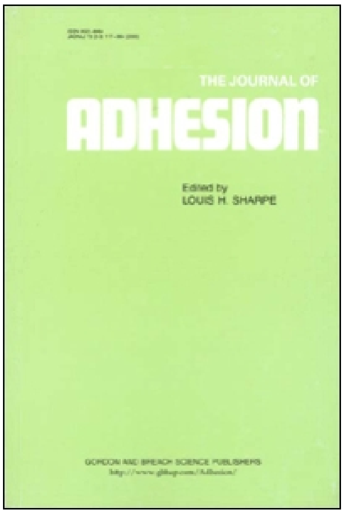

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Internal Stresses Adjacent to a Hole Through a Multilayer Wiring Board†

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The normal displacement field close to copper plated-through holes (PTH) in multilayer laminated circuit boards that is generated during thermal expansion is strongly inhomogeneous. By adhering a thin, and therefore flexible, microscope cover slip to the top surface of the laminate, Fizeau optical interference fringes can be generated between the cover slip and an adjacent optical flat and used to map the displacement field; the precise distribution of these fringes changes when the distance between the two is changed by thermally expanding or contracting the laminate. Thin plate elasticity theory applied to the cover slip permits the distribution of normal stress in the laminate to be estimated. Moving radially outwards from the centre of a PTH the normal stress is found to oscillate in sign in a highly damped manner such that the amplitude is insignificant beyond the first cycle. The largest normal stresses in the laminate are found to act at a radial distance corresponding to the outer edge of the copper surface pad. Thus, with increase of temperature, there develops a circular locus of tensile normal stress in the laminate\pad combination at a radius less than, but immediately adjacent to, the edge of the pad and a locus of normal compression in the laminate alone at a radius slightly greater than that for the outside edge of the pad. Both the tensile and compressive peaks increase at a rate of 1.6 MPa/K. With decrease of temperature the opposite holds true except that the stressing rate is lower at 0.6 MPa/K. The fact that, independent of whether the temperature is increased or decreased from room temperature, there exist annular regions of tensile stress within and normal to the plane of the laminate explains the occurrence during changes of temperature of hidden delaminations, including, in multilayer circuit boards, debonding of interlayer copper conductors. The similarity of this configuration to bolt holes in composite structures is discussed.

KEY WORDS Multilayer wiring board; moire fringes; thermal stress; plated through hole (PTH); optical interferometry; reliability.

1 INTRODUCTION

In general, composite multilayer circuit boards have large through-thickness thermal expansion coefficients. The mismatch in thermal expansion between board and copper in the vicinity of a PTH causes large stresses to develop during soldering or environmental temperature excursions. Heat absorbed and lost by

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the circuit board gives rise to inhomogeneous expansion and contraction causing the board to self-stress. In the vicinity of a PTH, the fact that the through-thickness thermal expansion coefficient of the board may be two to three times larger than its in-plane coefficients of copper, gives rise to complex localised deformations and causes plastic deformation and fracture of the PTH copper barrel.[1-3] These deformations have previously been examined using both holographic and mechanical[4] techniques. This paper describes a novel optical interference method for examining the deformation which also allows estimates to be made for the stress field in the PTH vicinity.

2 EXPERIMENTAL

In this study a 2.5 mm thick 11-ply polyimide-glass fibre (0°/90° weave) multilayer circuit board manufactured by Martin Marietta Corp was used. Plated through holes were of 0.8 mm diameter and the thickness of copper plating was 30 μm. The ends of each hole were teminated by 0.5 mm thick copper pads in the form of a flat ring with internal and external diameters 0.8 mm and 2 mm respectively, this pad thickness being somewhat larger than the usual thickness of 0.05 mm used on most MLB. As pointed out by Hagge,[1] this configuration is similar to a bolted joint, the head of the bolt being analogous to the copper surface pad, which acts as a "grip" on the multilayer circuit board. This is particularly so in the case of hollow bolts where the bolt now constitutes a lining analogous to the copper sleeve on the walls of a PTH.

The through-thickness displacement field of the board during thermal cycling was recorded at given temperatures by photographing Fizeau optical interference fringes, generated by the optical system of Figure 1, between an optical flat and the free surface of a thin glass cover slip adhesively bonded to the upper surface of a horizontally-supported board. This experimental configuration is an adaptation of that used by Sargent and Ashbee to examine deformation in adhesive joints due to water uptake.[5] Since the laser is a source of monochromatic coherent light, the optical flat can be located some distance from the specimen assembly. This minimises heat transfer to the optical flat.

The interference fringe patterns reflect precisely the surface topography of the cover slip and, since the cover slip is thin, also the underlying circuit board; they are contours of constant distance between the cover slip and the optical flat, the contour level with respect to the flat differing by $\lambda/2$ from one dark or bright fringe to the next. Heating of the circuit board leads to deformation in the neighbourhood of the PTH and, in particular, changes the shape of the cover slip which, in turn, alters the pattern of interference fringes. Direct observation and recording of these changes could be used to measure increments of the deformation. However, it is more convenient to process the information in the fringe patterns by superimposing, on the interference pattern photographed initially at room temperature (20°C), subsequent photographs of the modified pattern at different temperatures. The superimposition generates moiré fringes,

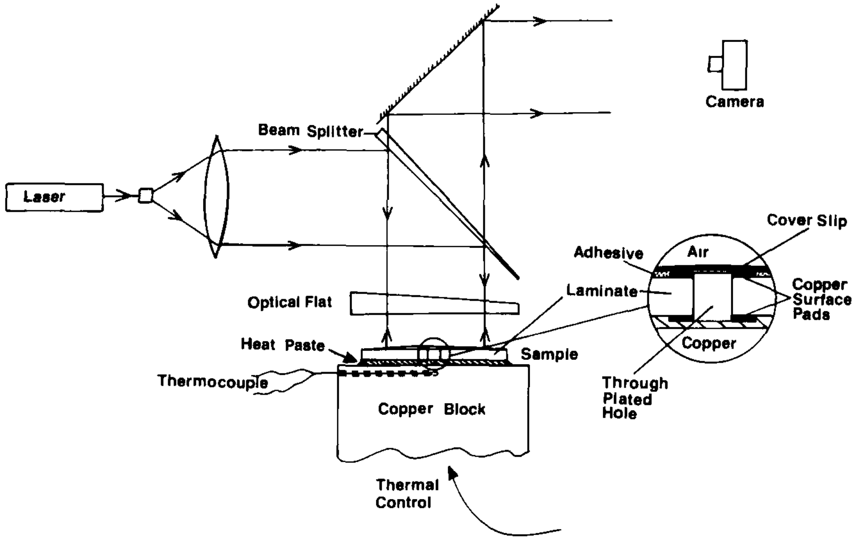


FIGURE 1 Optical system used to generate and record interference fringe patterns around a through-plated-hole in a composite multilayer circuit board.

the spatial distribution of which faithfully follow changes in shape of the cover slip.[5]

When patterns with nearly-identical periodic structures are made to overlap, moiré fringes are generated. In the present experiments it is the photographic images of the interference pattern that constitute the nearly-identical periodic structures and it is small differences in the pattern, seen on comparing the image photographed at a given temperature with an image taken at the initial temperature, that give rise to the moiré effect. In Figure 2 the fine lines, several hundred across the field of view, are the interference fringes and the much thicker dark loops are the moiré fringes. As the temperature changes, local deformations around the PTH cause the glass cover slip to move towards or away from the optical flat. This gives rise to displacement of the interference fringes and hence to generation of moiré fringes. Successive moiré fringes are loci of positions which differ by half a wavelength in displacement normal to the cover slip, in which case the number of moiré fringes, N, that pass a given point is related to the normal displacement, w, of the board by:

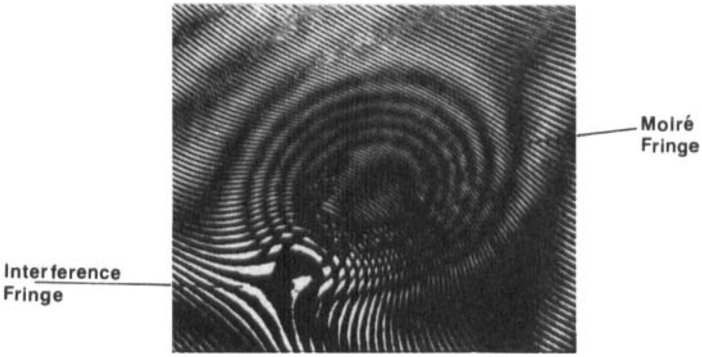
$$w = N\lambda/2$$

λ = wavelength of light (632.8 nm).

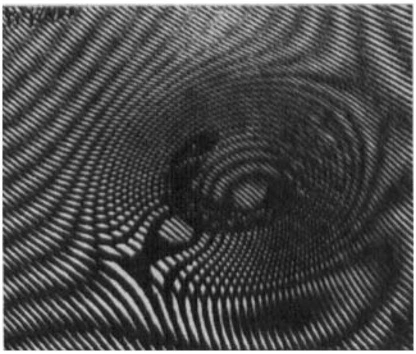
3 RESULTS

Figure 2 shows development of a sequence of moiré fringe loops in the vicinity of a PTH during a thermal cycling operation (−40°C to 50°C). The large displacements observed at high temperatures require moiré patterns to be formed between interference patterns recorded at successive temperature steps; the total displacement from that at the initial temperature is the sum of these. The displacement, normal to the board and across a hole diameter, is plotted in Figure 3. During cycling to low temperatures the laminate contracts to a much greater extent than does the copper sleeve. As a result the displacement has the form of a flat-topped dome and it is evident that the copper pad is behaving as a rigid body and does not itself deform. During the high temperature portion of the cycle the displacement takes the opposite form, the laminate now expanding and stretching the copper sleeve. In the latter case it should be noted that the copper surface pads are acting as "grips" restricting the expansion of the laminate by transmitting stress to the copper sleeve.

To ensure that the observed normal displacement in the locality of the hole relative to that remote from it is due to the presence of the copper sleeve and is

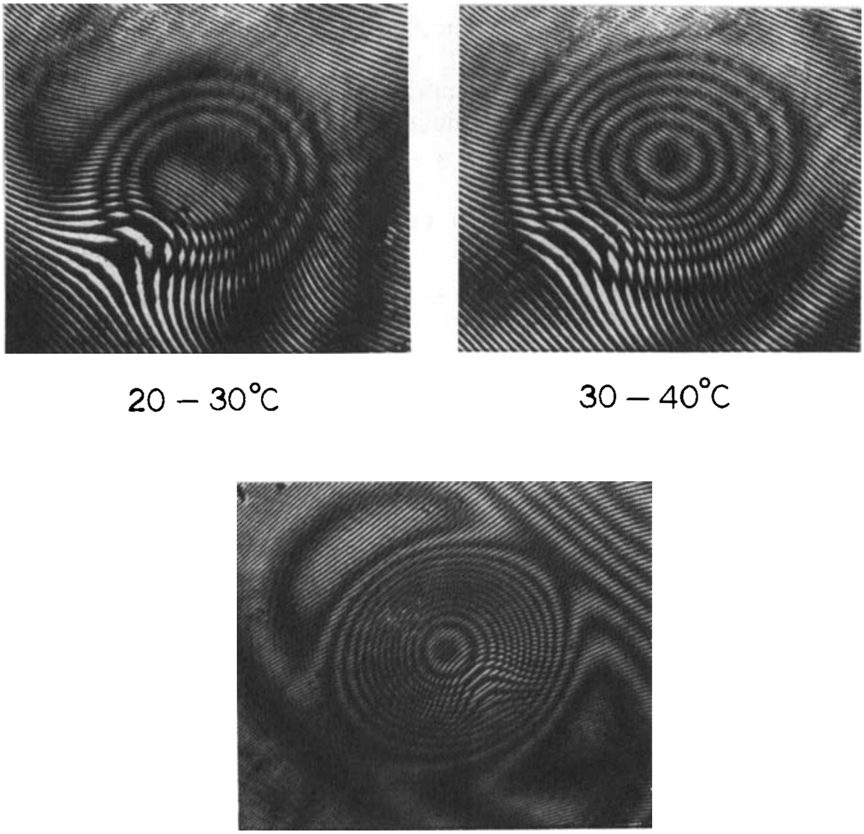


20 – 0°C



20 – -40°C

FIGURE 2 Moiré fringe loops created by superimposing two interference patterns recorded at the specified temperatures. The elliptical form of the moiré fringes derives from use of a non-parallel-sided beam splitter. The true fringe diameter corresponds to that of the minor axis in the loops photographed here.



20 – 30°C

30 – 40°C

40 – 50 °C

FIGURE 2 (*contd.*)

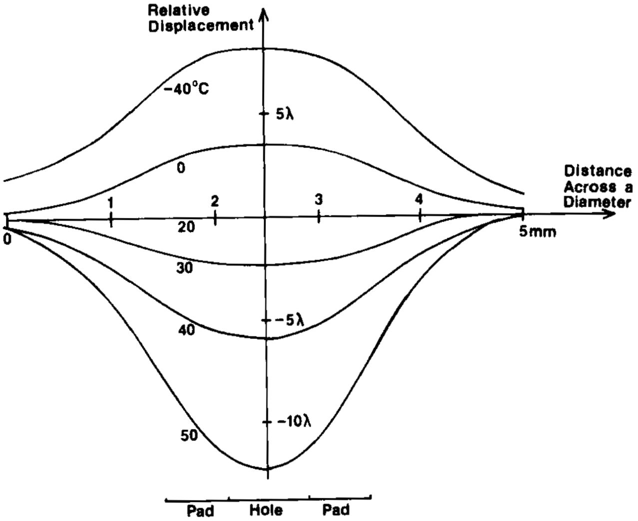


FIGURE 3 Normal displacements across a hole diameter, measured from Figure 2.

not, for example, an out-of-plane manifestation of the highly-anisotropic thermal expansion properties of the circuit board, the thermal cycling experiment was carried out for a coverslip bonded over a 0.8 mm hole that had no copper sleeve. No relative displacement was observed in the vicinity of the hole at any point in the cycle. This also confirms that the thin adhesive layer between the coverslip and the sample does not itself give rise to any significant through-thickness displacement.

4 ESTIMATION OF THE STRESS FIELD

It is evident from the measured displacements that large localised stresses are generated aroung the PTH. By way of Love's[6] analysis for the displacement field in a thin plate deformed by a pressure difference across its faces, estimates for the normal stresses in the glass cover slip have been calculated as follows:

$$D\nabla^4 w = -p$$

where p = normal pressure
D = flexural rigidity, given by $D = 2Eh^3/3(1-\gamma^2)$
E = Young's modulus (70 GPa[7]),
$2h$ = thickness (0.315 mm),
w = axial displacement,
γ = Poisson's ratio (0.3[7]), all of the cover slip

This analysis is valid for thin plates provided that the normal displacements are small so that the plate is subject to little lateral stretching. To a first approximation, the deformation of the cover slips used in the present experiments conforms to these criteria and the normal pressure, p, may be equated with normal stress. The axial configuration is more suited to analysis in cylindrical polar coordinates (r, θ, z) and the operator ∇^4 becomes

$$\frac{\partial^4}{\partial r} + \frac{2}{r}\frac{\partial^3}{\partial r} - \frac{1}{r^2}\frac{\partial^2}{\partial r} + \frac{1}{r^3}\frac{\partial}{\partial r}$$

There being no dependence on θ (axial circular symmetry) nor z (thin plate).

Figure 4 shows the first four differentials of $w(r)$ and $\nabla^4 w$ for the displacement at 50°C in Figure 3. It is evident that the shape of the fourth differential dominates the form of $\nabla^4 w$. However, there is a scaling difference between $\nabla^4 w$ and $\partial^4 w/\partial r^4$ and, in addition, further examination reveals that, in $\nabla^4 w$, the peaks at small radius are magnified with respect to those at larger radius. The differentials shown in Figure 4 were generated graphically by hand. The reason for this procedure lies in the difficulty of differentiating four times a discrete set of data points where a small amount of scatter in the initial displacement data leads to wild oscillations in the differentials. Between each differentiation step the curve was smoothed to avoid this problem and, in the absence of sufficiently sophisticated software, this was done by hand. To qualify this method Figure 5

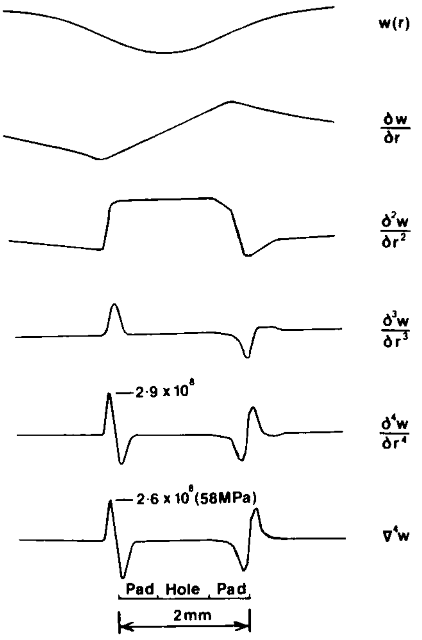


FIGURE 4 Graphical differentiation of the displacement $w(r)$ at 50°C, see Figure 3.

shows the minimum and maximum deviants of $\nabla^4 w$ derived from one half curve in Figure 3. This gives an error of ∓30% in peak height (maximum stress) and an error of ∓0.03 mm in radial positional. Positive stress values correspond to tension in the laminate (or laminate/copper pad combination) and negative values to compression.

Figure 6 plots the normal stress distributions across a diameter derived from the displacements at −40°C and 50°C as measured during the thermal cycle.

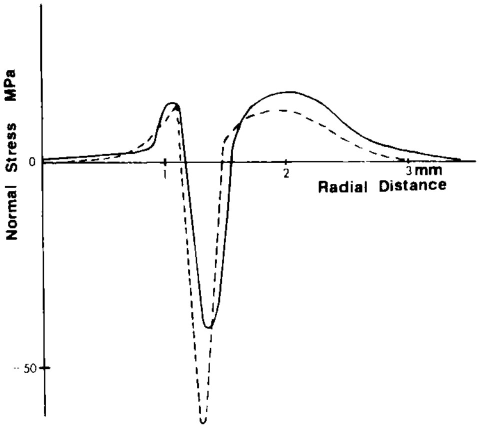


FIGURE 5 Maximum and minimum deviants obtained using graphical differentiation technique.

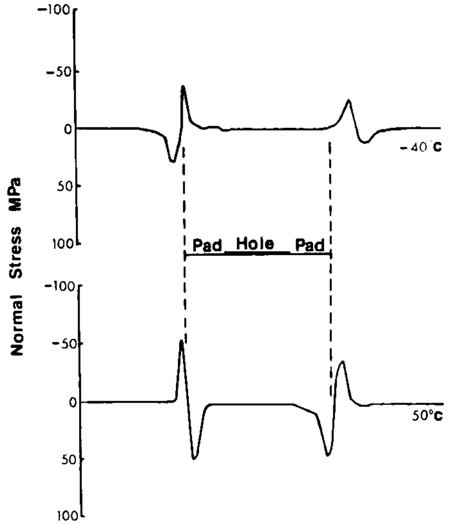


FIGURE 6 Radial stress distributions generated from displacements in Figure 3 for −40°C and 50°C during thermal cycle.

5 DISCUSSION

In Figure 6 the normal stresses shown are those generated at the extremes of the temperature cycle; they are opposite in sign above and below room temperature, and are associated with the outside edge of the copper surface pad. At high temperatures there exists an annular ring of normal tension in the pad\laminate combination at a radius slightly less than that of the copper pad, and an annular ring of normal compression in the laminate alone at a radius slightly greater than that of the pad. At low temperatures the opposite form is found. In both cases the only significant stresses are those in the locality of the pad edge. Those everywhere else are close to zero. Above room temperatures (20 to 50°C) the peak stresses increase at a rate of around 1.6 MPa/K whilst below (20 to −40°C) the rate is somewhat less at −0.6 MPa/K. The fact that, independent of whether the temperature is increased or decreased from room temperature, there exist annular regions of tensile stress within and normal to the plane of the laminate explains the occurrence, during changes of temperature, of hidden delaminations, including, in multilayer circuit boards, debonding of inter-layer copper conductors. The above results indicate that the largest normal through-thickness stresses in the laminate occur at high temperatures.

The deformation characteristics of PTH have been studied for many years[1–4] and characterised in terms of manufacturing parameters, copper ductility,[8,9] laminate fiber content and resin glass transition temperature. In all of these studies it was concluded that the PTH barrel extends plastically during soldering and also that the copper surface pads are rotated out of the plane of the laminate. Both these effects lead to fracture of the copper either within the barrel, leading to a barrel crack, or at the interface between the copper pads and the barrel at the ends of the PTH. In each case the fracture may be partial or complete; the former causes the electrical connection to be severed immediately while the latter can fail due to thermal fatigue crack extension. In earlier work[10] the authors have found that soldering operations on a PTH with the thick copper surface pads removed does, indeed, lead to plastic barrel extension. However, in the present experiment the effect of the thick copper surface pad is to reduce significantly the barrel extension but only at the cost of generating large tensile and compressive stresses in the laminate around the edge of the pad.

A somewhat similar distribution of thermal expansion stresses is believed to exist adjacent to bolt holes in thick laminates. As a general principle, it is recommended that the diameter of the bolt be larger than the thickness of the laminate and, in order not to impose any weight penalty, it is common practice to make the bolts hollow. Thus, the bolt hole is effectively lined with a metal sleeve, not unlike the metal sleeve deposited inside holes through printed circuit boards. Figure 7 compares the two cases and illustrates the possible origin of delaminations that are frequently found around but immediately adjacent to bolt holes. The situation at low temperatures can be examined by reversing the nomenclature in Figure 7. The largest normal tensile stresses in the laminate are found to occur at high temperatures and are believed to be those responsible for initiation of delamination. Note that subsequent temperature cycling will tend to propagate the delamination once initiated, Figure 7.

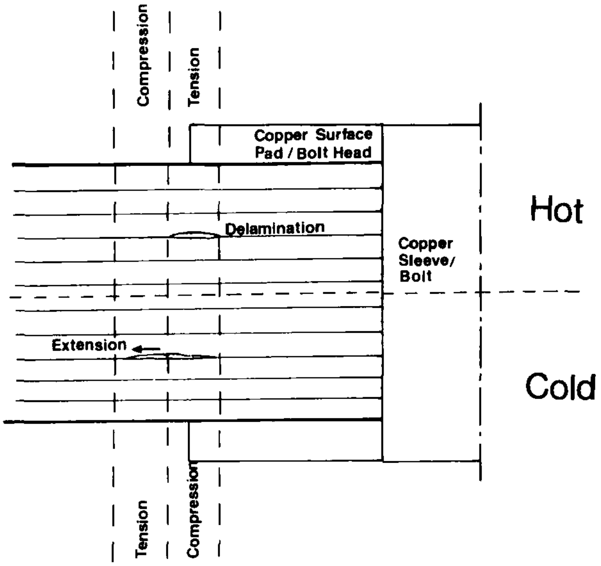


FIGURE 7 Comparison of the stress distribution and potential delamination sites around a through-plated hole and a bolted joint in a laminate.

Acknowledgment

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