The Compensation Problem and Solution Using Design of Experiments for Dense Multilayer Printed Circuit Boards

Wm. Gray McQuarrie
Isola
Chandler, AZ

Abstract

Imagine being able to accurately predict the correct artwork compensations prior to taking on a large quick turn order regardless of the board design, materials, or process. Such predictive power is possible and can be achieved without a lot of cost and complexity. This paper shows how small sets of designed experiments can be used to create a compensation model. Before a discussion of the design of experiments (DOEs), we will examine key processes and material variables that affect movement as demonstrated on real board design layout in a real production process. Only the few most relevant variables need to be included in the experimental design. A solution is presented that uses small experiments that provide the required information for constructing a general compensation model.

Introduction

Armed with the model building techniques of design of experiments (DOE), compensation predictions can be greatly improved. Using results from a real production job, this paper will present the most common compensation models used in the industry today and demonstrate their limited capability. The limited capability of these models is their faulty assumptions. One of these erroneous assumptions is that the prepreg in the multilayer board build plays a minor roll to the overall movement of the core layers. This paper will demonstrate that prepreg is one of the most important variables that affects the movement of thin cores and is an important variable in the experimental designs. Each DOE focused on an individual core type. The DOEs used only two control variables and two noise variables with 16 experimental runs. Configurations of the cores and the prepreg glass styles were the two control variables. The time period during lamination and the lamination press used in production were the two noise variables. From these small experiments coefficients were derived for each core type. These coefficients were used to generate a general compensation model. A model validation process is demonstrated on panels built in a different production plant. Validation of the model is an ongoing process and indicates where the model is performing well, where the model is weak, and where model improvements are needed to keep pace with rising technology expectations.

Typical Compensation Rules

For thin copper clad fiberglass core materials used to manufacture the different layers of multilayer printed boards (MLBs) it is necessary to develop values used to adjust the dimensions of the artwork image. This is because the core material moves during printed circuit board lamination. It is almost universally accepted in our industry that the direction of the glass will require different compensation values. Most glass styles have, (1) a warp direction which is the non-weave machine direction or glass roll length dimension; and (2) a fill direction which is the direction of the glass weave or glass roll width direction. The adjustment values for the artwork in the warp and fill directions are the artwork compensation values. There are different rules that shops have adopted in order to predict movement of circuit board layers and develop artwork compensation values. Some examples of typical compensation rules are:

1. A matrix with different compensation values by core regardless of circuit image or overall multilayer construction. For example, in such a matrix all 5 mil cores will be initially compensated by 0.50 mils/inch in the warp direction and 0.20 mils/inch in the fill direction.
2. A matrix based on circuit image and core thickness regardless of overall multilayer construction. For example, a 5 mil core signal over signal (s/s) will shrink 0.80 mils/inch in the warp direction and shrink 0.2 mils/inch in the fill direction. A 5 mil ground over ground (g/g) core will shrink 0.4 mils/inch in the warp direction and shrink 0.30 mils/inch in the fill direction.
3. A matrix or model based on production where the adjacent prepreg around the core is considered in the compensation prediction. This model considers some facets of the overall multilayer build. For example, a 5 mil s/g core with 7628 prepreg adjacent to the core will have different compensation values then a 5 mil s/g with 1080 prepreg adjacent to the core.
4. A rule where the warp direction is compensated 40% of the fill movement. If the 5 mil core shrinks 0.8 mils/inch in the warp direction then

the fill direction will shrink 0.32 mils/inch. This is a common approach where measurement capability is limited to one measurement axis.

5. A book keeping process of matching similar builds. For example if a 5 mil core moved 0.8 mils/inch in the warp direction but grew 0.1 mils/inch in the fill direction and a new part has a similar build of core, images, and prepreg then use these compensation values that worked in the past.
6. An analytical nonlinear model based on first principles that considers the overall resin % of the package with adjustment factors based on how cores have moved historically.

All of these approaches have a heavy reliance on historical information based on the movement observed from jobs run through the factory. These compensation rules describe feedback processes where errors can be amplified and can potentially shut down the production plant. For example, rule 1 above needs constant compensation adjustment, because on a 24” x 18” panel it is not unusual to have a +/- 10 mil error or +/- 500 ppm in the prediction for a specific core. In order to succeed with this rule it requires constant supervision of the compensation errors in the production population and constant adjustment of the compensation values. Unfortunately, ad hoc adjustments to get better will usually lead to process tampering. These adjustments escalate scrap rates with reduced production throughput. The loss of control on the compensation process happens very dramatically when measurement systems are incapable of accurate measurement and there are inadequate process controls around the unstable artwork material. The approach for determining compensation values, the measurement capability for material movement, and the process controls around the compensation process, define the registration compensation capability for a shop.

Typical Movements Seen on Real Product

If we use each of the 6 compensation rules above different outcomes of predicted values will occur. Consider the 10 layer board construction in Figure 1. How will the individual layers move?

Based on compensation rule 1 all of the cores should move the same. This also implies only one core layer needs to be measured such as layer 2 on the 2-3 core. Rule 2 also predicts that the movement should be the same and only one core layer needs to be measured based on the fact that all of the cores are 5 mil 0.5/0.5 s/g layers. Rule 3 would predict that the 2/3 core and the 8/9 core would move differently than the 4/5 core and the 6/7 core. Rule 3 assumes that the 2x2116 will move the same as 2116x106 or 2116x7628, which is a limiting assumption and has been found in fact not to be true. Rule 4 predicts that the fill direction will be 40% of the warp direction. Success with rule 5 depends upon whether a similar part has been used in the past and the process capability of the compensation process. Similarly success with rule 6 depends upon the prior jobs that were used to compose the critical adjustment factors. The actual movement for this part measured on a Fein Focus X-ray machine is shown in Figure 2 and Figure 3.

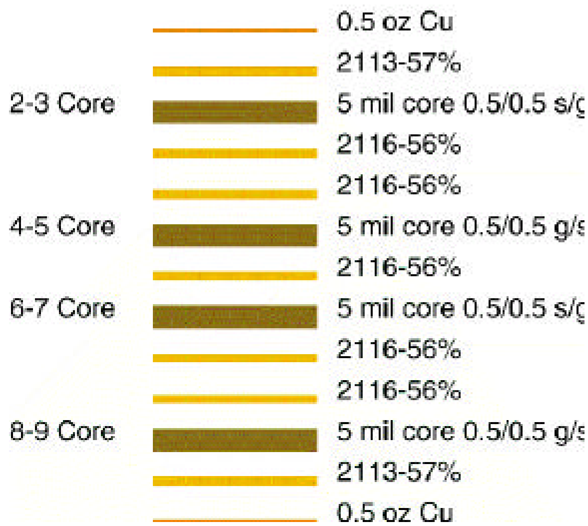

Figure 1 – 10 layer Board Construction

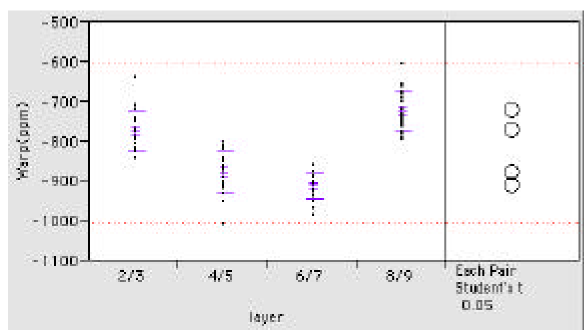

Figure 2 – Warp Direction (18”) Movement for 10 Layer Board

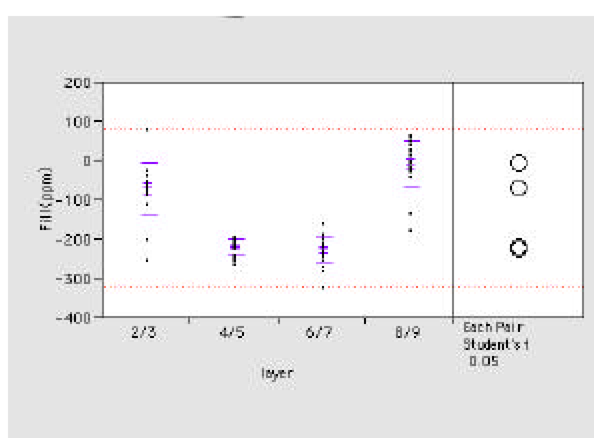

Figure 3 – Fill Direction (24”) Movement for 10 Layer Board

The units in Figure 2 and Figure 3 are in ppm. For example, -500 ppm means 500 ppm of material shrinkage or 0.5 mils/inch. Figure 2 and Figure 3 show that the cores moved differently! Moreover, Figure 3 shows differences in the spread of the data in the fill direction as seen when the 2-3 and 8-9 cores are compared to the 4-5 and 6-7 cores. Figure 2 and Figure 3 emphasize the need for a measurement system that can measure each individual core within a multilayer package. For example, if a shop uses only rule 1 using eyeball measurement on layer 2 after drill of only one panel, then it is possible to be off as much as 402 ppm in the warp direction and 402 ppm in the fill direction. The dotted horizontal lines in Figure 2 and Figure 3 show the difference between the maximum and minimum values for shrinkage, which is the 402 ppm difference. The overall registration error using rule 1 would be 568 ppm. For a 24"x18" panel the compensation error created from the model type and the measurement system would account for a 7 mil radial error (TPR) for 1/2 of a 24" dimension. A capability map assuming 2.0 mils of X and Y offset, 2 mils over 12 inches mils of angle error (0.0095 deg, which has 1.38 mils of x-offset to center), and 1.5 mils of drill wander is shown in Figure 4.

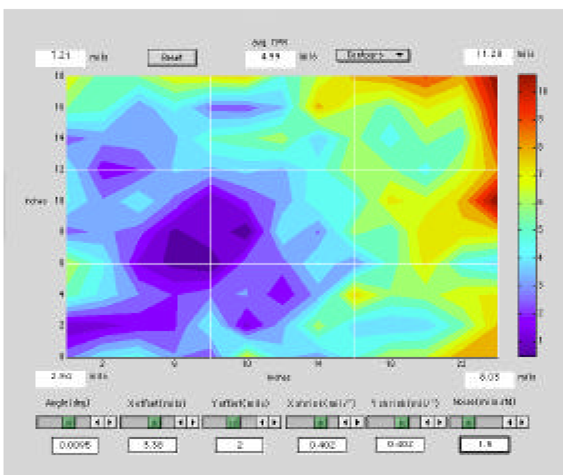

Figure 4 – Registration Capability Map Using Rule 1 + Eye Ball and 10x Loop

If you use model 1 employing a fixed compensation model and a poor measurement system, then this job would be expected to produce scrap problems with an edge of hole to edge of trace spacing of less than 10 mils provided there was no compensation adjustment for future jobs! Attempts to try to adjust the compensation based on measurements from one layer of one panel would produce an adjustment based on random noise. This noise would be amplified in subsequent adjustments and lead to potential manufacturing shutdown.

For this example rules 3, 5, and 6 may predict the movement better. All of these rules assume a significant prepreg effect; however, they are dependent upon historical information. Models derived from historical databases are biased to the type of jobs and MLB constructions run over a period of time. When a new part number uses a significantly different layup, then the compensation values in the model are no longer valid. The error from the prediction is significantly greater. This may lead to a compensation change activity or worse a model adjustment event. The problem is that the adjustment to the model is at best a fuzzy process. Moreover, there is resistance to make changes, because it is assumed that the prior assumptions for these rules are correct and there is a misguided sense that the rules should work. The advantage of the design of experiment approach is that small data sets can be gathered in a short period of time that lead to significant prediction power. Further, weaknesses in the DOE based model can be uncovered instantly and corrected using the recommended model validation process.

Key Variables

Often the lack of predictive power in the common industry compensation rules is explained by the instability or lack of consistency of the core material. A very few shops have resorted to baking the cores prior to use in production thinking there would be a big improvement. In tightly controlled multiple lot production studies using precise measurement equipment, the additional consistency seen from baking cores was 80 ppm or +/- 40 ppm. A large number of measured panels were required to see this difference. A true key variable that can dramatically drive the movement of the core is the prepreg. To date it is not universally accepted in our industry that the prepreg is key; however, not only does the prepreg glass style change the movement of the core, but the prepreg resin content also changes the movement of a core.

There is a common misconception in our industry regarding prepreg resin content and the consistency of movement of a core. For example, high resin constructions often have been thought to produce unpredictable movement. The logic used is that if the resin is too high then the cores will be swimming in resin producing inconsistent movement and registration scrap. Today, economical constructions use single ply prepregs and shops use low pressure lamination with increased lamination book height to increase production throughput. Economic constructions need high resin prepregs. How does the resin content of the prepreg effect registration?

An experiment was performed on an 8-layer MLB with 5 mil 1/1 cores where the 2-3 core was signal/signal, the 4-5 core was power/ground, and the 6-7 core was signal/signal. The 5 mil 1/1 cores were constructed using a 106/2113 construction. Two types of cores were produced: a high resin core with the 106 glass treated at 68% and the 2113 treated at 52% and a low resin core with the 106 treated at 62% and the 2113 treated at 45%. Two plies of 1080 prepreg were used in each dielectric opening. For the test a low resin 1080 treated at 60% resin content and a high resin 1080 treated at 70% were used for the low and high resin content prepreg materials. The experimental results were obtained by measuring the MLBs after multilayer lamination using a Fein Focus X-ray machine.

The experimental matrix is given in Table 1 below along with the average movement and standard deviation shown in parentheses.

Table 1 - Results of Prepreg Resin Content DOE

Prepreg	Core	23 Fill(ppm)	23 Warp(ppm)	45 Fill(ppm)	45 Warp(ppm)
High	High	-349(30.4)	-817.1(65.9)	-477.4(16.7)	-594.3(54.4)
High	Low	-257.7(49.8)	-828.7(68.9)	-467.7(25.9)	-604.5(58.8)
Low	High	34.4(72)	-861.6(54.1)	-86.1(40.3)	-731.9(56.4)
Low	Low	142.3(56)	-826.8(78.1)	-12.5(58.5)	-705.1(54.5)

Figure 5 below shows the results for the signal/signal 2-3 core in the fill direction

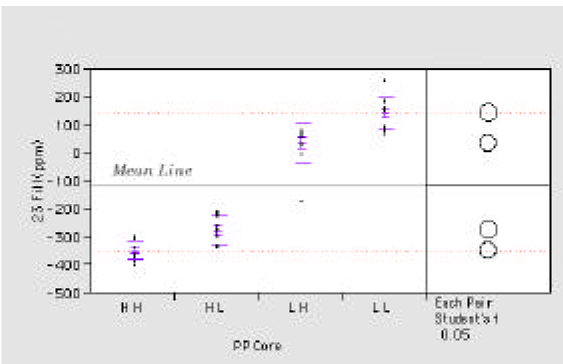

Figure 5 – Resin Content Effect – Fill Direction

The mean line shown in Figure 5 is the grand average of all of the experimental readings. The horizontal dotted lines show the average maximum difference between experimental runs. The four experimental runs are indicated on the x axis. For example H H is the high resin prepreg and the high resin core. The circles to the right show the 95% confidence interval about the mean for each of the four runs. The circles allow an easy determination of statistical significance. The fact that the circles are not overlapping means all of the runs are statistically different. Clearly the resin content of the prepreg has a greater degree of difference than the resin content of the core. Figure 6 shows the results for the power/ground 4-5 core.

The results in Figure 6 are surprising since it is commonly thought that the copper restrains the movement of the core from other forces. This suggests that the prepreg around the core may be more important than the amount of copper on the core.

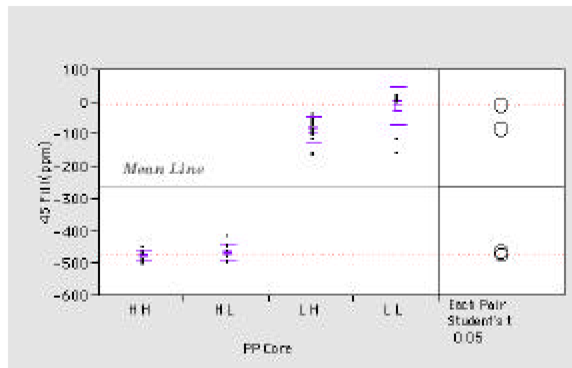

Figure 6 – Resin Content Effect – Fill Direction

There are differences in behavior between the warp and fill directions for resin content. Figure 7 shows the resin content data for the 2-3 core in the warp direction.

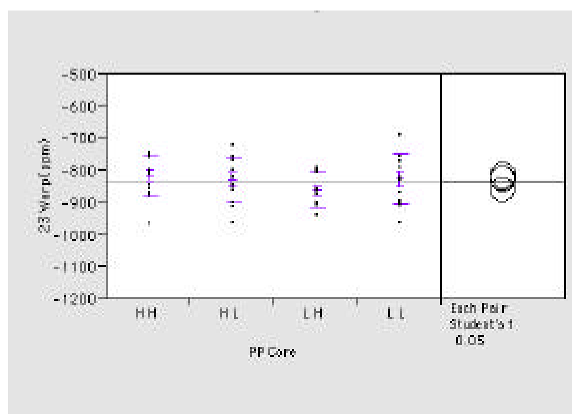

Figure 7 – Resin Content – Warp Direction

Note that resin content plays an insignificant role for this core, in this core configuration, using this prepreg style. Figure 8 shows the resin content data for the 4-5 core in the warp direction.

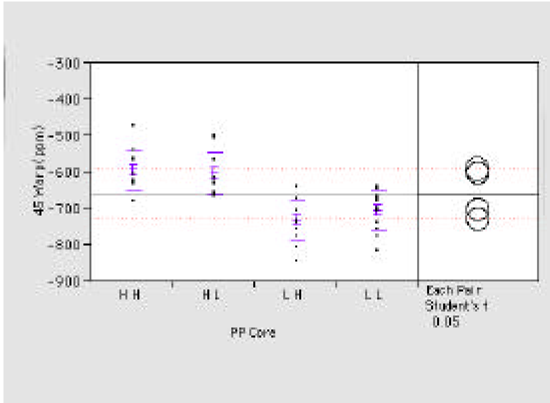

Figure 8 – Resin Content – Warp Direction

Figure 8 shows that the 4-5 power ground core is sensitive to resin content.

Another rule of thumb in the industry is that the fill direction is more unstable than the warp direction. This generalized statement, as well as the swimming in resin statement are neither accurate nor useful. By collecting production data and executing carefully planned and manageable designed experiments the true facts can be uncovered. Comparing Figures 2 and 3 representing the warp and fill data for the 10 layer board the standard deviation is tighter in the fill direction for the two inner cores (4-5 and 6-7) and looser for the outer cores (2-3 and 8-9). The issue for this inconsistency is a specific glass style in a specific direction and not a universal truth that a glass direction, such as the fill direction, is unstable for all glass styles. Analyzing Figures 5 through 8 using the 1080 prepreg the standard deviation in the fill direction is tighter than the warp direction, but the sensitivity to resin content differences is greater in the fill direction than in the warp direction!

Using a DOEs to Build a Predictive Model

The pressures of time, cost, and production schedules prevent an exhaustive study of every possible variable responsible for material movement. Using a DOE approach a number of variables can be examined at one time. Sets of small experiments were done on a specific core construction. An 8-layer MLB configuration was used since this represented complexities found in all multilayer boards . For example, an 8-layer board has cores separated from the outer copper with prepreg (outer core) and cores surrounded by other cores (inner core). There were two control variables used in the DOE. One control variable was the circuit configuration of cores 2-3, cores 4-5, and cores 6-7, such as ss/gg/ss. The other control variable was the prepreg used between the cores. Noise variables were included and they were the time period and the specific multilayer lamination press. A 16 run experiment was planned where there was a full factorial for the two control variables and a fractional factorial for the noise plus the control variables. The variable levels for the experiment are shown in Table 2.

Table 2 – Experimental Variables Levels

Variable Level	*Control Variables*		*Noise Variables*	
	Cores	**Prepreg**	**Time**	**Press**
1	ss/gg/ss	2x1080 (8 plies)	1 (4 days)	1 (vac)
2	gg/ss/gg	2x2113	2	2 (vac)
3	gs/ss/sg	2x2116	3	3 (vac)
4	gs/gg/sg	1x7628 (4 plies)	4	4 (assist)

In the prepreg column the number of plies of prepreg for each dielectric opening is indicated. For example the panels made with 1080 prepreg used 8 plies of prepreg while the panels made with 7628 used 4 plies of prepreg. The time periods were four days apart. The presses used included: press 1 and press 2, which were older full vacuum electric presses, press 3 was a new electric vacuum press with in-platen cooling capability, and press 4 was an old vacuum assist electric press with a different press cycle then presses 1 through 3. Both the control and noise variables were treated as categorical variables with four distinct levels in the predictive model.

There are many things that can go wrong with a designed experiment. Anticipating problems and including them in the design increases the probability of success. The noise variables were critical for the experiments since they would check the validity of the control variables. Having an experimental result that is unique for a particular day or on a particular press would by useless to production. In any experiment there must be an adequate sample size. Depending on the circuit configuration and the prepreg used the standard deviations could be quite large as seen in Figure 2 and Figure 3. On the other hand, producing too many panels would lead to a prohibitively expensive experiment. For the experiments one book of 10 panels were produced, which helped with experimental logistics, and provided adequate statistical resolution at a minimum of cost.

Figure 9 shows the results of the categorical linear model based for the 2-3 core on the experiment done on a 5 mil 1/1 core with a 1 ply 1652 glass construction. The upper row of graphs shows the warp model and the lower row of graphs shows the fill model.

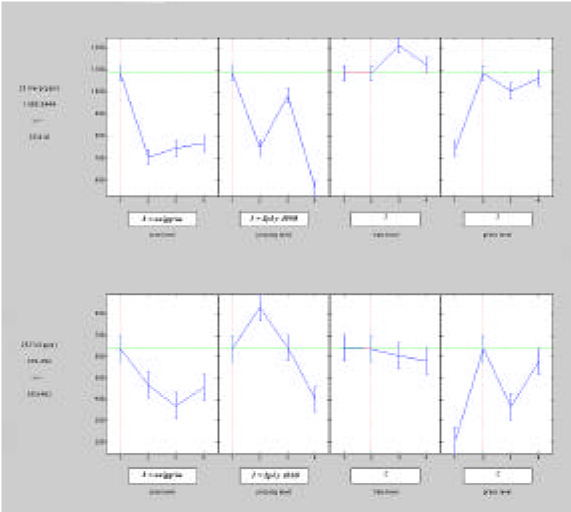

Figure 9 – Linear Model for the 2-3 and 6-7 Core (5 mil 1/1)

Refer to Table 2 for detail on the core, prepreg, time, and press levels. Figure 9 shows the compensation predictions in ppm. For example, the upper row of graphs in Figure 9 shows a level 1 core where the 2-3 core is signal/signal with a level 1 prepreg (1080) in time period 2 on lamination press 2 requires 1085 ppm of artwork growth to compensate for the material shrinkage.

There is a lot of information in Figure 9. The connected line in the prepreg graphs (2nd column of graphs) shows how the movement will change for the 2-3 core in the ss/gg/ss circuit configuration as the prepreg level is changed. Note, that in the warp direction, if the board went from a dual ply 1080 construction to a single ply 7628 construction, then the required compensation would change from 1100 ppm to 600 ppm or a difference of 500 ppm! Often when shops convert to single ply constructions they experience registration difficulties thinking that there is some instability associated with the 7628, or that suddenly some mysterious property controlled by the material supplier has changed. Ironically, the 7628 is actually more dimensionally stable than the dual ply 1080 construction for a 5 mil 1/1 core in an 8-layer board using a ss/gg/ss configuration.

Let's look at Figure 9 in more detail. The solid blue lines indicate the trend line for the variables. These trend lines change when interaction terms are considered in the model. Since Figure 9 represents a linear model with no interactions the trend lines don't change their shape. The computer software used to generate this graphic allows all 256 possible predictions to be examined easily, which is difficult, if not impossible in more simple stagnant graphs. The vertical dashed red lines indicate the setting of each variable and the horizontal green dashed line shows the prediction level. The vertical blue error bars seen on the solid blue trend lines show the 95% confidence interval for the prediction. For example, the difference between 1080 prepreg and 7628 prepreg is highly statistically significant because of the separation of the error bars. The overlapping error bars for the time period variable indicate that the ss/gg/ss configuration is stable. The error bars indicate the confidence interval for a prediction is approximately +/- 35 ppm in the warp direction. With the drift in time the confidence interval is about +/- 150 ppm. The press noise variable indicates a serious problem.

The experiment on the 5 mil core caught a press malfunction. Both in the warp and the fill direction there are non-overlapping error bars, particularly with press 1. The difference seen in the press type in the warp direction was 350 ppm and the difference in the fill direction was 420 ppm. This would produce a combined registration error of 546 ppm. When press 1 was investigated it was found to have a hydraulic malfunction, which prevented the achievement of full pressure during the press cycle. There were also calibration problems with this press. In tests with other cores, after the press problem was fixed, both the time and press variables had tighter overlapping bars. Figure 10 shows the model for the 4-5 core.

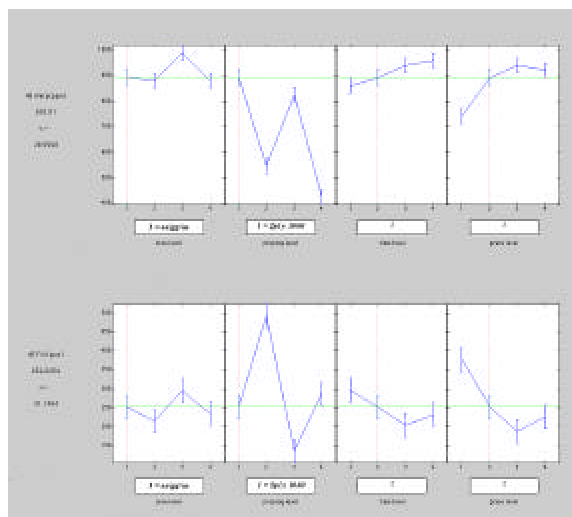

Figure 10 - Linear Model for the 4-5 Core (5 mil 1/1)

Note that Figure 10 shows a strong sensitivity with prepreg type as well as with the specific lamination press. Comparing Figure 9 and Figure 10 the amount of copper on the 4-5 core seems to be less important than the amount of copper on the 2-3 core. This is particularly surprising since the 4-5 core levels 1 and 4 were g/g and core levels 2 and 3 were s/s. Figure 10 shows consistency with the overlapping error bars for the time variable. Figures 9 and 10 show the significance of the prepreg and the significance of the lamination process in the movement of the multilayer cores.

Even with the press problem the results for the 5 mil core DOE can be used to build a model that includes the configuration of the cores in the 8-layer board and the effect of prepreg used to laminate the cores together. The resulting model shows strong interactions and predicts a wider range than the linear model used to check for noise effects. Figure 11 below shows the maximum positive compensation predicted in the fill direction for the 2-3 core.

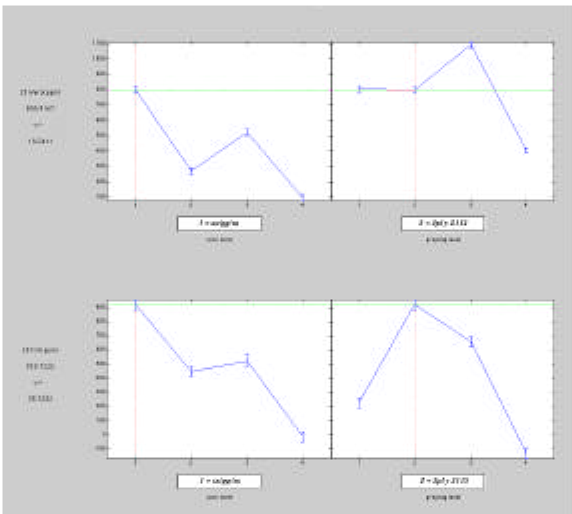

Figure 11 – Interactions Model Showing Maximum Positive Compensation in the Fill

Figure 11 shows that the maximum positive compensation in the fill direction for the 2-3 core is 920 ppm. This is obtained when the configuration of the cores is ss/gg/ss and the prepreg around the cores are 2 plies of 2113. Note that the compensation required in the warp direction is 800 ppm, which is 120 ppm less than the fill. This invalidates a common rule of thumb where the warp movement should always be greater than the fill movement. Using compensation rule 4 (40% of warp equals fill) would lead to serious registration difficulties.

Figure 12 shows the maximum negative compensation obtained in the fill direction.

The maximum compensation shrinkage for the fill direction is –242 ppm. The warp direction also requires compensation for material growth of –133 ppm. The negative compensation value means the material is predicted to grow in the fill direction when the core configuration is gs/ss/sg and the prepreg is single ply 7628. Even when it is detected, growth is often discounted in many printed circuit board shops as being a fluke, since it is a common misconception that the material must shrink. Figure 12 not only shows material growth in the fill direction but also in the warp direction! Again the 7628 is predicting the most dimensionally stable construction.

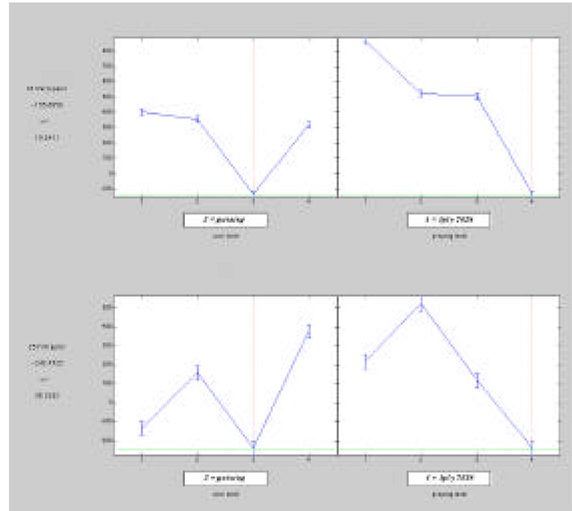

Figure 12 – Interactions Model Showing Maximum Negative Compensation in the Fill

Note that the trend lines change between Figure 11 and Figure 12 when the settings of the core and prepreg change. This is because of the interaction terms in the model. A way to think about the interactions in the model is to view it from the cores where different core configurations are going to react to prepreg changes differently. Conversely, the interaction can be thought of in terms of the prepregs reacting to core configuration changes differently. Bottom line, the overall movement of a core is sensitive to the architecture of the construction and the combination of materials.

Using the Model Coefficients to Develop the General Model

Up to this point the use of the DOE on the 5 mil 1/1 1x1652 core has provided us with a simple model of limited value. For example, there are many different core configurations, layer counts, and prepreg combinations that are not found in the simple boards built in the DOE. In fact, if you where to consider a 10 layer board with different core thickness, configurations, prepreg styles there are tens of thousands of possible combinations. This seemingly hopeless task of building a generalized model is surmountable using a focused strategy and setting the boundaries for the model.

The construction of a general predictive model follows these steps:

1. Determine the most frequently used core thickness noting similar glass constructions.
2. Determine the most frequently used prepreg styles.

3. Design a DOE that includes the minimum amount of design complexity with the noise variables.
4. Set the boundary conditions of the model by core thickness, configuration, prepreg styles, and number of layers.
5. Perform the experiments for each core.
6. Linearly combine the individual core models to generate different prepreg combinations.
7. Linearly combine the individual core models to derive different core configurations.
8. Use the 8-layer construction as a building block to generate predictions greater than 8-layers.
9. Validate the model using data base techniques.
10. Adjust linear combinations as required based on validation data.
11. Perform additional core experiments as required based on validation data.

A model with surprising predictive power for a large shop was designed and generated in one month using a 4 mil, 5 mil, and 8 mil core and 1080, 2113, 2116, and 7628 prepreg. When starting the modeling effort it is important to start small and not to try to conquer the universe of all possibilities in a one time costly mass effort. The goal should be to improve the current ability to predict movement and improve artwork compensations. Being focused on a specific goals with minimal complexity will ensure success in the model building effort.

In order to generate linear combinations of the models, the model coefficients need to be described. Table 3 below shows the model coefficients for the 23 core in the warp direction for the 5 mil 1/1 1x1652 core.

There are 25 terms in the model in Table 3 yet the 5 mil core DOE had only 16 runs. Only 16 terms are required to generate all of the 25 terms in this model. This is because all of the level 4 terms can be derived from the other terms. For example, the Prepreg (4) coefficient is equal to the sum of prepreg coefficients 1 through 3 times –1 or:

Prepreg(4) = -1x(Prepreg(1) + Prepreg(2) + Prepreg(3)) (1)

The Core(4)xPrepreg(1) coefficient is derived from the formula:

Core(4)xPrepreg(1) = -1x(Core(1)xPrepreg(1) + Core(2)xPrepreg(1) + Core(3)xPrepreg(1)) (2)

Table 3 – Model Coeffieients for the 23 Core in the Wrap Direction for the 5 Mil ½ 1X165Z core

Term	Coefficient
Intercept	-518
Core(1)	-257
Core(2)	116
Core(3)	78
Core(4)	63
Prepreg(1)	-237
Prepreg(2)	95
Prepreg(3)	-141
Prepreg(4)	283
Core(1)xPrepreg(1)	208
Core(1)xPrepreg(2)	-121
Core(1)xPrepreg(3)	-176
Core(1)xPrepreg(4)	89
Core(2)xPrepreg(1)	51
Core(2)xPrepreg(2)	35
Core(2)xPrepreg(3)	150
Core(2)xPrepreg(4)	-236
Core(3)xPrepreg(1)	-190
Core(3)xPrepreg(2)	-178
Core(3)xPrepreg(3)	77
Core(3)xPrepreg(4)	291
Core(4)xPrepreg(1)	-69
Core(4)xPrepreg(2)	264
Core(4)xPrepreg(3)	-51
Core(4)xPrepreg(4)	-144

The detailed mathematical machinery used to generate categorical models exceeds the scope of this paper.

In order to generate a prediction using Table 3 consider the example of an 8-layer board with core configuration 2 (gg/ss/gg) using 2116 prepreg throughout. The prediction would be the following sum:

Prediction = Intcp + Core(2) + Prepreg(3) + Core(2)xPrepreg(3) = -393ppm of movement [3]

The –393 ppm of movement predicted would require a positive 393 ppm of artwork growth to correctly compensate the material shrink. By assigning different weights using linear combination techniques to the coefficients different prepreg compositions around a core can be predicted by the general model.

The number of core configurations for an 8-layer can be expanded to all possibilities with the four configurations studied from the DOE. This expansion is similar to the techniques used to generate predictions with different prepreg combinations. Further higher layer count boards can be treated as 8-layer blocks in order to generate predictions from 6 layer boards to 24 layer boards using the outer core and inner core concept of the 8 layer board. An exact description of the linear combinations of the models, linear expansion, and block treatments is beyond the scope of this paper.

Model Validation

Validation of the model is essential to ensure good predictive reliability. The validation process can also give insight into additional simplifying assumptions as well as to determine areas where the model can be improved.

An example of model validation is presented with three cases: an 8-layer board using a combination of prepregs, an 8-layer board using a core configuration not part of the experimental design, and an 8-layer board using a core not included in any of the modeling experiments. All of the cases present validation data taken from a different plant than where the modeling experiments were performed. Tables 4, 5, and 6 show the model validation results for different cases.

Table 4 – 8 mil 1/1 Core Model Results with Mixture of Prepregs

Core	**Layup**	***Model Predictions***		***Actual Results***		***Error***	
	2116	**Warp**	**Fill**	**Warp**	**Fill**	**Warp**	**Fill**
2-3	***8mil 1/1 g/s***	377	140	229	263	-148	123
	7628						
4-5	***8mil 1/1 s/s***	442	206	397	311	-45	105
	7628						
6-7	***8mil 1/1 s/g***	377	140	382	205	5	65
	2116						

Table 5 – 8 mil 1/1 Core Model Results with a Non Tested Core Configuration

Core	**Layup**	***Model Predictions***		***Actual Results***		***Error***	
	7628(l resin)	**Warp**	**Fill**	**Warp**	**Fill**	**Warp**	**Fill**
2-3	***8mil 1/1 s/g***	254	297	396	258	142	-39
	7628(h resin)						
4-5	***8mil 1/1 g/g***	362	320	412	255	50	-65
	7628(h resin)						
6-7	***8mil 1/1 g/s***	254	297	348	188	94	-109
	7628(l resin)						

Table 6 – 8 mil Core 1/1 Model Results in Predicting the Compensations for a 14 mil Core 1/1

Core	Layup	***Model Predictions***		***Actual Results***		***Error***	
	1080 7628	**Warp**	**Fill**	**Warp**	**Fill**	**Warp**	**Fill**
2-3	***14mil 1/1 s/s***	461	479	404	436	-57	-43
	2113 7628						
4-5	***14mil 1/1 g/g***	461	208	382	280	-79	72
	7628 2113						
6-7	***14mil 1/1 s/s***	461	479	411	363	-50	-116
	7628 1080						

These Tables give immediate feedback and insight into the process and into the model. Table 4 shows an inconsistent error result in the 2-3 core and the 6-7 core: -148ppm versus +5ppm for warp and +123ppm versus +65ppm for the fill. Though the magnitude isn't serious, the result may indicate an instability in the movement. Often when there is poor registration the material's dimensional stability is near the top of the list of blame. However, the lack of dimensional consistency may be caused by the instability of the photo tool materials. A silver halide Mylar phototool is very sensitive to temperature and humidity and sensitive to usage. Without sufficient process controls it is not unusual to have over 500ppm error in the artwork in a significant percentage of the artwork population. This amount of error has been observed in several large shops. The best large shops check the artwork with each use and dispose of the artwork after 500 to 1000 hits. When validating the model the actual artwork being used must be measured for stretch so that the actual compensation error can be computed.

Table 5 indicates that the difference in resin content in the 7628 doesn't have much impact in the prediction results even though the model used doesn't include resin content. This suggests that a resin content variable or high resin prepreg type may not be needed in this model for 7628 resin variations. Table 6 shows a very encouraging result in that the 8 mil 1/1 core with 1x7629 may move the same as a 14 mil 1/1 core made with 2x7628. Finding cores that move in a similar fashion significantly reduces the model building work. Further the fact that the validation results are from a different plant than where the DOEs were performed suggests that there is some potential transportability of the model.

The three Tables show the tremendous potential of information revealed during model validation. For larger data sets and for better examination of the validation data, simple graphical techniques can be employed. Figure 13 below shows the results of the three tables presented graphically.

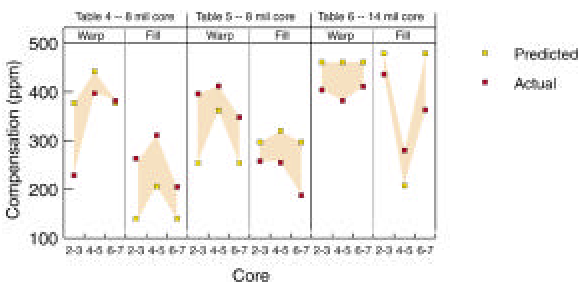

Figure 13 – DOE Model Predictions Versus Actual Measured Results

Figure 13 shows the model predictions as light yellow squares. The actual average results are shown as dark red squares. The shaded area under the points represents the compensation error between the predicted and actual results. Note how the outer and inner cores move about the same regardless of copper amount or prepreg style. The amount of copper seems to have a minimum effect on the movement except for the fill direction in Table 6. The DOE model did an excellent job of predicting this strong effect, which would likely be missed by the compensation rules discussed earlier.

The same type of graphical analysis can be made with the actual movement results using any of the other compensation rules. Figure 14 shows the analysis using compensation rule 4.

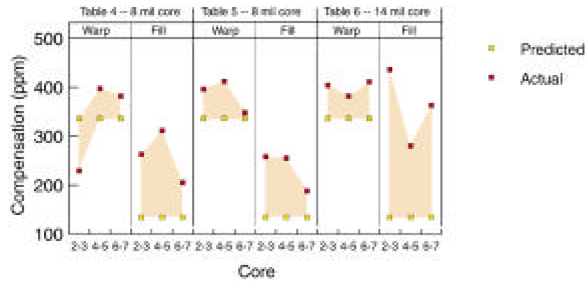

Figure 14 – Rule 4 Model Predictions Versus Actual Measured Results

For Figure 14 the average movement in the warp direction recorded in Table 4 was used for the predictive values of the warp direction. The Fill direction was computed by taking 40% of this value. As can be seen some of the predictions are surprisingly good in the warp direction. In the fill directions the predictions aren't very good especially with the data in Table 6. Figure 14 emphasizes the need to be able to measure movement in both the warp axis and fill axis.

Figure 15 is an important chart because it starts to uncover the value of the compensation model built using designed experiments.

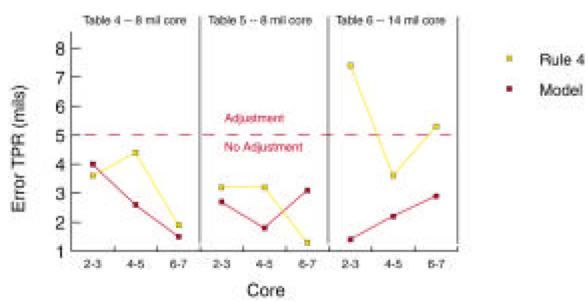

Figure 15 – Compensation Rule 4 Performance Versus DOE Model Performance

It is not uncommon for most shops to use an error value, such as a 5 mil compensation TPR, in order to trigger a compensation change. Figure 15 shows that two compensation change events would be triggered out of 9 core jobs for rule 4. This represents a compensation change percentage of 22%. Figure 15 shows that the DOE model would require no compensation change events with the three jobs presented. Improvement in the compensation tolerance TPR could be made with the DOE model by understanding the measured differences in movement between core 2-3 and core 6-7. For further demonstration of the predictive power of this model refer to the "Improving Compensation Error" section of reference 1.

Compensation changes are expensive. When compensation changes are perceived to be required and if the compensations aren't working reliably, then the shop either must release test lots for every new part number or release new parts and make production changes on the fly. This results in wasted product, wasted manufacturing capacity, and adds additional costs, which are likely to be substantial on an annualized basis. When a number of compensation changes are introduced, when production pressures are high, then process steps are skipped, old material is used, artwork is mixed, and the compensation change process becomes impossible to manage.

Conclusions

Current inflexible compensation rules and models do not provide the accuracy needed to launch large volume quick turn orders without doing large volume test lots. When the models do not work there is only the fuzziest insight as to what is wrong and what can be corrected to make the predictions better. The main reason for the failure with these traditional models is their faulty assumptions, which are treated as fact. Failure to meet production objectives encourages too many ad hoc adjustments or the introduction of fudge factors. This leads to increased production complexity, thus making the entire compensation process unmanageable in the long term. This paper has shown how sequential designed experiments done on specific core types can provide compensation coefficients that can be combined into a general model. In fact, these experiments only use two modeling variables and two process noise variables in 16 runs. Success is achieved by including key variables such as prepreg type and noise variables such as the mutilayer board lamination press. The implementation of these models produces a step change improvement in reducing compensation error. Further improvements come from an ongoing validation process. The validation process shows where additional work needs to occur to keep pace with rising technology levels as well as uncovering other possible simplifying assumptions.

Today there is no model that can effortlessly predict required compensations for every possible material, on every core construction, in any combination, using any multilayer process, in any plant. What is possible is to develop an effective model building strategy based on data from designed experiments that can be reliably maintained in order to effectively reduce overall compensation error.

References

1. McQuarrie, Gray. “Control of Key Registration Variables for Improved Process Yields on Dense MLBs.” IPC Technical Proceedings 1999: S15-5.
2. Kelley, E.; Christofferson, O. “A Comprehensive Examination of Design and Manufacturing Benefits Resulting from Improved Innerlayer-to-Drilled Hole Registration Capability.” CircuiTree, Aug. 1998: 66-96.
3. Holmes, Robert. “A Model for Re-Lamination Shrinkage.” IPC Technical Proceedings 1996: S17-9.
4. Jones, Brad. “Matlab Statistics Tool Box Users Guide.” The Mathworks. 1997.

Acknowledgements

The author is indebted to Dan Buxton of Hadco Phoenix and the support of the Hadco Phoenix management team during the time of this work. Special thanks to Brad Jones of SAS Institute for his ongoing support and statistical insights.