Predicting Dimensional Deformation During Lamination- for Multilayer Printed Circuit Boards

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ABSTRACT

Predicting dimensional deformation is a key issue facing manufacturers of printed circuit boards today using copper clad woven glass epoxy laminates. Registration budgets are getting tighter as digital designers are packing in more and more circuitry per layer to meet the requirements for space and miniaturization. A number of mechanisms have been proposed for the shrinkage in the X and Y plane for these composites ranging from pressure effects to tension changes during the process of manufacture to viscoelastic relaxation of strains during the re lamination process. This paper attempts a micro-mechanics approach to predicting the dimensional deformation. Models predicting the elastic properties and thermo mechanical properties are developed and validated and compared against experimental data. Model built on stress differential is created, tested and validated against simple structures exposed to different thermal histories. The work carried out provides insights and explanations for various phenomena such as the differences in thermo mechanical $T_{g's}$ in the X and Y direction. The model can also be used to predict warp and twist. A future path for further work, based on the validations is also outlined.

INTRODUCTION

Multilayer boards have long been used as the backbone of the electronics industry. These boards help reduce the space requirements and are seen in all electronic devices. The substrates are made of copper clad laminates which include woven fabric as the reinforcements and epoxy resin or a high performance resin such as high multifunctional epoxy, Cyanate esters or Polyimides may be used as matrix. The process of manufacturing multilayer boards involves exposing and developing images through a dry film or a liquid resist followed by etching to reveal the circuitry and finally stripping the dry film or the liquid resist. The etched circuitry is then covered with an oxide process which roughens the surface so that it can bond well with the prepreg (semi cured composite). Various layers are then assembled together interspersed with the prepreg and subjected to a re-lamination process. The boards are taken to a curing temperature and kept there to allow late cure cross linking. The boards are then cooled down. The next step involves drilling, followed by plating of the holes and the surface to complete the bare board. Registration becomes extremely important because the plated through holes provide the layer to layer connection and miss-registration can lead to scrapped boards due to lack of electrical connections. Board manufacturers keep a database and build regression models to predict the dimensional shrinkages during the process of relaminations but most of these models need to be constantly modified. There are multiple combinations of cores ranging in thickness from 40-1000 microns, multiple layers of prepreg and varying percentages of copper on each layer and it becomes almost impossible to predict the deformation in the absence of a mechanistic model. Additionally the shrinkages tend to be more pronounced in the warp direction as compared to the weft direction, again very hard to predict. Manufacturers compensate by increasing the registration allowance and this leads to wastage of space and increased cost. In this paper we will attempt to build a model that helps predict the dimensional movement as a function of CTE's and moduli of the constituent layers and as a function of the lamination temperature,

Models of dimensional stability:

Shrotriya et. al, have carried out an extensive investigation into the stress development of woven composite boards during re-lamination. They ascribe the stresses to viscoelastic processes in the matrix which result in time dependence of substrate properties. The focus of their attempt is on warpage and not on the dimensional stability. The effort is largely focused on development of elaborate mathematical models to characterize the behaviors of the residual strains but the mechanism/s that generates the stresses are largely ignored. [4]

Their approach outlines a linear viscoelastic analysis in conjunction with classical lamination theory applied to predict the warpage induced during the relaminations of a multilayer circuit board. They however point out crimp as one of the major factors affecting the differences in the CTE's between the warp and fill directions for the multilayer board.

Model for CTE's and Elastic moduli

Kwon and Cho have developed a multi scale and multilevel analysis scheme for predicting the coefficient of thermal expansion. The first module links the constituents, second module bridges the unidirectional composite to the woven-fabric material. The third module called lamination connects the woven fabric to the composite structure for which a Finite element analysis is carried out. Once the effective CTE of the laminated material is computed a full thermal stress analysis is carried out. The approach is FEA centric and would be tough to implement in woven styles with multiple variation in resin (matrix contents). A simpler

model is needed to compute and approximate to a good degree the thermal properties of the laminate.[2]
Dasgupta et. al, in their paper, work towards a homogenization scheme to compute the thermo mechanical properties and thermal conductivity. They go on to build numerical models that predict the thermo mechanical and thermal properties and these are compared to the experimental results. The focus in this endeavor is more on the mechanical properties such as accurate prediction of stiffness/moduli, Poisson ratios, and less on the CTE's. [1]
Naik and Ganesh in their paper work primarily on the experimental techniques to characterize the thermo mechanical properties. The paper does show data comparing the prediction to experimental data but not enough detail is given into the nature of the model. [3]
To summarize the literature survey does not offer major insights into the mechanism for shrinkage or even warpage experienced by the printed circuit bards during re lamination process. Some models proposed included the internal stresses, curing shrinkages, pressure effects but the magnitude of the shrinkages and therefore the stresses causing them does not seem to be in line with the proposed mechanisms.

CTE Model development

The CTE Model starts with the Schapery equation. Initially the author made various attempts to model the weave as a combination of 0 degree and a 90 degree ply with the appropriate area fractions but the model did not turn out to be a good fit. Instead a model was developed which used the woven fabric as a unit and area fractions in each direction were used to calculate the stiffness and the coefficients of thermal expansion.
To understand the impact of crimp; measurements were made for the 106 glass style which showed the crimp angle to be between 4^0 and 7^0 ,depending on the warp and the weft direction. The weft direction tended to look more loosely woven in comparison to the machine direction.
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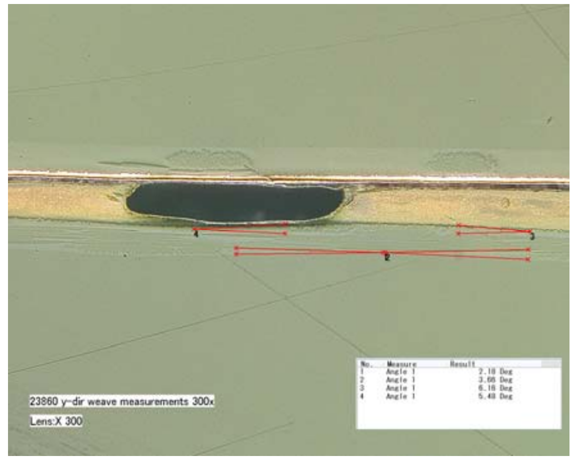
Crimp angle measurement X direction



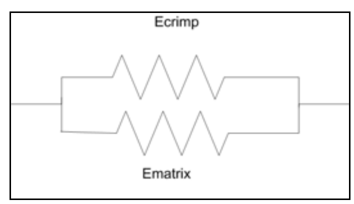
Crimp angle measurement Y direction
Pictures and measurements courtesy Isola ASL Lab

The following equations were used and calibrated against actual data made available courtesy of Isola USA Corp.

$$E_x = E_f * A_f * \eta_x + A_{mx} * E_m$$

$$E_y = E_f * A_f * \eta_y + A_{my} * E_m$$

Where η_x and η_y are the fiber efficiency factors due to the crimp or the weaving process. Initially the Krenchel model was applied but it did not work very well with the weft direction.



Modified Krenchel Model

The $\acute{\eta}_x$ and $\acute{\eta}_y$ are given by Cos^4 (θ) but the predictions did not match with the experimental data with the weft direction. This observation was in line with expectations since the fabric is loosely woven in the y direction and the Krenchel factor alone does not account for the load handling capability in the weft direction. Actual data was used for calibrating the model first with one glass style at different resin contents and then applied to other glass styles for validation and verification.

The thermal expansion was predicted using the modified Schapery equation for both directions while adjusting for the area fractions based on the number of warp and weft threads.

$$\alpha_x = \frac{\alpha_f * A_f * E_f * \eta_x + A_{mx} * E_m * \alpha_m}{E_f * A_f * \eta_x + A_{mx} * E_m}$$

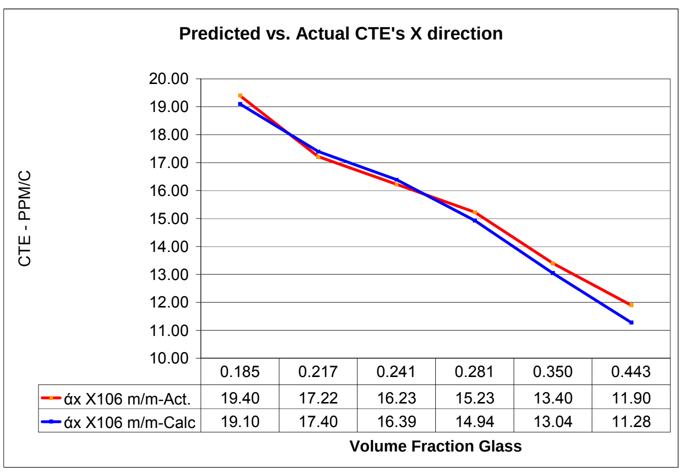
$$\alpha_y = \frac{\alpha_f * A_f * E_f * \eta_y + A_{my} * E_m * \alpha_m}{E_f * A_f * \eta_y + A_{my} * E_m}$$

Data used for modeling

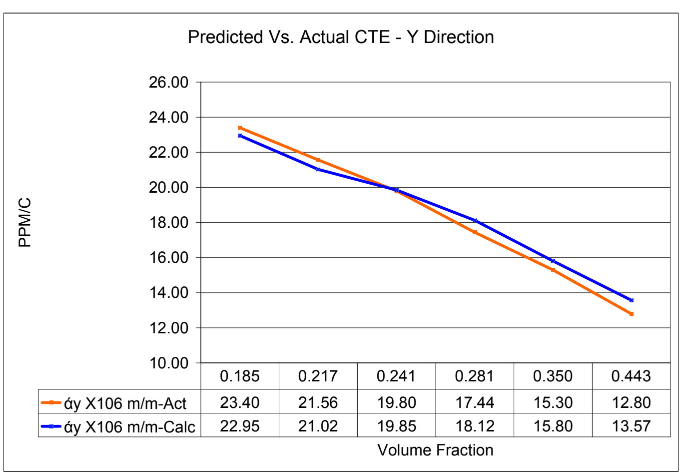
Glass	106	E_g- GPa	70.00
Warp	56	E_m -GPa	3.10
Weft	56	ν_{12}	0.1750
Weight G/sm	25	ν_{21}	0.1550
Glass	1652	$\acute{\alpha}_g$ X10^6 m/m	5.00
Warp	52	Density glass	2.50
Weft	52	Density Matrix	1.3710
Weight G/sm	141	ν_m	0.35
$\acute{\alpha}_m$X10^6 m/m	51.00	ν_g	0.20

Source: Isola data and JPS composite materials databook

Results CTE's and Moduli



Predicted vs. Actual X-CTE

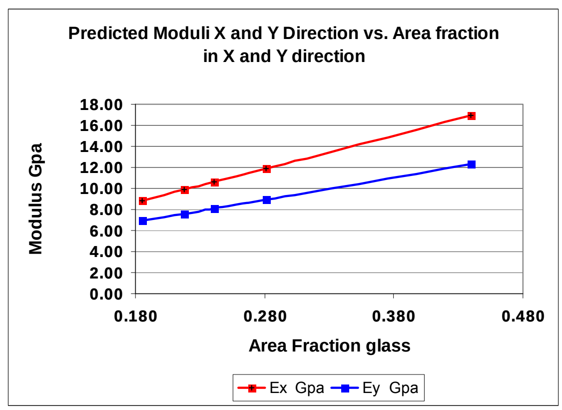


Predicted vs. Actual Y-CTE

Fiber efficiency

The above charts show very good agreement with the experimental data. The X- CTE numbers are closer than the Y-CTE numbers probably because of weaving inconsistencies leading to changes in the fiber efficiencies (due to crimp and other factors). The fiber efficiency in the X-direction was very close to 1. The crimp angle measured at 6-7 degrees gave a value of 0.98 consistent with the Krenchel model value of Cos^4 (θ) for $\acute{\eta}_x$. The value for the Y- axis during calibration was found to be very low at 0.68. This means that the loose weave in the weft (non machine direction has very low efficiency compared to the machine direction. The experimental data was collected using the 4-camera system for the in plane measurements.

Elastic properties were modeled using the above calculated fiber efficiency numbers. These numbers were not validated experimentally. The figure in the next column shows the predicted values of the moduli in the X and Y direction against the fiber fraction



Model development for shrinkage:

After reviewing various mechanisms, a model was developed that explains the shrinkages during the lamination process as a result of the mismatch in the stress levels in the matrix after yielding and cool down. Once the glass transition is reached during the process the matrix modulus drops to almost zero, the glass continues to expand with the temperature increase at a much lower rate due to its lower co-efficient of thermal expansion. On cool down the matrix is elastic again and cools at a rate determined by the properties of the matrix and glass. The difference in the yield stress and the cool down stress leads to the plastic deformation. The mechanics of the model are outlined below.
The theoretical basis of the analysis is the Classical Lamination theory. The model development starts with the

assumptions of the Kirchhoff's hypothesis. The constitutive equations are represented in the condensed form below.

$$\left\{\frac{N}{M}\right\} = \left[\frac{A}{B} \;\middle|\; \frac{B}{D}\right] \left\{\frac{\epsilon^0}{\kappa}\right\}$$

Where N and M are membrane stress resultants and moment resultants and ε^0 and κ are the strain and the curvature of the laminate geometric midplane [5]
The steps for the calculation are

A- Woven composite calculations

The effective properties of a composite layer are determined using area fractions in each direction and compensating for the crimp. The length factor is determined by using the specific wt which provides the data for length when used in conjunction with density. The efficiency factor for the warp and the weft direction is determined by calibrating the output of the model to experimental data followed by validation on other composites.
The laminate engineering/elastic constants and data are used to estimate the moduli in X and Y directions.
Glass styles of different types have different area fractions in X and Y direction and are calculated using the thread count in each direction.

The next step involves determining the S- Matrix shown below

$$\begin{pmatrix} S_{11} & S_{12} & \square \\ S_{21} & S_{22} & \square \\ \square & \square & S_{66} \end{pmatrix}$$

$$\text{Where } S_{11} = \frac{1}{E_X}\,,\quad S_{21} = \frac{1}{E_Y},$$

$$S_{22} = S_{21} = -\frac{\upsilon_{21}}{E_Y} = -\frac{\upsilon_{12}}{E_X}\,'\, S_{66} = \frac{1}{G_{12}}$$

Where ν_{12} and ν_{21} are the Poisson ratios, next step involves determining the Q- matrix, Q-Matrix is the inverse of S matrix.

The load and moment vectors are calculated using the equations shown below

$$\{N^T\} = \int [Q_K]\{\alpha_K\}\,\Delta T dz = \Delta T \sum_{K=1}^{N} [Q_K]\{\alpha_k\}(Z_K - Z_{K-1})$$

$$\{M^T\} = \int [Q_K]\{\alpha_K\}\,\Delta T dz = \frac{\Delta T}{2} \sum_{K=1}^{N} [Q_K]\{\alpha_k\}(Z_K - Z_{K-1})$$

Where Z_K Z_{K-1} are the distances of the K^{th} layer and $K-1$ layer from the geometric mid plane,
ΔT is the temperature difference from the point of zero stress
Next step involves determining the A, B and D Matrices

$$A_{IJ} = \int_{-\frac{t}{2}}^{\frac{t}{2}} [Q_{IJ}]_K\, Z\,dz = \sum_{K=1}^{N} [Q_K]\{\alpha_k\}(Z_K - Z_{K-1})$$

$$B_{IJ} = \int_{-\frac{t}{2}}^{\frac{t}{2}} [Q_{IJ}]_K\, Z\,dz = \frac{1}{2} \sum_{K=1}^{N} [Q_K]\{\alpha_k\}\left(Z_K^2 - Z_{K-1}^2\right)$$

$$D_{IJ} = \int_{-\frac{t}{2}}^{\frac{t}{2}} [Q_{IJ}]_K\, Z\,dz = \frac{1}{3} \sum_{K=1}^{N} [Q_K]\{\alpha_k\}\left(Z_K^3 - Z_{K-1}^3\right)$$

$$\begin{pmatrix} N_X \\ N_x \\ N_Y \\ N_{XY} \\ M_x \\ M_Y \\ M_{XY} \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{pmatrix} \begin{pmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{XY} \\ \kappa_x \\ \kappa_y \\ \kappa_{XY} \end{pmatrix}$$

Where ϵ_X, ϵ_y and γ_{XY} are the X and Y Strains
and κ_X etc are curvatures, next step in calculations is to add the differential CTE stresses into the Load Vector to predict the deformation

The above equations can also be used to predict the warp and twist as a function of the change in temperature.

Model- Predicting the dimensional deformation

The model relies on calculating the stress differential in the matrix on the cool down and applying it to the load vector after adjusting for the area. The laminate is stress free above the glass transition temperature, which is the thermal equivalent of yield. On the cool down the matrix is elastic again and experiences stress as a result of difference between the composite CTE and the matrix CTE. The higher the processing temperature, the greater is the stress and the consequent deformation. The equations below outline the mechanism and the model for predicting the deformation.

$$\sigma_{xm} = -\sigma_{mY} + E_m * (\alpha_x - \alpha_m) * \Delta T$$
$$\sigma_{ym} = -\sigma_{mY} + E_m * \left(\alpha_y - \alpha_m\right) * \Delta T$$

where σ_{xm} = Stress in the X − direction,
σ_{mY} = Yield stress for the Resin α_x, α_y are the CTE's in X and Y directions respectively. The stress in x and y direction is given by the equations below where A_{fx} and A_{fy} are the area fractions in the x and y directions

$\sigma_x = \sigma_{xm} * (1 - A_{fx})$

$\sigma_y = \sigma_{ym} * (1 - A_{fx})$

finally the loads in X and Y direction are calculated by multiplying with the thickness and assuming unit length

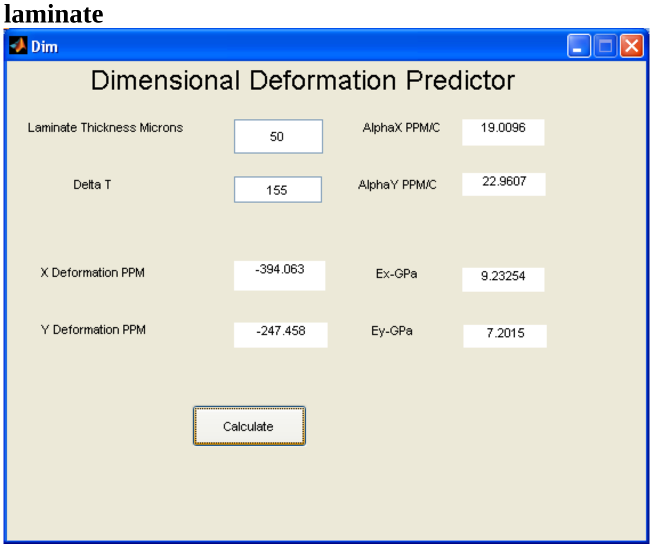
$N_x = \sigma_x * t$

$N_y = \sigma_y * t$

These loads are loaded on to the load vector to predict the deformation ϵ_x and ϵ_y

Computer Program

The Model was coded in Matlab using the GUI for ease of use. This window predicts deformation for a 50µ laminate

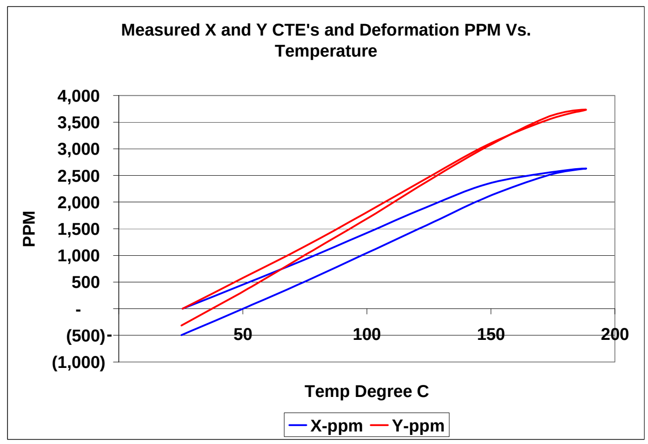


Matlab - GUI for the Dimension stability predictor

Experimental set up for validation

The 4-camera system at Isola USA Corp. measures the dimensions of the composite as the temperature is changed. Four holes are drilled in the composite approximately 10 inches apart and the composite is placed on the platens, which have heating and cooling capabilities ranging from -40^0 C to 250^0 C. Only contact pressure is applied and the composite is free to expand in the X and Y directions. This method is superior to other methods such as Thermo-Mechnaical analyzers with special fixtures because there is no contact and therefore the measurements are very accurate for the X and Y direction as there is no test equipment induced deformation.

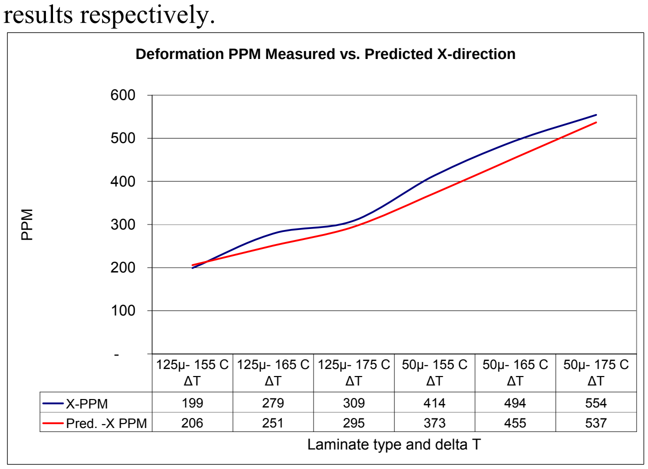
For the validation of the model the following Glass styles and Resin contents were chosen. Runs were set up for two different styles of glass -106 at 70.4 % and 1652 at 40.5 % with the intent to capture the entire range of volume fractions used in the PCB industry. The 4- camera system was used to take the unclad laminates up to three different temperatures of 200^0 C, 190^0 C and 180^0 C followed by cooling down to the starting ambient Temperature. The change from the initial start readings was taken using cameras which measure deformation in each leg. The data from opposite legs is averaged and the sample data from a run is shown in the chart below. The Matrix system used in testing is a high Glass transition temperature system with a T_g of 175^0 C (measured by a Differential scanning calorimeter). The Tg is defined by the mid point of the Transition and the softening occur earlier around 25^0 C or so.



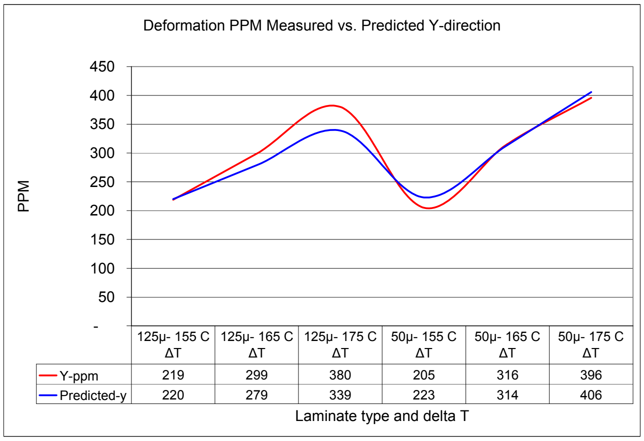
Experimental measurements for 106-70.4 % -50 Micron Laminate $T_{max.}$=190^0 C

Results

The results from the model show excellent agreement with the actual measurements. The attempt was aimed at very simple structure not including different configurations of copper, bonding sheets and mixed dielectrics. Single ply unclad laminates were used and the data came in very close; highlighting the accuracy of the model and validating the hypothesis. The R-Squared values ranged in the 0.92-0.97 range for the Y and X predictions versus the experimental results respectively.



X- Direction prediction vs. experimental number



Y- Direction prediction vs. experimental numbers

X and Y in plane TG discrepancy

The model also predicted the differences in the X and Y glass transitions which were observed during testing but often ignored as artifacts of measurement setup or attributed to residual stresses. These were clearly predicted by the model. The mechanism for this anomaly is simple. The composite CTE's in the Y direction are higher and therefore the gap between the matrix CTE and the Y direction CTE's are smaller, leading to higher strain for the same yield stress level. This clearly provides insight also into the mechanism of less dimensional shrinkage in the low temperature pressing operations. Here the Y direction does not even reach the yield point and therefore does not experience the deformation on the cool down. The difference in the yields point in X and Y direction could be as high as 10-20 Degree C depending upon the anisotropy in CTE's. The experimental work was only carried out on balanced plain weaves with equal warp and weft area fractions.

Conclusions

This study has helped achieve a breakthrough in understanding the mechanism behind the shrinkages or deformations seen in the PCB industry which seem to be unpredictable and inconsistent. The work has shown that the variability is caused by host of factors such as differences in Resin content, anisotropy to weave, weaving practices which could affect the Y-direction significantly, Pressing temperature and other factors such as the use of bonding sheet and the residual copper from the circuitry. The model and the experiments also clearly showed a strong co relation between the curing temperature and the shrinkage. The printed circuit board shops should avoid high curing temperatures. There is also scope for curing systems that cure at lower temperatures. The model could be of very high value to quick turn board shops which have to run scout
(Pilot) samples before the production runs as registration factors are unknown. The work here has shown that micromechanics models can explain the phenomena to a large extent and if the approach is applied holistically we may be able to develop a complete and accurate predictive model including all the other variables mentioned.

Future work

Work is ongoing to understand the impact of copper loading on signal and ground layers, the bonding sheets, multiple layer structures and different glass transition temperatures. A full fledged model tied to stack up will be developed as a SaaS tool.

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