Control of Key Registration Variables for Improved Process Yields on Dense MLBs

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Abstract

This paper explains the sources of registration error and outlines a path for improving process yield. In order to understand the sources of registration error, the error modes and how they combine must be explained. Understanding that there are several contributors to error a systematic approach focused on variation reduction can be applied to specific areas of the printed circuit board process. Applying that knowledge quickly leads to improved process yields.

Introduction

There are few problems as challenging or as important as registration in the printed circuit board industry. Examination of the scrap pile at drill or electrical test can be mysterious and aggravating. One circuit out of a lot or on a panel may be perfect and the next circuit may be a confusing pattern of errors that baffles the imagination. If the scrap fallout is serious, then there is pressure for immediate answers and actions. Often the wrong actions are implemented with unsatisfactory results. This paper will explain registration: the modes of error, how they combine, and where they reside in your process. Armed with this information you can then apply a systematic variation reduction program to improve process yields.

Understanding Registration Error

The four registration error modes are: (1) offset error; (2) compensation error; (3) angle error; (4) random noise. Each of these errors has a separate and unique behavior. These modes combine to produce complex and seemingly unexplainable patterns. Fortunately, each error mode by itself can be readily understood. In order to understand the magnitude of the errors the units of error and tolerance are defined.

DRA & TPR

The design rule allocation (DRA) refers to the distance between the edge of the hole wall at the true position to the edge of the next feature. The TPR is the true position radius, which is the radial error about the true position. Figure 1 shows the DRA and TPR defined graphically.

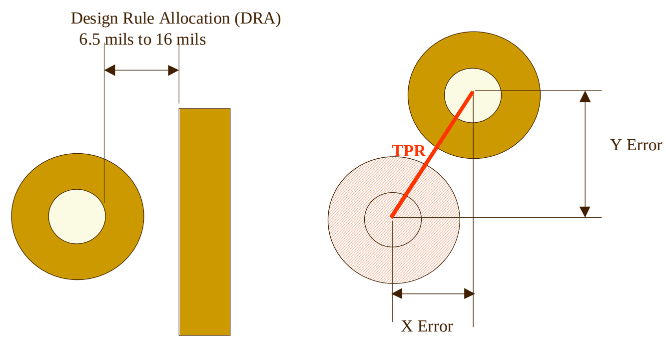

Figure 1 – DRA & TPR

The DRA includes spacing of features between all layers. Typically this information can be obtained from the CAD file where there are special programs that look at every feature on every layer and calculate the DRA. For some boards there are annular ring requirements to prevent the drilled hole from getting to the edge or beyond the pad. This is not universally true for all jobs. In this paper the DRA represents the tolerance because violating the DRA will create electrical shorts. Typically the DRA is between 6.5 mils to 16 mils where 6.5 mils is considered a challenging registration tolerance.

The TPR is the measurement of the registration error. Using the square root of the sum of the squares combines the X and Y errors into the TPR. The TPR and the DRA can be directly compared. The TPR must be less than the DRA in order to avoid registration scrap.

Offset Error

Figure 2 shows an output from the AlliedSignal Registration Simulator™ for an X (horizontal) and Y (vertical) offset error.

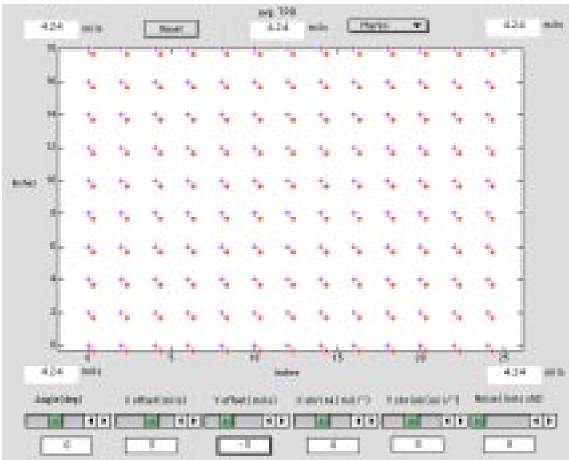

Figure 2 – Offset Error

The crosses (+) show the true position needed to achieve perfect registration. The stars (*) indicate the degree of registration error. Figure 2 represents an 18" x 24" panel where there are 130 graphic plots showing the registration error at each 2 inch interval over the panel. The boxes at each corner of the Figure indicate the amount of error as represented by the radius about the true position (TPR). The TPR is computed from taking the sum of the squares of the X offset error (3 mils) and the Y offset error (-3 mils) and taking the square root (4.24 mils). The average TPR from all of the plots is indicated in the upper center portion of Figure 2. As seen in Figure 2, an offset error is uniform across the panel surface. Offset errors are often associated with errors in tooling such as punch, pinning, and drilling.

Compensation Error

For dense multilayer printed circuit boards with tight design tolerances the innerlayer artwork CAD file coordinate information must be mathematically stretched or shrunk to compensate for material movement seen after lamination. Compensation errors are caused by inconsistencies in material movement, artwork that has become distorted with use or artwork that has changed because of environmental fluctuations, and errors made in making compensation judgements. Figure 3a shows a plot for X and Y compensation errors.

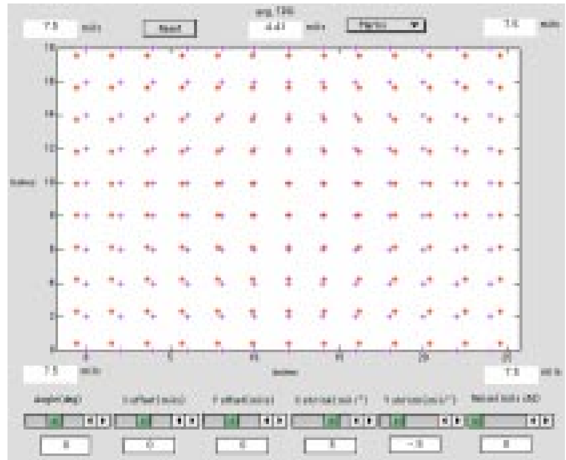

Figure 3a – Compensation Error

The error in Figure 3a is proportional. The X component of the error of 0.5 mils/inch produces an X error of 6 mils at the corner (0.5x24/2). The Y component of the error of –0.5 mils/inch produces an Y error of 4.5 mils at the corner. Combining the X and Y components gives a TPR corner error of 7.5 mils. Proportional errors in some part can be centered or optimized. A post etch punch is an example of a piece of tooling equipment that is designed to attempt to optimize proportional errors. Figure 3a shows a compensation error that has been perfectly optimized over the panel surface.

For proportional errors the corner TPRs will be greater than the average TPR. This is dramatically displayed in the contour plot in Figure 3b.

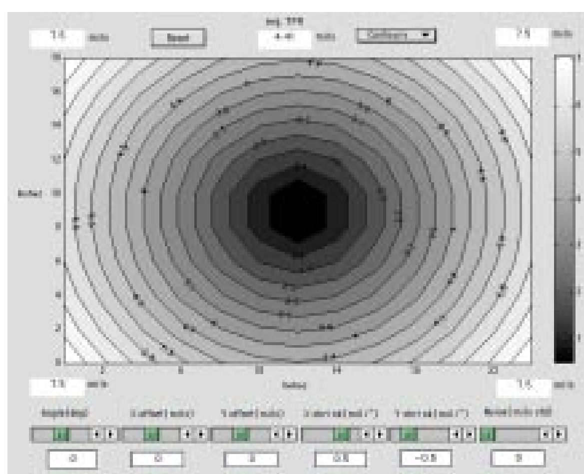

Figure 3b – Compensation Error Contours

Figure 3b begins to uncover the mysteries of the corners. It is not uncommon for the drill engineer and drill manager to be in front of the drill x-ray staring at the apparent corner instability. It has lead some to conclude that material might be moving, slipping, or rotating in pressing; therefore, there should be pins mounted at the corners during lamination. Whether this is correct in a specific instance is a question, but what can be seen in Figure 3b is that the corners are poorly registered because of compensation errors.

Angle Error

The angle error describes a rotation about a fixed position. For our purposes we will consider the center of the angle of rotation to be along the center of the bottom 24" edge. Angle error is another example of a proportional error. Angle errors are often discounted in printed circuit board shops, because they are difficult to measure and small angles aren't thought to contribute much to overall registration error. In order to appreciate why small angles of rotation are bad, visualize a triangle 12" long by 9 mils high. The resulting angle is only about 0.04 degrees!

Table 1 shows the TPR as a function of angle along the bottom panel edge.

Table 1 - TPR as a Function of Angle

radians	degrees	tpr(mils)
0.0001	0.00572958	1.20
0.0002	0.01145916	2.40
0.0003	0.01718873	3.60
0.0004	0.02291831	4.80
0.0005	0.02864789	6.00
0.0006	0.03437747	7.20
0.0007	0.04010705	8.40
0.0008	0.04583662	9.60

When the entire panel surface is considered the far corners produce even larger errors.

Figure 4 shows that a small rotation of 0.02 degrees about the center of the lower 24" edge will produce an average TPR of 4.21 mils with a lower left and lower right TPR of 4.19 mils and an upper left and upper right TPR of 7.55 mils.

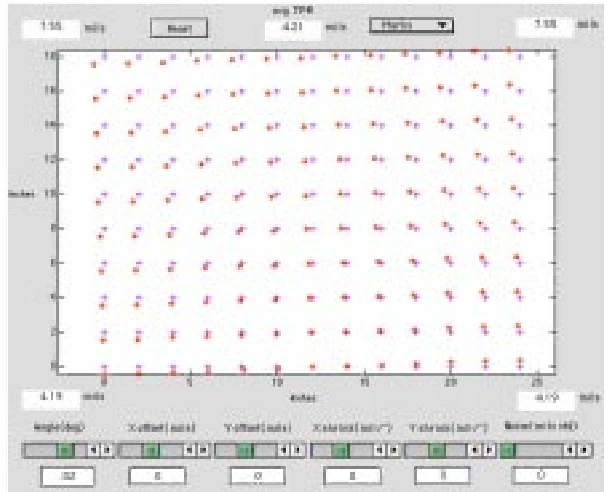

Figure 4 – Angle Error

In optimization processes, such as punching of cores after etching, angle errors can be produced by small calibration errors to the targets. Today's post etch punch machines have the targets located close to the centerline of the panel. A better way to punch tooling holes is to have the targets located at the four corners so that small calibration errors have less of an effect on the angle error.

Examining Figure 4, angle errors alone produce some potentially strange results. For example, the bottom half of the panel is much better registered than the top half of the panel. The registration error in the upper right corner is to the left and up and the upper left corner is to the left and down. The rotation is clear in Figure 4 because of the 130 plot array; however, examining real production panels the angle error is less clear and it is common to mistake the angle error for a compensation error. This is more apparent if only the left or right half of the panel is considered. An effort to compensate the angle error produces a larger compensation error with no change in the angle. The increase in TPR from a false compensation change can be surprising. A good measurement system that can separate angle error and offset error from compensation error is vital in order to prevent actions that cause process yields to decrease.

Random Noise

A perfect example of random noise occurs in drilling where the drill bit will wander and produce a population of points scattered about the true position. Figure 5 shows random noise over the panel surface.

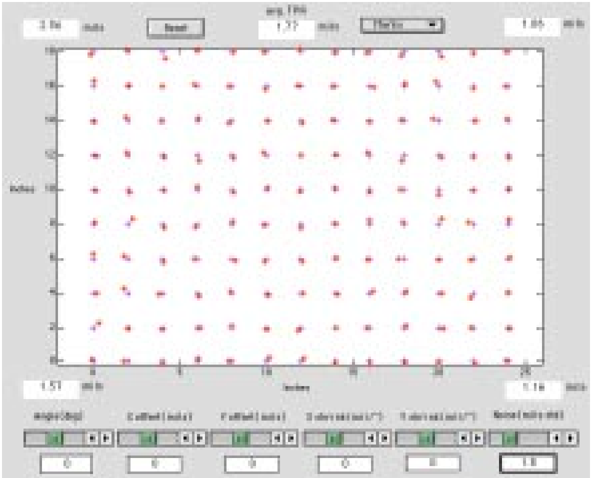

Figure 5 – Random Noise

The Registration Simulator assumes a normal distribution with equal standard deviations in the X and Y directions. Figure 5 shows a standard deviation setting of 1.5 mils.

Typically random errors are regarded as serious and there are usually active programs in a number of printed board shops to reduce random noise. However, efforts may not prove fruitful, because of the magnitude of the other three error modes. What is often not appreciated is if offset error, compensation error, and angle error are reduced, then more random error can be tolerated. With higher circuit density, more layers with more copper, and the need for productivity, conditions aren't favorable. With daily production pressure it is often impossible for the drill engineer to reduce random noise.

How Registration Errors Combine

Each registration error mode has unique properties. When the error modes combine they do so in a dependent and interactive way. What that means is that it is not correct to add the variances, which would be correct if the errors were independent. For example, compensation error from artwork, offset error and angle error from punch, and random noise from drill cannot be combined by using the sum of the squares. Moreover, this one-dimensional analysis does not provide insight on how the errors flow over the panel surface.

The Registration Simulator correctly combines the registration error modes and plots the error over the panel surface. By combining the error modes different registration effects can be achieved.

Some examples are:

- Poor registration in all four corners caused by X and Y compensation errors.
- Poor registration in all four corners caused by a rotation error in combination with either an X or Y offset error.
- Poor registration in half of the panel, but good registration in the other half of the panel caused by a compensation error in combination with an offset error.
- Poor registration in half of the panel caused by an angle error and an X and Y offset error.
- Poor registration in two corners caused by an angle error.
- Poor registration in one corner caused by an angle error, offset error, and compensation error.

What is clear from these examples is that the corners are most likely to have registration problems. Moreover, examination of a completed panel or circuit will often not determine correctly the cause for the registration error.

To see how error modes combine consider a real world example. Figure 6 is actual production data on 25 inner layer panels at a single post etch punch (PEP) machine.

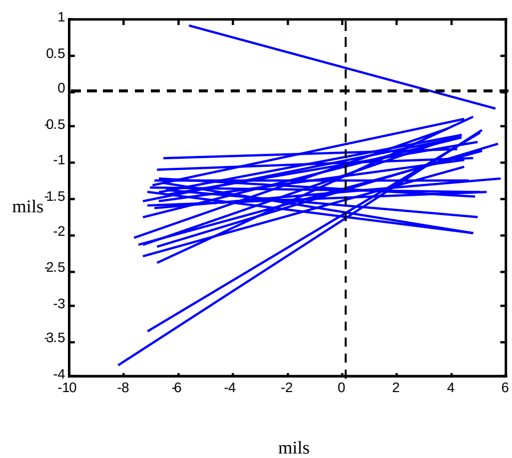

Figure 6 – Angle & Offset Errors at PEP

The panel layout was 3 circuits per panel. The board had tight registration tolerances, which was a 6.5 mil DRA. The cores punched in the Figure were 4 mil cores with 1 ounce copper and signal images. A visual optical inspection

system was used to measure the results of the punched cores.
The intersection of the dashed lines show the correct optimized position that the PEP machine failed to achieve.

The worst panel had the following:

- 0.014 degrees of angle error.
- -3 mils of X offset error.
- -2.5 mils of Y offset error.

For the angle error the axis of rotation will be assumed to be the center of the 18”x24” panel. Figure 7 shows the result over the panel surface from the combination of these errors.

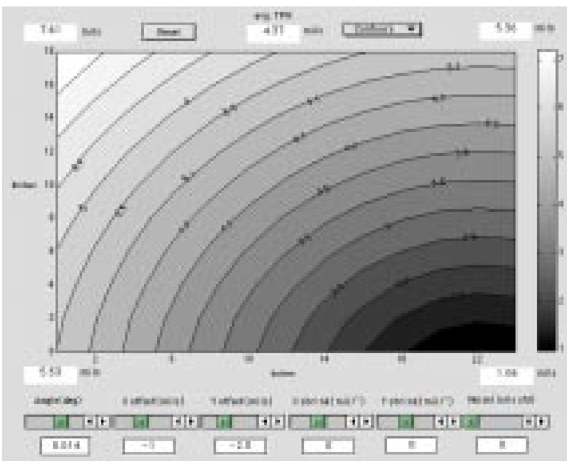

Figure 7 – Worst Case Error Combination

The –1 mil offset shown in the Figure was necessary to account for a centered angle error, which consumed 2 mils of positive X offset.

Figure 7 shows the amount of error relative to the true position. The Figure suggests that with the DRA of 6.5 mils that at least a 66% yield would be possible (2 good circuits out of every 3) with the worst case scenario, provided that there were no other errors. Besides the other errors there is another challenge. The errors in Figure 6 shows random offset and angle errors for the cores. This means there will be core to core errors where the error between each core will be at times larger than the error of the core from the true position.

Estimating Registration Process Capability

Continuing on with the example shown in Figures 6 and 7 an estimate of all of the production errors can be used to estimate final Yield. For example, consider these inputs derived from Figure 6:

- On average the angle between the cores is 0.012 degrees.
- The average X offset error is –2 mils.
- The average Y offset error is –1.5 mils.
- The average X & Y compensation error is 0.33 mils/inch.
- The random drilling noise from the small diameter drill bits has a 1 mil standard deviation (2 panels/spindle, new drill bits).

Figure 8 shows the net result in a contour plot. The dark areas represent good registration and the light areas represent poor registration. The range in registration error over the panel surface is from 0 mils to over 8.4 mils. Figure 8 shows with a 6.5 mil DRA that on average two circuits out of three will be good or there will be on average a 33% scrap rate. The actual scrap rate for this job varied from about 25% to 50% for a lot size of 40 panels. It is easy to assume that changes in scrap rate signify special causes. For example, when the scrap rate is 25% the process may be thought to be improving and when the scrap rate is 50% something has gone out of control. Knowing the average scrap rate of 33% and the lot size of 40 panels the 95% confidence interval for the scrap rate based on a binomial distribution can be easily obtained and is from 18% to 56%. Scrap information by itself is not a sufficient indicator to tell whether the process is improving or worsening. Reacting to seemingly large changes in scrap from one lot is a mistake.

Figure 8 illustrates that yield is a strong function of panel size. Yields could rise dramatically if two circuits per panel on a smaller panel size or on the same panel size (with the added cost of additional material scrap) was the panel layout. To offset the added cost, the improvement in registration error might allow drilling two panels per spindle if only one panel per spindle were to be used on the larger panel size. If the panel size cannot change then the error mode affecting registration needs to be improved.

One strategy to improve yield is to try to eliminate errors through careful manufacturing

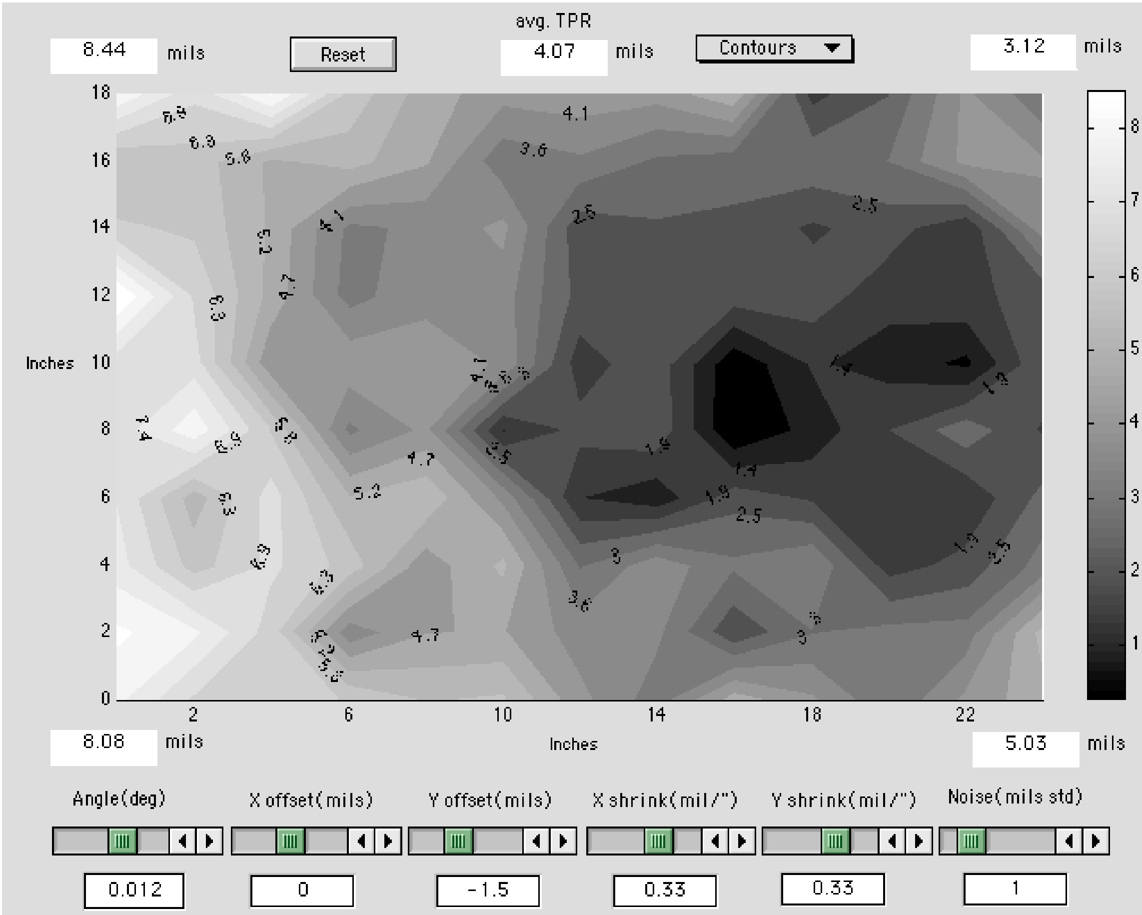

Figure 8 – Registration Capability Map

practices for special lots. For example, in order to achieve the desired capability it may require:

- Employing compensation values obtained from recent test books.
- Using fresh artwork that has been measured and verified to be within +/- 1 mil at the corner targets.
- Concentrating one operator and one machine at print and post etch punch to the job.
- Drilling one panel per spindle with a fix on one machine and one operator with fresh tooling pins, tolling pin fixtures, and new drill bits.
- Eliminating any old work orders or old inner layer cores from the plant floor.
- Keeping tight lot integrity by determination and vigilance of an expeditor assigned to the part number.

All of these items may be outside normal production practices, which means that the capability can only be maintained on a temporary basis.

A Systematic Approach – Using Six Sigma Tools

Depending on the level of job difficulty, the availability of equipment, and production process barriers, the systematic approach will not guarantee the elimination of special lots or occasional high scrap rates. What the approach will offer is a thorough understanding of what the long term issues are and what can be done in the short term. The approach is:

- Process Measurement
- Process Analysis
- Process Improvement
- Process Control

This approach will not work if there is a belief that the sources of variation cannot be found and permanent improvements cannot be implemented and controlled. If a shop considers ad hoc fire fighting as a strategy and cannot support a systematic approach then the problems will continue indefinitely.

As can be seen from Figure 6, process measurement is absolutely required to identify the registration error modes and whether they behave randomly, are associated with a machine, a shift, an operator, the time of the day, week, month, or year. The measurements of the process variables provide the data required for the process analysis. Without data from careful measurements the analysis is left to opinion and actions that are implemented fail to lead to real improvement.

Let's consider the previous example with the 18" x 24" multilayer board with 3 circuits per panel and a 6.5 mil DRA. With some data gathering, process analysis, and using the Registration Simulator we can explore process improvement options. One way to use the simulator would be to explore different high and low settings one variable at a time. One of the most powerful tools in the six-sigma arsenal is design of experiments (DOE). A better way to explore the possibilities would be with a 32 run fractional factorial that included all two factor interactions. Table 2 shows the settings used in the experiment and Figure 9 shows the results.

Table 2 – Variable Settings for DOE

Variable	low setting	high setting	% change
angle	0.005 deg	0.012 deg	58%
X offset	0.5 mil	1.0 mil	50%
Y offset	0.5 mil	1.0 mil	50%
X shrink	0.2 mil/"	0.33 mil/"	39%
Y shrink	0.2 mil/"	0.33 mil/"	39%
noise	0.4 mil std	1 mil std	60%

In Figure 9 moving top to bottom by row are the outputs of the average (avg) TPR, the upper left corner (ulc) TPR, the lower left corner (llc) TPR, the upper right corner (urc) TPR, and the lower right corner (lrc) TPR. Moving from left to right by column are the inputs of the angle, X offset, Y offset, X shrink, Y shrink, and Noise. From the graphs above an upward sloping line indicates that the lower settings are better, a downward sloping line indicates that the higher settings are better, and the horizontal lines indicate no effect. The error bars about the line are the 95% confidence interval for the regression.

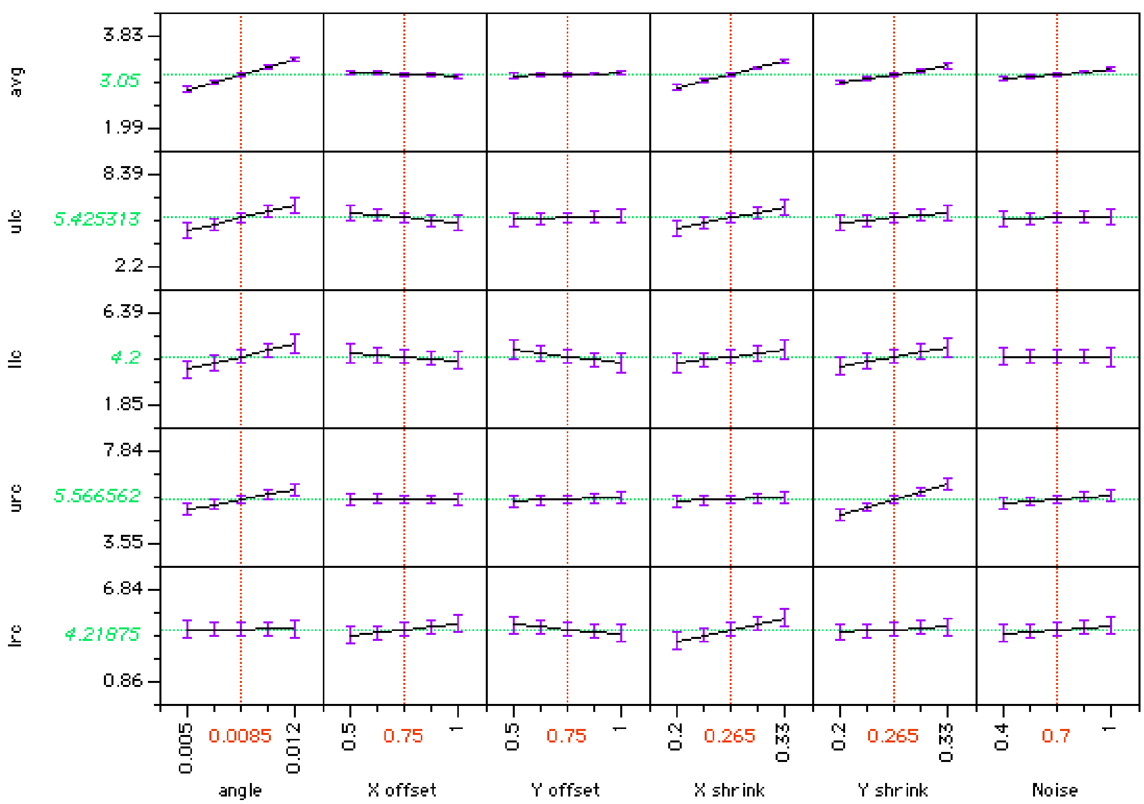

Figure 9 – Results from the DOE using the Registration Simulator

On a computer the graphs in Figure 9 are dynamic and the slope of the lines change with different variable settings because of the two factor interactions. Examining Figure 9 at its current settings the order of significant impact is angle, X shrink, Y shrink, and noise. Improvement of offset beyond 1 mil doesn't have a meaningful registration benefit.

Let's examine the options. Relative to angle error and compensation error the random noise has a small impact. In the process analysis it may require drilling one panel per spindle to achieve a 0.4 mil standard deviation. For the moment consider keeping the drill stack at two panels per spindle and raising the noise to a 1 mil standard deviation. Allowing drill noise is a departure from the control every variable method in the special lot case. The six-sigma approach emphasizes variation reduction of the most significant error. In reality it is impossible to control every variable all of the time.

Let's focus on the most meaningful steps that will lead to improvement. The recommended improvements are shown in table 3:

Table 3 – Recommended Improvements

Variable	From	To	% Change
angle	0.012 deg	0.0084 deg	30%
X shrink	0.33 mil/"	0.2 mil/"	39%
Y shrink	0.33 mil/"	0.2 mil/"	39%

The result from the Registration Simulator was an average TPR of 2.67 mils, an upper left corner TPR of 4.4 mils, a lower left corner TPR of 3.2 mils, an upper right corner TPR of 5.0 mils, and a lower right corner TPR of 4.03 mils.

Even though all of the TPRs are below the DRA of 6.5 mils, the Registration Simulator only shows the result from one panel. Since there is random noise, results will vary from run to run (panel to panel).

Figure 10 shows the result from 1000 simulation runs.

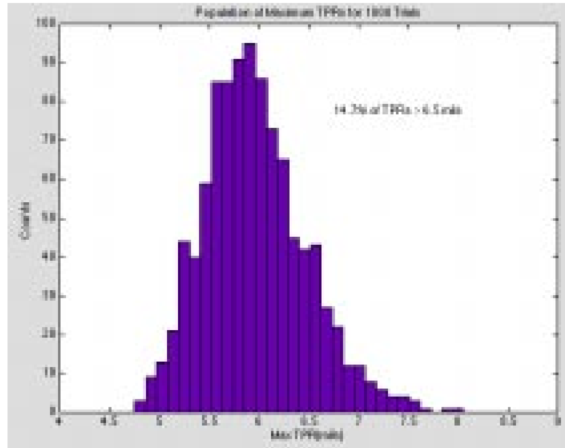

Figure 10 -Max TPR Results from 1000 Trials

Each run consisted of taking the maximum TPR value over the 130 locations on the panel surface. Even though 14.7% of the panels had maximum values over a 6.5 mil DRA that doesn't mean that there would be 14.7% scraped circuits. If 1000 simulation trials were done with the settings found in Figure 8, 100% of the panels would have maximum TPR values over 6.5 mils. A better estimate of the scrap rate is 14.7%/3 = 4.5% projected scrap.

If this board is drilled 1 panel per spindle then the drill wander may be able to be decreased to 0.4 mils standard deviation. Figure 11 shows the results from 1000 simulation trials.

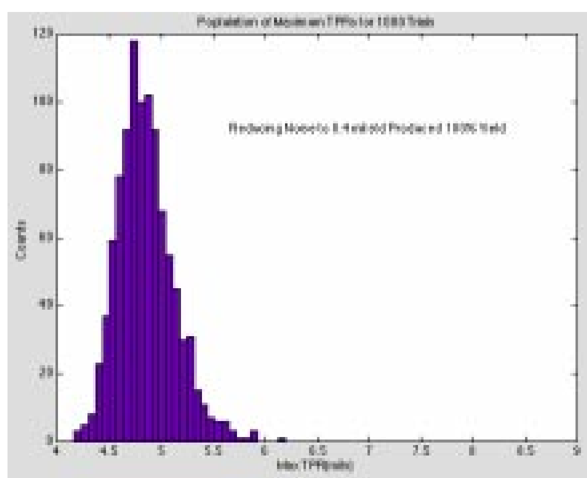

Figure 11–Max TPR Results from 1000 Trials

Figure 11 shows that there is less scrap when the stack height was reduced. Typically improving drilling by reducing stack height is a first move to improving registration yield; however, real improvement from this step will not be beneficial unless the other registration modes have small errors.

Improving the Process

Another tool in the six sigma arsenal is the Failure Modes and Effects Analysis (FMEA). The process analysis has given us some goals:

- Improve the angle error, with an axis of rotation about the center, to 0.0084 degrees maximum between cores.
- Improve the compensation error in both the X and Y dimension to a maximum of 0.2 mils/inch.
- Hold the offset errors to a maximum of +/- 1 mil in both the X and Y dimensions.
- After other actions have been taken, then consider reducing the drill stack height to 1 panel per spindle.

All of the items listed above represent challenges to any printed circuit board fabricator. For example, keeping the angles and offsets at the levels required for a 6.5 mil DRA is a major challenge. In the post etch punch area alone there may be a lot of work such as refurbishing or replacing the die sets, precision table alignment, calibration of the cameras, cleaning or replacing motors and drive shafts, updating PM schedules, purchasing service contracts, purchasing special measurement equipment, a schedule for punch tests, and control charts on important parameters. The number of tasks that come to mind is daunting and not likely to occur without clear project management and support.

In order for improvement to occur a team composed of plant personnel, engineers, and first line managers would be required with a charter that would champion the goals such as those listed in Table 3. A process map and cause and effect diagram would be completed. This would bring all of the issues to the table to identify their location in the process, the outputs they effect, and their contribution to registration error.

After this work has been completed a failure modes and effects analysis (FMEA) can be applied. An example FMEA with post etch punch items is shown in Figure 12. The FMEA considers each process inputs' severity, occurrence of the item failing, and the ability to detect and control the input within specification. From the FMEA the risk priority number (RPN) is computed. Ranking the RPNs tells the team the actions that need immediate attention. The team then returns to the FMEA and then records the actions to be completed, by whom, and by when. Further the improvement in severity, occurrence, and/or detectability is entered and the projected RPN improvement is computed. The FMEA is the focal point for improvement efforts that can be reviewed by upper management to determine the progress and the success of the project as well as whether there are adequate resources for the important items.

Case Study – Improving Compensation Error

Angle error, offset error, and random noise all have mechanical sources that can be understood. The most poorly understood error is compensation error, which has mechanical and material sources. The need to compensate the CAD file data and the inability to predict the

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	OCC	Current Controls	DET	RPN
What is the process step/ Input under investigation?	In what ways does the Key Input go wrong?	What is the impact on the Key Output Variables (Customer Requirements) or internal requirements?	[illegible]	What causes the Key Input to go wrong?	[illegible]	What are the existing controls and procedures (inspection and test) that prevent eith the cause or the Failure Mode? **Should include an SOP number.**	[illegible]	
Using different PEP machines to punch a single lot.	This creates a mixutre of punched hole locations within a lot.	The mixutre of settings and machine conditions within PEP causes random angle and offset errors within a lot.	10	The offset adjustments made by untrained operators and the lack of a machine service schedule means the machines will punch differently. Production pressures	10	No controls.	10	1000
Improper offset adjustments made in process.	The machine is incorrectly aligned causing the punched holes to be incorrectly placed.	The offset adjustments effect both the angle errors and the offset errors.	10	Improper procedures allowing unskilled operators to make adjustments. Improper measurement tools. Improper panel sampling.	10	The current controls are for the process engineer to write the procedure for the operator.	8	800
Panel flatness on the machine table.	The panel isn't flat under the camera causing poor alignment with the target patterns.	Poor alignment of the targets will cause the true punch locations to be off. This will produce angle errors and offset errors.	10	Differential copper weight from one side of the panel to another side of the panel. Unbalanced core constructions.	8	Indicate the core side of the panel that will reduce curling with a stamp.	5	400

Figure 12 – FMEA Example on Post Etch Punch

compensation values prior to production brings about a complex artwork compensation process. When a shop is loaded with dense board designs, then the complexities of the compensation process and the burden of managing numerous compensation changes can cause periods of instability with high scrap rates that will bring a shop to its knees.

A simplified process map for a compensation process from a large printed circuit board shop is shown in Figure 13.

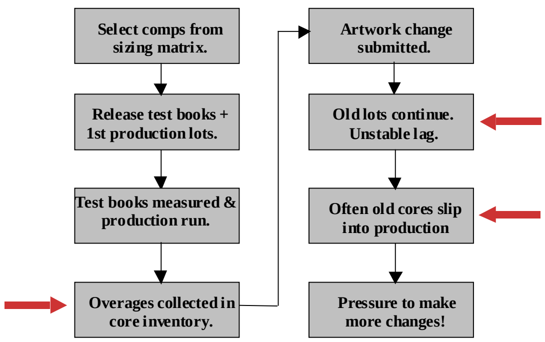

Figure 13 – Simplified Process Map

The red arrows indicate areas of the process that are very unstable. In a feedback process, which Figure 13 describes, adding the wrong information will cause small mistakes that create large errors. This happens when the feedback information is wrong or the feedback happens after a long lag period. The nature of printed circuit board shops with large amounts of work in process greatly limits the ability to remove the detrimental lag time. Incomplete information and delay of input also limits the ability to make compensation changes on the fly. Making compensation changes after full production lots have been released is nothing more than process tampering, which leads to escalating scrap rates. One way to improve compensation error is improving the accuracy of compensation predictions for a job prior to production.

An artwork compensation team was formed in a large printed circuit board shop. During the development of a process map with cause and effect activities a number of issues came forward. Some examples were:

- Large artwork errors discovered when measuring inventory artwork packages.
- Differences in movement between press types.
- Poor predictions of thin cores (especially 10 mil cores and below).
- Multiple artwork packages with different compensation values on the production floor.
- Multiple core lots with different compensation values on the production floor.

The highest item from the FMEA with an RPN of 700 was the inability to predict accurately the compensation for thin cores.

A well defined metric is critical in order to determine improvement. The metric for compensation accuracy was defined as the maximum compensation TPR found between the layers of a multilayer board measured on a Fein Focus x-ray machine with a resolution of 0.1 mils. The baseline was a population of 16,000 measured panels collected over a two month time frame (this was a representative fraction of actual production). Figure 14 shows the baseline measurement results as a histogram.

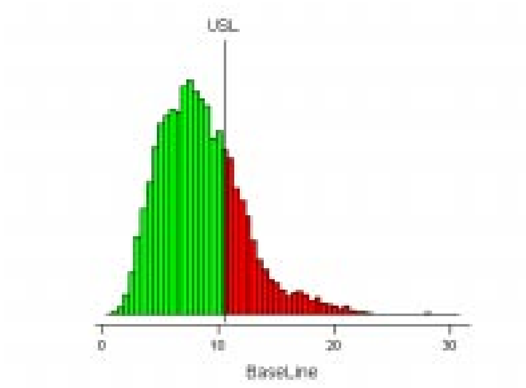

Figure 14 – Compensation TPR Baseline(mils)

The goal for the compensation team was to eliminate 25% of the variation as defined by the histogram area. The metric was defined as a Cpk with a goal line at the 25% mark as shown in Figure 14. The way the team stated the goal was to have a maximum TPR population with a Cpk no less than 1 given a 10.3 mil upper specification limit.

Once the metric and baseline were established the compensation matrix was examined. Figure 15 shows the compensation matrix. The matrix in Figure 15 was for 24” x 18” panels where the warp (grain) direction was 18” and the fill direction was 24”. The matrix above includes the amount of copper on the core by image and

core	signal/signal Warp	signal/signal Fill	signal/plane Warp	signal/plane Fill	plane/plane Warp	plane/plane Fill
2	13.986	-1.056	12.726	-4.056	9.99	-5.04
4	17.982	-1.056	16.722	-4.056	13.986	-5.04
5	15.246	1.992	13.986	-1.008	11.25	-1.992
6	13.986	4.992	12.726	1.992	9.99	1.008
8	12.996	3	11.736	0	9	-1.008
10	13.986	9.024	12.726	6.024	9.99	5.04
range	*4.986*	*10.08*	*4.986*	*10.08*	*4.986*	*10.08*

range Warp	range Fill
3.996	*3.984*
3.996	*3.984*
3.996	*3.984*
3.996	*3.984*
3.996	*4.008*
3.996	*3.984*

Figure 15 – Compensation Matrix

the thickness of the core. What is remarkable about the matrix is the lack of significant differences between core thickness types and core copper types. When the matrix was compared to actual production compensation values there was as much as a +/- 15 mil difference from the matrix values.

In order to improve predictions a series of designed experiments was planned for 3 different core types. These experiments consisted of precisely defined multilayer board component variables along with some process variables to ensure experimental validity. A series of different types of 8 layer boards were built for the experimental runs. Figure 16 shows the results of the experimental runs completed on 4 mil core.

Figure 16 shows the average prediction per run for the A and B variable settings. Each row in Figure 16 describes the setting of the variables and the average result for the run on each core and core direction. For example, for A = 1 and B = 1 the average movement of the 23 core in the X (18” warp direction) had a compensation estimate of 16.90 mils. This means the artwork would be grown to compensate for 16.9 mils of shrinkage.

Comparing Figure 15 with Figure 16 reveals a substantial source of compensation error. For example, a signal/signal 4 core in Figure 15(circled) in the warp direction has 17.982 mils of compensation. A signal/signal internal 4 core has 8.65 mils of compensation (A=2, B = 4). The difference between these two values is a compensation error

	Rsquare	0.87	0.91	0.9	0.78		
A	**B**	**m23x**	**m23y**	**m45x**	**m45y**	**m67x**	**m67y**
1	1	16.90	1.69	11.61	6.40	14.94	8.89
1	2	13.45	-1.71	9.27	3.48	12.53	-1.96
1	3	17.18	-4.33	11.95	1.29	16.55	-4.24
1	4	13.09	5.84	6.49	8.74	12.21	4.55
2	1	13.60	4.68	16.35	6.25	11.80	4.45
2	2	10.83	6.58	13.85	7.34	9.77	6.13
2	3	12.71	1.26	17.07	1.11	11.29	1.51
2	4	3.70	7.93	8.65	9.76	3.26	8.46
3	1	16.10	4.81	21.75	4.13	16.30	5.04
3	2	10.65	9.45	15.95	7.15	10.05	6.22
3	3	11.39	2.98	19.25	0.30	12.90	1.13
3	4	7.69	9.63	13.25	11.30	7.73	10.19
4	1	14.10	1.03	12.40	4.21	14.25	0.25
4	2	11.68	4.46	10.95	6.48	11.11	5.01
4	3	12.45	-0.20	10.66	0.69	12.15	-0.03
4	4	11.12	6.29	10.17	8.91	11.58	5.67
	Range	*13.49*	*13.95*	*15.26*	*10.99*	*13.29*	*14.43*
	Average	*12.29*	*3.77*	*13.10*	*5.47*	*11.77*	*3.83*
	GavgX	*12.39*					
	GavgY	*4.36*					

Figure 16 – DOE Results for Modeling 4 mil Core Movement

of 9.3 mils or 0.518 mils/inch or 518 PPM! This compensation error alone would produce on a 24" x 18" panel an average TPR of 2.6 mils and 4.7 mils at each corner provided there was perfect optimization. When the Y error is added to this same example we have an error of –1.056 mils minus 9.76 mils or 10.82 mils or 450 PPM. The combined effect of the X and Y compensation error yields an average compensation TPR of 4.21 mils with 7.13 mils at the corners.

The statistical validity of the model is shown in the upper highlighted box with the Rsquare label in Figure 16. The Rsquare values indicate the amount of variation that can be explained by the statistical model. For the 2-3 core and the 4-5 core there was a high degree of statistical validity. Since the 6-7 core was a mirror image of the 2-3 core the 6-7 data was not used in model building; however, the 6-7 data provides a measure of consistency.

Figure 16 shows that the compensation matrix shown in Figure 15 is too simple to be effective in making accurate predictions. The maximum range seen in Figure 16 was (21.75 mils – 3.70 mils) 18.05 mils in the X(warp) direction and 15.63 mils in the Y(fill) direction. The ranges for just the 4 mil core well exceed the ranges seen on all of the cores listed in Figure 15!

The same type of modeling occurred for two additional cores. From these three cores using statistical techniques a general model was made that accounted for all image layer types, how the images combined in the board, the number of layers for the board, different material combinations, and the panel size. Figure 17 shows a history of the worst case TPR. The results shown in Figure 14 are shown in Figure 17 in the first bars and lines indicated by the "baseline" label on the X axis. Indicated are the average (avg. TPR), the upper process limit (UPL) which is the average plus three times the standard deviation, the goal line, which was a maximum TPR below 10.3 mils, and a Cpk calculated from the UPL and the goal. Decreasing heights for the bars indicates improvement and an increasing positive slope for the Cpk indicates improvement.

There are three phases indicated in Figure 17. Phase 1 consisted of establishing the baseline and analyzing how the compensation process using the sizing matrix was working. Phase 2 consisted of implementing some easy items found in phase 1 and performing and analyzing the modeling DOEs. Phase 3 was the improvement phase realized from implementing the model built in phase 2. What is remarkable about the improvement seen in Figure 17 was this came from improving the compensation errors on only three core types. In order to reach a new plateau other cores would have to be studied and added to the model.

Figure 17 shows that improvements using the Six Sigma approach occurs in steps. The nature of the Six Sigma process – measure, analyze, improve, control – means that results will not be immediate. In fact, it may take weeks or months

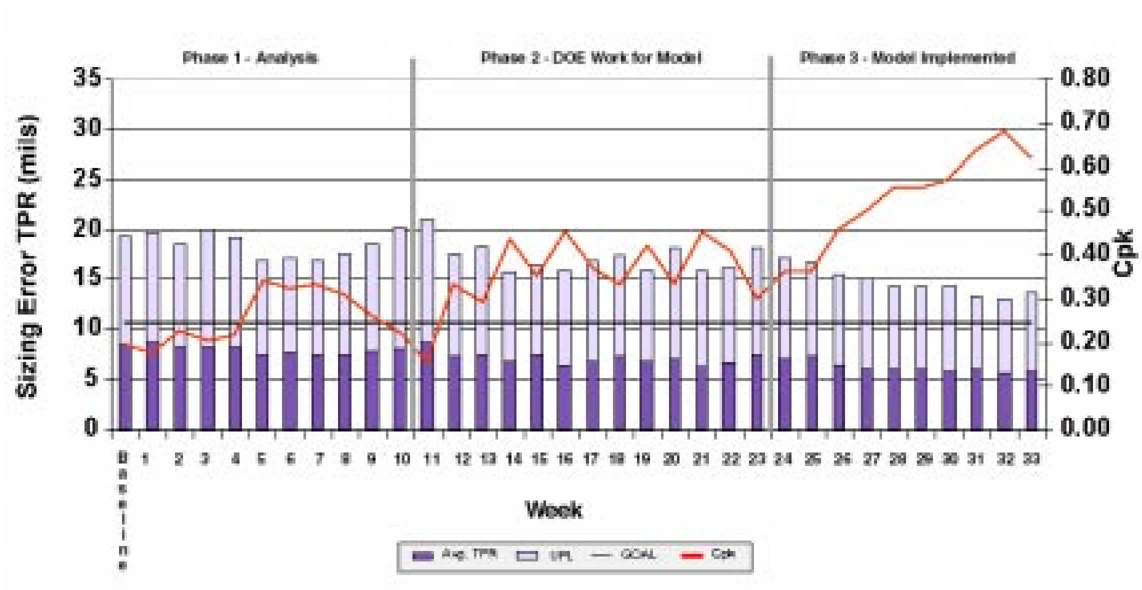

Figure 17 – History of Maximum TPR/Panel

until the investment in the time and resources pays off. Figure 17 indicates that it took 26 weeks before significant improvement was realized, but the improvement was sudden when the correct actions were implemented. The ad hoc fire fighting approach may appear to produce results in the short term, but when examined over a long period of time seldom is their real improvement. The Six Sigma approach does not guarantee finding short cuts for success, but if the proper work is completed real improvement paths will be found.

Conclusions

Registration problems can be elusive and challenging. Often registration problems seem to appear out of nowhere and cause a panic that leads to unfocused actions with a predictable drain on profitability. This paper has attempted to stop the panic by uncovering the mysteries of registration and explained a systematic plan of attack using Six Sigma tools. First, the registration error modes and how they combine over the panel surface were explained. Second, an example FMEA was presented that showed how offset error and angle error could be reduced in post etch punch. Third, a case study was presented showing how building a predictive compensation model reduced compensation error.

Often efforts to reduce registration error do not bring a lasting benefit. This doesn't have to be the case anymore. With proper measurement systems in place, the printed circuit board shop can be characterized and registration yield predicted. With proper implementation of the Six Sigma tools step function yield improvements can be realized.

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