A digital gradient sensor for nondestructive evaluation and stress analysis

Hareesh Tippur and Chandru Periasamy

A new technique based on digital image correlation enables inspection and failure characterization of transparent solids.

Optical transparency is an essential characteristic of many solids that are used in transportation, defense, and safety applications. Such transparent materials are used, for example, in automotive windshields, electronic displays, aircraft windows and canopies, hurricane resistant windows, bullet resistant enclosures, personnel helmet visors, and transparent armor. In some of these situations, the capacity of the structure to remain transparent and bear load during service, resisting shock and impact, is critical for human safety.

We have developed a new full-field measurement technique called digital gradient sensing (DGS) that can be used to detect the angular deflections of light rays propagating through optically transparent solids that are subjected to non-uniform mechanical stress fields, applied either quasi-statically or dynamically.1 This transmission mode technique has a relatively simple experimental setup (see Figure 1) and is based on the elasto-optic effect exhibited by optically transparent objects, where imposed stresses deflect light rays.

In DGS, we employ the 2D ‘Digital Image Correlation’ (DIC) technique to quantify optical angular deflections that can be as small as $1 \times 10^{-5}$ radians. The angular deflections are related to the spatial gradients of stresses, under plane stress conditions, that are encountered when thin (relative to the planar dimensions) sheets of material have mechanical stresses imposed upon them. We have demonstrated the feasibility of the method by examining the situation where a line-load acts on the edge of a relatively large planar sheet and produces severe local stress concentrations (see Figure 2). The spatial gradients of the measured stress can also be used to estimate the applied stresses.

We have also demonstrated the viability of using DGS to study material failure or damage on transparent planar acrylic sheets subjected to a dynamic line-load acting on an edge.2 We used DGS in conjunction with ultra-high-speed digital photography (200,000 frames/s) to perform time-resolved measurements. With finite element modeling we were able to successfully replicate the dynamic measurements made prior to material failure. Stress gradients measured near the impact point after damage initiation can also be used to characterize the failure mechanisms (see Figure 3).

We use DGS to study fracture mechanics and impact mechanics situations, i.e., to quantify stress gradients near crack and punch tips in transparent acrylic sheets. Crack-tip stress intensity factors measured under quasi-static and dynamic loading conditions using DGS agree well with analytical results and

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In addition, we made optical measurements of the effects of a square-punch impacting the edge of an acrylic sheet. Using the analogous crack-tip and punch-tip mechanical stress fields, we obtained stress intensity factors that were in good agreement with results from numerical simulations.

DGS can also be used to inspect defects and inhomogeneities in transparent media, such as glass panes. We used DGS to detect a heat affected zone that had been deliberately introduced into a Pyrex sheet sample (see Figure 4).\(^4\) The ability to detect optical inhomogeneities and quantify their extent has commercial value, and DGS can also be used to quantify angular deflection of light rays produced by a thin plano-convex lens, indicating its potential use in the metrology of refractive optical elements.

Another use for DGS is to study the deformation of opaque, thin structures and films in reflection mode. We modified the optical setup (see Figure 5) and demonstrated that the technique can be used to quantify surface slopes of specularly reflective thin plates (silicon wafers) undergoing out-of-plane deformation for the case of a clamped plate subjected to a numerical simulations.\(^3\) In addition, we made optical measurements of the effects of a square-punch impacting the edge of an acrylic sheet. Using the analogous crack-tip and punch-tip mechanical stress fields, we obtained stress intensity factors that were in good agreement with results from numerical simulations.

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We also evaluated the plate curvatures over the entire field from the measured surface slopes since stresses depend directly on curvatures in thin structures. Both our surface slope and curvature field results are consistent with analytical solutions. In Figure 6 the potential of the method for quantifying time-resolved, process-induced stresses by reflection mode DGS is demonstrated by evaluating slopes and curvatures of a silicon wafer coated with a polymer film as it cures in situ.

DGS is a powerful, yet simple full-field optical metrology technique. Its potential for engineering problems has yet to be fully explored. We are currently working on incorporating IR wavelengths into the methodology to visualize and quantify stresses and defects in electronic materials. We are also evaluating the applicability of reflection-mode DGS to stress analysis.

Author Information

Hareesh Tippur and Chandru Periasamy
Auburn University
Auburn, AL

Hareesh Tippur has worked extensively in the related fields of optical metrology and failure mechanics of solids. His research has led to the development of a coherent gradient sensing interferometer. He now focuses on the development of visible and infrared interferometers and the use of digital image correlation for understanding the dynamic failure mechanics of novel materials.

References