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When Precision is not good enough

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Abstract
As PCB designs become ever more complex with more sequential build up layers, tighter annular ring designs and broader range of advanced materials, understanding the effect of material distortion is critical to maintaining yields. Determining the inner layer scale factors to compensate for various material movements is also becoming increasingly difficult and with the additional constraints of the “quick turn” market there is no longer the luxury of running scale factor test batches – the first batch made must be delivered to the customer.

Latest generation drilling and imaging equipment provides the ability to automatically scale the drill program or image to match each panel manufactured. These capabilities ensure accurate registration of the relevant processes, but if scale errors have already been made on the inner layers, these errors are being followed throughout the manufacturing process and will ultimately be delivered to the end customer. To provide products of nominal dimensions to the customer, the original inner layer scale factors must be accurate and an intelligent compensation system should be used at these processes to reduce or eliminate the effect of variations upon the product received by the customer.

This paper analyses the data from a variety of product designs and constructions made at numerous facilities worldwide and demonstrates the influence of this variety upon the required scale factors. By comparing production results over two years and additional experimentation by the author, this papers shows that the variations exhibited can not be accounted for by simple look up tables and a more complex model is required to accurately predict the correct scale factors for new product designs. The paper will also outline the concept of an intelligent compensation system and how this could be applied to the manufacturing processes.

Introduction

Since the departure of most high volume PCB manufacturing to the Far East, many of the surviving PCB shops in the West have turned to the manufacture of quick turn and low/mid-volume high technology products. The increased density of PCB designs provide tighter annular ring availability and therefore less tolerance on positional accuracy of each process to the board being manufactured. With the introduction of sequential build up technology and designs incorporating blind, buried or micro vias, the number of processes that must be registered to each other has expanded rapidly.

At one time fabricators could select the construction of the PCBs based upon layer count and use standard inner layer scale factors proven to work for this construction. When a new construction came along, a small volume pilot lot would be manufactured to determine the required compensations prior to manufacturing the volume production. With the increased functional demands of the PCBs, the constructions have become prescribed by the designers and the number of possible material and process combinations has grown far beyond a standard list and fabricators face new constructions on a daily basis. The variety of materials used is also growing as the laminate suppliers introduce new ranges of advanced materials to meet the functional requirements of the designers. Each new material and construction requires it’s own unique set of inner layer scale factors and with the additional demands of the quick turn industry and introduction of lean manufacturing principles, there is no longer the opportunity to determine scale factors using pilot lots.

Significant developments in the accuracy of the latest generations of drilling and imaging equipment has allowed the capability to automatically compensate either drill program or image to match the actual dimensions of the boards down to a panel by panel level. The improved repeatability of these production methods prevents the introduction of further random dimensional errors to the boards in production but existing dimensional errors are not removed and the subsequent processes must follow any existing errors on the product. The features on the final product delivered to the customer will therefore not be at nominal dimensions and the effect upon the customer may be exacerbated if the fabricator chooses to use panel by panel compensation instead of batch level compensation.

Though panel to panel variations may still exist, the ability to correctly predict inner layer scale factors prior to commencing manufacture will remove the systematic scaling error so that it is possible to provide nominal dimensional product at the end of the manufacturing process. This paper looks at the ability to determine inner layer scale factors by considering a number of factors including core thickness, copper layout and prepreg selection.

Data Collection

By automatically capturing production data from a number of fabricators, it was possible to examine the influence of different construction/design parameters upon the scale factors. In essence to get a detailed knowledge of exactly what scale factor was required to manufacture product to nominal dimensions.

For each product in the data set, the construction and materials used is recorded – the core materials are defined by supplier, resin system, thickness and construction, whilst prepreg materials are defined by supplier, resin system, glass cloth and resin content. For each inner layer, the percentage copper distribution and initial scale factors has been recorded. Scale error data measured by x-ray co-ordinate measuring systems, x-ray drills and vision drill systems post lamination and prior to drilling has been automatically collated for each inner layer of the products within the data set. Using the average scale error for each layer of a product, it is possible to determine how the initial scale factor values should be modified to provide the optimal scale factors.

The total data set collated contains more than 20,000 different core records each with their own copper patterns and different constructions. All the results shown in this paper are based upon a single common resin system and concentrates on the thin cores predominant in complex multilayer products.

Results

The results shown in table 1 compare the average scale factor required for each core thickness for a standard single lamination multilayer construction. Scale factor values are shown as a percentage and for comparison, the effective movement over a 609mm (24 inch length) is shown.

Table 1 – Average Scale Factors by Core Thickness

Core Thickness Microns (mils)	Grain Direction (Warp)		Fill Direction (Weft)	
	Scale Factor %	Total Movement over 609.6mm (24 inches)	Scale Factor %	Total Movement over 609.6mm (24 inches)
50 (2)	100.0877	535 microns (21.1 mils)	100.0306	187 microns (7.3 mils)
75 (3)	100.0871	531 microns (20.9 mils)	100.0314	191 microns (7.5 mils)
100 (4)	100.0751	458 microns (18.0 mils)	100.0309	188 microns (7.4 mils)
125 (5)	100.0686	418 microns (16.5 mils)	100.0299	182 microns (7.2 mils)
150 (6)	100.0628	383 microns (15.1 mils)	100.0384	234 microns (9.2 mils)
175 (7)	100.0515	314 microns (12.4 mils)	100.0438	267 microns (10.5 mils)
200 (8)	100.0563	343 microns (13.5 mils)	100.0443	270 microns (10.6 mils)
250 (10)	100.0551	336 microns (13.2 mils)	100.0411	250 microns (9.9 mils)

From the results, it can be seen that the required scale factor in the grain direction decreases as the core thickness increases and the required scale factor in the fill direction increases as the core thickness increases.

The average values do not provide accurate scale factors for all the products in the data set as can be seen from the standard deviation information shown in Table 2. If six standard deviations are taken to be representative of the total variation, the anticipated dimensional variance across the panel length for the data set can be calculated. The table below shows the effect of the variation over a standard distance of 609.6 mm (24 inches).

Table 2 – Standard Deviation of Scale Factors by Core Thickness

Core Thickness Microns (mils)	Grain Direction (Warp)		Fill Direction (Weft)	
	Standard Deviation (%)	6 Sigma Variation over 609.6mm (24 inches)	Standard Deviation (%)	6 Sigma Variation over 609.6mm (24 inches)
50 (2)	0.0359	±657 microns (±25.9 mils)	0.0223	±407 microns (±16.0 mils)
75 (3)	0.0275	±504 microns (±19.8 mils)	0.0161	±294 microns (±11.6 mils)
100 (4)	0.0285	±521 microns (±20.5 mils)	0.0203	±370 microns (±14.6 mils)
125 (5)	0.0247	±452 microns (±17.8 mils)	0.0196	±358 microns (±14.1 mils)
150 (6)	0.0224	±410 microns (±16.1 mils)	0.0175	±321 microns (±12.6 mils)
175 (7)	0.0197	±360 microns (±14.2 mils)	0.0142	±259 microns (±10.2 mils)
200 (8)	0.0203	±371 microns (±14.6 mils)	0.0160	±292 microns (±11.5 mils)
250 (10)	0.0202	±369 microns (±14.5 mils)	0.0154	±282 microns (±11.1 mils)

As the core thickness increases, the variation around the average scale value decreases in both axes. The range of variation shown in the 6 sigma spread is in excess of almost all design rules and would result in either misalignment of cores or scale errors in the product.

Clearly core thickness alone provides insufficient knowledge and to increase the accuracy of scale factor selection, more detailed parameters should be taken into consideration when selecting the inner layer scale factors. The first parameter considered in this analysis is the construction of the cores.

Effect of Core Construction

Most fabricators will use a single core construction for a given core thickness where possible, but when laminate of this construction is not available the vendor may supply an alternative construction. The average scale factor values in Table 3 show the effects of switching construction for products with a single lamination cycle and Table 4 shows the required scale factors by construction for sequential build up products with 2 lamination cycles.

Table 3 – Scale factors by construction for a single lamination cycle

Core Thickness Microns (mils)	Construction	Grain Direction (Warp)		Fill Direction (Weft)	
		Scale Factor %	Total Movement over 609.6mm (24 inches)	Scale Factor %	Total Movement over 609.6mm (24 inches)
75 (3)	1 x 1080	100.099	604 microns (23.8 mils)	100.034	207 microns (8.2 mils)
75 (3)	1 x 2113	100.085	518 microns (20.4 mils)	100.031	189 microns (7.4 mils)
100 (4)	1 x 2113	100.085	518 microns (20.4 mils)	100.033	201 microns (7.9 mils)
100 (4)	1x106/1080	100.074	451 microns (17.8 mils)	100.039	238 microns (9.4 mils)
100 (4)	1x 2116	100.071	433 microns (17.0 mils)	100.027	165 microns (6.5 mils)
125 (5)	1x 2116	100.069	421 microns (16.6 mils)	100.018	110 microns (4.3 mils)
125 (5)	1x 1652	100.066	402 microns (15.8 mils)	100.032	195 microns (7.7 mils)
125 (5)	1x 2165	100.068	415 microns (16.3 mils)	100.037	226 microns (8.9 mils)

Table 4 – Scale factors by construction for two lamination cycle products

Core Thickness Microns (mils)	Construction	Grain Direction (Warp)		Fill Direction (Weft)	
		Scale Factor %	Total Movement over 609.6mm (24 inches)	Scale Factor %	Total Movement over 609.6mm (24 inches)
75 (3)	1 x 1080	100.125	762 microns (30.0 mils)	100.046	280 microns (11.0 mils)
75 (3)	1 x 2113	100.110	671 microns (26.4 mils)	100.043	262 microns (10.3 mils)
100 (4)	1 x2113	100.103	628 microns (24.7 mils)	100.041	250 microns (9.8 mils)
100 (4)	1x 2116	100.095	579 microns (22.8 mils)	100.038	232 microns (9.1 mils)
125 (5)	1x 2116	100.093	567 microns (22.3 mils)	100.036	219 microns (8.6 mils)
125 (5)	1x 1652	100.073	445 microns (17.5 mils)	100.043	262 microns (10.3 mils)

In the case of both the 75 and 100 micron cores, changing the construction can cause up to a 0.0140% change in the required scale factors for a single lamination and failure to compensate for this would lead to a dimensional difference of 85 microns (3.4 mils) over a 609.6 mm (24 inches) panel. For products with two lamination cycles, the effects are greater with up to 0.0200% change required and a dimensional difference over 609.6 mm (24 inches) panel of 122 microns (4.8 mils).

Table 5 – Standard deviation of scale factors by construction for a single lamination cycle

Core Thickness Microns (mils)	Construction	Grain Direction (Warp)		Fill Direction (Weft)	
		Standard Deviation (%)	Variation over 609.6mm (24 inches)	Standard Deviation (%)	Variation over 609.6mm (24 inches)
75 (3)	1 x 1080	0.036	±658 microns (±25.9 mils)	0.017	±311 microns (±12.2 mils)
75 (3)	1 x 2113	0.025	±457 microns (±18.0 mils)	0.016	±293 microns (±11.5 mils)
100 (4)	1 x 2113	0.028	±512 microns (±21.0 mils)	0.021	±384 microns (±15.1 mils)
100 (4)	1x106/1080	0.032	±585 microns (±23.0 mils)	0.023	±421 microns (±16.6 mils)
100 (4)	1x 2116	0.025	±457 microns (±18.0 mils)	0.017	±311 microns (±12.2 mils)
125 (5)	1x 2116	0.023	±421 microns (±16.6 mils)	0.018	±329 microns (±13.0 mils)
125 (5)	1x 1652	0.024	±439 microns (±17.3 mils)	0.017	±311 microns (±12.2 mils)
125 (5)	1x 2165	0.026	±475 microns (±18.7 mils)	0.023	±421 microns (±16.6 mils)

Table 6 – Standard deviation of scale factors by construction for two lamination cycle products

Core Thickness Microns (mils)	Construction	Grain Direction (Warp)		Fill Direction (Weft)	
		Standard Deviation (%)	Variation over 609.6mm (24 inches)	Standard Deviation (%)	Variation over 609.6mm (24 inches)
75 (3)	1 x 1080	0.022	±402 microns (±15.8 mils)	0.017	±311 microns (±12.2 mils)
75 (3)	1 x 2113	0.023	±421 microns (±16.6 mils)	0.014	±256 microns (±10.1 mils)
100 (4)	1 x2113	0.020	±366 microns (±14.4 mils)	0.016	±293 microns (±11.5 mils)
100 (4)	1x 2116	0.021	±384 microns (±15.1 mils)	0.019	±347 microns (±13.7 mils)
125 (5)	1x 2116	0.021	±384 microns (±15.1 mils)	0.016	±293 microns (±11.5 mils)
125 (5)	1x 1652	0.032	±585 microns (±23.0 mils)	0.018	±329 microns (±13.0 mils)

The standard deviations of the scale factors for the products in the sample are shown in Tables 5 and 6. The results show that even when the construction is considered, the variance is comparable to that where the construction is not specifically identified. Therefore attempting to predict scale factors based upon core construction alone may result in errors greater than the available annular ring on some products.

Effect of Copper Pattern

Etching copper from the inner layer causes stresses induced during the initial core lamination process to be relieved. The more copper removed, the more stress relief that is expected. This effect is expected to be magnified on thin single ply construction cores than on the thicker cores with multiple plies of thicker glass cloth. Therefore identifying the amount of copper removed (or retained) is a further factor that could enhance the prediction of inner layer scale factors.

In our large data set, the data has been grouped according to the percentage of copper retained on each of the inner layers – layers with less than 30% copper have been classified as "Signal", layers with 30-70% copper as "Mixed" and those with greater 70% as "P&G". Figures 1and 2 show the average required scale factors for different core thicknesses and constructions with either "Signal" both sides, "Mixed" both sides or "P&G" both sides.

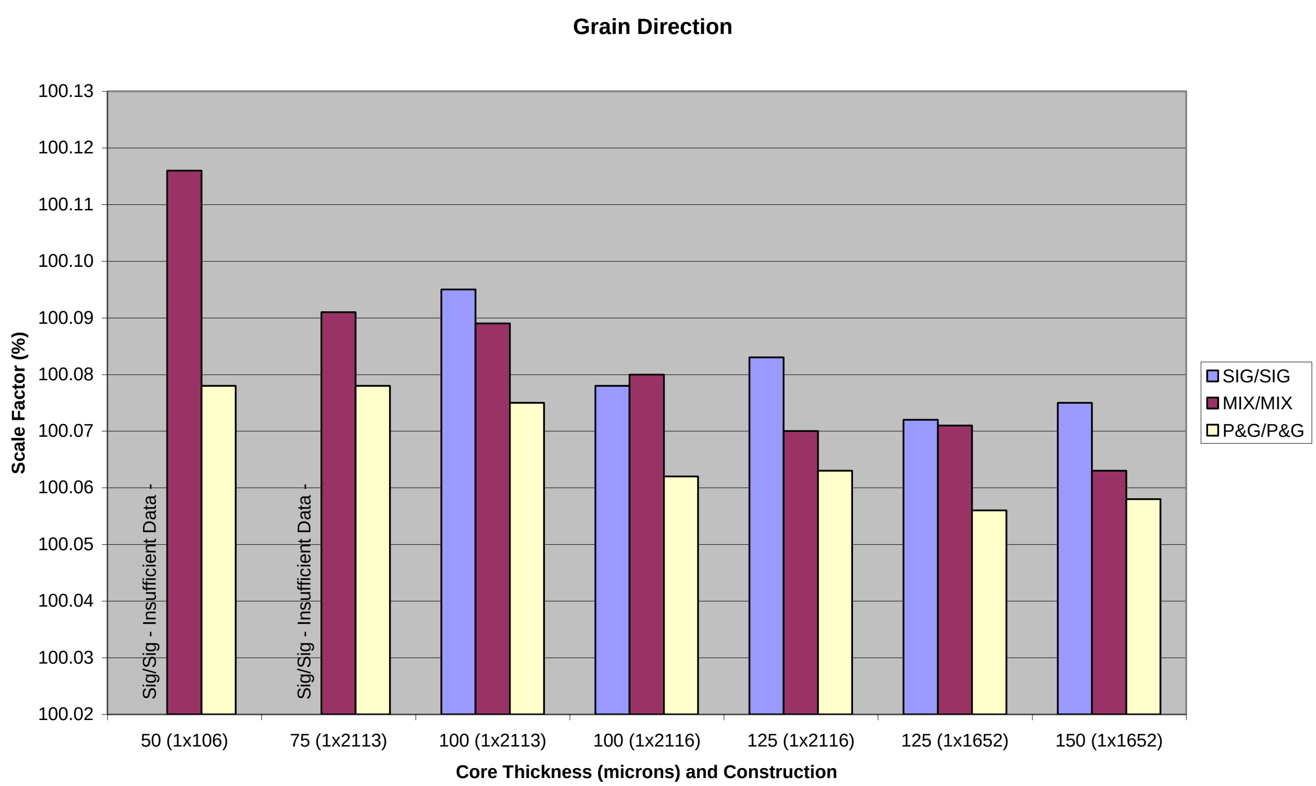

Figure 1 – Effect of Copper Distribution on Average Required Scale Factor in the Grain Direction

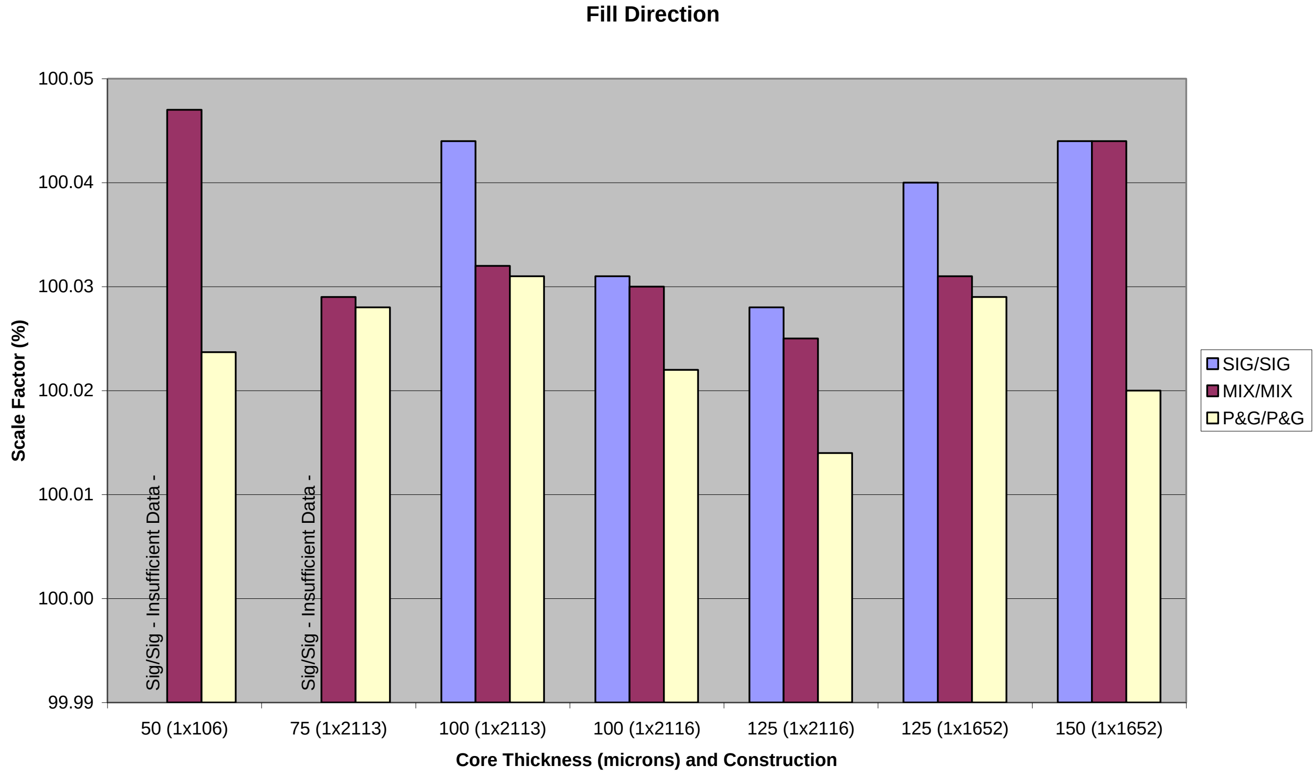

Figure 2 – Effect of Copper Distribution on Average Required Scale Factor in the Fill Direction

The results show that the amount of copper remaining on either side of the core does have an impact upon the required scale factor. Cores with large areas of copper etched from both sides, such as those with signal designs on both sides, will shrink more during the lamination process than those with power or plane designs on both sides. Those cores with a mixed design on both sides will move less than the double signal cores and more than the double plane cores.

Table 7 – Standard deviation of scale factors by construction and copper design for single lamination cycle products

Core Thickness Microns (mils) and Construction		Copper Layout	Grain Direction (Warp)		Fill Direction (Weft)	
			Standard Deviation (%)	Variation over 609.6mm (24 inches)	Standard Deviation (%)	Variation over 609.6mm (24 inches)
50 (2)	1 x 106	M/M	0.037	±677 microns (±26.6 mils)	0.016	±293 microns (±11.5 mils)
50 (2)	1 x 106	P/P	0.030	±539 microns (±21.2 mils)	0.021	±386 microns (±15.2 mils)
75 (3)	1 x 2113	M/M	0.026	±475 microns (±18.7 mils)	0.016	±293 microns (±11.5 mils)
75 (3)	1 x 2113	P/P	0.023	±421 microns (±16.6 mils)	0.017	±311 microns (±12.2 mils)
100 (4)	1 x 2113	S/S	0.032	±585 microns (±23.0 mils)	0.026	±475 microns (±18.7 mils)
100 (4)	1 x 2113	M/M	0.029	±530 microns (±20.9 mils)	0.021	±384 microns (±15.1 mils)
100 (4)	1 x 2113	P/P	0.019	±347 microns (±13.7 mils)	0.013	±238 microns (± 9.4 mils)
100 (4)	1 x 2116	S/S	0.027	±494 microns (±19.4 mils)	0.021	±384 microns (±15.1 mils)
100 (4)	1 x 2116	M/M	0.025	±457 microns (±18.0 mils)	0.014	±256 microns (±10.1 mils)
100 (4)	1 x 2116	P/P	0.021	±384 microns (±15.1 mils)	0.014	±256 microns (±10.1 mils)
125 (5)	1 x 2116	S/S	0.023	±421 microns (±16.6 mils)	0.017	±311 microns (±12.2 mils)
125 (5)	1 x 2116	M/M	0.023	±421 microns (±16.6 mils)	0.014	±256 microns (±10.1 mils)
125 (5)	1 x 2116	P/P	0.019	±347 microns (±13.7 mils)	0.014	±256 microns (±10.1 mils)
125 (5)	1 x 1652	S/S	0.024	±439 microns (±17.3 mils)	0.015	±274 microns (±10.8 mils)
125 (5)	1 x 1652	M/M	0.025	±457 microns (±18.0 mils)	0.017	±311 microns (±12.2 mils)
125 (5)	1 x 1652	P/P	0.026	±475 microns (±18.7 mils)	0.017	±311 microns (±12.2 mils)
150 (6)	1 x 1652	S/S	0.020	±366 microns (±14.4 mils)	0.019	±347 microns (±13.7 mils)
150 (6)	1 x 1652	M/M	0.022	±402 microns (±15.8 mils)	0.016	±293 microns (±11.5 mils)
150 (6)	1 x 1652	P/P	0.023	±421 microns (±16.6 mils)	0.017	±311 microns (±12.2 mils)

The standard deviations of the observed scale factors for these groups as shown in table 7 indicate a reduction in standard deviation in most cases when the copper distribution is factored in. This confirms that copper distribution is fundamental in determining inner layer scale factors.

For the thinner cores, the standard deviation of the groups is reduced as the retained copper area increased, however the 125 microns and 150 microns cores using a single ply 1652 glass cloth construction show an increase in standard deviation as the retained copper area increases.

Effect of Adjacent Materials

The lamination process uses elevated temperatures and pressures to cause the resin contained within the prepreg materials to initially melt and flow, then gel and finally cure. Once the resin has cured, the materials adjacent to a core from the prepreg glass cloth and nearest cores will begin to influence the movement of the core as it is returned to room temperature due to the different physical properties of these materials with their varied ratios of glass, resin and copper.

The material closest to the core is the sheet of prepreg which is used to bond the material to the next core, copper foil or other prepregs. Figures 3 and 4 show the influence of adjacent prepregs on either side of the core. In this analysis prepregs of the following glass cloth styles were considered: 1080, 2113 and 2116.

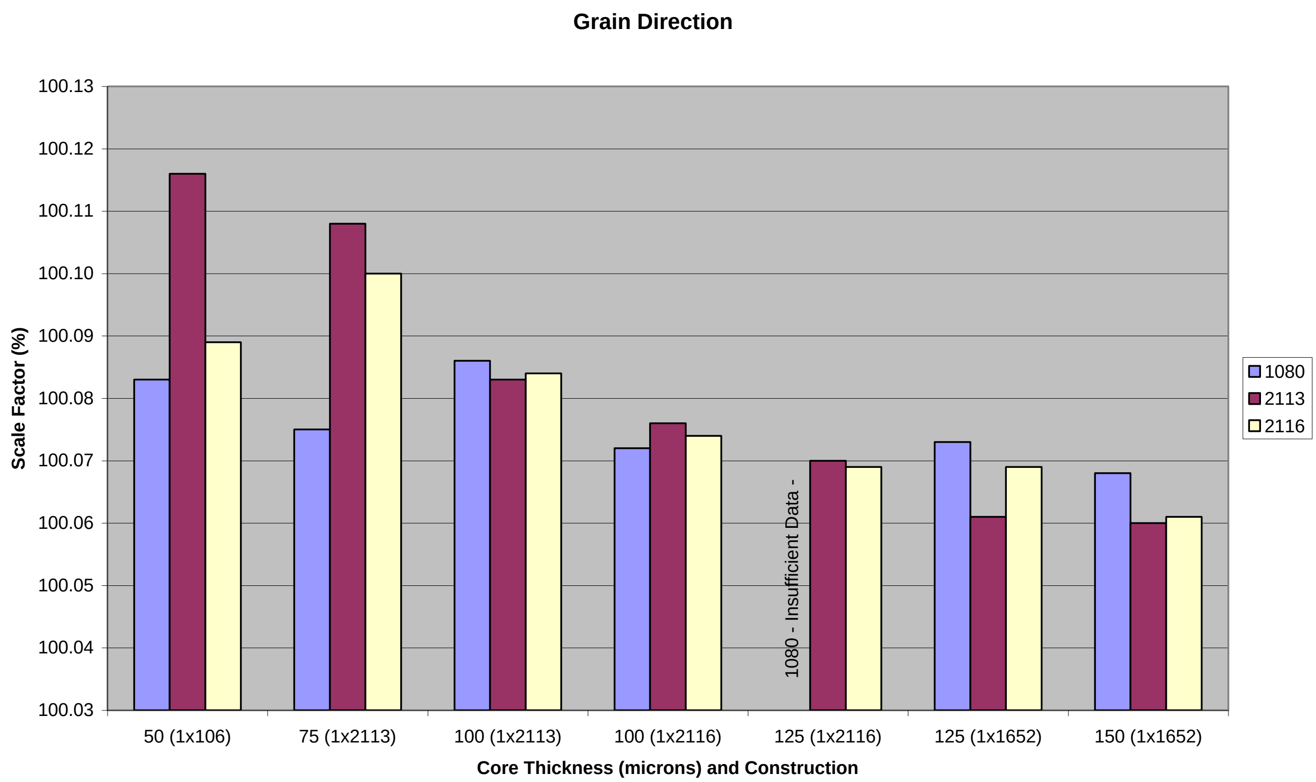

Figure 3 – Effect of Adjacent Prepreg on Average Required Scale Factor in the Grain Direction

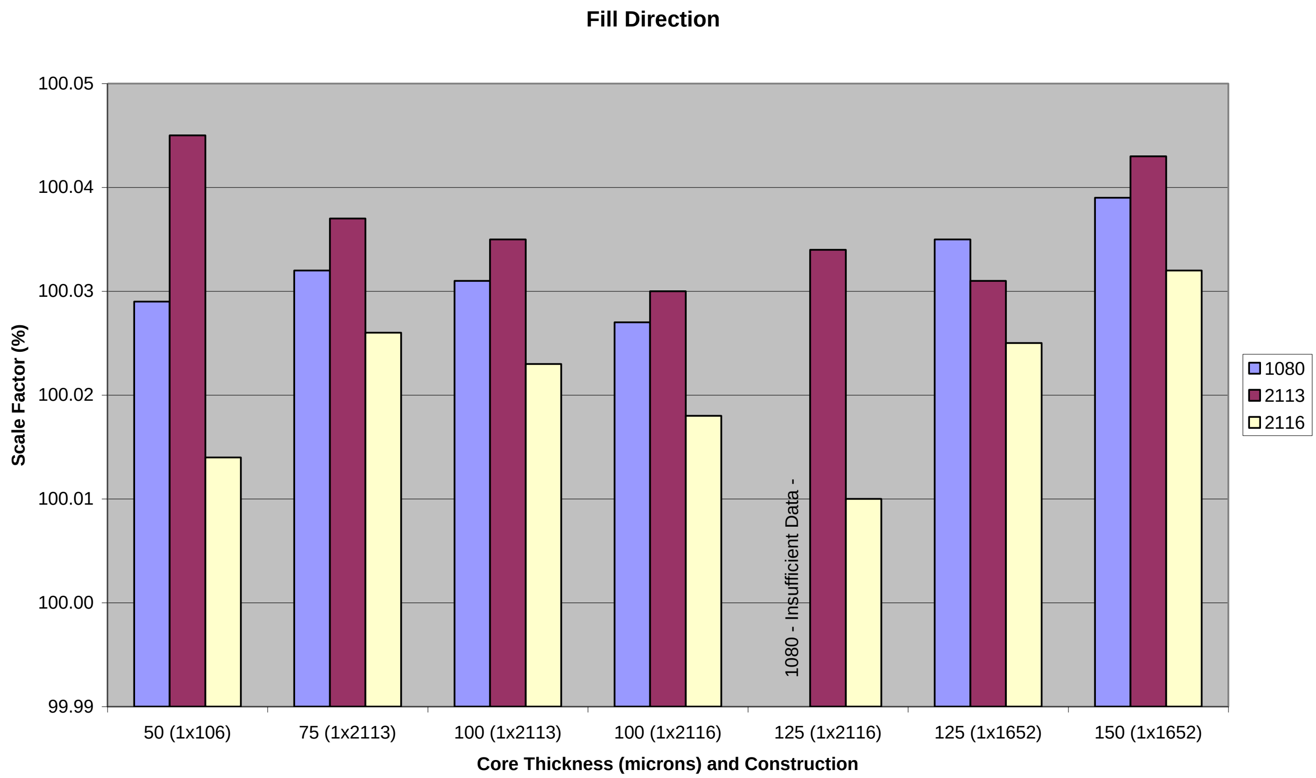

Figure 4 – Effect of Adjacent Prepreg on Average Required Scale Factor in the Fill Direction

The results show that changing the prepreg adjacent to a core may have an effect upon the overall dimensional changes and therefore the required scale factors. The next adjacent prepreg and/or core in the construction can also be expected to exert influence over the material movement of a core during processing. Further work is underway to analyse this interaction in more detail.

Conclusions

In this paper we attempt to quantify the influence of discrete features known to affect scale factors. We have shown that the variation defined by the standard deviations indicates that a model utilizing these features alone would not be sufficient to accurately predict inner layer scale factors. As the number of materials and design combinations increases, a simplistic model would become even less accurate.

The typical size of a laser drill capture pad is 75 to 100 microns over the drill size creating an annular ring of 37.5 to 50 microns, assuming scale errors in one axis only, the largest dimensional error across the length of a panel without break out of the drill holes from the pads would be 75 to 100 microns i.e. less than 0.017% scale error. With the lowest observed standard deviation of 0.013% for any of the groups identified, there is at best around 81% confidence of predicting within the required tolerance i.e. the applied scale factors would be incorrect for 19% of cores in the best case.

A more complex model considering many more parameters and influences is required. Such a model also needs to be capable of “tuning” the influence of each factor according to the overall combination of materials and to learn rapidly from only a small set of data for each possible factor.

All the data required to develop such a system is widely available to the modern PCB fabricator, but the quantity of data prevents engineering resource from interpreting and reacting in the required time frame. An integrated artificial intelligence is required to automatically enhance prediction models and provide optimum production data in real time.