Micromechanics of multilayer printed circuit boards

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Analytical and experimental techniques are reported for the evaluation of micromechanical components in multilayer printed circuit boards. The concern in this investigation comes from the *Z*-axis thermal mismatch between epoxy-glass and copper that generates stresses when the board is subject to a temperature change. Finite-element modeling for both plated through-holes (PTH) and buried via (PV) structures is used to calculate the stresses in the copper barrel and at the via junctions. A simple experiment is designed to measure the thermomechanical strain in the PTH barrel. Also discussed are the PTH peel and PV pull techniques which have been used to characterize the barrel-laminate adhesion and the via junction strength.

Introduction

A multilayer printed circuit board (MLB) is a laminated composite which comprises a number of layers of power planes, dielectrics, and signal lines. Because of the requirements for high-density packaging, the design of interconnections between components or modules becomes important. The conventional interconnection between circuit layers and the surfaces is achieved by the mechanically drilled [1] plated through-holes (PTHs). A typical cross section is shown in **Figure 1**. In the IBM 3081 processor technology, for communication between the printed circuit lines on each side of a signal core, a new type of laser-drilled via called a programmable via (PV), shown in **Figure 2**, has also been used. These tiny PVs are buried within the circuit board and totally surrounded by epoxy-glass. Because of the requirement for the tremendous number of PTHs and PVs in today's technology, these interconnections are made so small that they can be examined only under the microscope. Accordingly, micromechanical modeling and testing must be used to analyze those small PTHs and PVs. An overview of the advances in IBM 3081 technology and design process was given by Pittler et al. [2]. A discussion of the board design and the associated manufacturing process was given by Seraphim [3].

To meet the performance required mechanically and thermally, these MLBs are designed with a content of glass yarn sufficient to provide a thermal match with copper circuits in the signal plane (*X-Y* plane). However, due to the absence of fibers in the direction normal to the board (*Z*-axis), a mismatch in thermal expansion occurs between the laminate and the PTH barrel whenever the board is subject to a temperature change. For the integrity of the PTH, thermal strain in the *Z*-direction becomes the main concern. During the manufacturing of MLB, perhaps the most severe thermal excursion for the PTH occurs in the soldering operation. The circuit board usually attains a high temperature well above the glass transition temperature (T_g) of epoxy-glass. The difference in thermal expansion normally results in a large thermomechanical strain in the copper barrel.

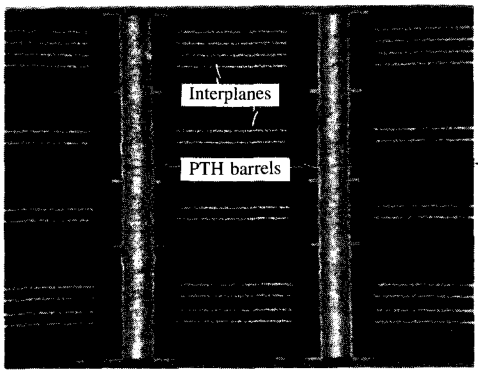


Figure 1

Cross section of a plated through-hole.

Figure 2

Cross section of a typical programmable via.

Toward the understanding of the mechanics of PTH, a simple analytical model was developed by Oien [4] to obtain the relationship between the thermomechanical deformation of a PTH and its failure mode. In the present paper, a linear elastic finite-element analysis was used for simplicity. An axisymmetric model was first generated for a typical PTH. Thermal stresses were then calculated with and without the presence of solder and pin. In order to understand the effect of a cracked barrel on solder flow, a PTH with an initial crack gap was also modeled.

In order to measure the thermal strain in the barrel, we have designed a hot plate experiment to study the PTH behavior. Deformations in the copper barrel as well as in the laminate were measured. A substantial increase in barrel strain at temperatures above T_g was distinctly observed. A technique using a LVDT displacement sensor was also developed by Ammann and Jocher [5] to measure the central barrel strain.

Since the reliability and the integrity of a circuit board often depend on the adhesion characteristics of the composite, various methods have been used to characterize the bond strength at copper-copper or copper-laminate interfaces. Among those destructive testing techniques, the peel test is perhaps the most effective and simplest to perform. This is because the peel load creates a high local stress at the interface and tests the bond in its weakest mode. For many years, the conventional PTH pull test has been used to test the barrel strength, where the barrel is pulled out of the board by applying a load to a pin soldered in the PTH. However, because of the roughness in the hole a large amount of scatter was always observed in the pull strength. Also, because of the shear type of failure in the copper, this test does not really characterize the adhesion. A peel test was then developed for this purpose. The procedure of peeling through the thickness of a cross-sectioned PTH sample not only provides the copper-laminate adhesion but also determines the strength at copper-copper connection.

PV junctions, just like PTH-interplane junctions, are mechanically and electrically critical joints. They are formed from copper deposits plated in two stages [6]. The nature of the bond between the two copper layers is ideally supposed to be "metallic" with minimum mismatch of lattice array. For the reliable performance of MLBs in subsequent processing, handling, and field operations, the quality of these junctions must be good enough to withstand thermal shocks, mechanical abuse, and strains due to incompatibility with surrounding materials of the board. Therefore, the development of a representative and reliable technique to monitor the quality of the via junctions became an inevitable task.

To evaluate the quality of via junctions, the previous techniques, although faster, used either soldering or welding involving high temperatures (300°C–750°C) which were feared to deteriorate the bond before testing. Besides, interference of surrounding material (glass and epoxy) remained during testing. This resulted in low strength and large scatter in the data. The technique discussed in this paper eliminates all the problems encountered in the past and has been proved to be appropriate and reliable.

In an attempt to make this paper more complete, we have included and extended some of the work which was discussed in a recent paper [7].

Finite-element modeling

Knowing that the composite board is made of biaxially woven glass fabrics, epoxy, and copper, one can expect the board to have anisotropic thermal and mechanical properties. In the calculation of the equivalent material properties, two realistic assumptions can be made to simplify the model. First, one can decompose the composite into a number of layers of unidirectional laminates, based on the fact that the crimps in the glass fabrics are small. Second, the

Table 1 Materials properties used in modeling (10^6 psi = 7 GPa).

	Pin	*Solder*	*Copper*	*Epoxy/Glass*
E (GPa)	140	21	119	$E_{xy} = 22.4$; $E_z = 1.6$
ν	0.3	0.3	0.35	$\nu_{xy} = 0.02$; G_{xy} = 0.63 GPa
α [(10^{-6}) mm/mm/°C]	5	17	17	$\alpha_{xy} = 15$; $\alpha_z = 90$

composite can be considered orthotropic by assuming isotropy in the plane of the board. The material properties used here for the constituents are shown in **Table 1**.

ANSYS [8], which is a large-scale, general-purpose finite-element program, was used throughout the entire analysis. In modeling the PTH and PV, due to the symmetry of structural geometry and loading, a two-dimensional axisymmetric analysis was proved to be appropriate. Linear elasticity was also assumed here to simplify the analysis.

• *Plated through-holes (PTHs)*

Axial stresses due to temperature loading were first calculated for a typical PTH which is shown in Fig. 1. Because of the symmetry with respect to the center of the board, only one half of the PTH was analyzed with the application of appropriate boundary conditions. This symmetrical layup is believed necessary in preventing warpages due to lamination. The simulated finite-element model is shown in **Figure 3**.

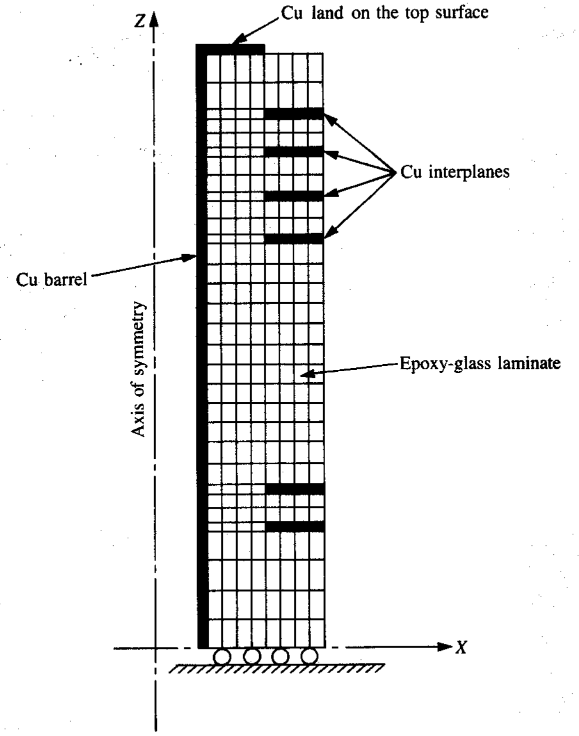


Figure 3

Finite-element model of PTH.

By using this model on the ANSYS program, the stress distribution was obtained for a 10°C temperature change. Because of the greater thermal expansion of epoxy-glass, the copper barrel was stretched along the Z-axis and acted as a constraint to the composite. Maximum tensile stress in the barrel is approximately 28 MPa (4000 psi compared to copper tensile strengths in the neighborhood of 35 kpsi), while epoxy-glass is under compression in order to be in equilibrium.

In general, a wave-soldering process is used for this type of board. The soldering temperature could be as high as 215°C for eutectic solder. Based on the present analysis, one can easily see that large plastic deformation in the PTH barrel is expected during soldering, especially at temperatures above T_g (T_g = 125°C for epoxy-glass).

When solder flows into the PTH during wave soldering, it is very possible that pumping action occurs in the lower half of the hole, while the upper half is under capillary action. An interesting question arises: If there existed an initial barrel crack, which could be due to plating deficiency or copper quality, would this crack open enough to cause solder flow to stop? To answer this question, a model was created to calculate the crack gap growth with respect to barrel thickness, initial gap, and PTH spacing. The results are shown in **Figure 4**. In all cases, if no debonding occurs between the barrel and the laminate, the gap growth is very small; i.e., the solder flow is not affected by the thermal

Cu thickness (mm × 10^2)	*Gap* (mm × 10^2)	*PTH spacing* (mm)	Sig_{max} (MPa)	*Gap growth* (mm × 10^4)
1.27 (0.5 mil)	2.54 (1 mil)	1.27 (0.05 in.)	41.82 (6065 psi)	1.42 (5.6 μin.)
2.54	2.54	1.27	28.72	1.85
3.81	2.54	1.27	22.7	2.11
2.54	2.54	2.54	60.21	3.43
3.81	2.54	2.54	52.41	4.32
2.54	2.54	2.54	61.62	2.3

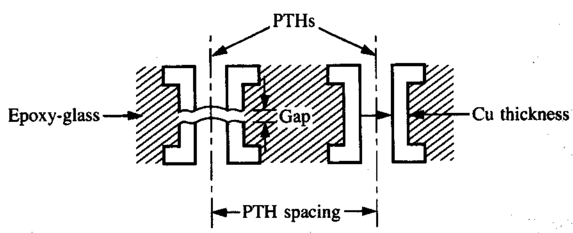
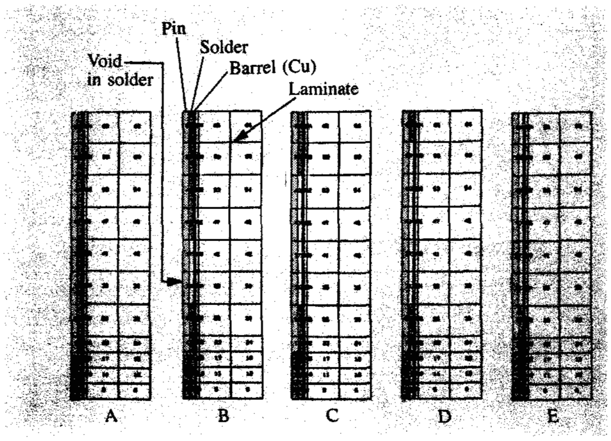


Figure 4

Finite-element results for PTH with initial crack gap (ΔT = 10°C).



Pin	30.32	33.75	32.02	29.55	14.57
Solder	5.96	5.86	4.72	2.89	
Barrel	30.42	36.64	36.16	37.40	51.83

Figure 5

Maximum σ_z stresses (MPa) for $\Delta T = 10°C$.

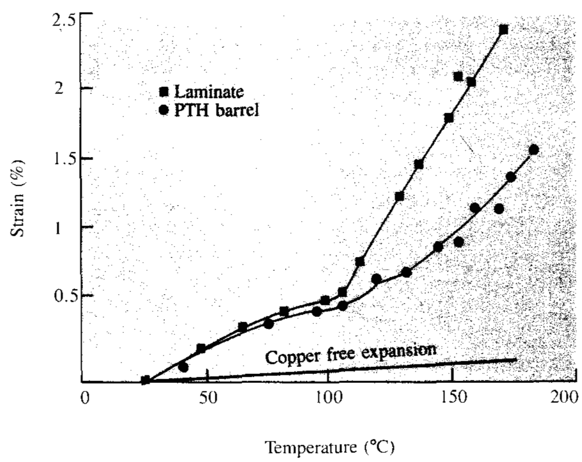


Figure 6

Thermal strain in PTH barrel length.

expansion unless the initial gap was large. However, if debonding does occur at the barrel-laminate interface, one can expect the crack to grow freely with the board expansion and to result in defective soldering. In today's production of IBM's circuit boards, peel tests performed at elevated temperatures have shown good barrel-laminate adhesion characteristics, which in turn ensure the PTH integrity.

Since the PTH barrel is reinforced with solder and pin after the soldering process, one would like to know how these additional materials affect the barrel stresses under a thermal loading. The finite-element results for $\Delta T = 10°C$ are shown in **Figure 5** with respect to 2.5-mm (100-mil) PTH spacing. It is seen that the presence of solder and pin reinforces the PTH and reduces the barrel stress by approximately 40% (Case E vs Case A). For comparison, the values were also calculated for holes with partial solder fill or solder voids. As one would expect, the presence of a solder void results in greater barrel stresses (Cases B, C, and D vs Case A).

- *Programmable vias (PVs)*

Because of the importance of the PV in the interconnection technology of MLB, a significant amount of work has been done to study the performance and behavior of this tiny, complicated structure. A typical PV, which is used to interconnect the signal planes, is shown in Fig. 2. The center of the plated via is usually filled with pure epoxy as a result of subsequent lamination. Again, due to its symmetry in geometry and loading, an axisymmetric model was generated with regular four-node isoparametric elements, in conjunction with some crack-tip elements [9]. These special elements were used to interpret the stress singularity at the sharp edge of the copper-copper interface.

A temperature loading of $\Delta T = -10°C$ was first analyzed. Tensile stresses are observed in epoxy and epoxy-glass regions due to their greater thermal expansion. It is interesting to know that normal stresses at the copper-copper interface are not uniform and they vary from tension to compression. This can be explained as a bending effect resulting from the particular shape of the PV.

To study the PV in the module site, where the laminate is constrained by the PTHs, mechanical loading was applied to simulate the temperature loading. Due to the presence of a PTH, a buried PV is subject to tension when $\Delta T < 0$, as can be seen from the previous results for PTH modeling. Finite-element results for the case with $\sigma_{z\infty} = 7$ MPa (1000 psi) were analyzed. They revealed that the entire structure is mostly under tensile stresses except in the center of the connection interface. These compressive stresses are again due to the bending effect.

Several other cases with respect to various geometry and PV locations were also investigated. It was observed that, in all cases, stresses are much higher at the edge of the connection, where stress concentration occurs.

Experimental techniques

- *Thermal excursion experiment*

In order to measure the thermomechanical strain in the PTH barrel when the MLB is subject to a temperature change, a simple but appropriate technique was developed using a temperature-controlled hot plate. A cross-sectioned, thin PTH sample is placed on the hot plate, which sits on an *X-Y* micrometer stage. Because the temperature gradient is small in the sample, and also because the symmetry is preserved with respect to geometry and loading, this one-half PTH sample readily simulates the expansion behavior of a whole PTH in the board.

The sample was slowly heated to various temperatures; the displacement measurements were made under a microscope. For the case of a 4.6-mm- (0.18-in.) thick MLB made of epoxy-glass and copper, the strain of the copper barrel and of the region between the PTHs is plotted in **Figure 6**. Note that, above the glass transition temperature of epoxy (~125°C), the board expands drastically in the *Z*-direction. As a result of this, a PTH barrel experiences much higher strains in this temperature range.

It should be pointed out here that in this test, the board thickness was used as the gauge length to calculate the total strain in the barrel length. Since the barrel strain is not uniform throughout the hole, the measured strain represents only the average value, which is about 80% of the maximum strain. An improved technique using a hot stage microscope is under investigation for better temperature control and greater accuracy.

- *PTH peel test*

The importance of the barrel-laminate adhesion leads to the question of how to experimentally determine the bond strength. Since the conventional PTH pull test was not appropriate for this objective, a cross-sectioned PTH peel test (**Figure 7**) had to be developed. Hurdles were encountered due to the large aspect ratio and the small size of the hole. After much experimentation for feasibility and consistency, this technique was proved to be reliable. Although it may be time-consuming for use in production quality control, this technique is a good tool for development work, for ranking and comparison of various products and processes.

Since both peel angle and peel rate could have significant effect on the measured peel strength, which in fact is an apparent adhesion strength, a 90° peel at a constant cross head speed was used. It is very important to keep these two parameters constant during peeling. The 90° angle can easily be achieved by the application of a long string joining the Instron cross head and the copper barrel. This causes the loading to remain always perpendicular to the sample without constant adjustment of the sample position. As to the effect of peel rate, it is as expected that the faster the peel rate, the greater the peel force. In order to standardize the test, a constant peel rate of 0.125 mm/min has been used.

Sample preparation is critical for this test. Our experience is that no more than one quarter of the barrel should remain on the sample; otherwise, the barrel is likely to break during peeling, probably due to the curvature of the PTH barrel.

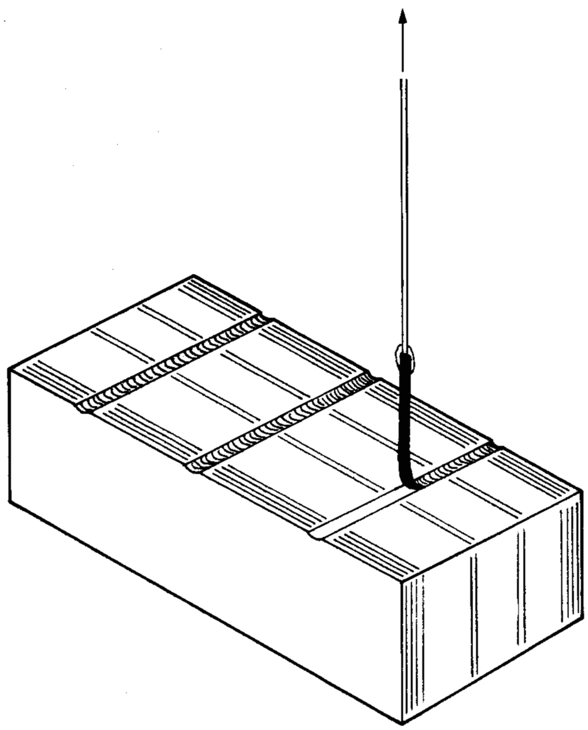


Figure 7

PTH peel test.

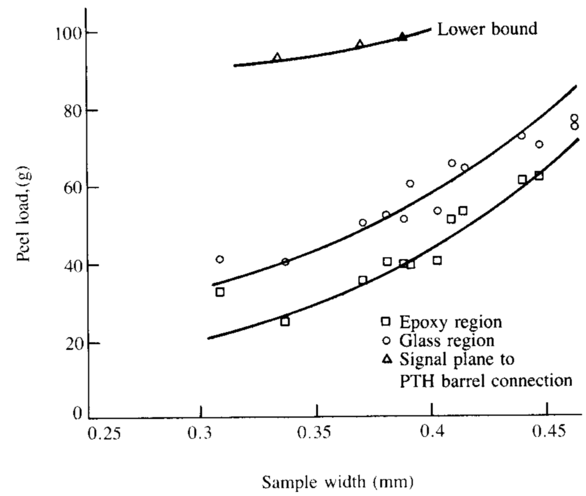


Figure 8

Typical PTH peel strength data for a 4.6-mm-thick MLB.

Valuable information was obtained from this test. Peeling through the layers of the composite showed mostly adhesive

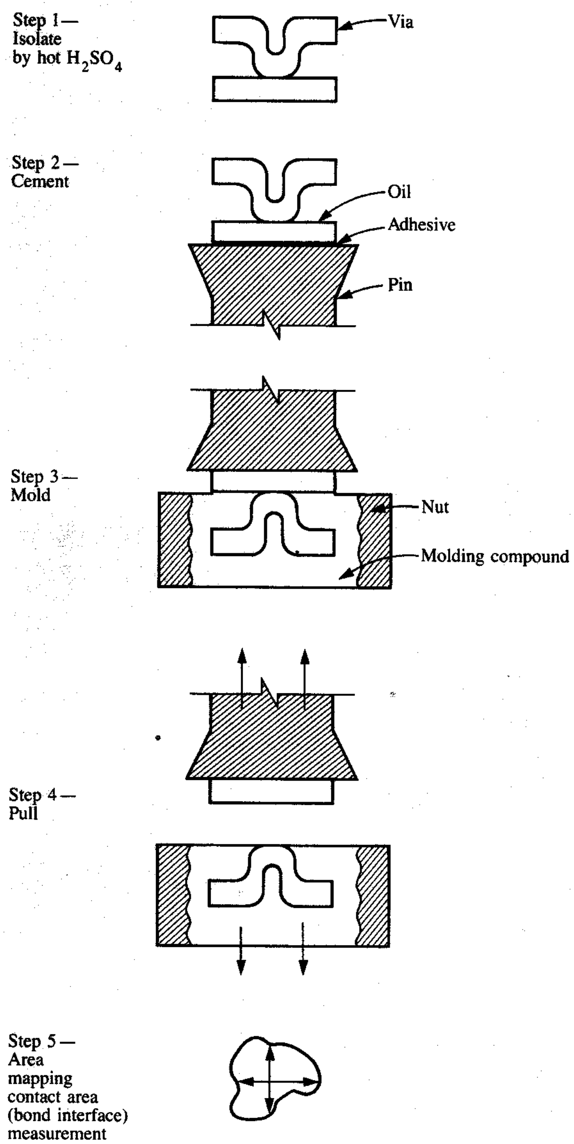


Figure 9

Micromechanical testing of programmable via.

failure at the barrel-laminate interface, except in the region with perpendicular glass fibers. Mechanical interlock between plated copper and fiberglass may have resulted in this cohesive failure in the copper. The typical peel strength data for an MLB are plotted in **Figure 8**. It is good to know that interplane connections (copper to copper) always experience greater strength than that of the epoxy or glass region. This can also be observed from the sharp radius generated when peeling through a copper connection. Because of the strong bonding of copper to copper, the barrel often breaks when peeling through the copper interconnection and only the lower bound of the strength can be recorded. Interface strengths, however, are found to be in the neighborhood of 30 kpsi, indicating a very good copper-to-copper joint.

• *PV pull test*

From the theoretical considerations, a simple mechanical pull test to measure the bond strength of a via was judged appropriate. Compared with a PTH, a PV is even smaller in size and more complex in geometry. This makes the development of a testing technique an even more challenging task. None of the routine equipment was directly applicable to do this testing except for an Instron tensile test machine to measure the pull force. Grips and fixtures had to be specially made for this micromechanical testing.

For consistency of testing, a procedure was developed comprising five steps: isolation, cementing, molding, pulling, and area mapping. **Figure 9** illustrates these steps.

Isolation of a via from a printed circuit board was necessary to avoid the interference of board materials (epoxy and glass strands) during the pull tests. This was achieved by the dissolution of epoxy in hot (85°C) concentrated sulfuric acid. **Figure 10** shows such an isolated via without any damage from dissolution. Cementing the pin to a via by a room-temperature-setting adhesive was used to avoid damages resulting from high-temperature joining techniques. Molding the inverted via-pin assembly was necessary to avoid the via wall failure before the separation at the bond interface during pulling. These three steps eliminated all the problems encountered in the attempted prior techniques by others.

The technique was successfully used to evaluate the quality of the via junctions. It proved to be sensitive enough to rank the processes according to the observed bond strength.

The data obtained for several different processes in via production were consistent and reproducible. The standard deviation ranged from ±5% to ±10%. This is due to the crude method used for measuring the contact area, which appeared to be of irregular shape (Fig. 9, Step 5). To further improve the accuracy of the results, use of an image analyzer in conjunction with the microscope is recommended for precise measurement of contact area.

Although the testing procedure seems complicated and time-consuming, automation by means of suitable fixturing and simultaneous testing of a number of samples can reduce the time considerably, if the testing has to be done on a routine basis.

Discussion

On the basis of today's level of complexity in electronic packaging, one can expect a more sophisticated mechanical design in the future. Since experimental techniques and closed-form solutions are not always available for analyzing tiny and complex structures, finite-element modeling becomes a valuable tool in solving this type of problem.

Although a peel test is easy to perform and ideal for ranking and comparison, the interpretation of the peel strength (e.g., g/mm) deserves a comprehensive mechanics analysis [10, 11]. It is learned, from a finite-element modeling of copper peeling off epoxy laminate, that peel strength varies with copper thickness and elastic moduli of copper and laminate. That is to say, peel strength is only an apparent adhesion strength. Moreover, the peel load is not linearly proportional to the actual adhesion strength; a small increase in the adhesion strength causes a much larger increase in the applied peel load. This occurs because the applied bending moment, rather than the applied load, plays the important role in peeling.

In view of the fact that the thickness, moduli of Cu, and laminate material are fairly constant for the same product, and that 90° peel maintains the same moment arm during the test, it is obvious that the results of the peel test can be relied upon in assessing the relative adhesion strength of PTH barrels.

The PTH peel test appears to be a good technique for barrel-laminate adhesion for thick MLBs, even with large-aspect-ratio PTHs. However, it does not appear to be adequate for thin boards because of the short working length of the barrel. To obtain barrel-laminate adhesion for short PTH (<2 mm), a cross-sectioned PTH pull technique could be used, where a normal force is applied to the barrel and the tensile strength of the bond is directly measured. With the pull technique, an averaged barrel-laminate adhesion rather than the through-thickness variation can be determined.

The quality of the bond produced at the via junction and PTH junction should be the same as long as the same process conditions are maintained in both cases. Therefore, the evaluation of the quality of bond at the via junction should also be indicative of the quality of bond at the PTH-interplane connection. This has been verified by the results in PTH peel tests.

Summary

This study has shown that the finite-element analysis is a valuable tool for analyzing the stress distributions in PTHs and PVs of printed circuit boards, because of their extremely small dimensions.

For PTHs, such analysis indicated that stresses leading to plastic deformations of the PTH barrel are possible during soldering operations. However, such risks can be reduced by having a strong barrel-to-laminate adhesion, good ductility of Cu deposits, pin reinforcement, and voidless solder in the PTHs.

The importance of the PTH barrel-laminate adhesion led to the development of the PTH peel test. The test is useful in evaluating the relative quality of PTH adhesion to epoxy, glass, and copper interplanes.

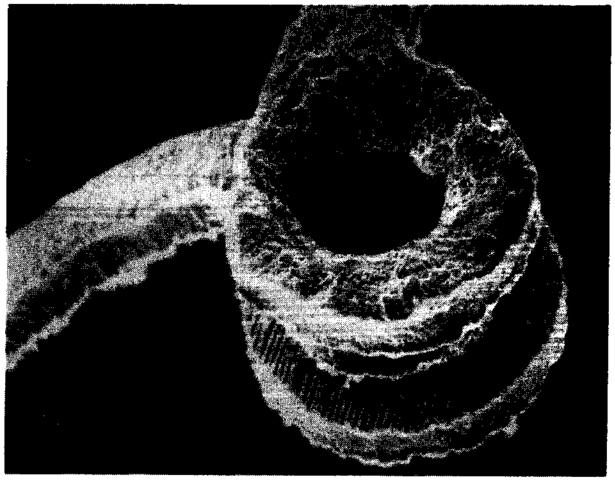


Figure 10

Isolated programmable via.

In the case of PVs, the analysis showed that, because of the particular shape of the PV, the stresses at the Cu-to-Cu interface of the PV are due to the bending effect, resulting in mostly tensile stresses except for the compressive stresses in the center of the connection interface.

Consistent with this analysis, a mechanical pull test was devised to measure the strength of the via junction. The test was found to be useful for optimizing the quality of the Cu-to-Cu bond at the via junctions influenced by different variables in production processes.

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