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THERMOELASTIC INSPECTION OF LAYERED MATERIALS: DYNAMIC ANALYSIS

by

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SUMMARY

A thermoelastic technique is presented for the inspection of layered materials such as coated or adhesively-bonded structures. The surface of the material is slightly heated by a short laser pulse, inducing flexural vibrations of the bonded layer which are monitored with a sensitive optical probe. Excitation mechanisms using either laser-generated convergent surface waves or localized thermal stress are discussed. Applications to the detection of delaminations in metal-to-honeycomb laminates are described. Such a technique is attractive because it is non-contact, fast and easy to scan over large surfaces. Moreover, it has a unique capability to nondestructively monitor the mechanical response of the bonded layer to a tensile lifting stress.

INTRODUCTION

Layered materials such as metal-to-metal or metal-to-honeycomb laminates are widely used as light-weight primary structures. Such materials require careful inspections during the fabrication process, as well as during the service life to detect any extended bonding defect, which would severely affect the resistance of the structure to tensile or shear loading.

Radiography and ultrasound are the approaches which are most frequently used for the inspection of bonded materials at the present time[1-3]. Although such techniques have reached a high level of sophistication, they still have some intrinsic limitations. Radiography can only detect defects which produce a lack of material, such as gross porosity or resin filleting. Resonant acoustic bond testers require a time-consuming manual scanning over the inspected surface, while automated pulse-transmission ultrasonic testing systems require cumbersome water-coupling configurations which are inadequate for in-service inspections. Moreover, ultrasonic methods can only detect defects producing a discontinuity in the acoustic impedance of the material, which is not always correlated to a lack of mechanical strength of the bonded structure.

For such reasons, a research program is under way at the Industrial Materials Research Institute to explore new approaches for the inspection of layered materials which could result in faster and less cumbersome techniques. Methods requiring no contact or water-immersion of the piece are particularly desired because such methods can be applied where access is difficult or possible from one side only. Non-contact methods such as holographic[1,2,4], or IR thermographic[1,2,5] techniques are difficult to practically implement for a number of reasons. Holography is strongly affected by environmental disturbances, usually requiring that the inspected object be mounted on a vibration-isolated table during the double-exposure period. As for thermography, it suffers from low-emissivity and spurious reflectivity problems when inspecting metallic surfaces, unless such surfaces are previously anodized[6].

In this paper we describe a thermoelastic technique by which the surface of the layered material is heated by a short laser pulse producing a slight flexural displacement which is monitored by a sensitive laser interferometer. As in the thermal-loading holographic approach, no contact is required with the inspected surface; in our case, however, the duration of the whole signal is so short that low-frequency ambient vibrations do not interfere with the measurement. Preliminary results obtained with a heating period longer than the mechanical response time of the unbonded layer have been previously reported[7,8]. This paper focusses on the time-dependent features of the detected signal when the laser heating period is sufficiently short, and shows how such features can be used to increase the signal-to-noise ratio and to gain additional information on the extent of the unbonded area. Two non-contact loading techniques are presented and compared. Ultrasonic loading using a laser-generated convergent surface wave will be described in the next section. The thermoelastic loading technique will be analyzed in the following section, where some applications of practical interest will be described.

ULTRASONIC LOADING

Laser generation and detection of ultrasound is an attractive technique because it is non-contact, easy to scan by optical methods and deployable on remote or awkward-shaped testpieces[9]. An ultrasonic pulse is generated in the material to be inspected by irradiation with a short laser pulse, and the echoes from subsurface defects are detected by a laser interferometric probe [10,11]. Keeping the source and the probing beams on the same side of the sample makes it possible to inspect pieces which are accessible from one side only.

The most straightforward approach for laser-based ultrasonic testing consists in superposing, through a dichroic mirror, the source and the probing beams, which can thus be easily scanned collinearly by a single mirror. However, the high laser energy required to produce optically detectable ultrasonic echoes at normal incidence results in strong air instabilities over the irradiated surface which overshadow the echo signals[12]. A more convenient approach for the inspection of bonded structures makes use of an annular-shaped heating beam collinearly superposed to the probing beam[12]. The experimental configuration is shown in fig. 1a. A 1.5 cm diameter annular-shaped YAG laser pulse, 15 ns long, obtained by focusing the beam through an axicon[12] is incident on the surface of the bonded structure to be inspected (4 mm-thick Aluminium plate epoxy-bonded to a massive substrate). Thermoelastically generated bulk acoustic waves propagate within the material and are eventually detected after reflection at the bonded interface by the laser probe focused on the center of the annulus. Compared to the spot-heating approach, such a technique has the advantages of avoiding air instabilities, exploiting the higher generation efficiency of ultrasound at an oblique angle[9], while taking advantage of the focussing effect of the converging surface wave which results in a higher signal with moderate surface heating. Figs. 1b and c show the detected signal when the plate is either unbonded or well-bonded to the substrate, respectively. The surface displacement signal is normalized in nm per unit of the incident laser pulse energy. The small longitudinal (L) and shear (S) echoes reflected from the bonded interface are seen to disappear almost completely in the well-bonded case, because of the good acoustic coupling to the substrate through the thin adhesive layer.

Also shown in figs. 1b and c is the strong dipolar pulse (R) generated by the Rayleigh wave propagating along the surface from the irradiated annulus to the probed point. Surface waves are generated very efficiently in the thermoelastic regime while not suffering of the strong attenuation related to the three-dimensional spread of bulk waves. In order to take advantage of the particularly high signal level of the surface-wave pulse, the possibility to characterize an unbonded layer by analyzing its interaction with a convergent surface wave was taken into consideration. Such an interaction turns out to be most informative when the thickness of the layer is of the same order as the surface-wave wavelength, typically 0.5 mm in our case.

Fig. 2a shows the experimental configuration for the evaluation of such an approach. An unbonded layer was simulated by machining a flat-bottomed hole on a bulk Aluminum sample. The diameter and the depth of the hole varied from 5 to 10 mm and from 0.25 to 1 mm, respectively, while its shape was either circular, square or triangular. The heating laser annulus, either partial or full, was typically 15 mm in diameter. Fig. 2b shows the signal detected far from the hole, in a bulk-material area. The Rayleigh wave has the familiar dipolar shape visible in fig. 1. The longitudinal P-wave pulse[9] is also visible in such a photo. Fig. 2c shows the signal obtained on a circular hole of 5 mm in diameter and 1 mm in depth. As we can see, the detected pulse is strongly deformed in such a case, with the appearence of multiple pulses probably generated by mode conversion of the converging pulse at the hole border. Fig. 2d shows the case of a flat-bottomed hole 0.5 mm deep. In this case, the plate thickness is comparable to the surface-wave wavelength, so that large mode conversions are expected, in particular to Lamb waves. Indeed the detected signal is quite different from the bulk-material signal, fig. 2b.

A detailed analysis of the acoustic pulse propagation in the unbonded layer would be very complex and is out of the scope of this paper. We shall only make some empirical observations in order to evaluate such an approach as compared to alternative loading techniques for the inspection of layered materials. First, it can be said that the presence of a subsurface hole can clearly be inferred by simply observing the shape of the detected signal. The deformation of the signal is strongly dependent on the ratio of the plate thickness to the wavelength of the acoustic pulse, as figs. 2c and d show. Little variation of the signal shape was observed with a variation in either the diameter or the shape of the hole, from circular to square or triangular, or when the plate was monitored slightly out of its center. This seems to indicate that the observed signal is related mainly to the flexural properties of the plate at the point of convergence of the surface wave. Finally, the amplitude of the detected signal is much larger than the amplitude of the thickness-related echoes of fig. 1b, making the surface-wave loading approach more attractive than the pulse-echo approach from the point of view of signal detectability.

THERMOELASTIC LOADING

The results obtained in the previous section suggest that high-amplitude signals can be obtained by exciting flexural fluctuations of the unbonded plate. Such fluctuations may however be excited more effectively by alternative thermal loading techniques, as will be shown in this section.

Description of the method

Fig. 3 shows the experimental apparatus used for the vibrational analysis of layered materials by the thermoelastic loading technique. A pulsed YAG laser is partially focused on the surface of the layer to be inspected. The transient thermoelastic strain field which develops within the surface-heated layer is shown in the insert. Such a field results in a strong lifting moment which causes the layer to displace in a direction normal to the surface if the layer is not well-bonded to the substrate. Previously reported finite-element[8], as well as analytical[13] investigations show that optimum lifting efficiency at constant laser energy density is obtained when the irradiated area is nearly equal to half of the area of the subsurface unbonded region.

The surface displacement, which is typically of a fraction of a micrometer for an average layer heating temperature of a few degrees Celsius, is monitored during and after the heating pulse by a focused He-Ne laser interferometric probe which can reach a sensitivity of 0.02 nm if closely focused on the surface[12]. The relatively low heating level required in this case makes it possible to avoid the previously mentioned air instabilities[12], even if the heating and the probing beams are collinear. The signal detected by the interferometric probe under pulsed irradiation of the surface is the resultant of three components: the increase δ in the layer thickness produced by the linear thermal expansion of the material, the variation ϵ in the optical path length seen by the interferometer because of the variation of the refractive index of the air above the irradiated area as a result of heating, and finally the displacement ω produced by the bending deformation of the layer which contains the information on the bonding strength.

It can be shown[13] that, for a heated area much larger than the thermal propagation depth during the signal observation period, the linear expansion component is equal to:

$$\delta = a_T \frac{E}{\rho\ C_p} \qquad (1)$$

where E is the absorbed energy density and a_T, ρ and C_p are the coefficient of linear thermal expansion, the mass density and the specific heat, respectively, of the heated layer. As for the refractive index component, its ratio to the linear expansion component in the isobaric approximation and for a thermal propagation depth smaller than the layer thickness is equal to[13]:

$$\frac{\varepsilon}{\delta} = \frac{n_o - 1}{n_o\, T_o\, a_T} \sqrt{\frac{\alpha_g}{\alpha}} \tag{2}$$

where n_o is the refractive index of air, T_o is the ambient temperature, a_T is the coefficient of linear thermal expansion of the layer, α_g and α are the thermal diffusivities of the air and of the layer respectively. For most materials the ratio ε/δ as given by eq. 2 is smaller than 10%, so that the refractive index contribution to the detected signal is usually negligible with respect to the thermal expansion component.

The third component, produced by the bending deformation of the unbonded layer, cannot be reduced to a simple analytical expression. A more involved thermoelastic analysis of a rigidly clamped circular plate[13] may be used to obtain specific solutions for given values of the plate parameters, as well as to acquire a physical insight on the effect of the different geometrical and thermomechanical properties. For an order-of-magnitude evaluation of this technique, it may be retained as a rule of thumb that the ratio between the bending and the thermal expansion components is typically $w/\delta \approx (a/\ell)^2$, where a is the radius and ℓ is the thickness of the unbonded plate. We can thus conclude that the signal w will be clearly discernible from the component δ, which is independent of the layer adhesion to the substrate, whenever the radius of the unbonded area is much larger than the depth of the delamination. Such a requirement is in line with the industrial concern, as the tendency of a delamination to grow catastrophically is strongly dependent on the diameter of the unbonded area.

Previously reported experimental investigations[8, 13] made use of surface heating periods which were much longer than the mechanical response time of the thermoelastically deformed plate. In such a case, the layer expansion is quasi-stationary, and no transient oscillations are observed. The work reported here deals with the case of a heating period much shorter than the elastic response time of the layer. Moreover, the plate is assumed to be thicker than the thermal propagation depth during the observation period. In such a case transient flexural vibrations of the impulse-loaded plate are expected, particularly at the first harmonic frequency of a clamped circular plate which is in the thick-membrane approximation[14]:

$$f_1 = 0.47 \frac{\ell}{a^2} \sqrt{\frac{Y}{\rho(1-\nu^2)}} \qquad (3)$$

where Y is Young's modulus and ν the Poisson ratio of the plate material. As the thermal expansion component, eq. (1), has no time-dependent features after the absorption of the heating pulse, the experimental observation of discrete resonances in the layer movement is a clear indication of an unbonded area. A considerable increase in the signal-to-noise ratio is thus possible by a dynamic analysis of the detected signal. Moreover, the value of the main oscillation frequency may provide further information on the geometry of the delamination, such as the extent of the unbonded area if the thickness of the layer is known.

Experimental Results

Aluminum samples with flat-bottomed holes of different sizes were analyzed by this technique. Fig. 4a shows the experimental configuration. Fig. 4b shows the signal obtained on the thick portion of the sample. The small signal obtained in this case, which is constant apart from the electronics-limited rise-time, represents the linear thermal expansion of the heated material. Figs. 4b and c show the signals obtained over a flat-bottomed hole of 5 mm in diameter and of 1 and 0.5 mm in thickness, respectively. As we can see, most of the additional displacement signal is strongly modulated at a thickness-dependent oscillation frequency which is a clear indication of the presence of a subsurface defect. The oscillation frequency obtained in the case of the 0.5 mm-thick plate, fig. 4d, is in reasonably good agreement with the theoretical resonance frequency obtained from eq. 3, while in the case of the 1 mm-thick plate, the observed resonance frequency was smaller than the theoretical value by nearly 45%. This is related to the inadequacy of the thick membrane as well as of the rigid boundary approximations for relatively thick plates. The agreement with the theoretical expression was better with plates having a larger a/ℓ ratio.

A comparison of fig. 4 with fig. 2 shows that the amplitude of the signal detected with the thermoelastic loading technique is larger than the signal obtained with the ultrasonic loading method, while its frequency contents is lowered. This is particularly true for a/ℓ ratios of the order of 10 or larger, as fig. 4d shows. Lower-sensitivity and lower-frequency-range commercial interferometers can thus be used with the thermoelastic technique, such as a Doppler vibrometer[15] which can easily inspect rough surfaces at operating distances of more than 1 m.

The same technique was used to inspect a metal-to-core Aluminum laminate in which artificial bonding defects were produced by crushing the honeycomb core over a nearly 1" X 1" area before bonding to the skin. Fig. 5a shows the experimental configuration. A 2.6-5/32-10N Aluminum core was bonded on the top surface to a double-sheet of Aluminum, the two layers having a thickness of 0.3 mm and 0.6 mm, respectively. The bottom layer was a single-sheet 0.3 mm-thick. The adhesive was Hysol 9628.

The thermoelastic signal obtained on the double-sheet side of the laminate with a 3.5 mm-diameter, 50 mJ/pulse YAG beam was of the order of 20 nm both on the well-bonded and on the unbonded regions. Such a surface displacement, which is much higher than the expected linear thermal expansion contribution of the top Aluminum sheet, is believed to be produced by the relatively large elastic strain of the adhesive layer at the metal-to-core interface. An additional oscillatory contribution of the order of 5 nm in amplitude is obtained on the unbonded area, a signal which would hardly be detectable by the previously reported maximum-displacement recording technique[6]. The short-pulse approach presented in this paper allows however to significantly increase the signal-to-noise ratio by proper filtering. Figs. 5b and c show the magnitude spectra of the transients detected on a well-bonded and on the unbonded region, respectively. If we neglect the low-frequency components, we can see that the oscillatory component at nearly 8 KHz on the unbonded area shows up clearly against the background. The value of such a frequency is in agreement with eq. 3 if we assume an effective unbond radius of 1.75 cm. Fig. 5d shows the signal obtained on the bottom, well-bonded 0.3 mm-thick layer. The 95 KHz component visible in this expanded spectrum, corresponding to a 2.8 mm-radius circular plate from eq. 3, is attributed to the oscillation of the plate over a single honeycomb cell, which behaves as an unbond if the YAG diameter is smaller than the cell-size.

DISCUSSION

The non-contact time-resolved observation of thermally-induced oscillations of a bonded layer appears to be a very promising approach. Both the ultrasonic-loading and the thermoelastic-loading techniques described in this paper present some advantages and some disadvantages. Ultrasonically loading by a thermoelastically-produced convergent acoustic wave provides signals which are unaffected by the linear thermal expansion as well as the air-density contributions observed with the thermoelastic-loading approach. Moreover, the full potential of such a method concerning the investigation of the mechanical and damping properties of the adhesive layer by an analysis of its interaction with the converging wave has not yet been fully exploited. However, the magnitude of the detected signal is relatively low, while its interpretation is not straightforward.

As to the spot-heating thermoelastic technique, it has the advantages of providing an easily interpretable signal of relatively high magnitude, particularly for large a/ℓ ratios. Moreover, the strong dependence of the flexural resonance frequency on the diameter of the unbonded plate provides a simple way to evaluate the size of the unbonded area when the thickness of the inspected layer is known.

As previously mentioned, the pulsed thermoelastic method was initially developed in order to avoid the ambient vibration problem encountered with the holographic technique[7]. It was however quickly realized that the spot-heating thermoelastic technique has another important advantage with respect to the extended-area thermal-loading holographic technique, namely that it provides a much larger lifting efficiency of an initially flat layer[8,13]. Another attractive feature of the point-by-point interferometric technique is its sensitivity to displacements much smaller than a light wavelength, requiring heating temperatures quite smaller than with thermal-stressing holography. Finally, the present paper shows that a vibration analysis is possible with the pulsed thermoelastic method, thus combining the potential of the thermal-stressing and of the acoustic-stressing holographic methods[4] in a single non-contact technique. On the other hand, holography provides directly a full picture of the inspected area, while the point-by-point interferometric technique requires that the surface be optically scanned. This paper shows however that the short inspection time of each point, typically 1 ms or less, allows a surface to be inspected in a period which compares quite favorably to the period required to expose, develop and interpret the fringe pattern recorded in the hologram.

The vibration analysis which is made possible by the thermoelastic technique presents some analogy with other vibratory inspection methods using tapping or acoustic impact techniques[1,16]. The non-contact nature of the thermoelastic technique allows however to inspect the free oscillations of the surface without perturbing or obstructing its motion. More importantly, the vibration of the structure is optically monitored in the same area where it has been thermoelastically excited, thus avoiding the strong propagation or air-coupling losses suffered by the acoustic wave when detected by a microphone or by a transducer attached at one end of the structure.

When comparing the thermoelastic technique to other methods, it should be emphasized that this technique has a unique capability to remotely monitor the mechanical response of the bonded layer to a tensile lifting stress. The only other technique by which the structure is nondestructively tested under a pulling stress perpendicular to the bonded interface is the vacuum-suction holographic technique[17], which is quite cumbersome and can be applied only on flat and smooth surfaces. Such a capability opens the possibility to detect lack-of-adhesion defects* where the two adherents are in physical contact but with zero adhesive strength[8]. Such interfaces are essentially transparent and thus undetectable by ultrasonic methods[18]. Another limitation of ultrasonics is its limited detectability of thin delaminations when filled with a coupling liquid such as water. Such defects can still be detected by the thermoelastic technique, as fig. 6 shows. In this experiment, two lack-of-adhesive unbonded areas, nearly 1" in diameter, were produced under a 0.82 mm-thick Cu-Be layer epoxy-bonded to a massive substrate, as fig. 6a shows. Figs. 6b to d show the signals obtained from the well-bonded area, the air-filled unbond and the water-filled unbond respectively. As we can see, the water-filled unbonded area, fig. 6d, presents a relatively large thermoelastic displacement as compared to the well-bonded area, fig. 6b, and oscillations can still be seen even if more rapidly damped than over the air-filled defect, fig. 6c. The low-frequency fluctuations visible in such signals are believed to be produced by the combined effect of thermal expansion, adhesive yielding under traction, thermal relaxation across the layer as well as electronic high-pass filtering.

CONCLUSION

A novel approach for the nondestructive inspection of layered materials by a thermal-loading interferometric technique has been described. Although still in its infancy, such a technique appears to be very powerful and presents several practical advantages with respect to more mature techniques such as holography. Two different noncontact loading techniques have been presented and discussed, while the benefits of a spectral analysis of the excited transient have been demonstrated. This approach is quite attractive because it is fast, noncontact and thus easy to scan over irregular surfaces, and because it provides a sensitive and quantitative measurement of the mechanical response of the bonded structure to a lifting tractional force.

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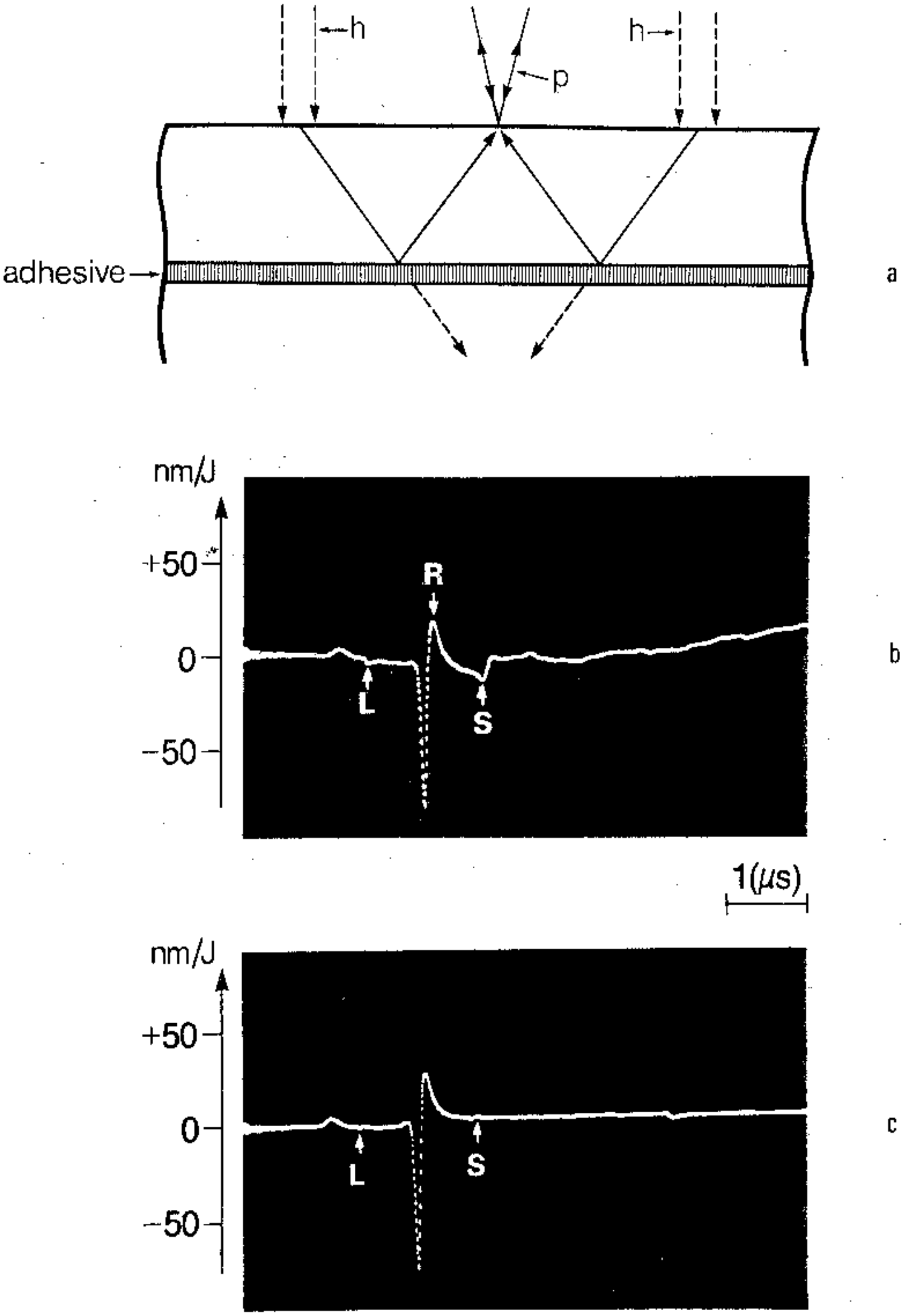

Fig. 1: Inspection of adhesively bonded structures by laser-generated ultrasonic bulk waves; (a): experimental configuration, where h is the cross-section of the annular laser beam and p is the focused probing beam; (b): signal detected in an unbonded area, where L and S indicate the longitudinal and shear reflected echoes, respectively, while R is the surface-wave pulse; c): signal detected in a well-bonded area. The vertical scale is in nm per unit energy of the incident laser pulse.

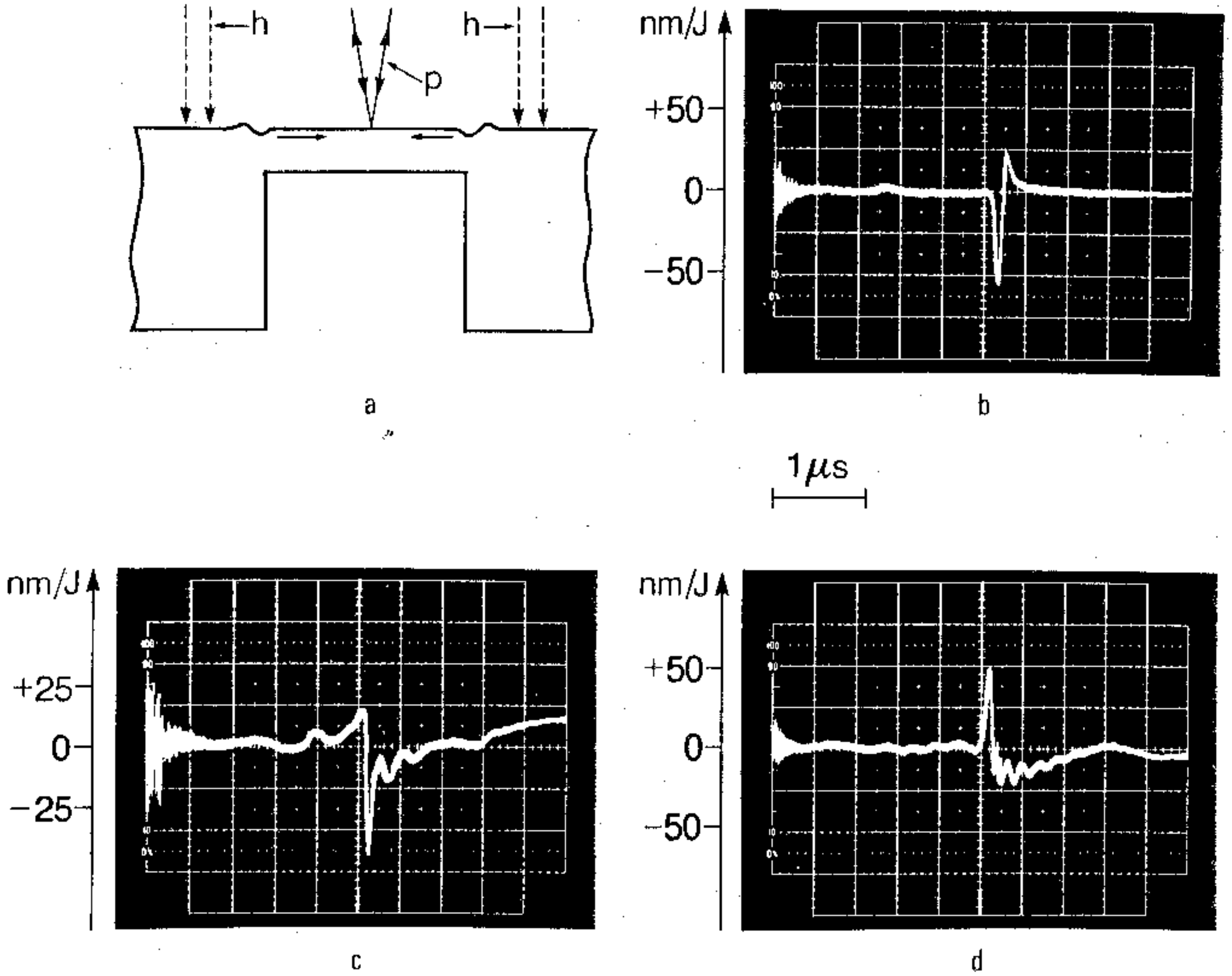

Fig. 2: Inspection of an unbonded plate by the laser-generated ultrasonic surface-wave loading approach. (a): experimental configuration, where h is the cross-section of the annular laser beam and p is the focused probing beam; (b): signal detected in the bulk-material area; (c): signal obtained on a 5 mm-diameter, 1 mm deep plate; (d): signal obtained on a 5 mm-diameter, 0.5 mm deep plate.

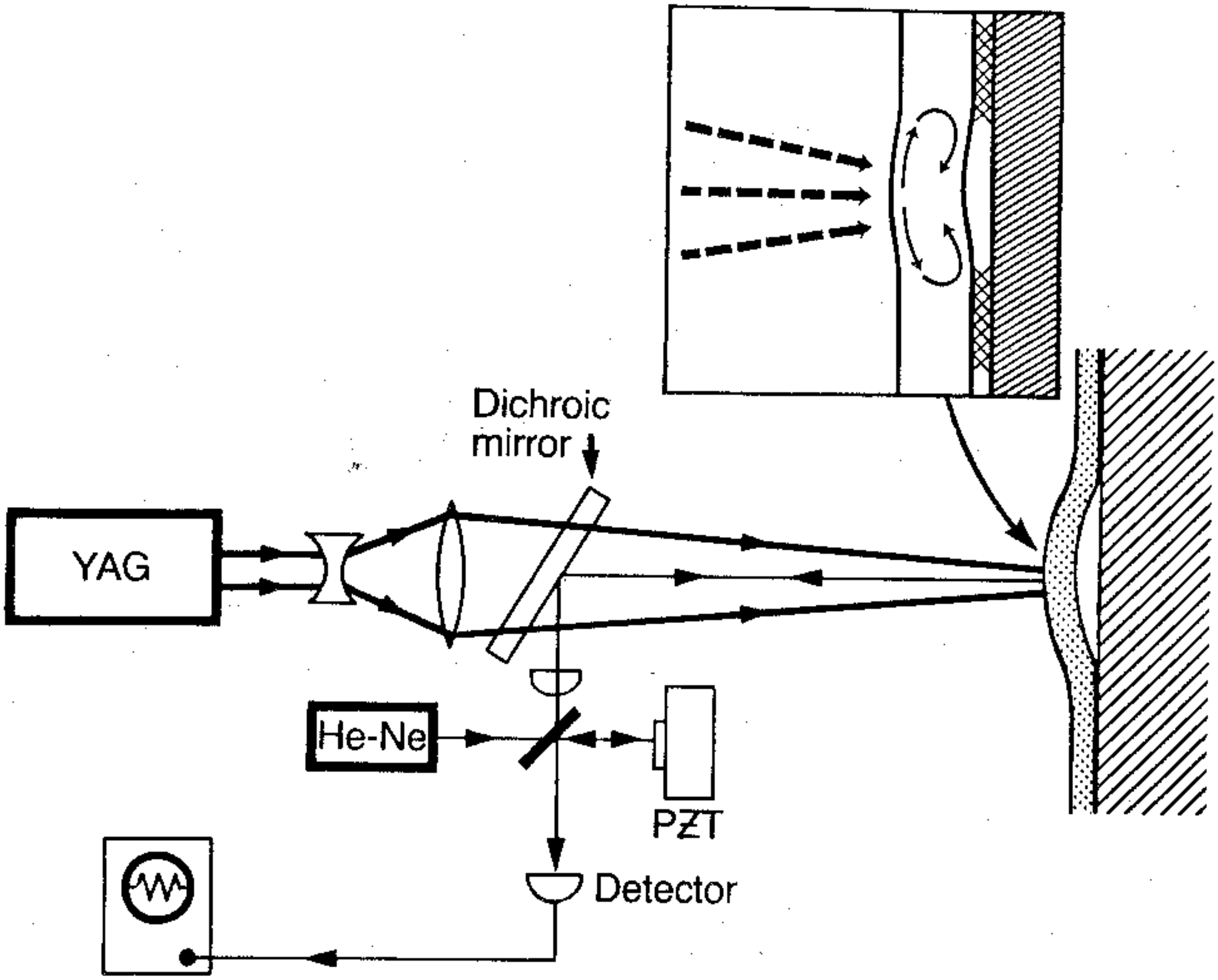

Fig. 3: Schema of the experimental apparatus for the inspection of a layered structure by the thermoelastic loading technique. The insert shows the transient strain field within the bonded layer after the surface-heating laser pulse.

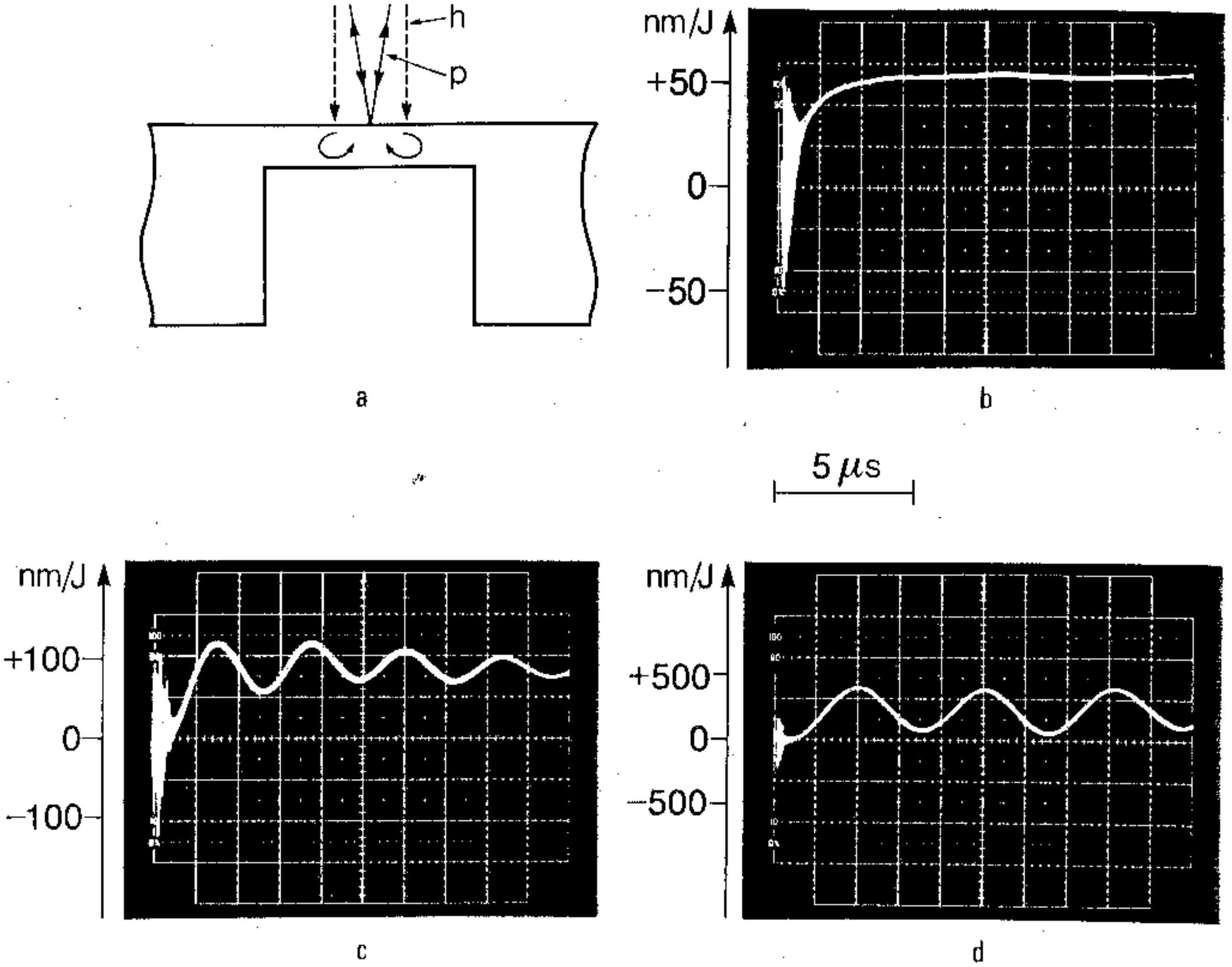

Fig. 4: Thermoelastic inspection of an unbonded plate; (a): experimental configuration, where h indicates the heating YAG beam and p the He-Ne interferometric probe; (b): signal obtained in the bulk-material area, showing the linear thermal expansion component; (c): signal obtained on a flat-bottomed hole 5 mm in diameter and 1 mm deep; (d): signal obtained on a flat-bottomed hole 5 mm in diameter and 0.5 mm deep.

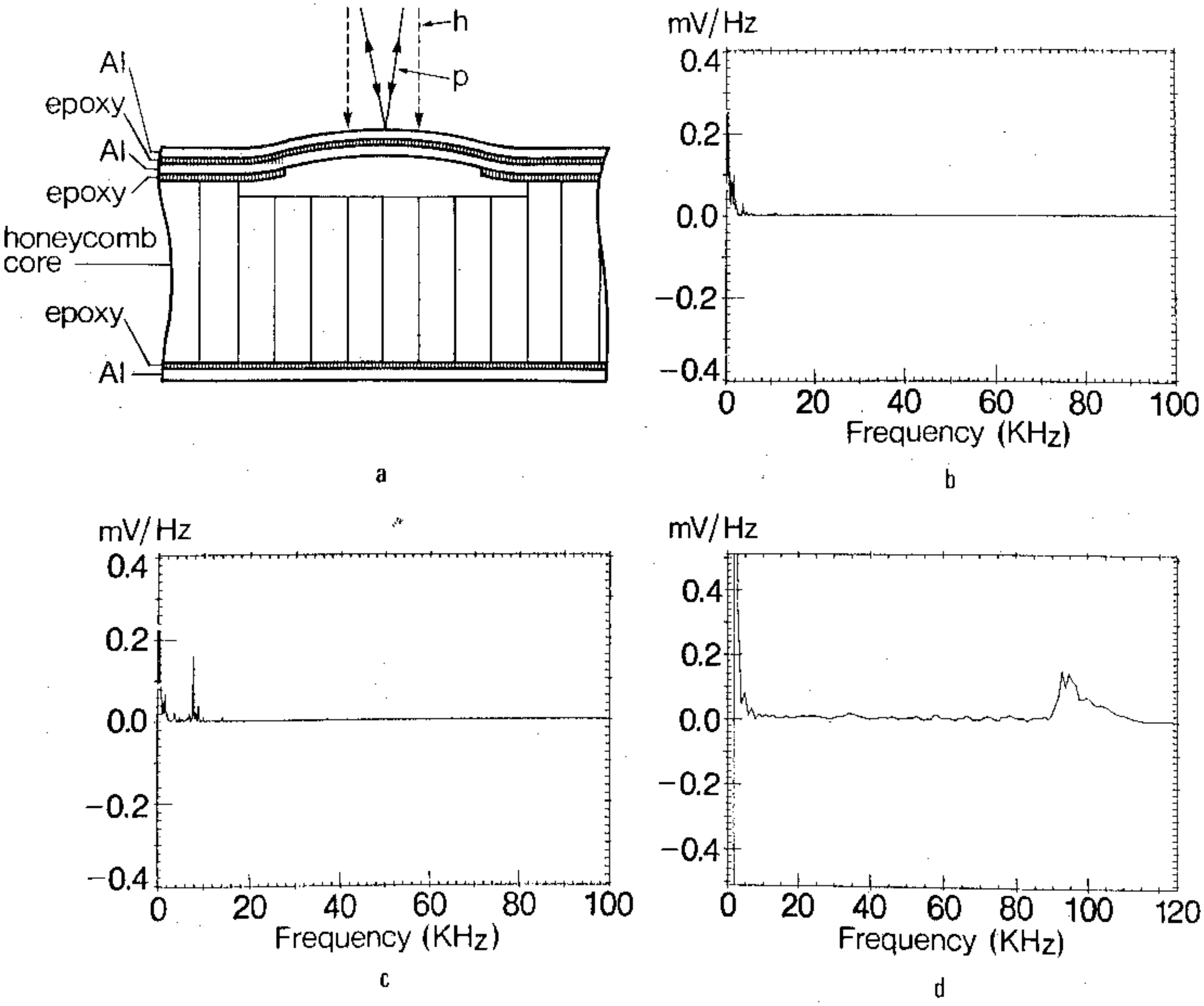

Fig. 5: Thermoelastic inspection of a metal-to-core laminate by the thermoelastic technique; (a): cross-section of the inspected laminate with a crushed-core, nearly 1" X 1" unbond; h and p denote the heating and the probing beam, respectively; (b) to (d): magnitude spectra of the signal detected: (b) on the top surface in a well-bonded area, (c) on the unbonded area and (d) on the bottom, well-bonded surface at the center of a honeycomb cell.

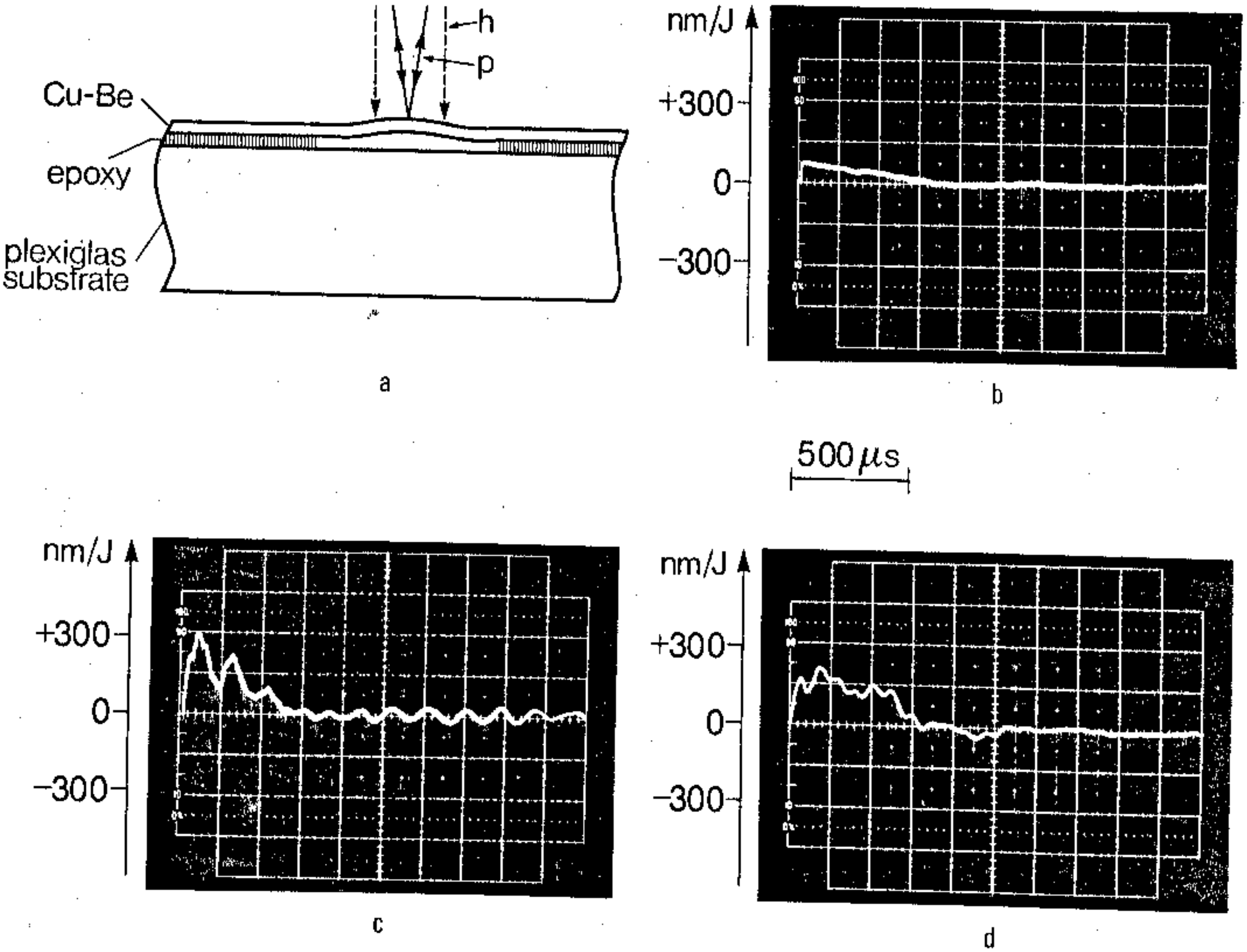

Fig. 6: Thermoelastic inspection of a 0.82 mm-thick Cu-Be plate adhesively bonded to a plexiglas substrate with nearly 1" diameter lack-of-adhesive defects; (a): experimental configuration, where h and p denote the heating and probing beams; (b): signal obtained on a well-bonded area; (c): signal obtained over an air-filled missing-epoxy bonding defect; (d): signal obtained over a water-filled bonding defect.