Presented at IPC Printed Circuits Expo® 2002
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An FEA Study of Image Transfer in Printed Wiring Boards

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Abstract
A concern in the manufacture of laminate PWB's is the transfer of interior circuit patterns to the surface of the board. This can lead to difficulties in forming the external circuitry. Typically, a number of identical boards are assembled, separated by metal sheets (separator plates) and pressed. As layer counts have increased and the metal separators have migrated towards thin aluminum, image transfer has become a bigger concern.

A study is conducted using Finite Element Analysis to examine the deformation and stress field within the laminate and along the separator plates to better understand the mechanisms of image transfer. The analysis focuses on the thermal growth of the composite during a fabrication cycle using a 2-d slice model of a "book" having orthotropic linear elastic material property sets. A comparison is provided that illustrates order of magnitude agreement between predicted FEA deformations and observations, and measurements made in a sample board.

Introduction
In the manufacturing of multilayer printed wiring boards (PWBs), the multiple layers are usually laminated together in a hydraulic press. It is typical to press several boards at the same time, in each of the openings of the press. Metal plates are used as separators between the PWBs to facilitate separating them after pressing and to provide a flat surface to the outer copper for external circuit processing.

For many years, the industry standard for metal separator plates was 0.158cm (0.062") stainless steel (usually 300,400 or 600 series). These plates have uniform, smooth flat surfaces that impart a smooth surface to the external copper of the PWB. They are usually thick and hard enough to prevent any build-up of pressures, due to the internal circuit patterns, from deforming the external copper. This deformation is commonly called "image transfer".

Although stainless steel separator plates have many good properties, they also have some limitations. Due to their thickness (which in many cases is the same as the PWB), they severely limit the throughput of the pressing process. In addition, the maintenance of the plate surface is critical. Any scratch, dent or attached debris will cause a defect on the PWB. Additionally, since most PWB manufacturers use multiple sizes of panels, they need to stock multiple sizes of plates. This can be expensive and take up storage space, as they will want to have enough to handle peak demand for that size (or they limit the number of panels they can press at a giving time). These issues resulted in other materials being examined as separator plates.

In the mid to late 80's, the use of aluminum separator plates began to grow. These plates are typically 0.038cm(0.015") thick and are used once.

Since the aluminum is about one quarter the thickness of the stainless steel, more boards can be processed per press opening. Surface defects were reduced, since by using the aluminum once and recycling it, the PWB is exposed to a clean, defect free surface. Additionally, since the aluminum is usually purchased to order at the same time as the laminate, prepreg and copper the inventory issue is addressed.

An additional improvement to the use of aluminum for separators is made by attaching the external copper foil to the aluminum. The attachment is done by either gluing or welding the materials together along the edges. This makes handling easier and eliminates the potential for resin dust and other debris causing defects on the external copper of the PWB.

The benefits of aluminum separators are many, but an issue has limited the usage of aluminum separator plates. This is the concern over image transfer.

As previously mentioned, image transfer is the deformation of the external copper and the underlying prepreg due to the pressure differences during pressing caused by the internal circuit pattern. If the transfer is severe enough, it will affect the ability to drill and/or circuitize the external layers. Image transfer tendencies have increased as the number of layers per given thickness of PWB have increased. This is occurring at the same time that external features are getting smaller and are harder to produce.

Several attempts have been made to minimize image transfer. Most involve the use of putting back steel separator plates between some or all of the PWBs when pressing. This improves the image transfer, but reduces press efficiency and can lead to warpage (due to the different CTE between aluminum and stainless steel).

Others have tried to increase the thickness of the aluminum (up to 0.051cm/0.020") or try different alloys (that are stiffer). This has met with some success if the particular PWB had marginal image transfer.

Regardless of what has been tried, most attempts at solutions have been by trial and error. This involves the use of manufacturing time and materials that can get very expensive. It was decided that a more scientific approach should be used to address image transfer.

The generation of a mathematical model using Finite Elemental Analysis (FEA) appeared the best way to approach image transfer. With a working, verified model, we will be able to run simulations varying many factors without having to make actual product. Hopefully, this will lead us to the most effective way to minimize this phenomenon.

In order to verify the model will also needed a way to quantify the image transfer. This technique was developed as well.

Models and Methods

Two types of models were considered for this analysis. The 1st and subject of this paper is an actual sample board which was used to validate the approach. The second is a sequential paper involving a parameter study of an ideal board used to optimize the separator plates and prevent or control the imaging process. Both involve a steady state idealization of the pressure-temperature process needed to manufacture a stack or book of PWBs. The two studies differed in the lay-up or geometry of the individual PWB within the stack. A typical book is squeezed isostatically and cycled from room temperature through the glass transition (Tg) temperature[1] of the prepreg resin in order for the to bond with the adjacent metal layers. The major simplification of this analysis is the use of the quasi-steady state thermal loading to reflect the pressure/temperature process. All materials are treated as linearly elastic solids but with orthotropic properties. A major concern is for the for the increased stress effects due to thermal expansion, especially for the prepreg resins. These materials contain a reinforcing in the horizontal or x-plane but have little or none in the y-plane leading to a variation of nearly an order of magnitude higher in the respective CTE's. The property sets[2,3,4] used in this analysis are given in the Table 1.

Table 1 - Material Property Sets

Material Description	Elastic Modulus (M PSI)	Yield Strength (K PSI	Poisson Ratio (----)	CTE (ppm-F)
Steel	29.0	43.0	0.300	6.5
Aluminum	10.0	31.9	0.340	12.8
Copper	18.7	5.0	0.344	7.7
Prepreg - x	2.0	-----	0.350	5.5
Prepreg - y	0.3	-----	0.280	38.9
Paper	0.6	7.3	0.400	0.1

The model geometry used in this analysis was taken from the PWB obtained from a major manufacturer. It was designated a Grade 5 sample (on a scale of 1 to 5, with 5 being the most severe) and is one of the best examples of the image transfer phenomena in their quality program. The sample, as received was originally 12 x 18 inches in size. We examined the board and selected an area with significant visual deformation to use as our test case.

Prior to cross sectioning, the subject area was characterized using a WYKO Surface Profiler, Model 2000 RST. This instrument is an interferometer[5] that determines surface data by combining the path of light reflecting off the test part with light from an internal reference surface. When the two paths combine, the light waves interfere and produce fringe patterns. Using VSI (Vertical Scanning Interferometry) mode, the target is scanned moving downward along the sample so that every point on the surface produces an interference signal. At evenly spaced intervals, "digital frames" are captured and processed to produce a surface height profile or topographic map. The surface profiler used throughout these characterizations has a vertical range of 500 μm and a resolution of less than 1 nm. An image of the area we selected can be seen in Figure 1.

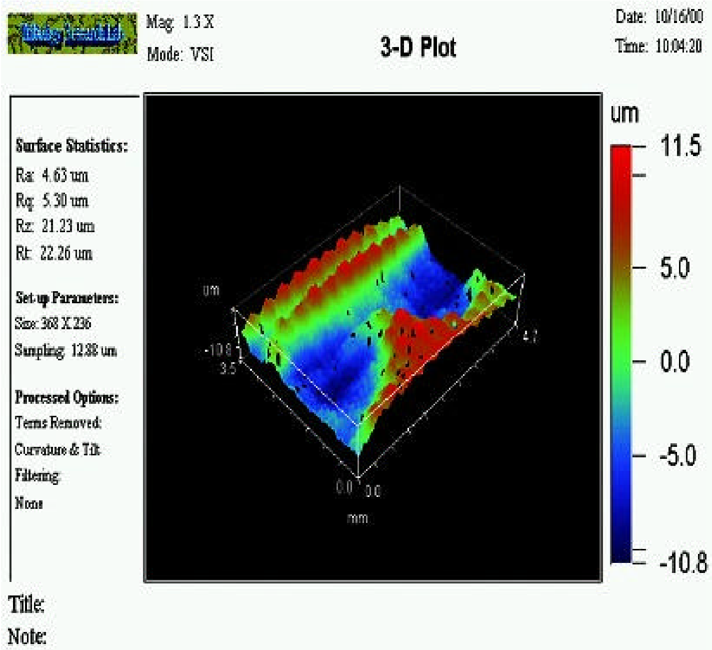

Figure 1 - Surface Profile of Test Area on PCB

The test area was cross-sectioned and digitized to measure the component layer thickness. The cross-sectioned image can be seen in Figure 2.

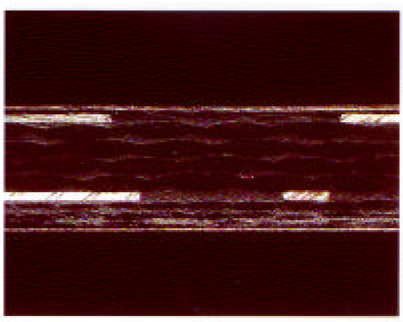

Figure 2 - Cross Section of Grade 5 Quality Sample

From the digitized images, it was determined that 1 and 2 oz. copper was being used for the metal layers and from 2 to 9 mils in thickness for the prepregs. The separator plates were assumed to be 10 mil thick aluminum. In addition to these internal card dimensions, there is a steel platen, registration plate and paper lagging used on at the top and bottom of the stack. The model section of the stack is represented in Figure 3.

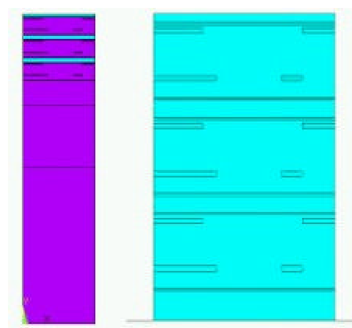

Figure 3 - 2-D Slice Model and Card Geometry

The FEA analysis was performed using the commercial ANSYS Code, Version 5.5. Two types of 2-D solid elements were tried; the linear Plane 42 and quadratic Plane 82 elements, both with 2 DOF. The mesh densities were varied for both elements and eventually produced similar order of magnitude results. The overall solution times were similar allowing the use of the quadratic elements to improve the accuracy of the results. For the ½ geometry model, 7,410 elements were used containing 20, 210 nodes.

The assumptions used throughout the modeling scenarios were:

- Steady State thermal problem
- Linear elastic solids with plane stress
- Orthotropic material properties
- h-method,
- 2-D Section using horizontal and vertical symmetry planes
- 300 psi compressive force,
- 255 F Temperature Differential.

Symmetry planes were used to reduce the model size and solution times during the modeling effort (two along the vertical sides and one along the top surface). Additionally, there were 2 equivalent methods of applying the compressive loading. The 1st by applied the loads directly at the corner nodes on the platens. The 2nd used a distributed load along the upper boundary. The bottom platen was held fixed and non-deformable. The second method was eventually adopted due to the physical aspects of the resultant stress field associated with a slice model. The meshed model can be seen in Figure 4.

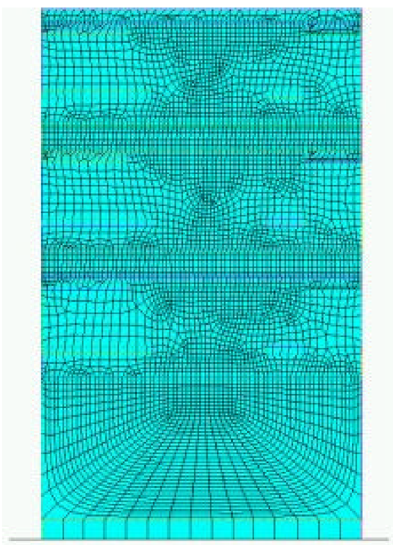

Figure 4 - Finite Element 2-D Slice Model of a 6 PWB Book with Upper and Lower Platens

The FEA theory[6] can be expressed as a matrix of equations in the following form;

$$[M]\{\ddot{U}\} + [C]\{U\} + [K]\{U\} = \{F\}$$

The displacements are represented as U and M, C, and K are the mass, damping and stiffness of the material system. Assuming steady state behavior allows us to drop the first 2 terms on the left leaving the following;

$$[K]\{U\} = \{F\}$$

In the absence of the temperature field, the F on the right hand side of the equation would simply represent the compressive loading. The addition of the temperature field changes the magnitude of the loading F by accounting for the forces being generated by the thermal growth of the material system. As the geometry's become more complex, the flexibility of the FEA becomes increasingly attractive method for analyzing odd shapes and their local deformation due to stress. The applied BC's and loading can bee seen in Figure 5.

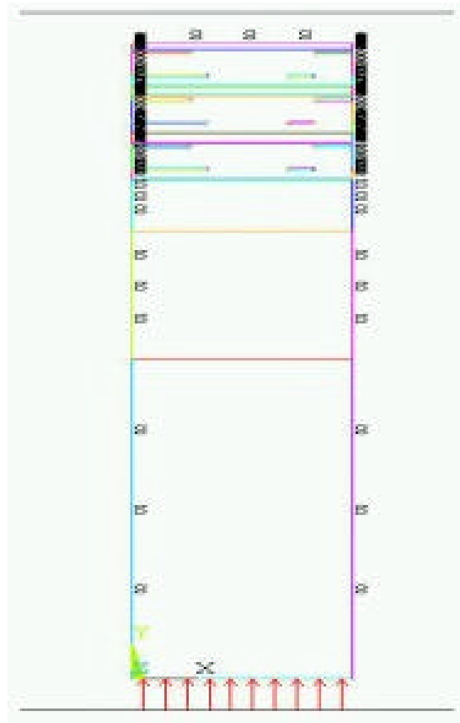

Figure 5 - Finite Element Model with Reaction Along Bottom Surface and Symmetry Planes on Sides and Top

Results and Discussion

The validation for this FEA modeling approach is considered successful if we can determine a "magnitude of order agreement" in the deformation being observed and predicted along the aluminum / copper interface at the separator plates. The area of interest as determined by the WYKO images in Figure 6 indicates surface topology differences on the order of 20 microns.

The y-axis deformation as predicted by the ANSYS model is seen in Figure 7 and on the order of 1.4 mils or 40 microns. The corresponding Von Mises stresses developed in this region are in the range of 43 kips as observed in Figure 8. The highest stress regions are in the copper surface elements near the edges of the internal via's. These grow larger moving from the center symmetry plane toward the platens and peak in the card nearest the platens. Comparing these maximum stresses with the Yield Stress thresholds indicate that the materials are being plastically strained and hence likely to remain deformed after completing the process.

On a purely visual or physical scale, a comparison of the deformation patterns within the PWB is similar in nature with the analysis patterns. One example being the narrowing of the copper surface layer and the first internal metal layer as seen in the Figure 9.

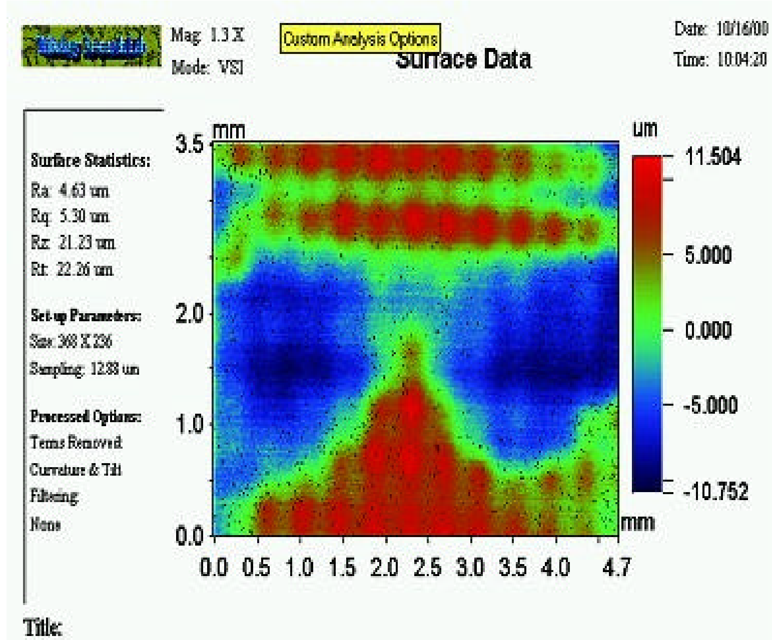

Figure 6 - Surface Profile of Target Area with Stylus Lines for X-Section Dimensions

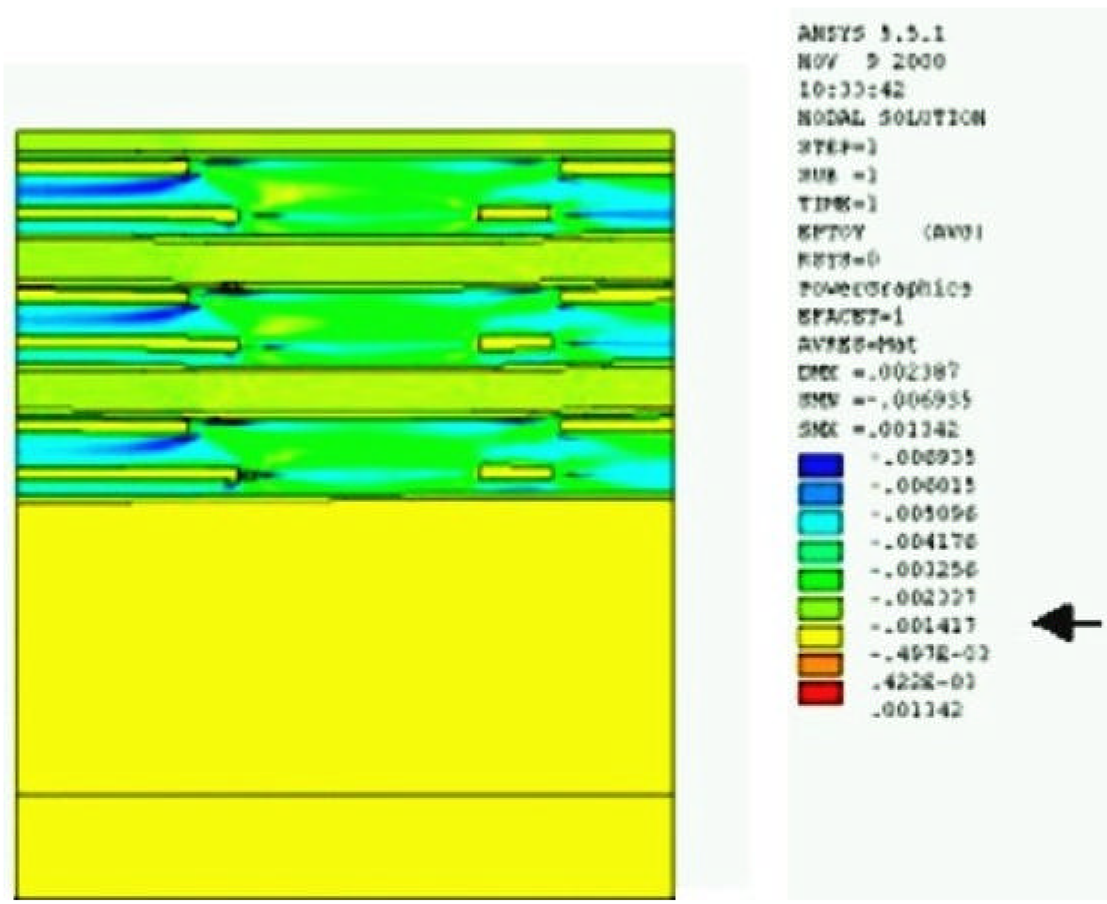

Figure 7 - FEA Results of the Y-Axis Deformation in Inches

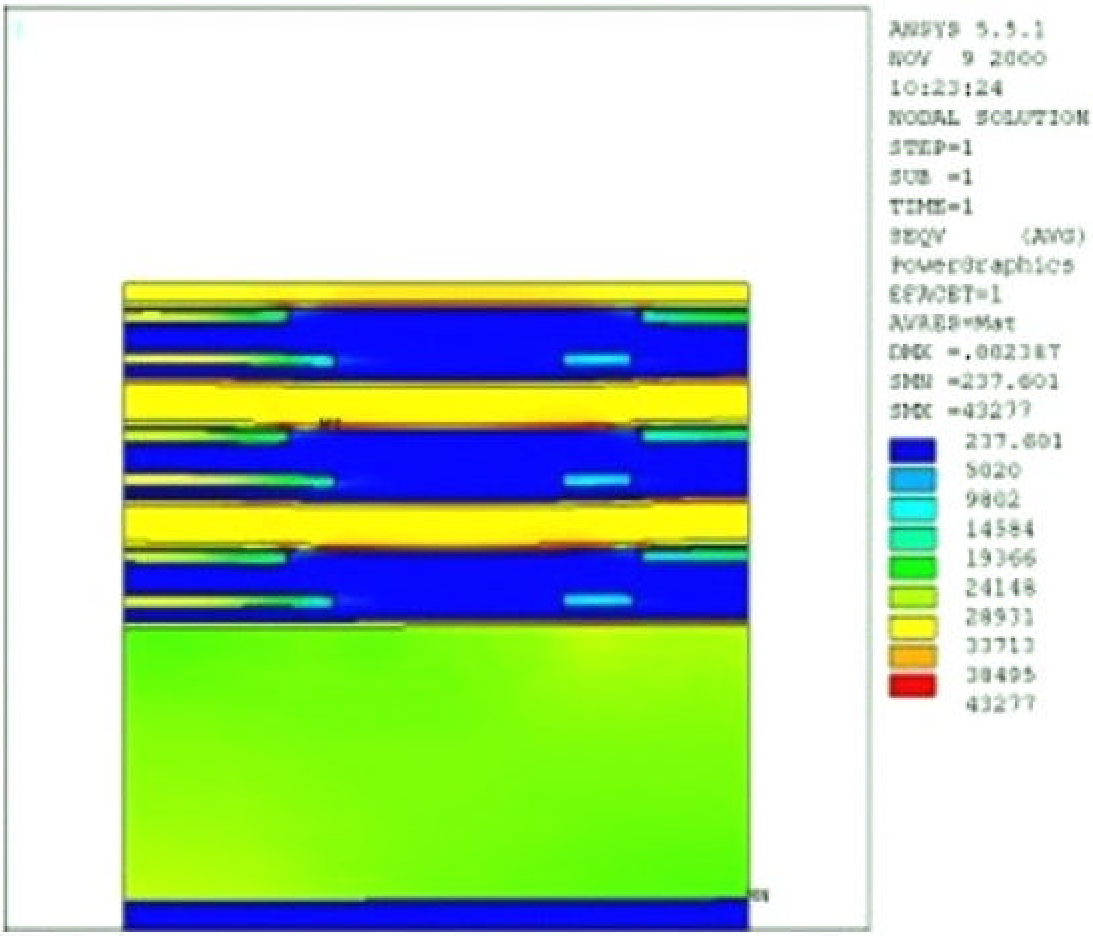

Figure 8 - FEA Results of the Von-Mises Stress in PSI

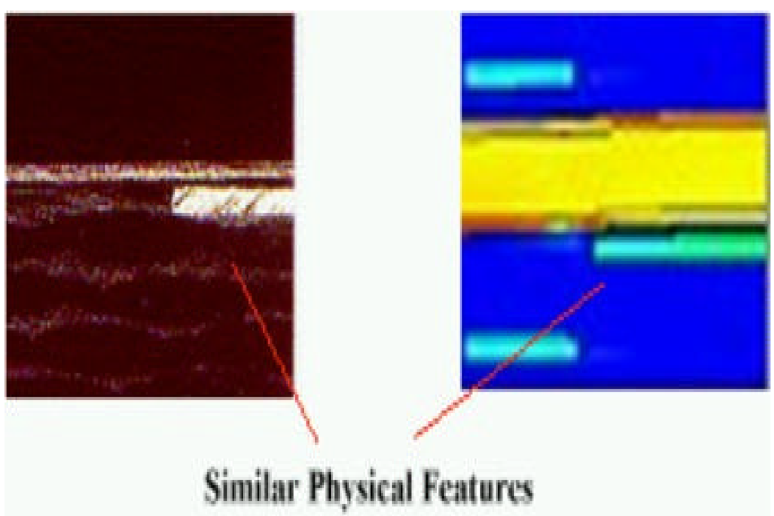

Figure 9 - Visual Comparison of Deformed Features

Conclusions

The quasi-steady-state modeling approach provides a magnitude of order agreement with the deformations observed in the process sample. The image transfer is known to become progressively worse moving thru the book toward the platens, which is also reflected in the FEA analysis. There are visual deformation features in both the cross sectioning and FEA analysis that would also suggest the validity of the approach.

The material properties and response of the prepreg resins appear to be a major factor in producing the image transfer. Additional analysis using isotropic property sets have indicated the stresses within the book remain below the Yield Stress thresholds and would therefore lack the plastic behavior necessary for permanent deformation.

The temperature cycling of the book is a basic process requirement to bond the laminate into a single composite. It also is necessary to allow the flow of resin material into the voids or internal vias within the laminate. Overall, the thermally generated contractions and resulting stresses of the resin within the vias appear to be a major contributor to the image transfer features as observed in the FEA analysis, cross-section and WYKO images. The surface characterizations also reveal the fiber weave of the underlying prepreg resin but is a order less in magnitude than the variations around the vias.

Good engineering practice or lay-up suggests the use of symmetric PWB construction to control or minimize the image transfer phenomena. Comparisons of Grade 2 cross-sections and WYKO measurements, Figures 10 & 11, show an example of this practice. The fiber weave pattern still remains visible within the samples as well, the contraction around the vias.

Based on these observations, the use of a symmetry plane in the center of the book is questionable and should be replaced with a full slice model. The use of elastic elements is also confusing when examining plastic behavior but does however demonstrate the presence of stresses in excess of the yield threshold for the material system being modeled.

The modeling effort, provided a satisfactory implementation of the FEA code, is only as good as the property sets being used for the various materials. A literature review of the copper and aluminum components showed a high degree of variability in the elastic modulus and yield stress values. The characterization of the prepregs would also appear to be a critical feature of this analysis due to its role in the laminate behavior. A transient analysis could improve the understanding of the problem but should reflect some aspect of the fluid behavior as it moves and flows through the composite. Some efforts were also made to characterize the resins using rheological techniques including a Dynamic Mechanical Analyzer (DMA) to verify the elastic modulus of the composite material but were not included in this analysis. Inspections of additional cross sections indicate the use of multiple types of prepregs having different warp and weave patterns. This suggests a variation in the orthotropic behavior between layers which was not accounted for in this analysis.

Overall, this FEA analysis seems to have captured the essence of the image transfer phenomena, given the complexity of the material properties and process by achieving a general "order of magnitude" agreement between the analysis and observation. It is unreasonable to assume the image transfer can be totally eliminated but should be possible to control the phenomena within a process tolerance. Within this context, understanding the behavior of the prepregs appears to be pivotal item in predicting the behavior of the laminate during the manufacturing process.

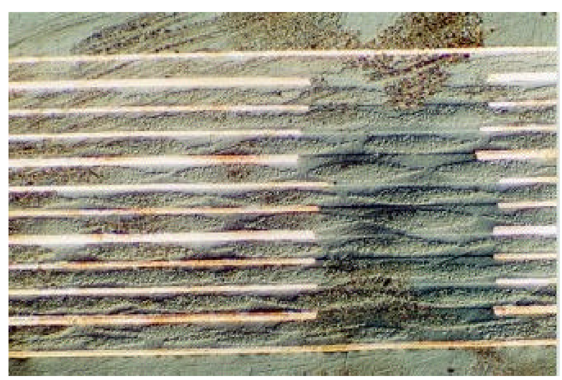

Figure 10 - Grade 2 Quality Sample Cross Section

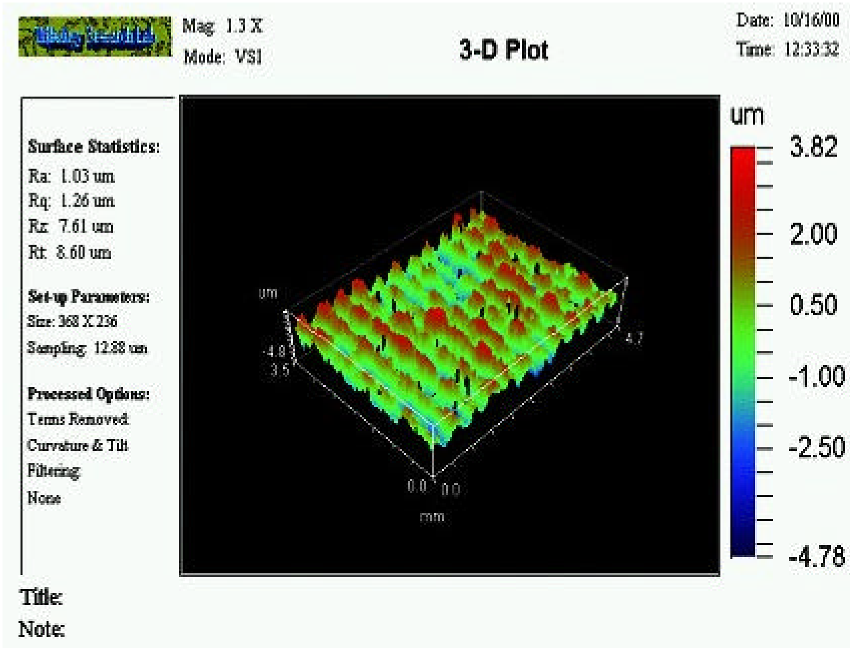

Figure 11 - Grade 2 Quality Sample WYKO Surface Profile Measurements

Acknowledgments

We gratefully acknowledge the support and funding of the Integrated Electronics Engineering Center (IEEC) without whom, this work would have not been possible. We also acknowledge the generosity of the major PWB supplier and Park-Nelco in providing the material samples and technical insight into the production process. Lastly, we appreciate the many discussions with the faculty, staff and graduate students at Binghamton University including J. Pittarressi, F.Andros, S.Watson and W. Grivas. Thanks to you all!

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