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The Importance of CTE in Multi-Layer Registration and Improved Measurement Methods

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Significance of the Problem

The current worldwide market for printed circuit boards is approximately $40 billion, with the multi-layer printed circuit boards (MLB) comprising approximately 40% of the market. One of the most perplexing processing problems is poor registration in multi-layer lay-ups. This leads to hundreds of millions of dollars in scrap and lost productivity, and compromises performance in high-end applications. Significant progress has been made over the years to identify the critical components responsible for improved reproducibility and reliability. However, as pitch (conductor spacing) becomes finer; the registration problems of multi-layer board fabrication become more severe. Better analytical tools are needed to meet this new challenge.

Background

Interlayer registration and dimensional stability have been topics of ongoing concern to all fabricators of multilayer boards. Recent trends toward increased package density, increased layer counts, smaller circuit features, thinner dielectric spacing, and the production of boards on larger panels have exacerbated the problem. Numerous studies have been conducted to find the "holy grail" allowing one to compensate artwork properly and improve productivity by making it right the first time. These studies range from empirical evaluations,[-3] to sophisticated analytical models,[4-6] to complex design of experiments programs using production parts[7, 8]. To date most fabricators rely on full-scale lamination simulation tests or historical data tracking methods as the only ways to predict movement characteristics of the material.

Interlayer registration is a complex problem involving a myriad of materials and processing issues. Because of the intermingling of tooling, processing and material issues it is often the root cause of "finger pointing" and conflict between material supplier, board fabricator and OEM customer. It has been, and continues to be, responsible for considerable loss in productivity and business both for the suppliers and customers.

Most fabricators use one of three primary methods to predict artwork compensation factors. The first method attempts to assign "standard" compensation factors to innerlayers as a function of laminate thickness, construction, copper weight and layer type (signal or plane). Rather than looking at the laminate components of a multi-layer board, the second method groups designs into families and uses the same factors for all boards in a family. In a third method, shrinkage and growth is measured on pre-production or first-lot trial boards, and compensating factors are then applied to future production lots. The first two approaches are inaccurate and the third is expensive and impractical for short interval orders. Some fabricators have achieved improved results through the use of semi-empirical methods in concert with data-based expert systems, to predict compensation factors.

Over the years, numerous mechanisms have been proposed which are directly related to the raw material properties or process variables. Both have been invoked to account for observed mis-registration behavior. In 1984, numerous potential drivers identified and concluded that the situation was so complex that the best solution was to find a better material.[1] Experience accumulated since 1984 now gives us a better understanding of the relative importance of each of these factors. A series of articles described the various tooling and process issues affecting multi-layer registration, and attempts at predictive compensation modeling[7-9]. The primary registration variables have been summarized.[2]

Artwork growth and shrinkage
Misalignment of artwork
Misalignment of innerlayers on the tooling
CTE mismatch
Excessive external stress during lamination
Asymmetric circuitry
Improper layout of inner layer edge borders
Material inconsistencies (laminate dimensional stability)
Residual stress
Pressure/flow effects
Cure shrinkage
Tooling Plate effects

Importance of Thermal Expansion

Although there is no doubt that all of the above factors play a role in multi-layer registration, it is generally recognized that the mismatch of in-plane thermal expansion coefficients (CTE) is often the driver. Innerlayer cores do not always contain the same glass-to-resin ratio, due to the various glass styles in use, and hence, their CTE may be different. Even if the glass style is consistent, the amount of copper circuitry may influence the effective CTE of the composite. The bonding sheets generally do not have the same resin content as the innerlayers and therefore will have different CTEs. Not only is the CTE of the laminate materials important, but that of the copper foils and tooling plates also play a role. All of these CTE differences can lead to problems in maintaining accurate registration between layers.

In his 1997 article, Holmes concludes that laminate and finished PWB CTEs are the dominant factors. He suggests that the other factors listed above only play a minor role (they can of course, be the assignable cause of much frustration, if left uncontrolled). He then goes on to develop an empirical approach based on multi-layer circuit board registration experiments to derive artwork correction factors. He also concludes that micro-mechanic and/or directly measured laminate CTEs would lead to good predictive capabilities.

For measurements of laminate expansion to be valuable in registration studies, their precision must exceed 100 parts per million over the range of temperatures encountered in a typical re-lamination operation.[ref] It is also desirable to measure thermal expansion and CTE on production-size components.

Conventional methods such as thermal mechanical analyzer (TMA) and use of strain gauges are not adequate. TMA uses small samples with dimensions typically less than an inch. This has two drawbacks, 1) measurement precision is poor and 2) insufficient sampling of a complex, inhomogeneous, laminate may lead to erroneous estimates of CTE values appropriate for larger production laminates. In addition, because TMA requires contact with the sample, buckling is often problematic for thin laminates. Similarly, strain gauges for measurements of in-plane expansion use small samples, require significant temperature corrections, and perturb the laminate expansion by virtue of being bonded to the surface.

Non-Contact CTE Measurements

In order to overcome the limitations inherent in TMA and strain gauge measurements, a non-contact measurement approach is desirable. The Automated Thermal Expansion Coefficient measurement system (ATEC) uses non-contacting optical methods to measure CTE on production-size laminates from ambient temperature to 250^{o} C. The ATEC is a new tool that has the precision necessary to generate critical data needed to improve multi-layer registration.[10]

Figure 1 illustrates the measurement concept for the non-contacting measurement system. For this measurement system, the laminate is sandwiched between two heated platens. Both the upper and the lower platen have small observation ports. The upper port is for illumination while the lower port is for visualization of the laminate. Generally, a hole is drilled in the laminate and used as a target (fiducial). The separation of both the illuminators and the imaging cameras from the heated platens is sufficient to maintain a constant temperature. Thus, while the laminate is heated, the sensors remain in a fixed position and can be used to measure the relative change in the laminate fiducial positions as a function of temperature. The laminate is resting freely on the lower platen and the upper platen is lowered such that it is in close proximity to the laminate. This provides a stress-free uniform heating of the laminate.

The system uses 4 cameras to view target holes drilled in laminates in a square pattern, 10” on a side. The motivation for using four cameras as well as their 10” separation arises from historical reasons. This non-contacting approach was originally developed to measure laminate dimensional stability (IPC 2.4.39). By using optical image processing methods to determine the hole center, subjective, operator measurement errors are removed. Furthermore, in contrast to manual measurements where individual data points are often entered by hand, this system automatically collects and processes the data and generates final reports without the need to manually input any dimensional measurement data. With the addition of heated platens above and below the laminate, we can use the same hardware to measure the thermal expansion.

Magnified images of the four target holes are displayed continuously on a monitor. From high magnification images of the hole, standard machine vision algorithms are used to determine each hole's center position. This allows one to continuously measure the position of the four holes, thus we can determine the laminate strain on four "legs" of the square camera pattern. The dimensional change for each leg of the laminate is plotted as a function of temperature. Thus, we directly measure the expansion averaged over a 10" span. By fitting this expansion vs. temperature curve with a straight line we can precisely determine the CTE.

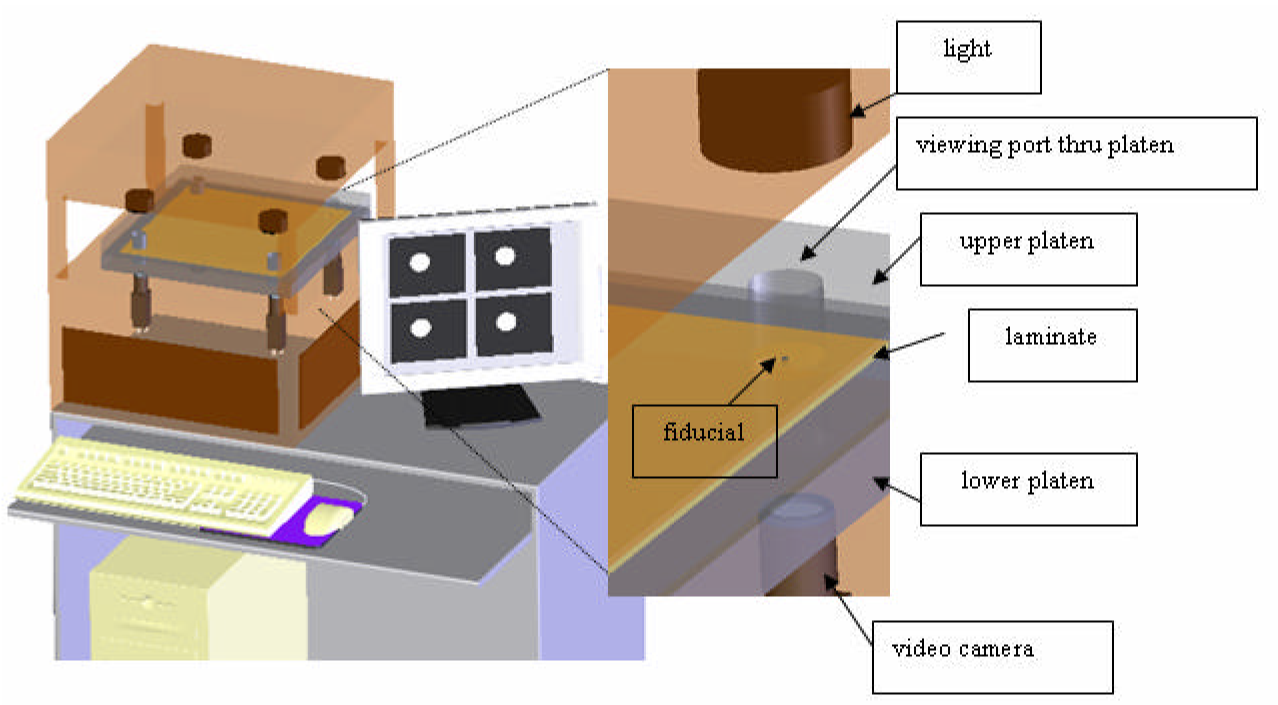

Figure 1 - ATEC Optical Measurement of CTE

The magnification of the lenses and cameras is calibrated using a reticule specially designed for the purpose. This sets the distance scale of the CTE measurement. The temperature of the platens is measured using platinum resistance thermometers (RTDs). The calibration of the RTDs is checked using standard glass thermometers. Since the distance and temperature are calibrated against independent standards, the measurement of CTE (the slope of the expansion curve) is an absolute measurement and not dependent on a standard whose expansion is known.

Movements of the fiducial holes are accurate to ±1 micron while changes in temperature are measured to $\pm 1^{o}$ C. We have studied laminate materials', CTEs in both the warp and fill (X and Y) axes typically in the range of 10 to 20 ppm/^{o}C for temperatures below the resin Tg. For these conditions, CTE accuracy is about ± 0.5 ppm/^{o}C. In some cases where thin or non-symmetric samples exhibit curl, or do not lie flat for other reasons, the repeatability is somewhat larger, ±0.7 ppm/^{o}C.

In order to be useful as a tool to improve multi-layer registration, it is important that reliable, precise CTE measurements can be made on production size laminates. Holmes, in his 1997 article indicated that precision of more than 100 ppm is required. Figure 2 shows the long term stability of the system used in this study. In this case we continuously monitored the thermal expansion of a 0.060" steel calibration plate. The plate was held at a constant temperature of 50^{o} C over a period of 400 minutes. These results show that the maximum excursion is less than 12 ppm while the mean standard deviation is 4.9 ppm.

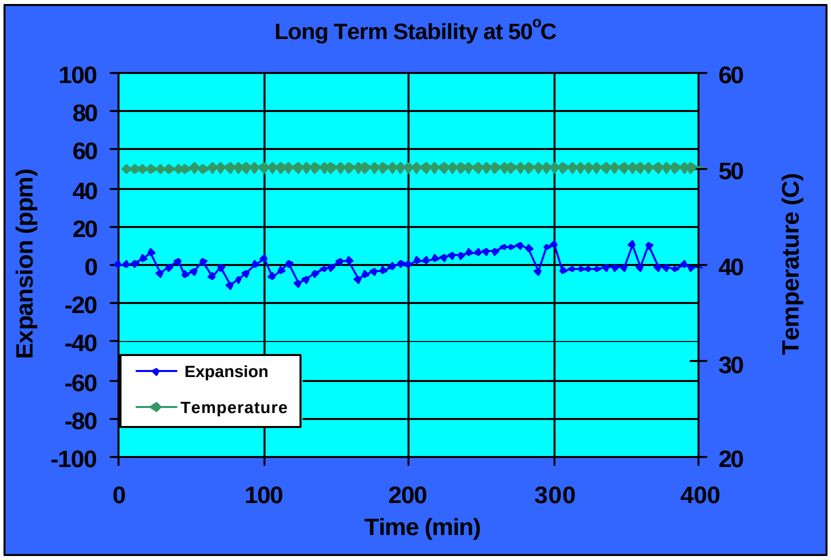

Figure 2 - Long Term Temperature and Dimensional Stability

Figure 3 plots both the temperature and the expansion of a steel calibration plate over the temperature range from 30°C to 110°C. In this case we show a stepwise heating profile, where the platen temperature is raised in 20 degree C temperature steps with a 15 minute hold at each temperature. The continuous plot shows the measured expansion of a .060" steel calibration plate. The vertical axis on the right gives the temperature while the vertical axis on the left shows the expansion in parts per million. This data shows that it takes the system approximately 7 minutes to increment the temperature by 20°C. The dimensional variation in the calibration plate appears to equilibrate within a few minutes after each temperature step. Again we see the precision of the measurement is better than 10 ppm.

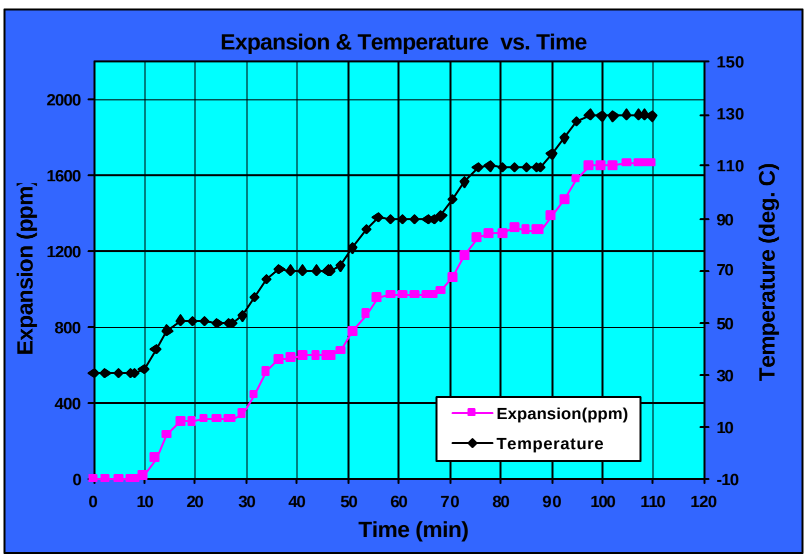

Figure 3 - Step-Wise Heating Profile and Laminate Expansion

Laminate Expansion and Heating Profile
Typical CTE Data

Copper Foil & Tooling Materials

Before investigating the thermal expansion of multi-layer laminates it is of interest to first measure isotropic materials such as steel or copper foil. Figure 4 shows the results of three repeat measurements on a 0.060" thick 10" by 10" stainless steel plate. Although difficult to resolve in this display, we have plotted 4 independent measurements for a stainless steel calibration target. The slope of a least-squares-fit gives the average CTE value for this material, 17.84 ppm/°C. The thermal expansion as a function of temperature is well fit with a straight line and is quite repeatable.

Similar results are given for 2 oz. copper foil in Figure 5. However, in this case the data were obtained from a single temperature excursion of the measurement system. Results are plotted for all four legs of the measurement system. Because the material is uniform and isotropic, all expansion curves overlap. For this copper sample the average thermal expansion coefficient is 17.10 ppm/^{o}C.

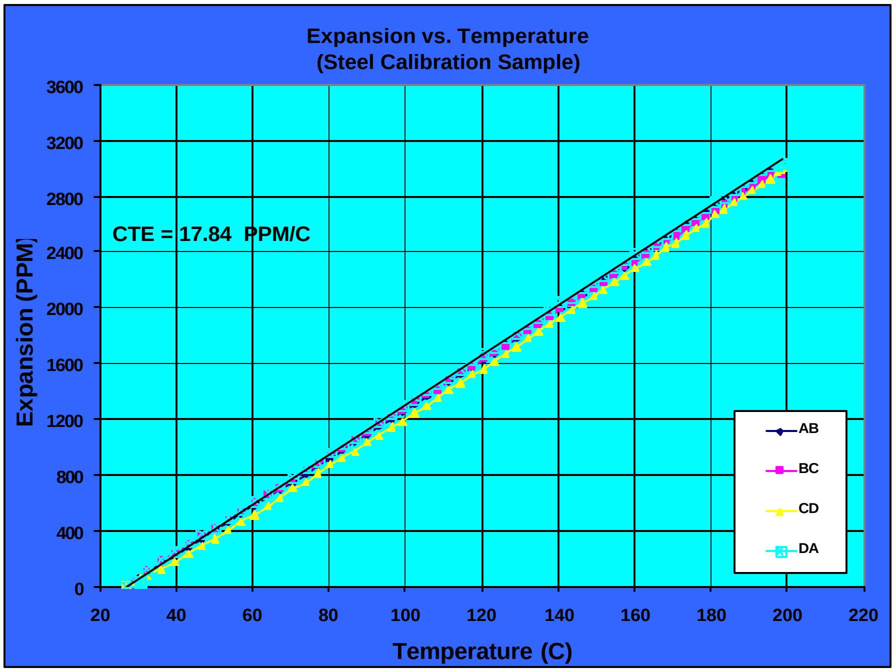

Figure 4 - Measured Thermal Expansion of a 0.060" Thick Stainless Steel Calibration Plate Three independent Measurements are Plotted

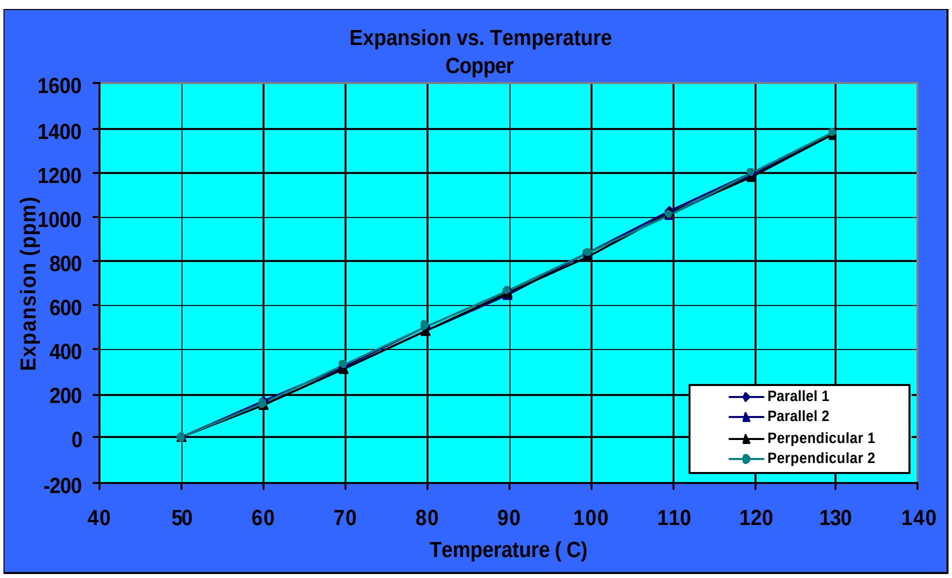

Figure 5 - Measured Thermal Expansion of a 2oz. Copper Foil

CTE of Laminates

While most dielectric laminates offer excellent electrical properties and manufacturing flexibility, they do possess a relatively wide range of in-plane thermal expansion coefficients. Laminates used in printed circuit boards are comprised of woven glass fabrics impregnated with resin. As such, they are mechanically anisotropic. The CTE is dependent on a variety of constituent material properties e.g. glass style, resin properties, copper thickness, resin content. The CTE is also influenced by several processing variables.

Woven glass fabrics used in printed circuit laminates generally have asymmetric weaves characterized by different yarn counts in the warp (machine) and the fill direction. This gives rise to different mechanical and thermo-mechanical properties in each direction. The CTE is not a constant over the temperature range used for lamination. Thus, the expansion data is not readily fit with a straight line. The detailed expansion profile is different for different laminate constructions.

Figure 6 shows a representative thermal expansion profile of an unclad laminate measured over the temperature range from 50^{o}C to 200^{o}C. As with all system traces, there are 4 simultaneous measurements made, 2 along the warp or machine direction and 2 parallel to the fill direction. This data clearly illustrates that this laminate is anisotropic. The expansion in the fill direction exceeds that in the warp direction to a considerable extent. At the highest temperature measured, the fill expansion is in excess of 2200 ppm while the total warp expansion is only 1400 ppm.

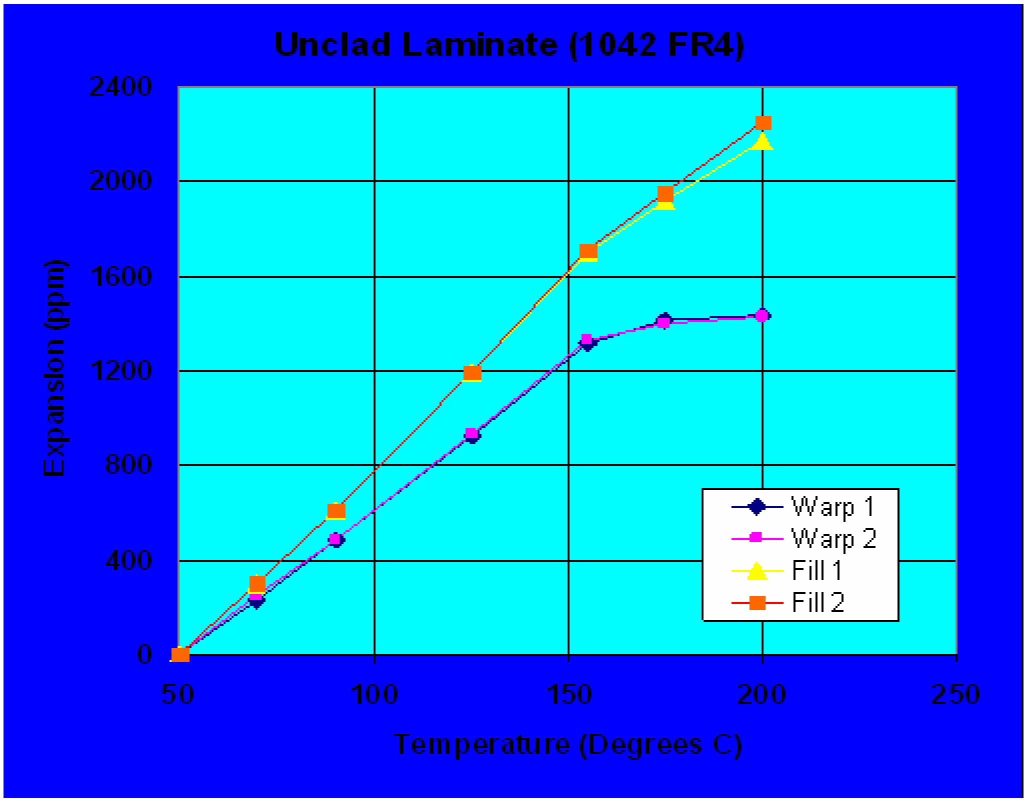

Figure 6 - Data on Unclad Laminate showing the Anisotropic Nature of Laminate Expansion

It is also evident that the CTE (slope of these curves) is not constant over the temperature range. The FR4 resin system used for these laminates has a glass transition temperature of ~130^{o}C. Both the warp and the fill curves depart from a linear dependence above 130^{o}C. This is particularly noticeable for the warp curves.

At first glance, one might think that this behavior is somewhat counter intuitive. The thermal expansion decreases with increased temperature. However, careful analysis shows that this behavior is expected from micromechanics models of composite CTE. The composite CTE is a function of both the modulus of the constituents as well as their respective CTEs. Once above the resin glass transition, the resin modulus drops to a low value and the composite CTE is dominated by the properties of the glass yarns. (~ 5 ppm/^{o}C).

The difference in the behavior of the fill and warp directions can also be qualitatively explained by composite micromechanics. The glass yarns in the warp direction are generally considered to be straighter than those in the fill direction. Because in the weaving and treating process the warp yarns are under tension, they tend to have reduced undulation relative to the fill yarns. The warp direction yarns approximate the micromechanics models better than the fill direction yarns. As such, the reduction in slope of the expansion curves above the resin glass transition is usually more pronounced in the warp direction and in better agreement with that predicted by the micromechanics theory which is based on composites reinforced with unidirectional filaments.

To illustrate the system's ability to measure the effects of weave undulation and departure from 0º-90º unidirectional composite behavior, CTE measurements were performed on two different laminates. The first laminate was produced using 106 glass-style. This style has 56 warp yarns and 56 fill yarns, creating a balanced "square" weave. Composite micromechanics theory predicts that CTEs should be equal in both the X and Y direction for a laminate with equal numbers of 0º and 90º unidirectional fibers. However, Figure 7a clearly shows that the woven fabric results in a fill direction CTE that is higher than the warp direction CTE, despite the balanced thread count. This is an indication that the fill yarns are providing less reinforcement in the resin matrix.

A second laminate was produced with an experimental glass style, having about 60% more yarn in the fill direction compared to the warp direction. In this case, the measurement (Figure 7c) shows nearly identical CTEs in both direction, and quantitatively demonstrates the amount of "extra" fiber required to compensate for the undulation effect in the fill direction.

The system's ability to measure production-sized components is advantageous in analyzing and quantifying the effects of copper-cladding and circuit patterns on respective laminates and innerlayers. Comparing Figure 7a (unclad) to 7b (copper clad) shows the effects of copper-cladding on a thin 0.002" laminate. In Figure 7b, the copper dominates the CTE result, due to its higher combined thickness and the relatively low laminate modulus. Figures 7d and 7e are measurements on unclad and clad laminates produced with 7628 glass. This laminate is much thicker than the one made with the 106 fabric. The copper has less influence on the clad CTE result, due to its lower relative thickness. In addition, the 7628 based laminate has a higher modulus than the 106 laminate.

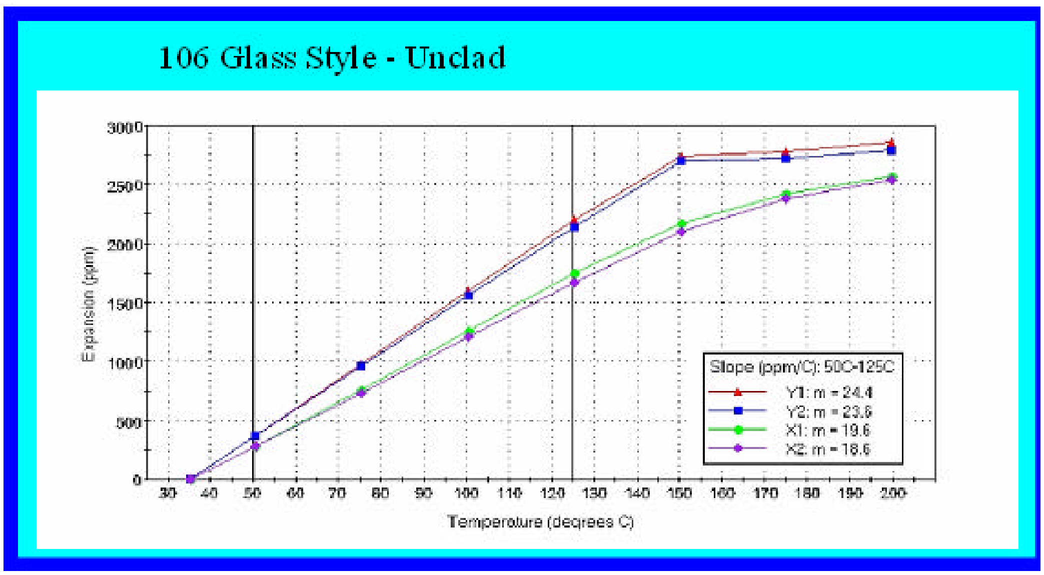

Figure 7a - Unclad

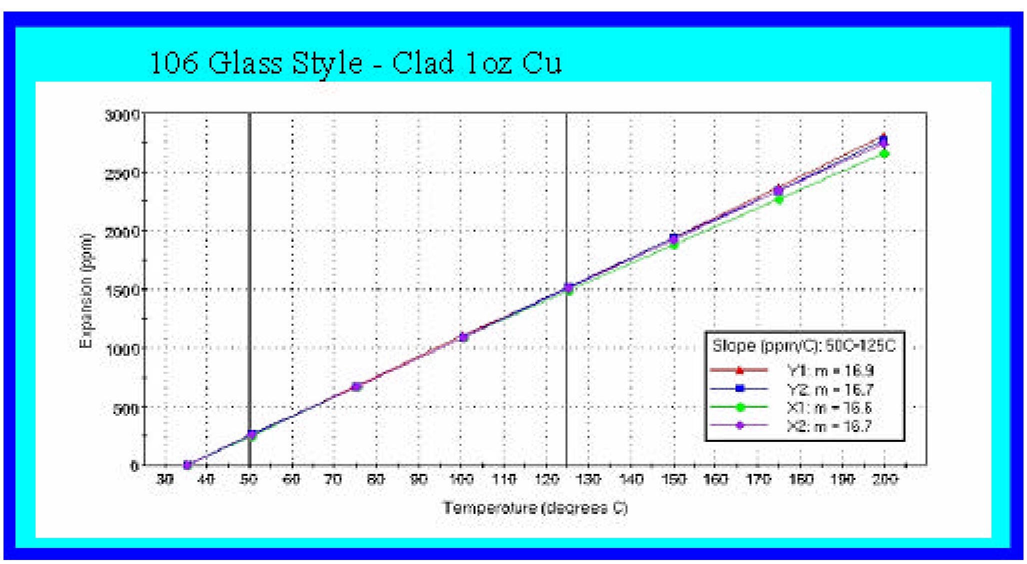

Figure 7b - Copper Clad

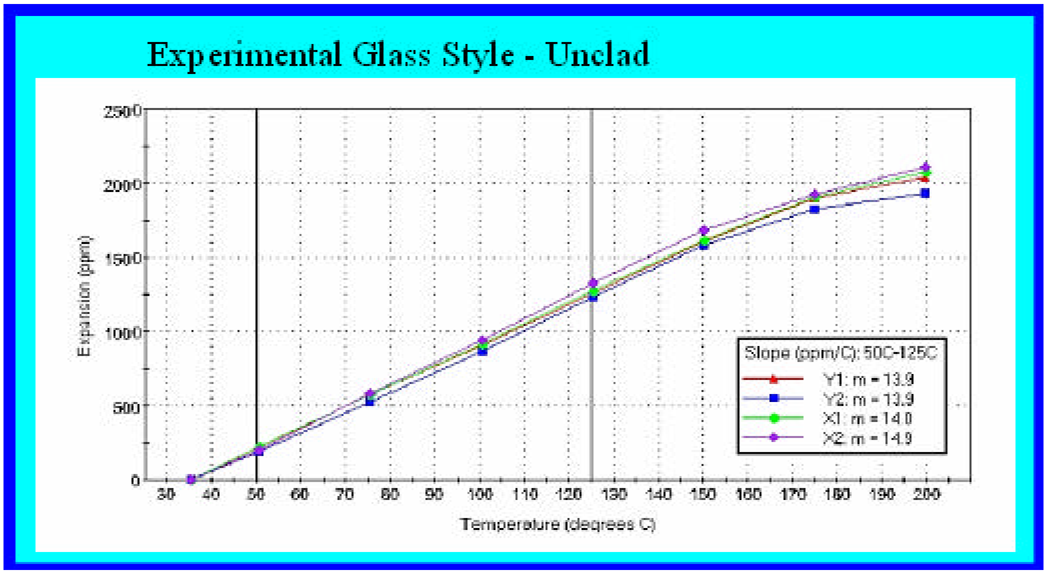

Figure 7c - Measurement Nearly Identical CTEs in Both Direction

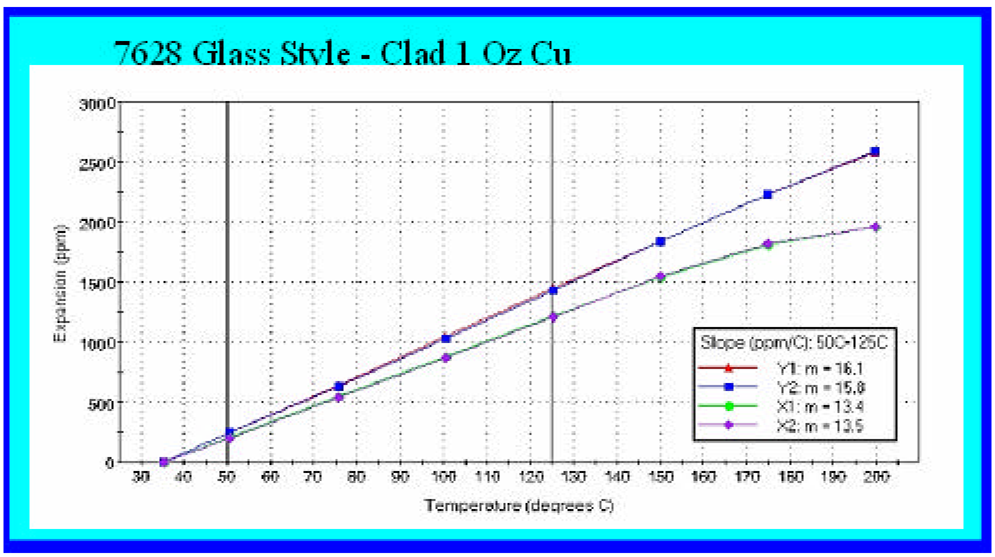

Figure 7d- Measurements on Unclad Laminates

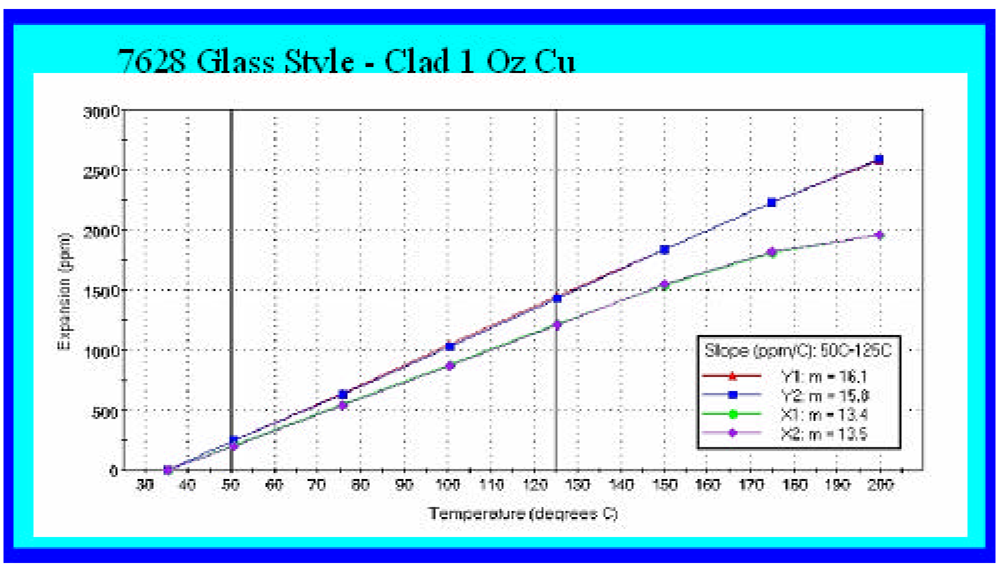

Figure 7e - Measurements on Clad Laminates

Expansion Display

The system simultaneously measures the movement of 4 points on a laminate as a function of temperature and/or time. Accordingly, there are a number of ways to characterize the data. The standard analysis method is to simply measure the distance between two points as a function of temperature. This results in an expansion versus temperature plot from which we extract the CTE (e.g. Figure 6). For printed circuit board processing, we may want to know more detail on how the laminate moves with temperature and assess the effects of copper circuit patterns on material movement. We have been experimenting with several methods, which help us visualize the laminate or innerlayer movement and distortion in more detail.

One such display is called the "Center of Mass" Expansion Display. Without going into the details of the mathematics, the center of mass display involves calculating the center of the four target holes at each temperature interval and then plotting the distance of each hole from this point. We define the center point at ambient temperature as the origin. This permits us to plot the laminate movement on a highly magnified scale. This display accentuates any laminate or layer distortion that may be present.

The result of doing this procedure is an exaggerated view of how the laminate or layer distorts with temperature. If the material is isotropic the displayed image should be a square. For example Figure 8 shows the expansion diagram corresponding to the copper data shown previously in Figure 5. Each data point along each leg represents the expansion for a 10^0C temperature increment. At the highest temperature, 130^0C, all points from each leg are connected with a straight line. As expected for an isotropic material, the expansion diagram is square indicating equal expansion on each leg measured. It is interesting to note that the diagram is rotated indicating that the copper foil was rotated relative to the cameras. Our calculations show that this rotation was very small, on the order of 0.001 degrees.

Thermal expansion data and a somewhat more complex expansion diagram are shown in Figures 9a and 9b. This laminate is highly anisotropic, exhibits measurable variability along each of the four positions measured and shows a somewhat unusual behavior above the glass transition temperature. The rectangular and trapezoidal character of the center of mass expansion display can clearly show anisotropy and non-uniformity. On etched innerlayers, in-plane distortions or non-uniformity caused by highly unbalanced circuit patterns can be visualized with this technique.

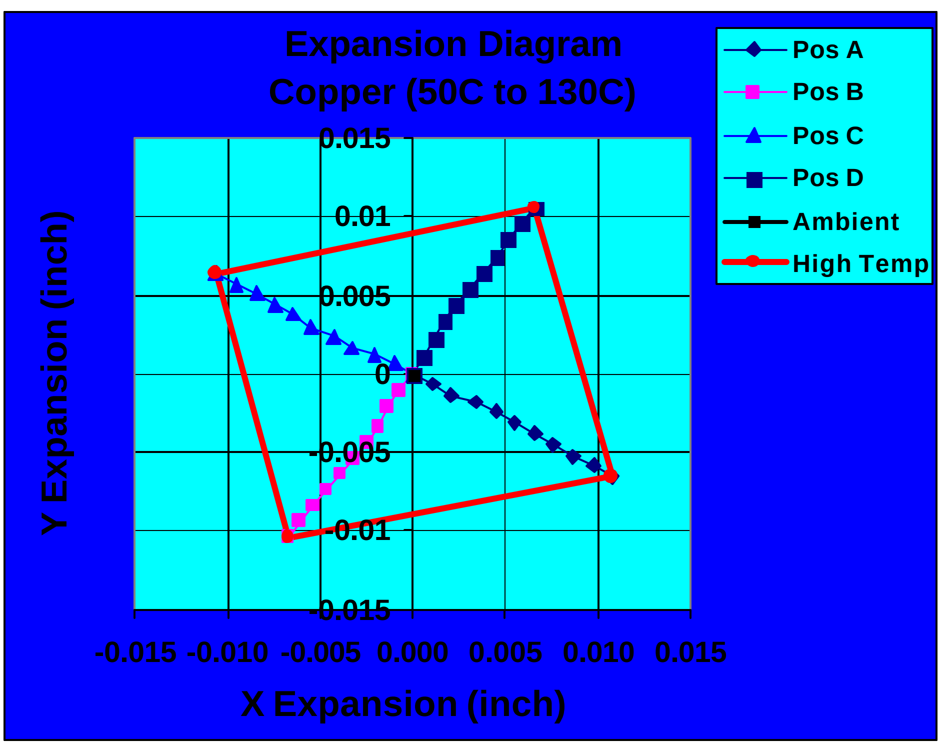

Figure 8 - Center of Mass Expansion Diagram for Copper Foil Data shown in Figure 5

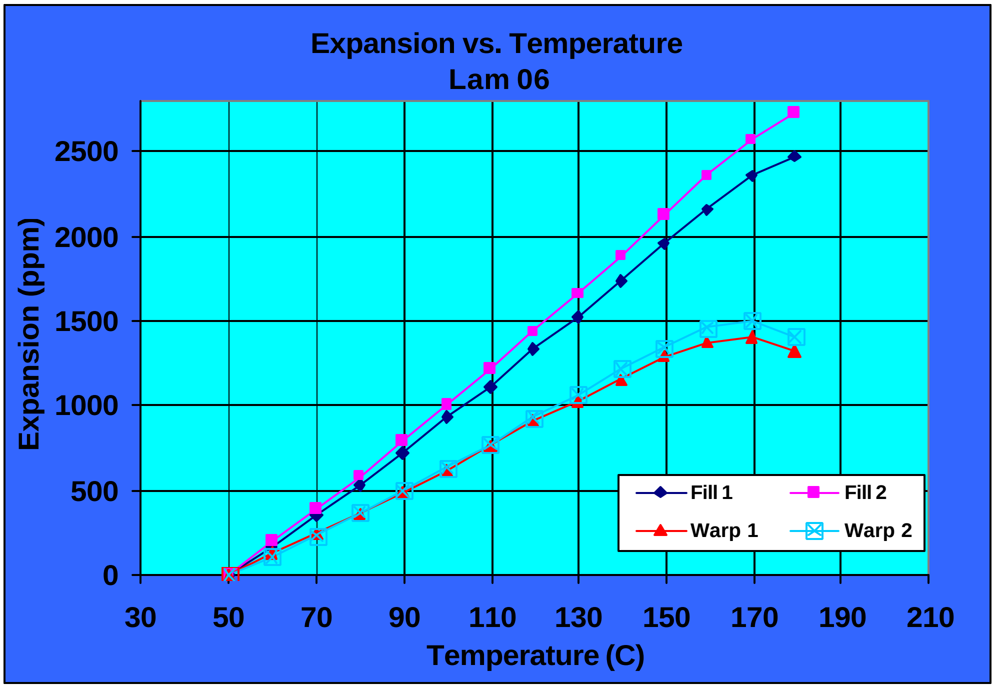

Figure 9a - Thermal Expansion Measurement on Asymmetric Laminate

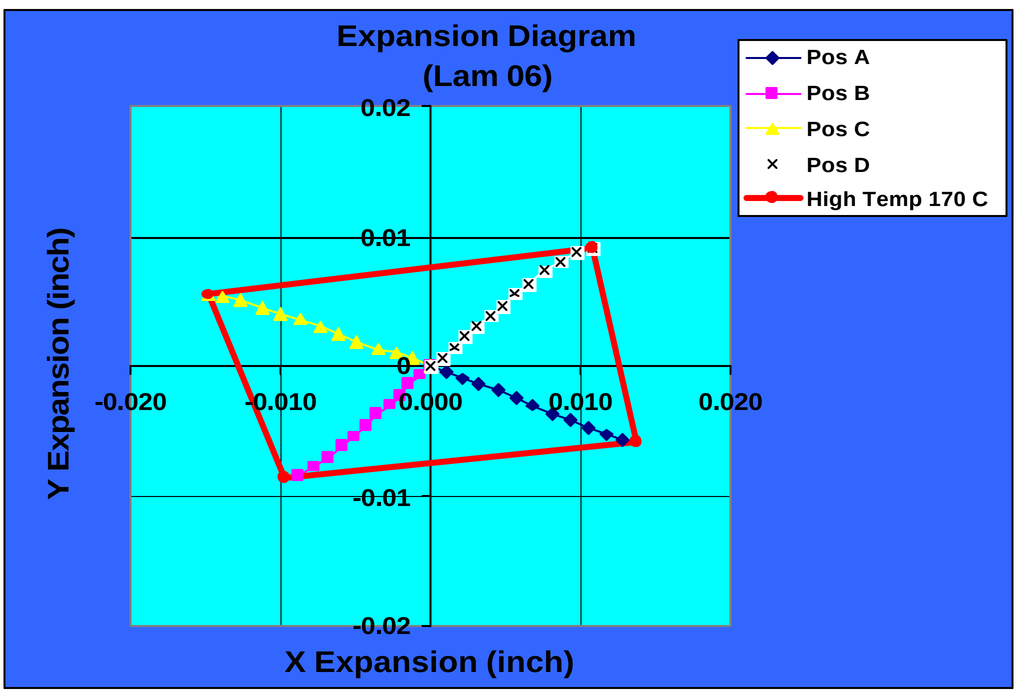

Figure 9b - Center-of-Mass Expansion Display for Laminate Data from Figure 9a

Summary and Conclusion

Precise measurements of thermal expansion properties on production-size laminates, innerlayers and re-laminated circuit boards can be used to improve our understanding of multi-layer registration problems, better characterize materials and formulate artwork compensation factors. Because the laminate CTE is not constant over the re-lamination temperature range, it may be desirable to use the total thermal expansion instead of the CTE to characterize these materials. For example, the inclusion of thermal expansion values in semi-empirical and/or data-based expert systems should greatly improve artwork compensation prediction capability. The laminate / innerlayer expansion displays provide a new way to visualize in-plane laminate and inner layer movement as a function of temperature. It provides not only a new way to characterize laminates, but also a means to experiment with the fundamental influences of glass geometry, resin content, circuit board construction, lamination processes, residual stress reduction and innerlayer circuitry and border patterns.

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