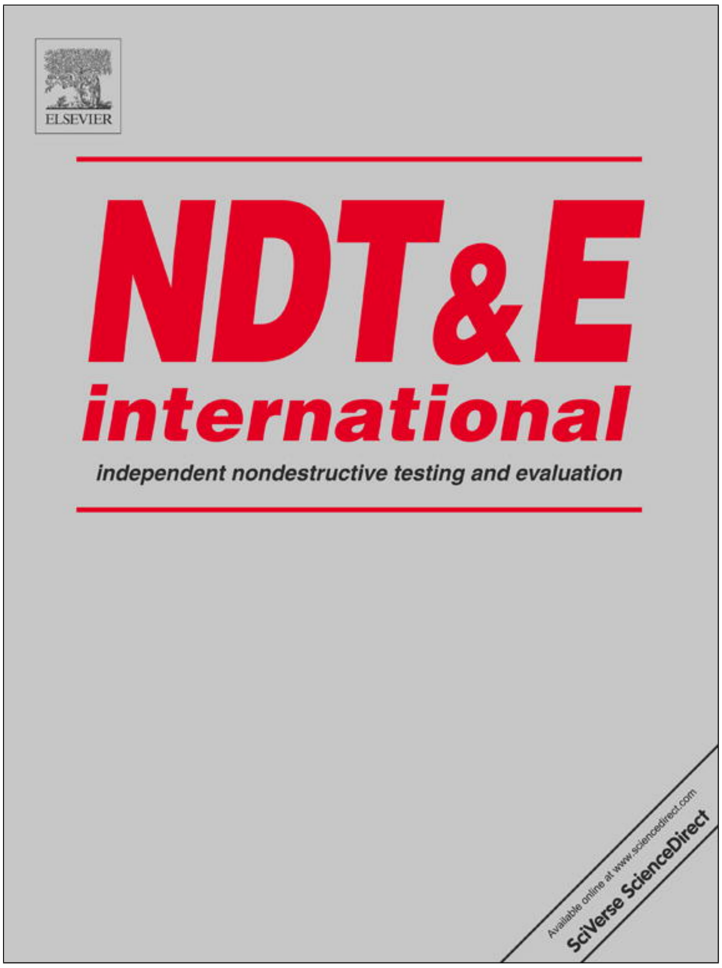
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Nondestructive evaluation of transparent sheets using a full-field digital gradient sensor

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ABSTRACT

A full-field, non-contact, optical inspection tool for transparent materials is demonstrated. The technique is sensitive to refractive index and thickness variations caused by inhomogeneities and defects in an otherwise uniform sheet stock. The technique utilizes a 2D digital image correlation method to visualize and quantify angular deflections of light rays in two orthogonal directions to assess the uniformity. The principle of the method and its feasibility is demonstrated by visualizing the heat affected zone in a uniform borosilicate sheet sample.

1. Introduction

Many engineering materials are transparent and are produced as film and/or sheet stock. Examples include transparent ceramics (e.g., window glass) and a variety of polymers (e.g., PMMA, polycarbonate, epoxy, acetate). Such materials require inspection and evaluation against unintended optical inhomogeneities, inclusions, and other defects before they are released to the market. A variety of inspection tools including visual inspection methods are employed for this purpose. Techniques which utilize machine vision are relatively more popular in recent years due to their high throughput [1]. Other sophisticated techniques based on dynamic holography [2] and integrated photoelasticity [3] have also been proposed in the past for evaluating transparent crystals and glass. A few others have also reported inspection techniques based on acousto-ultrasonic methods [4,5].

In this work, a 2D Digital Image Correlation (DIC) based methodology called Digital Gradient Sensing (DGS) that exploits refractive index variations due to defects and inhomogeneities is demonstrated to quantify angular deflections of light rays in planar media. The method has been recently demonstrated to study mechanical stress gradients near stress raisers under both static and dynamic loading conditions [6,7]. The current popularity of DIC methods and availability of a number of image registration and analysis software packages make the proposed method attractive for commercialization purposes as well. In the following, first the working principle of the experimental method of DGS and the necessary experimental setup are described. Next, a set of validation experiments for the method are presented. Following that, detection of a heat affected zone (HAZ) in borosilicate glass is demonstrated using DGS.

2. Working principle and experimental procedure

Fig. 1 shows the schematic of the DGS experimental setup. It consists of a digital camera, a transparent planar specimen, and a target plane coated with random black and white speckles, positioned along the optical axis. Two broadband white light sources are used for illuminating the target plate uniformly. The camera, fitted with a long focal length lens, is located at a large distance (L) from the specimen. The camera is then focused on the speckle plane using a relatively small lens aperture (or a large $F^{\#}$) without the specimen in position. An image of the speckle pattern on the speckle plane is recorded and is used as the reference image. Then, the specimen is placed such that its mid-plane is at a known distance Δ from the speckle plane. The refractive index of the specimen and any non-uniformity due to defects would make the speckles appear distorted, and is recorded by the camera as the perturbed image.

The speckle pattern distortion in the perturbed image could be due to the local refractive index and thickness changes in an otherwise uniform specimen. (The local thickness changes could

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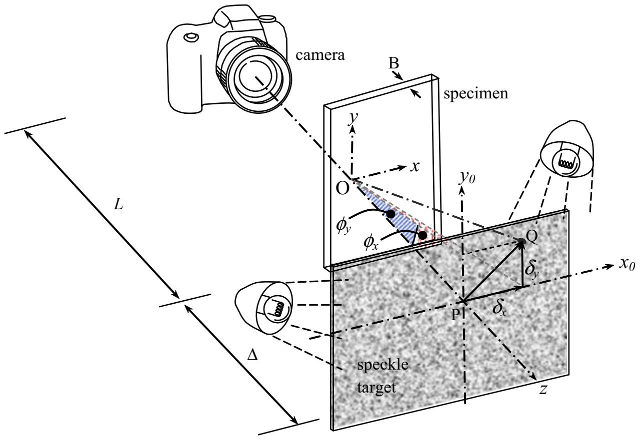

Fig. 1. Schematic of the experimental setup for DGS method.

be a result of thermo-mechanical loads [6] and/or imperfections/inhomogeneities.) That is, the net optical path change (δS) of light rays due to the specimen can be expressed as a combination of changes in its thickness (δB) and refractive index (δn)

$$\delta S(x,y) = (n - n_0)\,\delta B(x,y) + B\,\delta n(x,y) \tag{1}$$

where n is the nominal refractive index of the object being inspected, B is the nominal thickness and n_0 is the refractive of air or any other medium in which the setup is implemented. If a generic point P in the reference image displaces to Q in the perturbed image, the displacement components δ_x and δ_y in the x- and y-directions, respectively, can be quantified by performing a 2D speckle correlation between reference and perturbed images. The angular deflection of light rays ϕ_x and ϕ_y relative to the specimen plane coordinates can then be obtained as

$$\tan\phi_{x;y} \approx \phi_{x;y} \approx \frac{\delta_{x;y}}{\Delta} \tag{2}$$

for small values of displacements relative to Δ (or, small angular deflections). The magnitude of these angular deflection fields can be used to visualize and quantify the optical anomaly, if any, in the specimen.

3. Constant thickness plate

It is well known that light rays refract as they travel through dissimilar transparent media, resulting in a shift in their optical path. In Fig. 2 let a light ray traveling in air and incident at a point O on a transparent, optically homogeneous, planar medium of uniform thickness B and refractive index n at an angle θ_i relative to the surface normal. Due to the refractive index differential between air and the planar medium, the light ray will deflect towards the normal to the surface for $n>1$. Let this refracted ray make an angle θ_r with the normal. As the light ray exits the planar medium at Q′, it will now deflect away from the normal, parallel to the original incident ray. On the other hand, the path of the light ray would have been OQ in the absence of the second medium. Thus, the vertical distance δ_y between Q and Q′ is a result of the difference in refractive indices of the two media and the thickness of the second medium. This displacement can be quantified using DGS. In turn, it is possible to quantify the refractive index of a transparent constant thickness sheet using DGS, based on laws of refraction.

To verify the above, a commercially acquired, constant thickness, cast PMMA plate was used to obtain the displacement fields, δ_x and δ_y. The 2D schematic of the experimental setup to measure

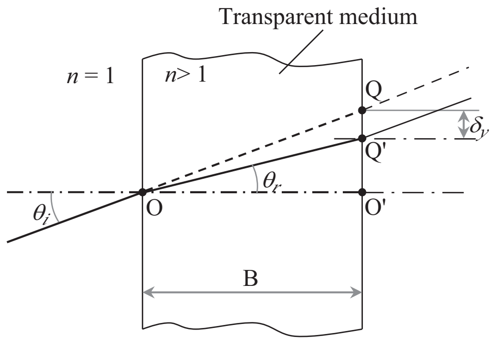

Fig. 2. The optical path change of light rays traveling through media of different refractive indices.

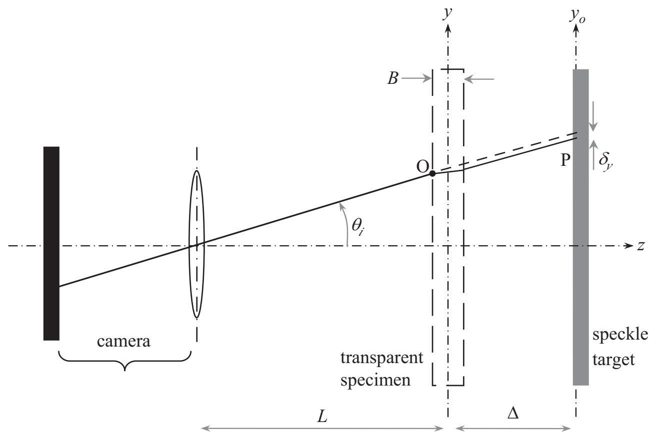

Fig. 3. Schematic of the experimental setup used to capture the optical path change of light rays traveling through media of different refractive indices.

δ_y is shown in Fig. 3. A target plane with the speckle pattern was placed at a sufficiently large distance ($L \sim 1275$ mm) from a camera (Nikon D100 digital camera fitted with a 28–300 mm lens using an extension tube and aperture setting #11). A reference image of the speckle pattern was recorded first. Then, a clear PMMA plate (thickness $B = 9.4$ mm) was introduced between the camera and the speckle plane. The distance from the mid-plane of the specimen to the speckle plane, Δ was 30.7 mm. A second image of the speckle pattern, this time through the PMMA plate, was recorded. The size of the image recorded by the camera was approximately 64 mm × 42 mm rectangle in the central region of the PMMA sheet.

The recording of the speckle fields used a pixel resolution of 1504 × 1000 pixels (1 pixel = 43.54 μm on the target plane). The second speckle image can be considered to be the perturbed image whose δ_y field is given by

$$\delta_y = O'Q - O'Q' = B(\tan\theta_i - \tan\theta_r) \tag{3}$$

Using the law of refraction and small angle approximation, $\theta_r \approx \theta_i / n$. Therefore, Eq. (3) becomes

$$\delta_y = B\theta_i\left(1 - \frac{1}{n}\right) \tag{4}$$

Now, from Fig. 3, $\tan\theta_i = y_0/(L+\Delta)$. Substituting this relation in Eq. (4), and using paraxial approximation (small θ_i), we get

$$\delta_y = \frac{By_0}{L+\Delta}\left(1 - \frac{1}{n}\right) \tag{5}$$

A similar expression for the horizontal component of displacement, δ_x, is implied. It is evident from the above equation that the displacement fields δ_x and δ_y are linear functions of the x- and y-

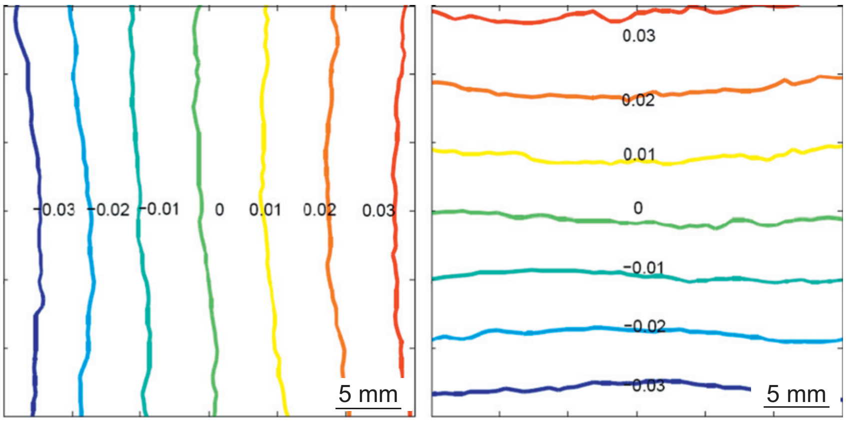

Fig. 4. Contour plots of measured δ_x (left) and δ_y (right) fields. Contour levels are in mm.

coordinates, respectively, of the specimen. Hence, the contours of constant δ_x and δ_y should be equally spaced. In addition, for an optically homogeneous medium, the contours should be parallel to the two coordinates.

The in-plane displacement fields were extracted from the undeformed and deformed images by performing 2D digital image correlation. The contour plots of the experimentally obtained δ_x and δ_y are shown in Fig. 4. As expected, the contours are equidistant and parallel lines. The magnitudes of displacements increase monotonically in both x- and y-directions in δ_x and δ_y fields, respectively. Any departure from the parallelism can be attributed to the lens aberrations, optical inhomogeneity and non-uniformity of thickness of the specimen besides other experimental errors [7]. An average value of refractive index computed based on the contour spacing is $n \cong 1.44$, which is close to that of commercial PMMA reported in the literature [8,9].

4. Inspection of glass for inhomogeneities and defects

In view of its simplicity and quantitative full-field optical measurement capability, the potential application of DGS as an inspection tool was explored. It involved measurement of angular deflections of light rays in glass, where DGS was implemented as an inspection tool to investigate optical inhomogeneities and defects. A borosilicate glass plate of dimensions $50 \times 50 \times 2.8$ mm^3 was deliberately exposed briefly to the flame of a blow torch (flame diameter was approximately 10 mm) in its center. This introduced thermal stresses and local refractive index changes in the specimen upon cooling. The process left no measurable thickness changes or coloration. A sample subjected to blow torch flame and photographed with an unrelated printed matter in the background is shown in Fig. 5. Evidently, the heat affected zone (HAZ) cannot be visually identified in the photograph. The schematic of the experimental setup used to visualize and quantify the resulting optical inhomogeneity is as shown in Fig. 3. Again, a Nikon D100 digital camera fitted with a 28–300 mm lens and an extension tube was placed at a distance $L \sim 1000$ mm from where the glass specimen was positioned. A target plane decorated with a random black and white speckle pattern was placed beyond the specimen location at a distance $\Delta = 27.1$ mm from the mid-plane of the glass plate with the heat affected zone. The camera was focused on this speckle plane when the specimen was not in the path of observation. The aperture was set to #11 in the lens and the sensor resolution used was 1504×1000 pixels (1 pixel = 35.6 μm).

A reference image of the speckle plane was recorded first in the absence of the specimen. Then, the specimen with HAZ was

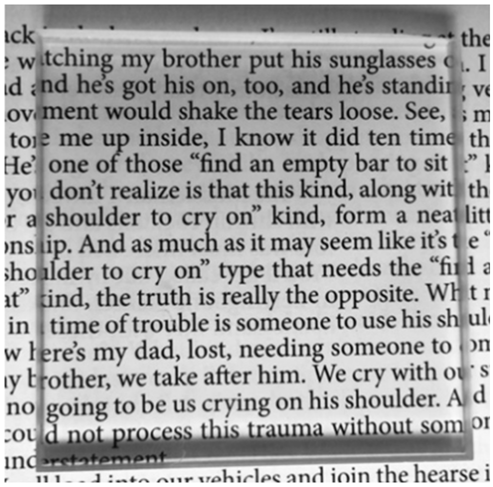

Fig. 5. Photograph of a borosilicate glass sample after brief exposure to blow torch flame in the center of the specimen. Optical inhomogeneity is invisible to the naked eye.

moved into a position as shown in Fig. 3. This introduced perturbation to the optical path when viewed through the defective specimen. The distorted image was recorded using the same camera settings used to record the reference image. The two separate recordings are shown in Fig. 6. Evidently, the two images seem nominally identical despite the perturbation of the speckle image due to HAZ in the central part of the image. The two images were then processed using 2D DIC method to obtain δ_x and δ_y fields. The angular deflection fields (ϕ_x and ϕ_y) were then obtained by dividing δ_x and δ_y by the separation distance Δ (Eq. (2)). The results are plotted in Fig. 7. The angular deflection contours show a clear evidence of a nearly circular heat affected zone in the mid-field of view, signified by a dense cluster of contours along the periphery of the HAZ. Away from the HAZ, the field consists of nominally parallel angular deflection contours along the horizontal and vertical directions in the ϕ_x and ϕ_y fields. The parallel contours can be explained by the reasons provided in Section 3. (That is, in the absence of any defects, the angular deflection contours are essentially orthogonal parallel lines.) The lower limit of measurement accuracy of DGS for similar experimental parameters (focal length of the lens, camera-specimen-target distances, speckle field, magnification, sub-image size, etc.) is shown to be of the order of 5×10^{-5} rad [7]. In view of this, the contour levels not only provide a qualitative indication of the HAZ and its size but can be used to quantify the orthogonal angular deflection levels if necessary.

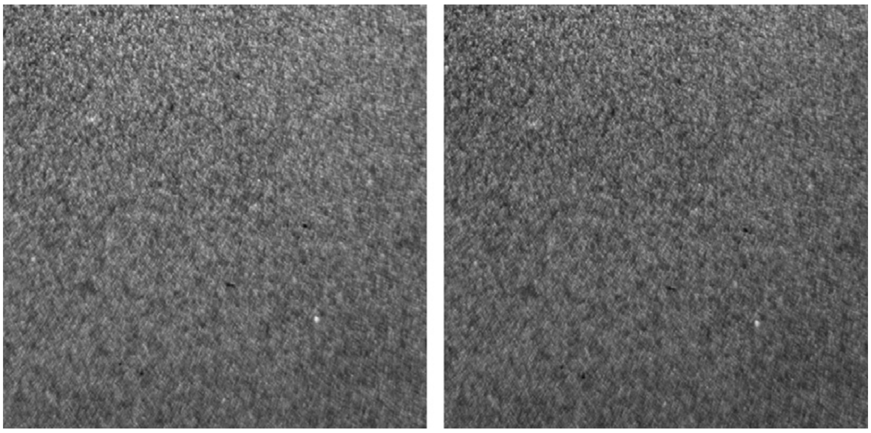

Fig. 6. Reference (left) and perturbed (right) image of speckles recorded through an optically inhomogeneous borosilicate glass plate. (The perturbation of speckles is not readily discernible to the naked eye).

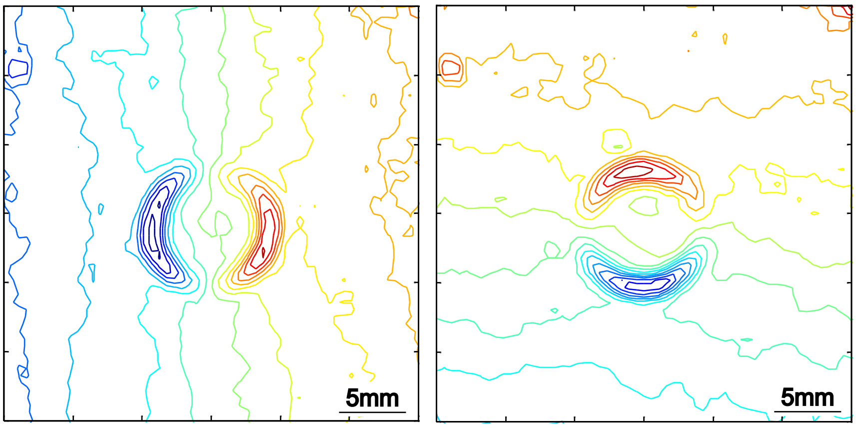

Fig. 7. Angular deflection contours, ϕ_x (left) and ϕ_y (right) in a thermally stressed borosilicate glass plate. Contour interval$=1\times10^{-4}$ rad.

5. Conclusions

A speckle image correlation based methodology called Digital Gradient Sensing (DGS) is proposed as an optical inspection tool for evaluating transparent sheets. It exploits refractive index variations caused by inhomogeneities and defects to evaluate angular deflections of light rays both qualitatively and quantitatively. The current popularity of digital image correlation methods and the availability of a number of commercial software packages for image registration and analysis make the proposed method rather attractive to implement relatively easily. The working principle of the experimental method of DGS and setup are described. The ability of DGS to detect the heat affected zone (HAZ) in borosilicate glass is successfully demonstrated.

Acknowledgments

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