ANALYSIS OF TIME-RESOLVED SHEAROGRAPHIC METHODS WITH

CONTROLLED THERMAL STRESSING

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INTRODUCTION

Electronic shearographic interferometry is a nondestructive evaluation (NDE) technique in which qualitative detection of subsurface defects is readily achieved. In both industrial and laboratory environments, various full field stressing methods, including vibration, vacuum, thermal and mechanical loading, have been employed to produce characteristic deformations which can be monitored shearographically [1,2]. However, quantitative measurements of parameters such as defect depth are difficult to make with these techniques. This paper presents the results of using controlled thermal stressing with shearography in an effort to expand the quantitative capabilities of the technique. The use of controlled thermal-stressing allows a totally noncontact inspection technique with a large standoff distance to monitor the time-dependent deformations of test specimens. Typically laser power levels of tens of milliWatts are sufficient to generate measurable deformations.

Other investigators have employed interferometric techniques to observe out-of-plane deflection owing to thermal loading from different sources. Harris and Woods [3] used holographic methods to examine the deflection of unbonded regions in layered composites subjected to area heating with hot air. They concluded that inplane thermal expansion was the primary mechanism producing increased displacement over disbonded regions. Kaufmann and Vest [4] used double exposure holography to demonstrate the time-dependent deformation of a thin aluminum plate resulting from the propagation of a thermal wave. It was also found that the use of a slowly modulated laser heating source improved detection of certain flaw types over uniform heating.

Previous work on thermal stressing with shearography has addressed several issues. These include the evaluation of thermal stressing techniques for optimum flaw detection [5] and the identification of systems where shearography may outperform or complement other NDE techniques [6]. Most of the efforts have concentrated on using step-function heating with a laser employing different beam profiles, however, other heating sources such as a heat gun, a flash lamp and microwaves have been used to locate disbonds. Several systems have been identified in which the signal of interest is greater for shearography than that for infrared techniques such as time-resolved infrared radiometry (TRIR) [7]. It was observed that shearography was more effective than thermographic techniques for detecting coating disbonds since the large coating thickness limited the thermal signal from disbonds. For composites with an aluminum honeycomb structure, both techniques clearly reveal disbonds between the core and graphite epoxy skin. However, for composites with a Nomex™ honeycomb structure, the shearography signal over a disbond is the same as for the aluminum honeycomb while the thermographic response does not change between good and bad regions owing to the small difference between the thermal properties of the air and Nomex™.

The other area of investigation has been concerned with analyzing the shearography measurements for quantitative characterization of flaws in layered systems. Results have been reported on the time-dependent fringe pattern evolution for test specimens simulating disbonds of different dimensions [8]. It was observed that the signal characteristically varied with the depth and the width of the flaws which were simulated by flat-bottom holes. In this paper, analytical solutions for thermoelastic responses are compared with experimental results to examine the potential for quantitative analysis of interfacial defects. Theory and experiment are first compared for samples which are thermally and elastically thick. Results are then presented for a series of plate specimens which are neither thermally or elastically thick.

TIME-RESOLVED SHEAROGRAPHIC TECHNIQUE

In the work presented here, a time-gated argon ion laser source (Coherent Innova 90-5) was used to generate time-dependent thermoelastic deformations. The object of the time-resolved shearographic measurement technique is to monitor the temporal development of the thermoelastic deformation and the associated plate bending. In all cases the temperature rises generated in a given specimen are less than 5 K.

The experimental configuration for shearographic detection is shown in Fig. 1. Light from an expanded and filtered beam of a 25 mW Helium-Neon laser (Spectra Physics Model 127) is diffusely scattered from the surface and is collected by optics in a Michelson interferometer configuration. In this arrangement, one of the mirrors is tilted with respect to the other which results in a sheared image collected by a CCD camera (Pulnix TM-745). A filter placed in front of the camera eliminates imaging reflections from the heating beam. A frame grabber/processor (Perceptics Series 425) in a host computer (Macintosh IIfx) is used to capture images at video rates with a spatial resolution of 512 by 512 pixels.

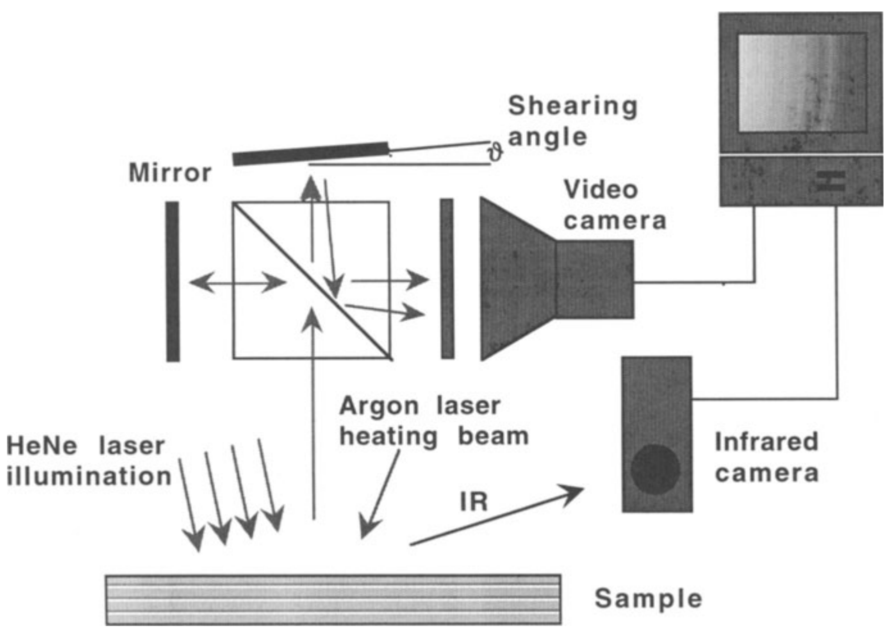


Figure 1. Experimental setup for shearographic imaging system.

In the shearographic method, light that scatters from two points on the object, separated by the amount of shearing, Δx, interfere at one point on the detector. If the two wave fronts have intensities I_a and I_b and random phases ϕ_a and ϕ_b, the recorded intensity is:

$$I = I_a + I_b + 2\sqrt{I_a I_b}\cos(\phi_b - \phi_a). \tag{1}$$

Shearographic images are formed by subtracting a reference image, I_0, of the object in an undeformed state from images, I_t, recorded during stressing. These images can be generated at video rates using onboard video subtraction with the frame grabber. The intensity at each point of the shearographic image is given by :

$$I = I_t - I_0 = k\left[\sin\left(\frac{\Delta\phi}{2} + \phi_{random}\right)\sin\left(\frac{\Delta\phi}{2}\right)\right]. \tag{2}$$

For small amounts shearing, Δx, and near normal illumination, the phase is approximately given by [9,10]:

$$\Delta\phi = \frac{4\pi}{\lambda}\frac{\partial w}{\partial x}\Delta x. \tag{3}$$

In the preceding equation for $\Delta\phi$, w is the out-of-plane displacement and λ is the wavelength of the HeNe laser. Equation 2 describes a fringe pattern, modulated by random speckle noise, in which each fringe contours a constant directional derivative.

Two examples of fringe pattern development are shown in Fig. 2 for 25 mm wide plates which are (a) 0.5 mm and (b) 1.5 mm thick. Fringe positions are tracked as a function of time in order to analyze the temporal development of the thermoelastic deformations.

ANALYSIS OF A THERMAL BUMP ON THICK SPECIMENS

To assess the potential for quantitative flaw analysis by time-resolved shearography with thermal stressing, experimental and calculated results are compared. The deformation on the surface of an isotropic half space is examined first. This choice of geometry minimizes the number of boundary conditions which must be considered, allowing for the greatest simulation fidelity.

The Laplace-Hankel transform of the quasistatic portion of the solution at the surface, with the transform pairs (t, s) and (r, p), respectively, is:

$$\hat{\bar{w}} = \frac{\gamma\kappa Q}{k}e^{-a^2p^2}\left[b^2s^2\left(\beta^2+p^2\right)\left(\frac{\alpha}{\xi}-1\right)R^{-1}\right] \tag{4}$$

where

$$R = \left(\beta^2+p^2\right)^2 - 4\alpha p^2\beta$$

$$\alpha^2 = p^2 + a^2s^2 \qquad \beta^2 = p^2 + b^2s^2$$

$$\xi^2 = p^2 + s^2c^2 + \frac{s}{\kappa}$$

The development of this expression is described elsewhere [11]. Numerical methods are used to invert Eq. (4) for evaluating the displacements and directional derivatives resulting from laser heating. The time-dependent fringe positions are calculated from this data.

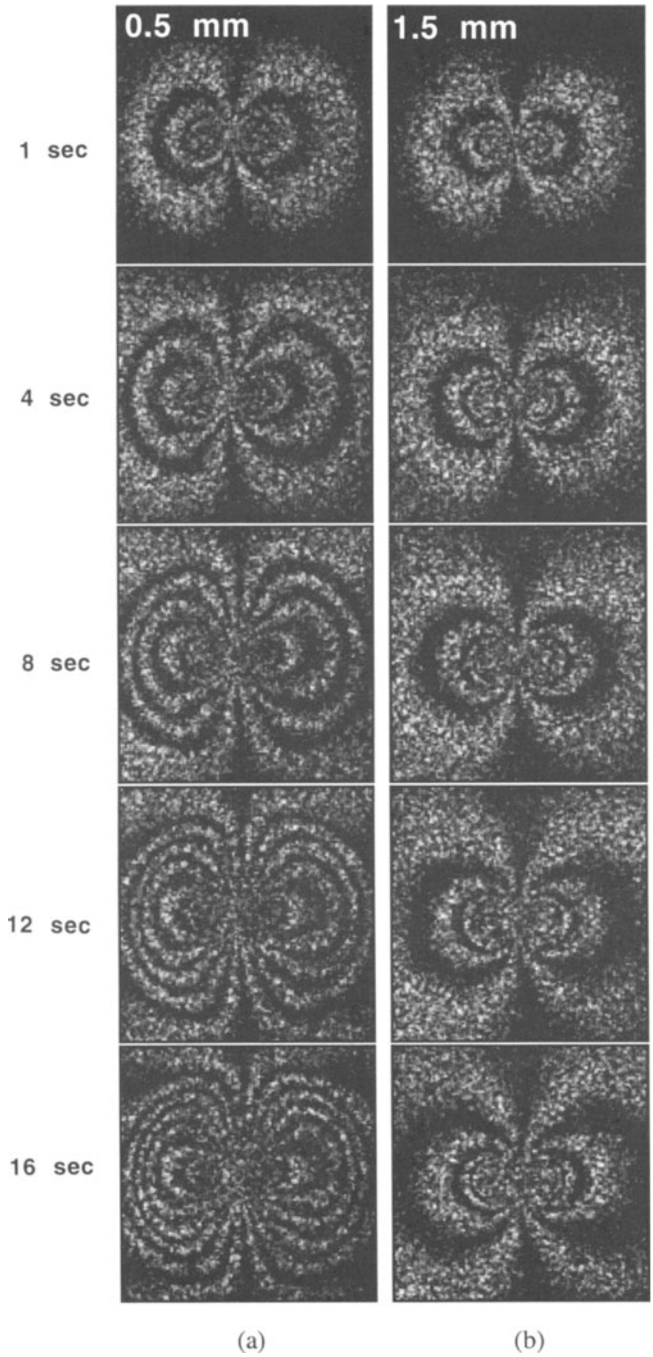
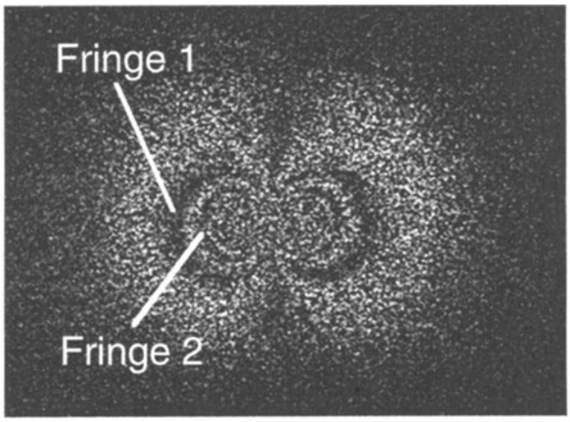


Figure 2. Shearographic fringe pattern evolution for (a) 0.5 mm and (b) 1.5 mm thick plates subject to heating with a 40 mW, 2 mm diameter laser beam.

Supporting experimental results were obtained using a thermally and elastically thick slab of Delrin™, an alternating oxymethylene structure (OCH_2). The time dependency of the low order fringes of the shearographic image in Fig. 3a are sufficient to provide information about the surface deformation. The position of the first two dark fringes labeled in Fig. 3a are plotted in Fig. 3b as a function of time along with the results of the simulations based on Eq. (4). The calculations are only valid for times less than 5 seconds owing to complications with the inversion routine.

(a)



(b)

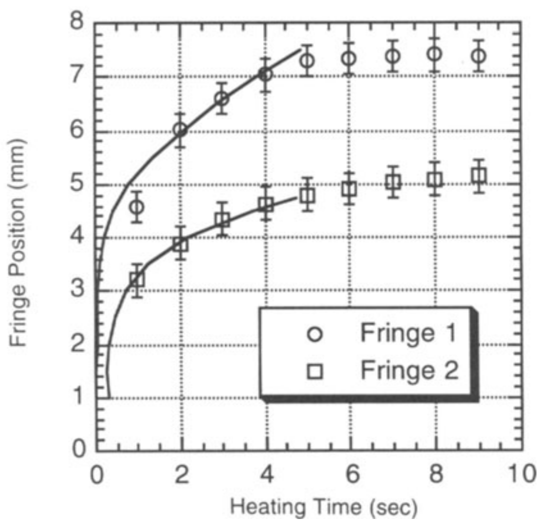


Figure 3. (a) Shearographic fringes from heating a thermally and elastically thick sample of Delrin with a 40 mW laser source, (b) Fringe position as a function of time - comparison of experiment (symbols) and theory (solid lines).

The agreement between theory and experiment is reasonable. Error in the data presented originates from the numerical limitations of the inversion routine and measurement error in the fringe positions, there are several inconsistencies between the experiment and model which contribute to differences. In addition, modeling results demonstrate that the surface displacement is a moderately strong function of beam radius. Therefore, it should be expected that deviations in the beam profile from an ideal Gaussian would influence the deformation. It is not expected that heat loss to air would be significant since the temperature rises are small and the differences between the effusivities (which governs heat conduction across an interface) of air and Delrin™ are large.

APPROACH FOR THIN PLATES

The time-dependent deformation of plate structures was also investigated. A plate geometry provides a simple model for disbond type flaws in real systems. As with the semi-infinite case an analytical model was developed for comparison with experiment and is described fully elsewhere [11].

The directional derivatives for 25.4 mm wide Delrin™ plates with thicknesses of 1.5, 2.0 and 3.0 mm are given as a function of time in Fig. 4a. It is evident from the calculation that the out-of-plane deflections are greater for thinner plates, as would be expected. Experimental results tracking the evolution of the first fringe for plates of the same dimensions are displayed in Fig. 4b. While the trends are similar, the agreement between experiment and theory is poor.

The same laser power (40 mW) and beam diameter where used to heat the plates for the thermally and elastically thick specimens. Therefore, it is expected that the out-of-plane deformations owing to thermal expansions in the plates would be similar to those observed in the thick samples. This portion of the deformation contributes to an earlier evolution of fringes than predicted by the thin plate theory. The slower plate bending mode develops with the lateral diffusion of the temperature field. These results imply that the use of plate theory to treat the thermal bending of plates does not accurately describe the deformations which occur.

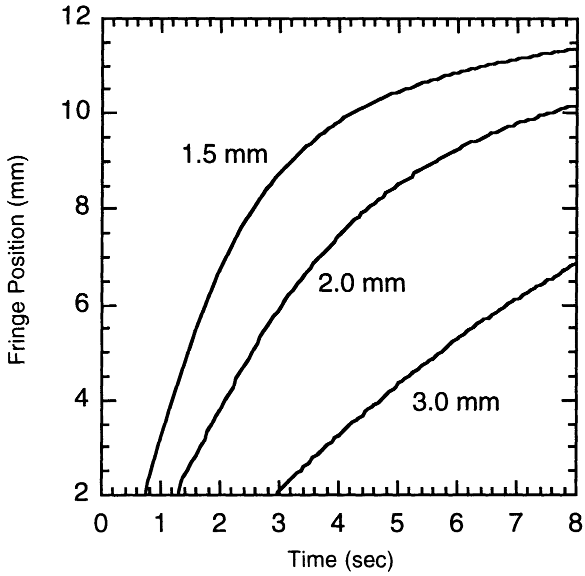
CONCLUSIONS

The possibility of performing quantitative defect analysis using shearography with controlled thermal stressing was investigated. It has been demonstrated that low laser powers provide sufficient impetus to produce characteristic deformations in layered material systems. The temporal development of the deformations owing to a diffusing temperature field were measured by tracking the position of shearographic fringes as a function of time. An analytical model for thermally and elastically thick specimens based on temperature-rate-dependent thermoelasticity theory was developed for comparison with experiment. Reasonable agreement was obtained between the observed results and calculations.

Thin plates with rigid boundaries were used to approximate disbonds in layered systems. The experimental results obtained were compared to simulations based on theory for the thermal bending of thin plates. While the trends were similar, the general agreement between model and experiment was very poor. This disparity can be attributed to the contribution of the thermal out-of-plane displacements, which are not accounted for with plate theory. A more sophisticated model, without the approximations of thin plate theory, must be used to accurately describe the deformations which occur in a thermally loaded plate.

Results in this work suggest that analysis of the time-dependent deformations resulting from controlled thermal stressing can be used to quantitatively characterize flaws in layered systems. To achieve this goal, a full plate model based on temperature-rate-dependent thermoelasticity is being developed. Experimentally, phase stepping shearography is being performed to measure slopes of the thermal deformation directly.

(a)



(b)

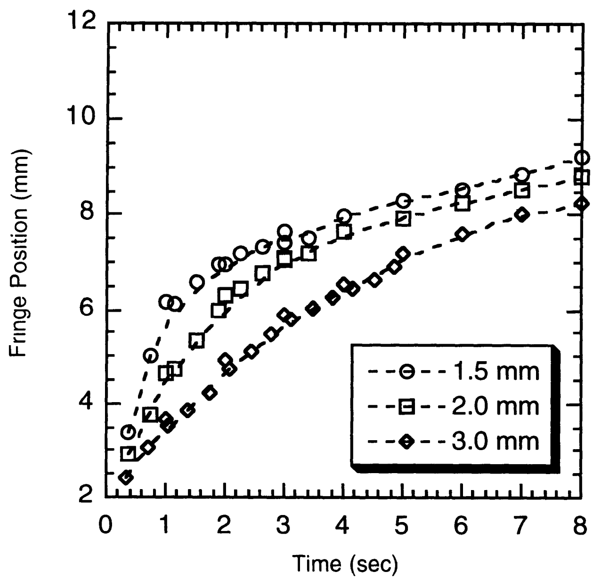


Figure 4. Fringe position as a function of time for plate thicknesses of 1.5, 2.0 and 3.0 mm. (a) theory, (b) experiment.

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