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Accuracy Validation Finds Hidden Problems Affecting DPMO

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Abstract

If you don't measure, you don't know. These are appropriate words for the application of statistical methods for measuring machine and process capabilities in surface mount technology (SMT) manufacturing.

Only through diagnostic measurement and analysis of SMT equipment can quality performance improvement be realized. Measured mean values can be used to ‘soft’ calibrate machines to a higher level of accuracy than available through original equipment manufacturer (OEM) standard calibrations.

With the complexity of high-speed automation combined with high accuracy requirements for product miniaturization, it is necessary to dig deeper with statistically significant data collection methods to understand and solve the root cause of sub-component machine failures which impact product quality.

When machines are allowed to run in ‘maximum accuracy mode', they are more confident and capable to produce today's high reliability electronics with fewer defects. Defect contribution in each process step needs detailed analysis to reduce cost. When costs are minimized, the underlying inherent process efficiencies go way up which contributes to higher productivity and bottom line profitability. The improvement effects of process optimization have a number of intrinsic benefits that can easily maintain high manufacturing productivity.

This paper discusses individual process step validation methods with real examples of improvement that contribute to defect per million opportunities (DPMO) reduction. In stencil printing the characterization considers accuracy of the alignment system and dynamic measurement of squeegee force. During placement, accuracy and placement Z-force are looked at to calibrate head/angle offset associations and dynamically check individual spindle forces and energy dissipation. All while each process step is characterized, the underlying objective is to verify OEM specifications and prove that machines are capable for intended quality performance. This allows engineers to streamline efforts and focus on other areas of improvement.

Introduction

Assembly of printed circuit electronics happens fast, with the average placement speed duration of 13ms per placed chip component, a lot happens in the blink of an eye. The human eye blinks at an average rate of about 260ms per blink during which a machine can dole out a whopping 20 placed components for every blink. That can be a significant number of placed defects if a machine’s accuracy is in question. How can a highly sophisticated automated robotic machine be in question? They’re designed to automate the very difficult, time consuming and precise placement of extremely tiny chip components; chip resistors or capacitors so small they can be mistaken for dust. With product miniaturization and increasing customer demand for high quality reliable products, production rates are pertinently pressed to meet profit margin targets. The expense of repairing defects is unnecessary with appropriate quality measures in place. While high profit margins and expensive manual defect repairs don’t mix in automated SMT assembly; it’s an engineer's nightmare trying to ‘see’ where so many defects are coming from with such demands being placed on production yields.

Real life examples of objective measurement methodologies in which a statistical approach is applied to validate quality metrics for extremely fast SMT assembly equipment will be discussed. A few important process steps in SMT manufacturing where the defect opportunities are immense will have the skin layers folded back so an appropriate surgical analysis can be performed. An engineering approach with statistics to help decide what actions are taken to solve problems related to failing equipment performance is the basis for bringing machine accuracy back into specification. Improving accuracy at the root level has many cost and efficiency impacts.

Methodology

Sound measurement practices begin with purpose-built tools that adhere to requirements for accurate and traceable measurement standards. The two main metrology standards organizations are the Physikalisch-Technische Bundesanstalt (PTB); the national metrology institute of the Federal Republic of Germany, and the United States equivalent entity is the National Institute of Standards and Technology (NIST). These organizations set the standards and define rules for Gauge

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Repeatability and Reproducibility (GRR) evaluations for measurement systems. Related documents describe the results of a standard gauge evaluation to the requirements of the "Guide to the Expression of Uncertainty in Measurement" (GUM). The testing requirements are part of a company's quality management system, and are made to verify that the tested measurement system is working within specification limits. General rules in metrology are that measurement systems must be 10x more accurate than the smallest production machine specification limit to be measured. This ensures that measurement error is not introduced into the results of the machine performance evaluation. In addition to measurement systems, there are measurement artifacts such as glass boards and glass components specifically designed and serialized for traceability and accuracy conformance. These artifacts are designed with high accuracy and low variation in mind, and follow a regular schedule of calibration to confirm the inherent accuracy specifications.

Two basic measurement methodologies exist in the metrology realm; Absolute and Relative. An absolute measurement methodology uses a zero point as a main reference for all measurements made from that 0,0 location. An additional reference is used to consider angle, and length error from measuring over longer distances needs to be minimized with a temperature-controlled measurement environment. Most often, absolute measurements are made with coordinate measurement machines (CMMs). CMMs are made to work in a clean and temperature-controlled room and therefore cannot be used directly on the production floor. Relative based measurement methodology employs global fiducials, local reference marks (measurement objects etched in glass) and a calibration grid that compensates for temperature expansion of the glass artifact. The calibration grid and global fiducials are measured each time a measurement is executed. The local reference marks are used to measure position with reference to a placed object in one field of view (FOV) of an external camera. Measurement algorithms automatically measure when reference fiducials and printed/placed objects are recognized in the FOV. Measurements are repeated in this manner based on pre-programmed coordinate locations. A relative methodology does not require a temperature-controlled measurement environment and can be used directly on the production floor and directly at the machine being evaluated. Relative based systems are usually used by independent service providers. For purposes of reference in this paper, a relative methodology and independent tools are used to collect data.

Process step dependent measurement tools are required to measure specific quality attributes within the process. For example, the component placement process reveals X-offset, Y-offset, Theta-offset and Z-Force characteristics for accuracy and repeatability; among others such as speed, tact time, components per hour (CPH) and other variables that make up specifications for a given machine. These documented specifications help prospective buyers understand the complete capability of the equipment that will assemble the circuit boards in their high-quality electronic products. As well, the specification data are used to compare one machine versus another so buyers can make educated decisions about what type, brand and model machine will fit best to their product manufacturing environment.

A note about specifications, the creation and use of a specification comes with general statistical rules. First, the target for collected mean values used to interpret accuracy and repeatability is defined with a plus/minus (+/-) window where any data will be presented. Second, the target values and units of measure, i.e. 25µm, must be displayed to give the user a picture of where data will sit in relation to the upper specification limit (USL) and lower specification limit (LSL) lines on a graphic figure. Third, the @ symbol connects the target and statistical pass/fail limit based on the number of standard deviations to be defined by the creator. Usually, a significant collection of sample data from multiple real machine tests are used to help understand performance and determine realistic capabilities before publishing a final specification for a given machine.

Diving deeper into quality characteristics requires a measurement methodology that uses a statistical approach to collect statistically significant sample sizes of each characteristic so a proper analysis can be completed. Each characteristic must be validated to make sure it meets the intended specification as the OEM has designed it for use. A valid test organizes a production realistic run where the machine operates as it normally does under full production load. Glass measurement boards, or other application specific measurement tools are used to replace actual printed circuit boards (PCBs) during the run. The machine performs its normal activity on the highly accurate measurement tool instead of a PCB which are known to exhibit high variation from board to board. Special glass with low coefficient of thermal expansion (CTE) is used to replace PCBs that are easily influenced by temperature swings in the production and measurement environment.

With a measurement methodology, highly accurate measurement system, components and appropriate documentation in place, one can begin to setup a machine capability test on any production machine in SMT manufacturing. These tests are used to validate specification performance and assess where improvements can be made in the accuracy of the machine in question.

Screen Printer Accuracy Evaluation

Problem Introduction:

Screen printing in SMT has the largest number of defect opportunities in any process step of the entire manufacturing line. Every single printed pad is considered an opportunity for defect. With 0402 metric [0.4mm x 0.2mm] (01005 inch [0.016in x 0.008in]) chip components becoming more popular in SMT manufacturing, the need for more accurate specifications and machine performance grows considerably. Successful screen printing the first time through for these devices is critical because manual repair is very difficult. Offsets in screen printing can create defects. The days of letting tin lead solder "auto-center" the component during reflow is diminishing. Whether the solder paste or the placed component is shifted, the result of either condition can lead to tombstoning, among many other defect types, as seen in Figure 1.

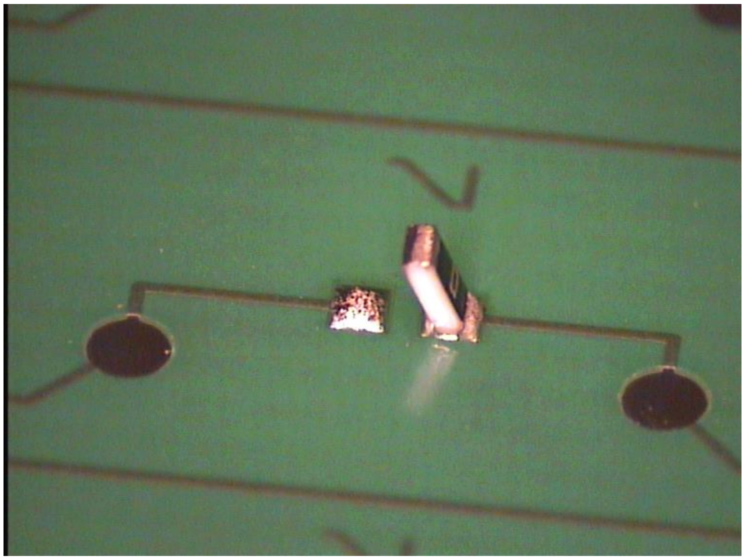


Figure 1 - Chip component exhibiting tombstone defect

During routine capability testing, a printer is found to have significant offsets which are highlighted with magenta color in Figure 2 below. The red lines depict the USL and LSL with the nominal target defined as zero. Each stroke direction data set shows minimal variation with offsets of approximately -85µm (-0.0033in) in the X direction and Y direction offsets of +30µm (+0.0011in) for one stroke and +65µm (+0.0025in) for the opposite stroke. Performing initial measurement of the system educates the user on how the system has been running in normal production since previous maintenance, calibration or other machine intervention. Production management confirm similar issues with printing offsets realized on customer product. The deviations found during the initial measurements can be from any number of reasons. Some are outlined as:

1. Improper OEM calibration techniques - meaning, the internal calibration method does not remove inherent offsets in the system.
2. Calibration stability - how long does a machine hold its calibration values? This can vary from OEM to OEM.
3. Normal wear and tear from running production.
4. Operator interventions - if allowed, operators thinking they know how to adjust a machine's mechanical and/or process parameters.
5. Machine crashes - things happen. either due to machine interference, operator inexperience, or improper setup.
   Running capability tests at regular intervals can help fine tune the frequency of the tests and identify how quickly a machine will begin to operate outside its specification limits.

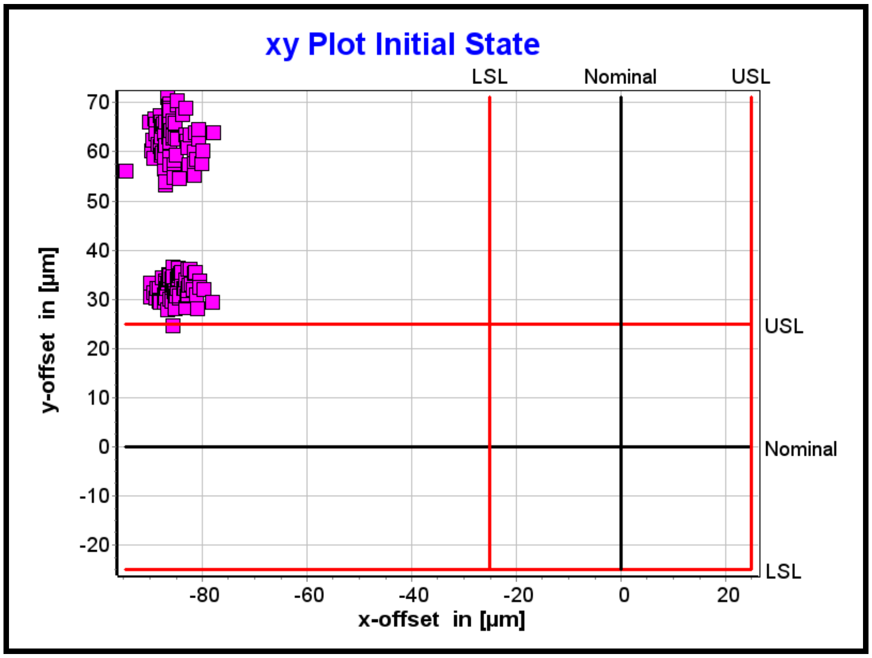


Figure 2 - Initial screen printer results with XY Plot by individual stroke direction

Evaluation Methodology:
When evaluating a printer, X and Y offsets in both squeegee stroke directions must be evaluated for individual system performance during the test as they both contribute to variation found in the total system. The method of measuring these offsets is depicted in Figure 3. SMT printing adhesive material is printed with reference to local reference marks in the glass board. The locality of the printed dot with relation to glass board measurement objects allows for a vision algorithm to make quick measurements in one FOV. To calculate a theta offset, a minimum of two X, Y position measurements are required.

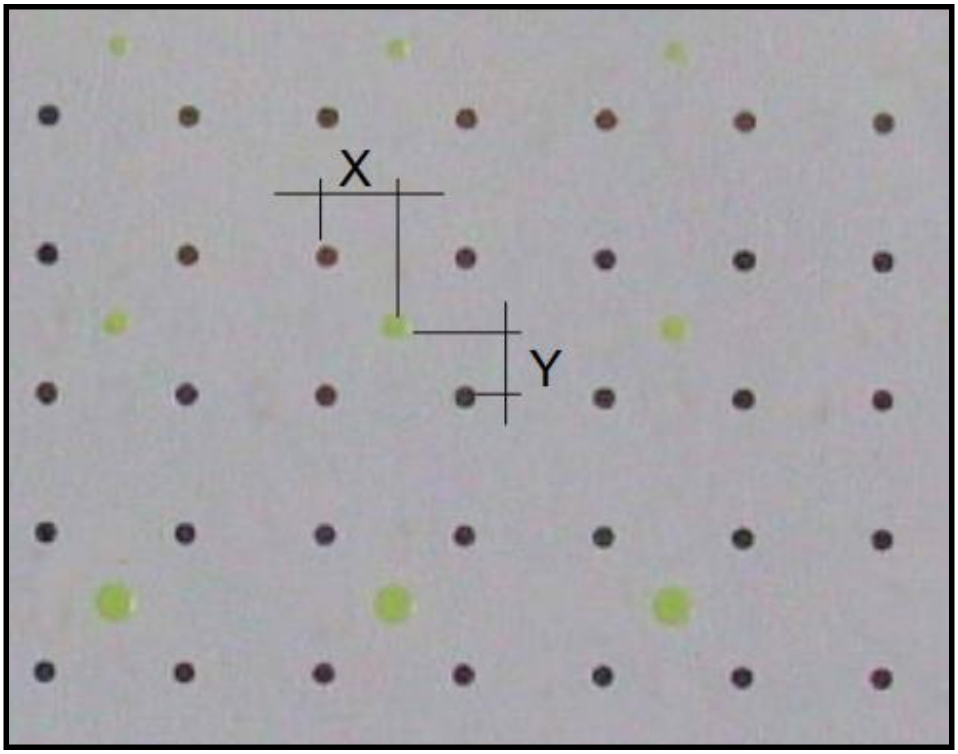


Figure 3 - Printed SMT adhesive on a glass board located near measurement objects

Further to two stroke directions, a look must consider evaluating the theta, X and Y axes of the machine in each stroke direction, in that order respectively. The reason for looking at theta first is because theta deviations appear as X and Y deviations and they must be evaluated and adjusted into the machine first, before X and Y axis offsets. Figure 4 shows theta offsets relative to stencil apertures. Unstable theta performance will show larger offsets at the corners of the printed area.

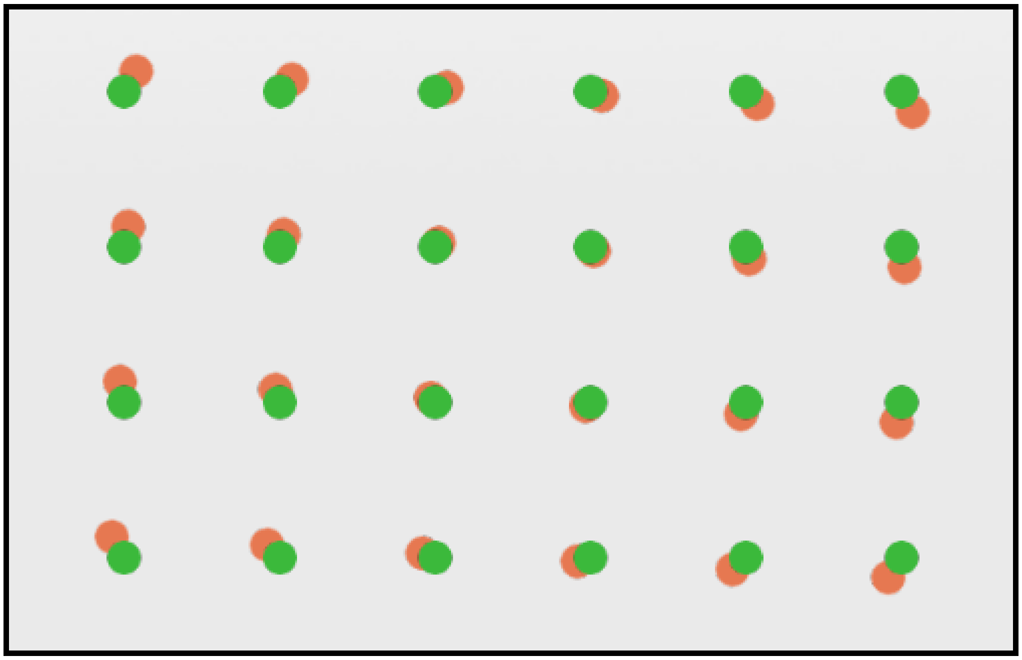


Figure 4 - A representation of theta print offsets shown relative to stencil apertures

Additionally, X and Y offsets are usually a calibrated adjustment in a machine calibration routine. Some OEMs have created the capability in their software design to allow the adjustment of theta, X and Y offsets into the machine for each print stroke direction. Figure 5 shows XY offsets relative to stencil apertures in both print directions. Both print directions MUST be analyzed and adjusted. When each print stroke exhibits individual offsets, the combination of these offsets fights each other when considering total system accuracy. For example, a -3µm (0.00012in) offset in the F2R stroke and +4µm (0.00016in) offset in the R2F stroke creates a 7µm (0.00027in) statistical range. Even a 7µm range when considering a 15µm specification will create an overall failure due to high standard deviation. If the single value results of this scenario were plotted, the graph would exhibit a sawtooth behavior.

This offset adjustment capability is likely in one of two places, hopefully both, as both ensure fully optimized machine performance after the test. The first place is in a software protected calibration field where new measured values can overwrite existing values. Two scenarios exist with regard to values that already exist in the calibrated fields: 1.) They can be zeroed and begin the test with no offsets in the machine, or 2.) New measured offsets can be added to or subtracted from existing offsets. The formula will depend on how the software applies offsets to the mechanical axis systems. Using a known good stencil and matching highly accurate glass board helps ensure low variation and well-matched stencil to board alignment. The expectation with these conditions is to present a good calibrated value to the machine that has come from a well-intentioned calibration setup. The usual reference of these calibration offset fields are known as “Global Offsets Calibration” or something similar. Adjusting offsets into these fields creates an inherent optimization of the machine’s accuracy performance.

The second and other likely place for offset adjustment is in a newly created process program for the accuracy test. While almost always possible, this method applies calibrated offsets only in that process program. For purposes of a test, this can be okay, but does not change the total accuracy performance of the machine for all process programs. These two adjustment possibilities should be discussed with machine process owners because there are risks and rewards for each adjustment technique.

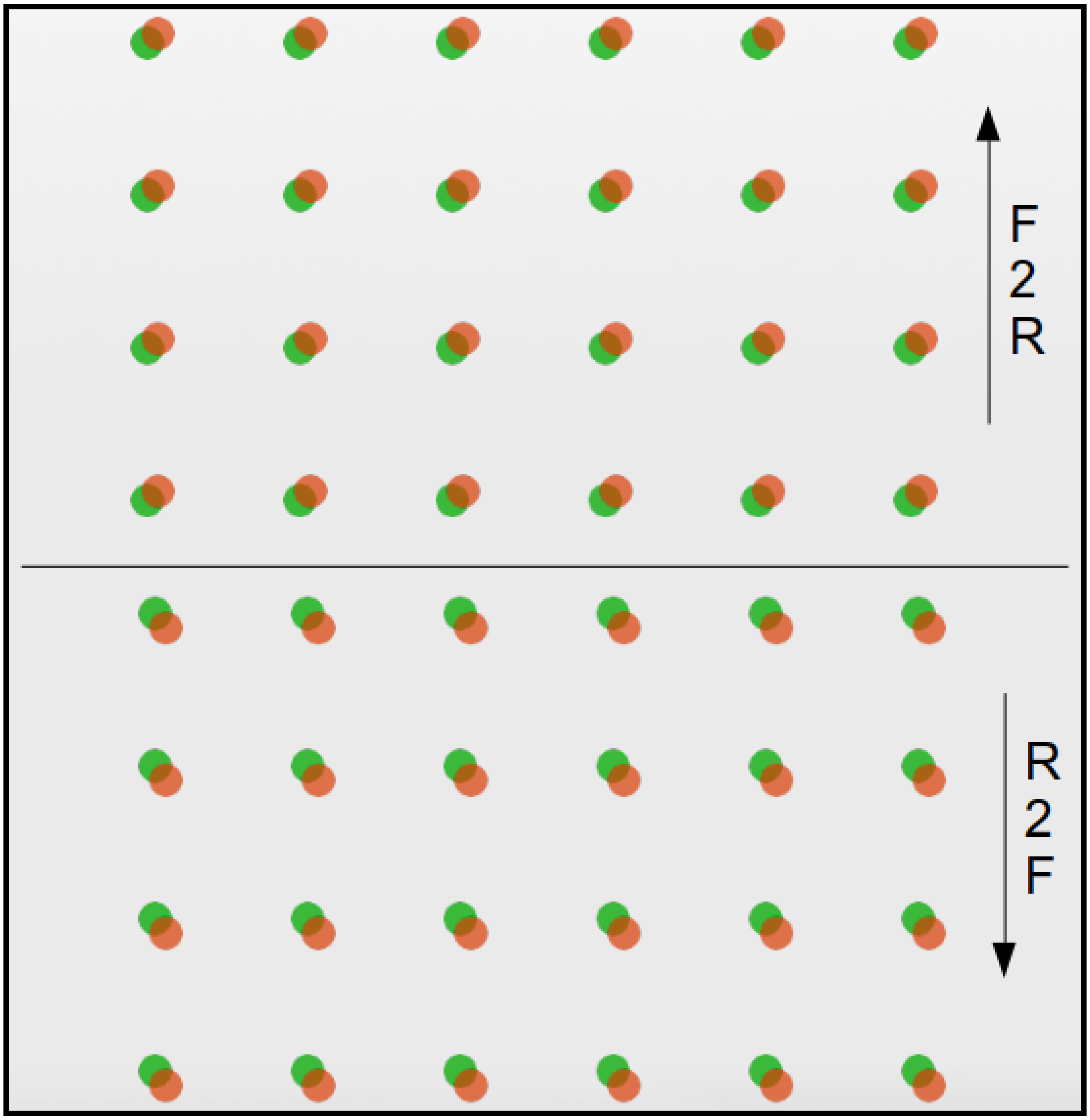


Figure 5 - A representation of print stroke offsets shown relative to stencil apertures

A screen-printing stencil is manufactured with a laser that cuts desired apertures into a stainless steel foil based on XY CAD locations in a Gerber file. It should be recognized that these laser cutting machines require regular calibration to maintain a square and accurate gantry that moves the laser head. If these cutting gantries and laser heads are not checked or calibrated, trends in the cutting performance of the system will find their way into stencil quality affecting production printing results. Figure 6 shows a representation of a stencil with an X-trend in the aperture locations based on desired CAD positions. A screen printer cannot correct for these trends in the stencil. Generally, the measured result of one print can indicate the quality of the stencil cutting process. Good single print standard deviations in X and Y should be in 2-3µm range. The stencil vendors who can reach these results generally have a tightly controlled quality system surrounding their laser cutting process. When one single print reaches the 5-6µm standard deviation range for either X or Y, the stencil accuracy quality will be more severely impacted causing issues with alignment to the board. The best matching of alignment will be based on quality and number of fiducials used during the alignment process.

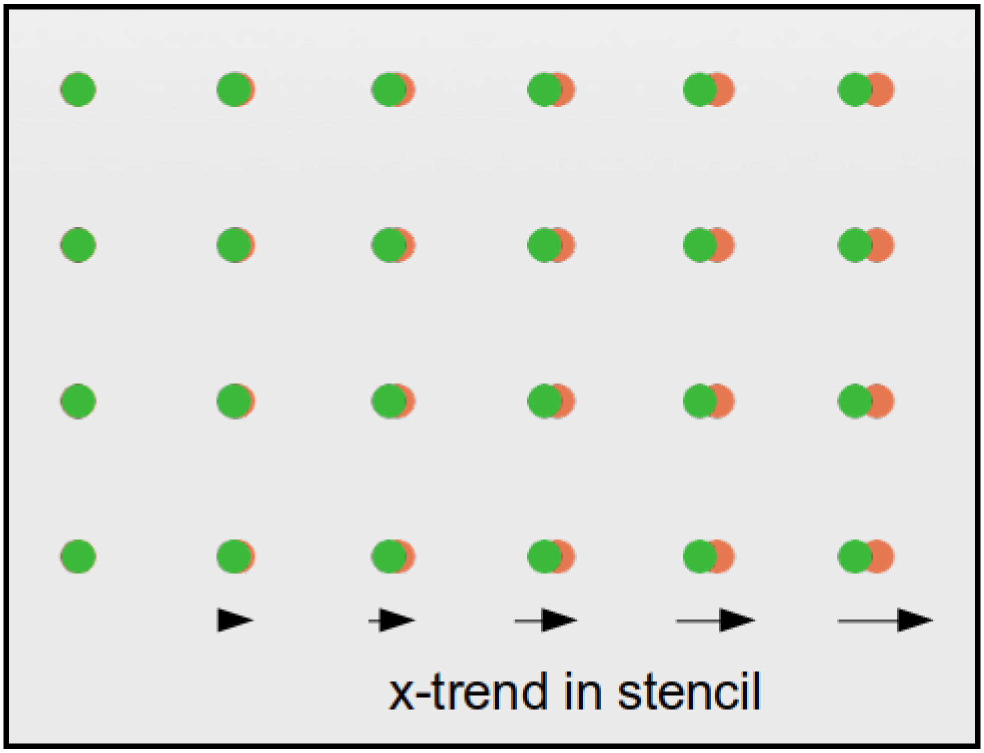


Figure 6 - Representation of X-trends from stencil laser cutting process

Figure 7 is a real example of a test performed on a printer with a focus on the Y axis. Results were graphed to look into the Y-offset as it relates to the Y-coordinate of the measured points across the entire glass board and over multiple grouped measurements. These results were used in this manner to check the accuracy of the stencil cutting laser. The trend shows a 20µm (0.00079in) offset over 100mm (3.937in) of Y travel. More clearly, it means for every 100mm of gantry movement in Y direction, there is a 20µm Y offset in the laser cutting position location.

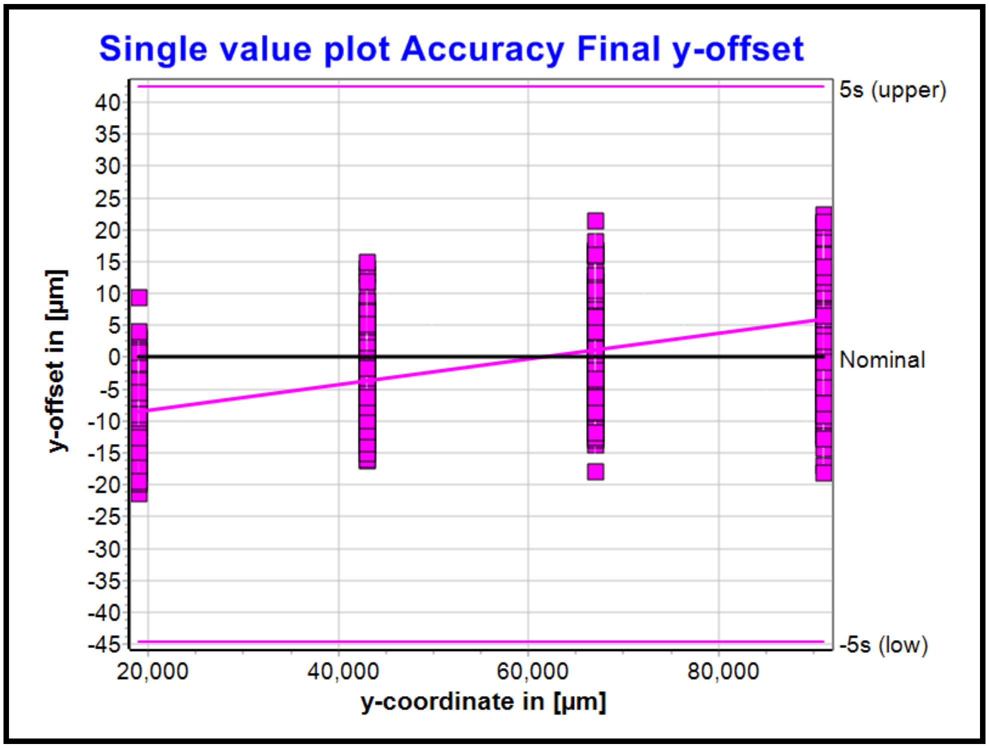


Figure 7 - Single Value Plot showing stencil laser cutting trend results

In the case of this test, theta (and X Y) offsets will be calculated over the whole printed board. A Board to Board calculation of standard deviation best fits measuring a screen printer based on how the printer operates in production. Essentially, the result of the same measurement point location on each board, over multiple boards, is used to calculate a standard deviation and understand mean shift for that group of combined data. This type of calculation can be described with Figure 8.

$$\bar{x} = \frac{1}{n \cdot m} \sum_{i=1}^{n \cdot m} x_i$$

$$s_j^2 = \frac{1}{m-1} \sum_{j=1}^{m} (x_i - \bar{x})^2$$

$$s_{BtB}^2 = \frac{1}{n} \sum_{i=1}^{n} s_j^2$$

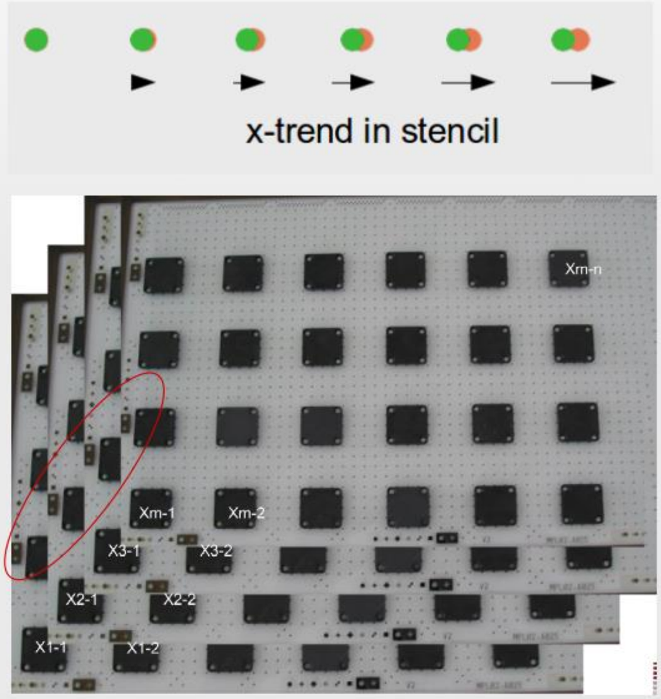


Figure 8 - Board to Board calculation formulas and illustrative graphic descriptions

Table 1 shows the Board to Board method as it relates to multiple positions over multiple measurements. The average range (R-bar) method is used to calculate the average of the subgroup ranges which helps understand variability and how the range of the subgroups changes over time.

Table 1 - Board to Board example of values representing multiple positions over multiple measurements

	Meas. 1	Meas. 2	Meas. 3	Meas. 4	R per Position
Pos. 1	-31	-20	-26	-28	11
Pos. 2	-24	-9	-15	-12	15
Pos. 3	-17	-6	-18	-12	12
Pos. 4	-7	3	-7	-4	10
Pos. 5	4	11	8	6	7
					$\bar{R}$
R per Meas.	35	31	34	34	11

Test Setup and Preparation:

A few things are needed to prepare for an accuracy test on a printing machine; one of which is a specification. Typical specifications for screen printers over the last 15 years or more have generally been +/-25µm@6-sigma. Only in the last few years have printer OEMs developed machines capable of +/-15µm@6-sigma. Alas, this is a properly formatted specification that can be used to calculate C_p and C_{pk} indices from standard statistical formulas found in Figure 9. The quick description of difference between C_m/C_{mk} and C_p/C_{pk} is earlier is known as short term capability with one test on one machine in the immediate time frame and the latter is defined as long term capability with multiple machine tests of the same machine over a longer period of time. The accuracy and repeatability attributes of a machine are both derived and interpreted from these two formulas. An expert in the field might be surprised how often the application of these definitions are stretched or misappropriately applied to published specification literature. The specification for the example described herein is +/-25µm@5-sigma.

$$C_m = \frac{USL - LSL}{6 \cdot \hat{\sigma}}$$

$$C_{mk} = \min\left(\frac{\bar{x} - LSL}{3 \cdot \hat{\sigma}}; \frac{USL - \bar{x}}{3 \cdot \hat{\sigma}}\right)$$

Figure 9 - Standard formulas for calculating C_m and C_{mk}

A specifically cut stencil pattern matches the grid spacing on a glass board designed for being handled in printers; a smaller size helps speed up test and makes cleaning easier after each print. The stencil foil is 100µm (4.0mil) thick and is mounted in a standard 29” aluminum tubular frame using stainless steel mesh to help tighten the foil in the frame to prevent movement of the foil during printing. Forty-eight round apertures are cut with 0.5mm diameter in a center justified image position, 24 of which will be used for measurement during each printed board through the machine.

A program is created with stencil and board, and all parameters are checked with mechanical loading of glass board to stencil print height to check snap-off setting. An adhesive printing material is used instead of solder paste due to consistent shape issues with Type 5 and even Type 6 solder creams. Nice, round, consistently sized print shapes are required for accurate and repeatable measurement. Pre-programmed dummy definitions create a known correlation reference against the actual printed deposit when recognized by the vision algorithm as the camera is moved to the measurement location.

Data Collection and Analysis:

The first print or two are used to dial in print parameters, if necessary. If print quality and deposit shape of the printed adhesive are good, a series of 6-8 prints are made with measurement of each printed glass board. These initial print results are separated into front and rear stroke groups with 72-96 data points determining each stroke’s mean and standard deviation values for theta, X and Y directions. The front to rear (F2R) stroke is designated the “rear stroke” as it moves forward in the machine. The rear to front (R2F) is known as the “front stroke” as it moves rearward in the work area. The theta offsets are checked for each stroke group. Relevant values are converted to the appropriate units of angle measurement used by the machine software. With the correct unit format, the theta values are adjusted into the Global Offset Calibration fields. Another 6-8 prints are made and measured each time to ascertain the offsets needed to analyze XY offsets. In the process of reviewing XY offsets, the new measured theta values for each stroke direction should be near to zero. If not, subsequent prints and adjustments should be made to correct theta offsets and realize mean values as close to zero as possible, before adjusting XY offsets. Figure 10 is an XY Plot that shows the remaining Y dependent stroke offsets after adjusting machine calibration parameters.

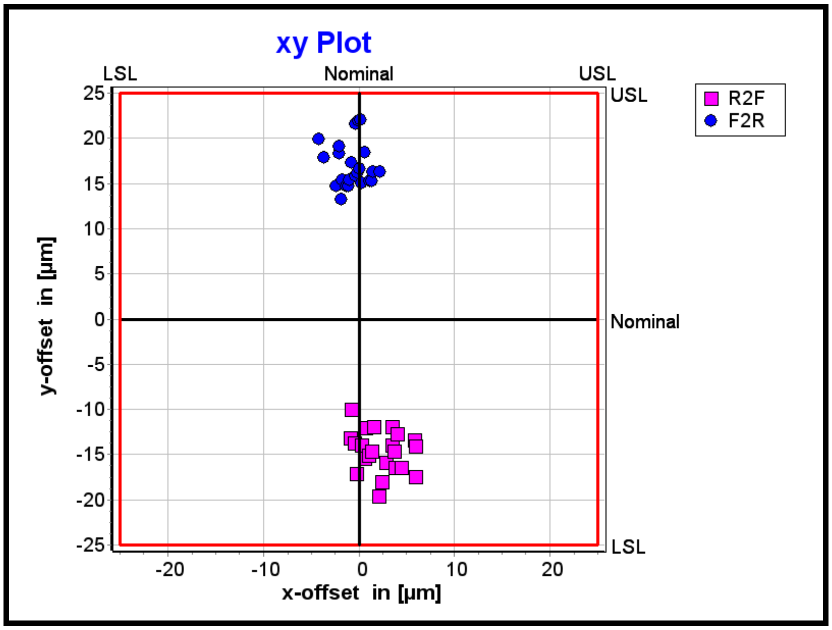


Figure 10 - Results after Global Offset Calibration completed

When theta, X and Y offsets are optimized to produce near zero mean values for each quality characteristic, an additional 25 prints are made and measured with no changes to the machine or measurement process. This is a statistically significant accumulation of printed and measured results for analysis. Twenty-five prints yields 600 measured values for a printer capability test. The overall offset adjustment progress to optimize the printers accuracy is summarized in Figure 11.

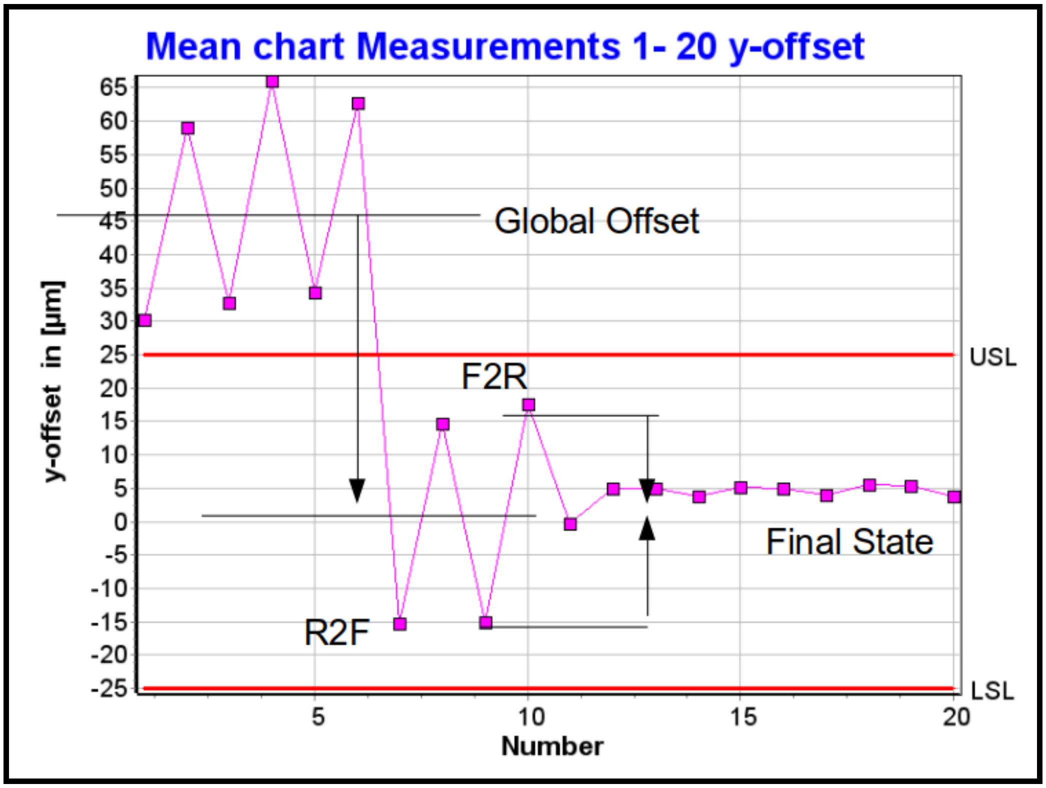
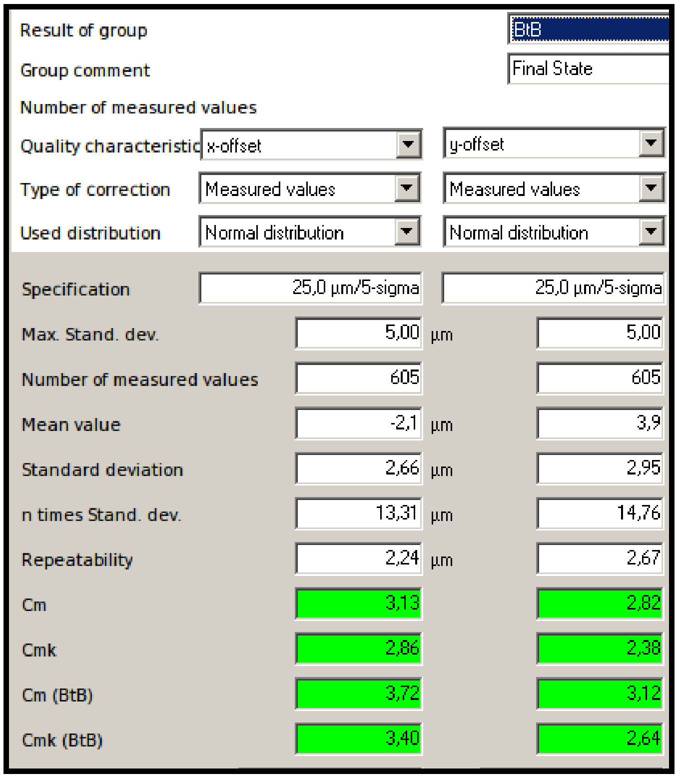


Figure 11 - Mean Chart displaying measurements 1-20 of printer accuracy test

Results and Conclusion:

After all adjustments, the 25 final measured print results are grouped together to verify actual performance against the specification limits as intended by the OEM. This protocol can be considered a Process Capability Analysis (PCA) style test because it considers real printing conditions with real production parameters specifically for this setup, otherwise sometimes known as a “wet test”. The results of this test confirm the machines capability and gives the end user a documented report of its performance and ability to provide quality printing results for future work until the next test interval. The final results shown in Figure 12 document two columns of statistical detail about the X (left column) and Y (right column) quality characteristics of the screen printer. The final capability result considers that all collected data is normally distributed and is tested with The Kolmogorov-Smirnov normal distribution test which confirms its normality. For clarity of understanding, the last four (4) rows of highlighted (green) fields display the calculated capability values of the system in two perspectives. The first, as mentioned and described earlier, the screen printer is evaluated with a Board to Board (BtB) methodology in mind, therefore the Cm (BtB) and Cmk (BtB) fields are the values of significance in reporting compliance to specification. The minimum acceptable 5-sigma result for this test is 1.67 for both quality characteristics. Secondly, for reference, the Cm and Cmk fields show the capability values with an inherently known Across the Board (AtB) methodology while using the standard formulas documented in Figure 9 above.



Result of group			BtB
Group comment			Final State
Number of measured values			
Quality characteristic	x-offset		y-offset
Type of correction	Measured values		Measured values
Used distribution	Normal distribution		Normal distribution
Specification	25,0 µm/5-sigma		25,0 µm/5-sigma
Max. Stand. dev.	5,00	µm	5,00
Number of measured values	605		605
Mean value	-2,1	µm	3,9
Standard deviation	2,66	µm	2,95
n times Stand. dev.	13,31	µm	14,76
Repeatability	2,24	µm	2,67
Cm	3,13		2,82
Cmk	2,86		2,38
Cm (BtB)	3,72		3,12
Cmk (BtB)	3,40		2,64

Figure 12 - Final results of printer capability analysis

The final combined mean values of less than 4µm (0.00016in) in both axes have been significantly improved over the initial results were approximately -85µm (-0.0033in) in the X direction and Y direction offsets of +30µm (+0.0011in) for one stroke and +65µm (+0.0025in) for the opposite stroke were found. Figure 13 displays the initial and final results in one graphic. Looking at the significance of the offset improvement, one can wonder how many defects were caused in this process? Purely reviewing the worst-case offsets of -85µm (-0.0033in) in X and +72µm (+0.0028in) in Y directions shows that solder paste was printed off pad causing the opportunity for component shifting during reflow. When chip components physically move during the reflow operation, they have a higher tendency to tombstone.

Other more significant printing challenges with 0402 metric [0.4mm x 0.2mm] (01005 inch [0.016in x 0.008in]) chip components, and 0.3mm (0.012in) pitch chip scale package (CSP) devices can occur with mis-aligned printing. 0402MM chip devices typically have a bond pad size of 0.178mm (0.007in). CSP devices typically have a 0.15mm (0.0059in) bond pad size with an expected stencil aperture size of 0.15mm as well. In the case of this initial printing result, the solder paste would be printed more than half off the pad with CSP and slightly less than half off pad with 0402MM. With the weight of CSP devices, they will not move as easily as chips during reflow. Mis-aligned printing comes at an expense, with either time spent to wash badly printed boards (if even an accepted practice) or rework them if they get through the reflow operation equates to lack of process efficiency and additional cost. These devices simply require more accurate printing and placement operations. Tighter control of machine maintenance and calibration through regular accuracy validation exercises is crucial to maintaining profitable SMT manufacturing.

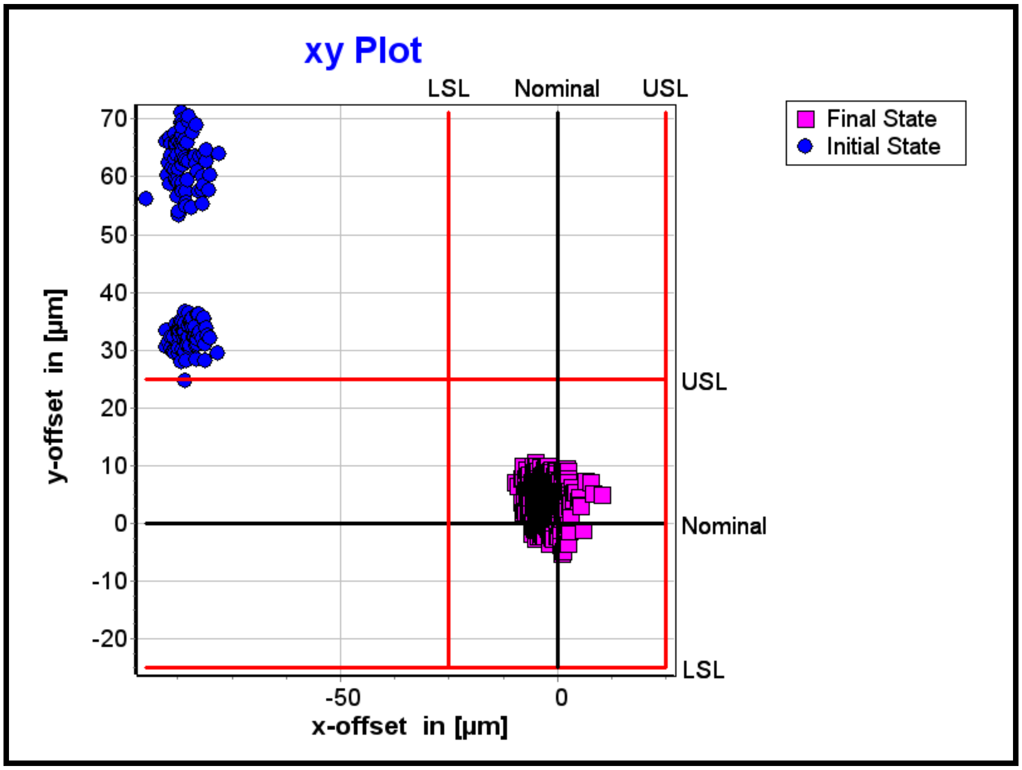


Figure 13 - XY Plot of Initial and Final Results from screen printer capability test

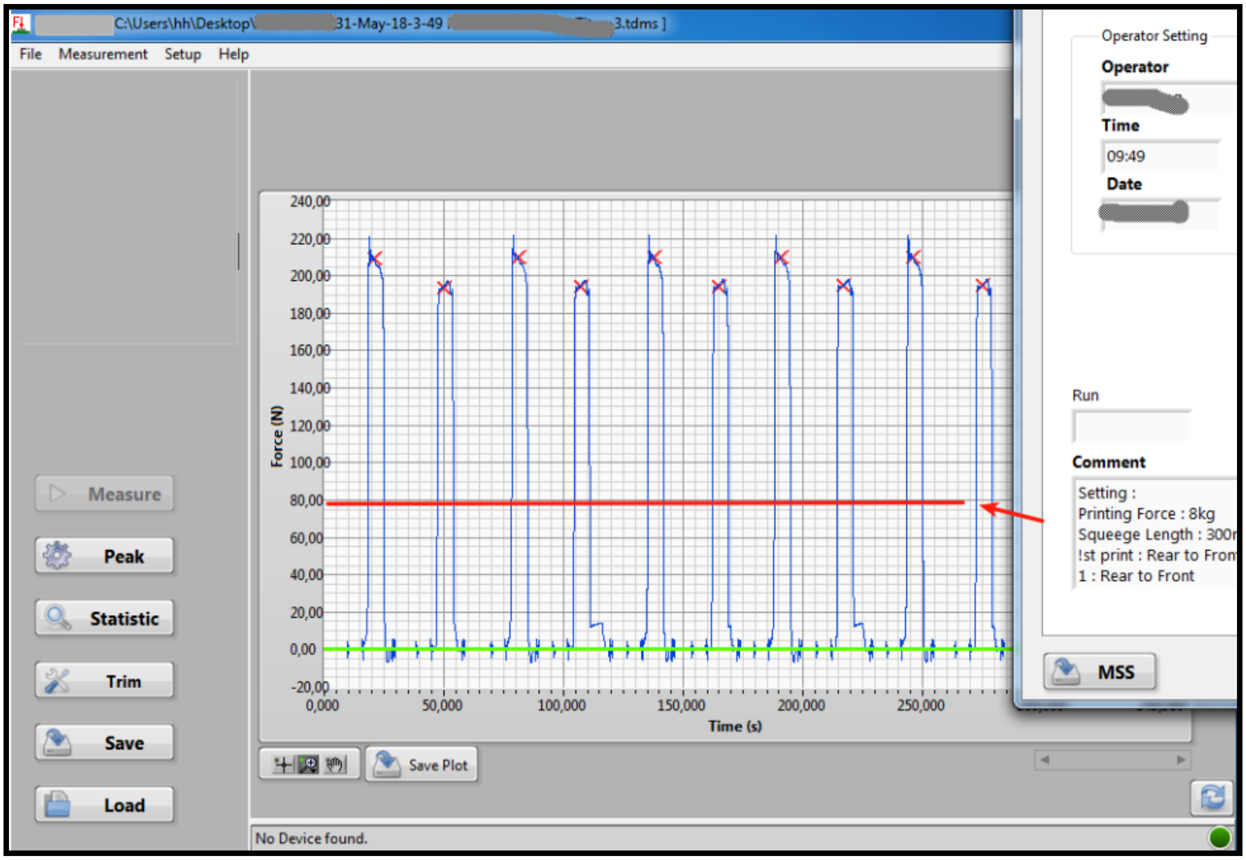
Screen Printer Squeegee Force Evaluation

Problem Introduction:

Another critical quality attribute in the screen-printing process is squeegee force. This is a setting that defines how much force is applied to a stencil while using squeegee blades to properly squeegee solder paste through the stencil apertures onto a PCB. Screen printer manufacturers design the capability into their software to independently adjust squeegee force setpoints for each print stroke direction. The generally accepted process rule to determine how much force is necessary is based on how long a squeegee blade is. This is loosely defined based on product dimensions and follows a simple formula. “For every inch of squeegee blade length, approximately 1 lb. of pressure is applied to the stencil.” Different OEMs use different units for determining the application of force in their squeegee system. Some systems have feedback capability while others have open loop systems which do not control force directly during the squeegee motion. For purposes of this evaluation case study, the units of force will be Newtons (N).

Process/Equipment Problem #1:

The excessive use of force in screen printing can have many ill effects to the quality output of the process. Some issues are “scooping” of paste from apertures during printing, early stencil wear, coining damage and squeeze out where improper gasketing of the stencil to PCB pads causes excess solder paste to be printed off pad and onto soldermask. In the case of this example, squeegee force measurement finds a grossly excessive amount of squeegee force as shown in Figure 14. The setpoint in the equipment for both F2R and R2F squeegee stroke directions is 8Kg which is approximately 80N identified by a red horizontal line.



[redacted] C:\Users\hh\Desktop\[redacted]31-May-18-3-49 [redacted]3.tdms]

Operator
[redacted]
Time
09:49
Date
[redacted]

Comment
Setting :
Printing Force : 8kg
Squeege Length : 300r
!st print : Rear to Fron
1 : Rear to Front

No Device found.

Figure 14 - Squeegee Force measurement with excessive force

Hardware Failure Problem #2:
Measurements were setup to perform scheduled interval capability testing. Machine is configured with closed-loop force feedback option. Random variation is seen in full test results depicted in Figure 15. With software analysis, problem is isolated to R2F stroke direction. Further diagnosis finds that the R2F encoder is moving during the print stroke. The encoder is designed not to move, but to hold and report position in continuance over a period of time. The failure mode is decreasing print force from beginning to end of print stroke.

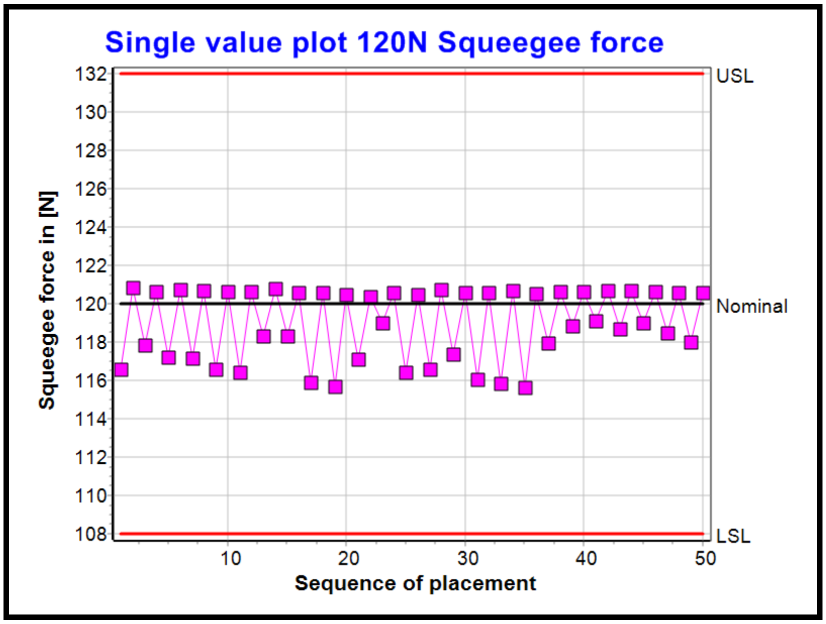


Figure 15 - Single Value Plot summary for squeegee force failure

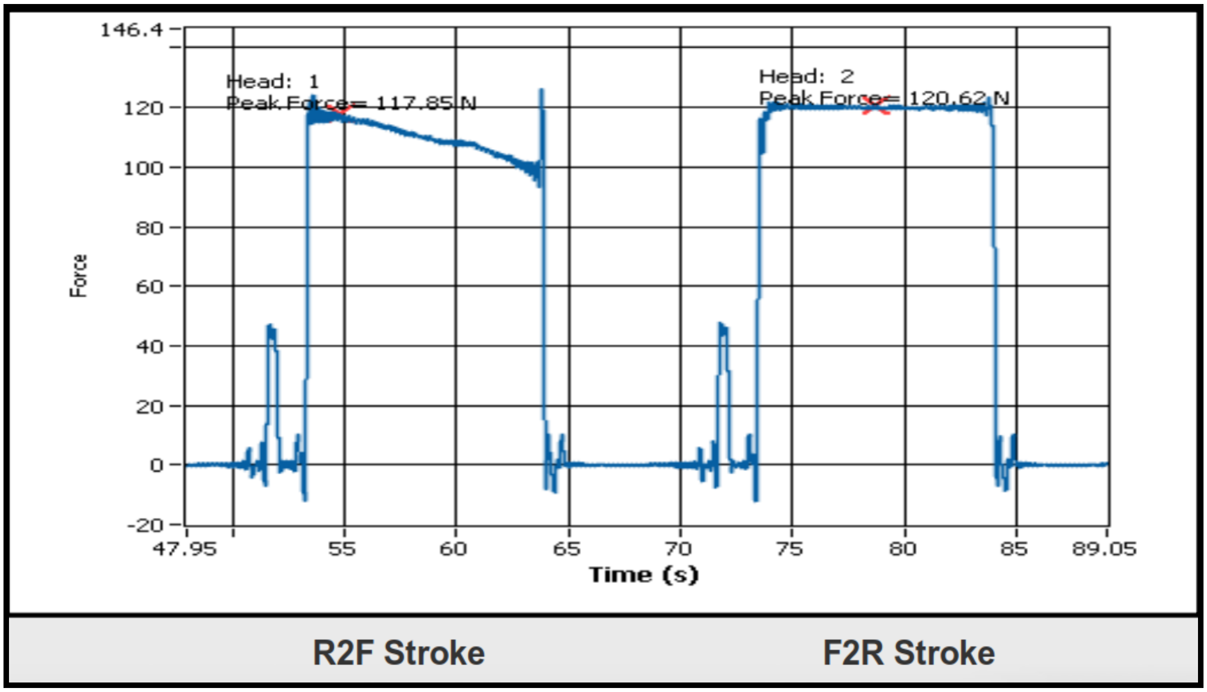


Figure 16 - Stroke Directions with R2F Failure Mode

Figure 16 shows a force-time curve of the failing R2F Stroke direction with decreasing force from beginning to end of print stroke. A new encoder was installed, and OEM calibration routine performed using measured values from force measurement tool. Figure 17 shows the final measured result with fixed encoder. How else would one find this problem without measurement of the process relevant characteristics?

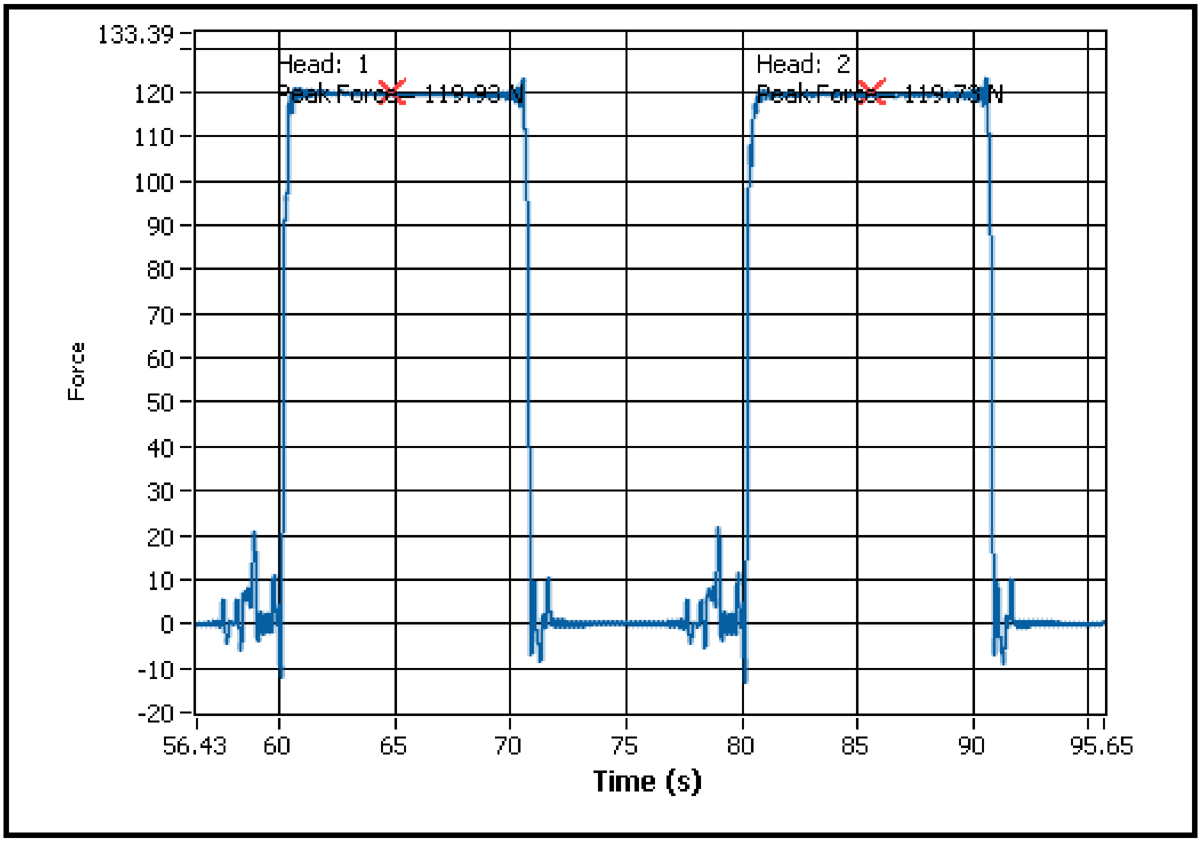


Figure 17 - Final Measured Result of Fixed Encoder

Evaluation Methodology:

A specifically designed software and measurement tool is used and placed in the worknest of the printer. The measurement application is designed to execute a capability analysis test for each squeegee stroke while the machine operates in normal production mode. Figure 18 illustrates the possible measured differences between print stroke directions in the same machine.

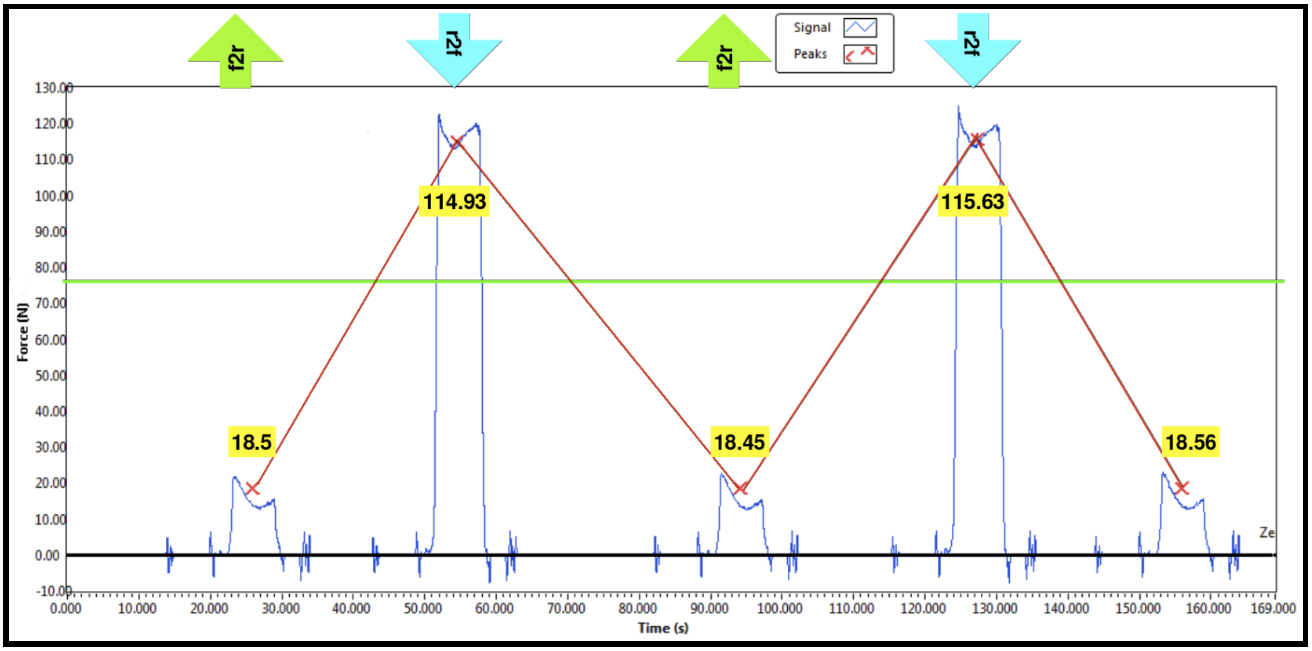


Figure 18 - Force Measurement Dialogue of Individual Print Stroke Directions

Because each manufacturer has their own worknest height dimension, the force measurement tool has different adaptable magnetic feet that secure the fixture to the base table of the machine. The XY size of the tool is constant with built-in force measurement strain gauges. A top surface plate which is printed on during the production style test is mounted to the strain gauges. Each of the strain gauges is connected to a measurement bridge device that reads the application of force from each strain gauge individually. The data streams coming from each strain gauge are interpreted into one signal which measures the accuracy of the setpoint and the repeatability of the force application during the entire stroke length as a force-time curve. The tool follows a regular calibration interval and is capable with a low measurement uncertainty (U) of +/-0.5N. As well, the tool has a measuring range of 2-500N which covers all squeegee force ranges which might be considered in SMT printing.

Test Setup and Preparation:

The test requires a machine program to be created. During the setup, production style parameters are set in the software of the machine. The tool, as seen in Figure 16, is loaded into the worknest of the machine and roughly centered from left to right and front to back. A PCB replica is used to trigger the conveyor and X board stop sensors. The replica looks like a square donut where the exterior front and rear edges sit on the conveyor transport rails while the interior fits around the top measurement surface plate. The replica is loaded into the machine automatically and moved to the printing position in the center of the worknest. The tool is manually centered and fine-tuned for non-interference fit inside the replica board. After this, the replica board is unloaded and reloaded to the print height position. Because a stencil is not used during this test, the stencil present verification sensor must be tricked to make the machine think there is a stencil loaded. Next, a squeegee height calibration routine is run to teach the height of where the printing surface is in relation to the squeegee blades. This ensures the machine knows where (and when) to apply the appropriate squeegee force when needed. The machine is configured to cycle the replica board into the machine, clamp to the rail, move up to print height, designated to wait for the squeegee stroke to complete a full stroke, lower back down to tooling height, unclamp from the rail, and cycle out of the worknest. The process is set to “rinse and repeat”.

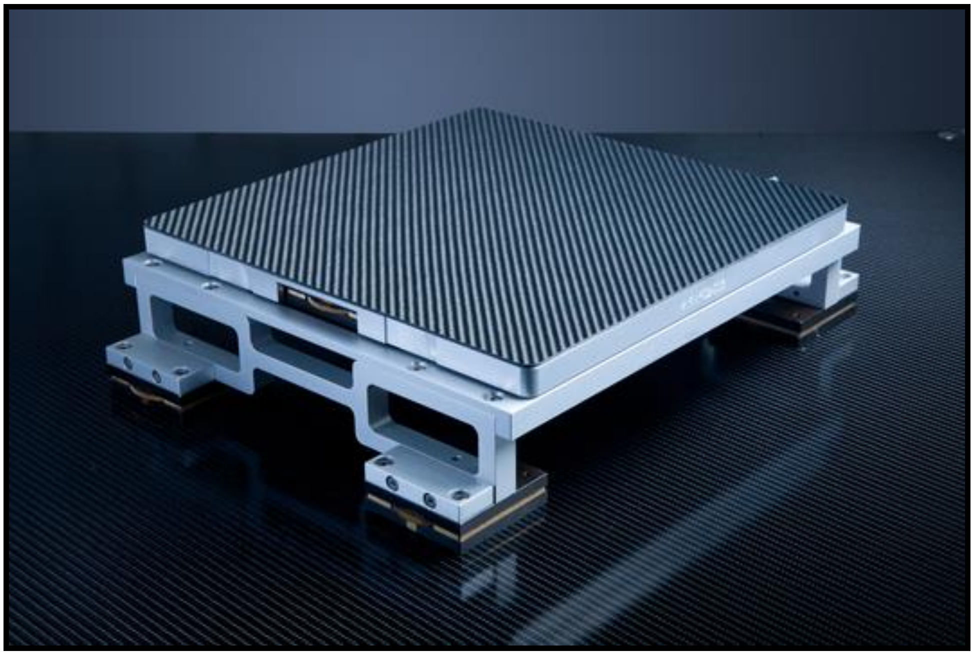


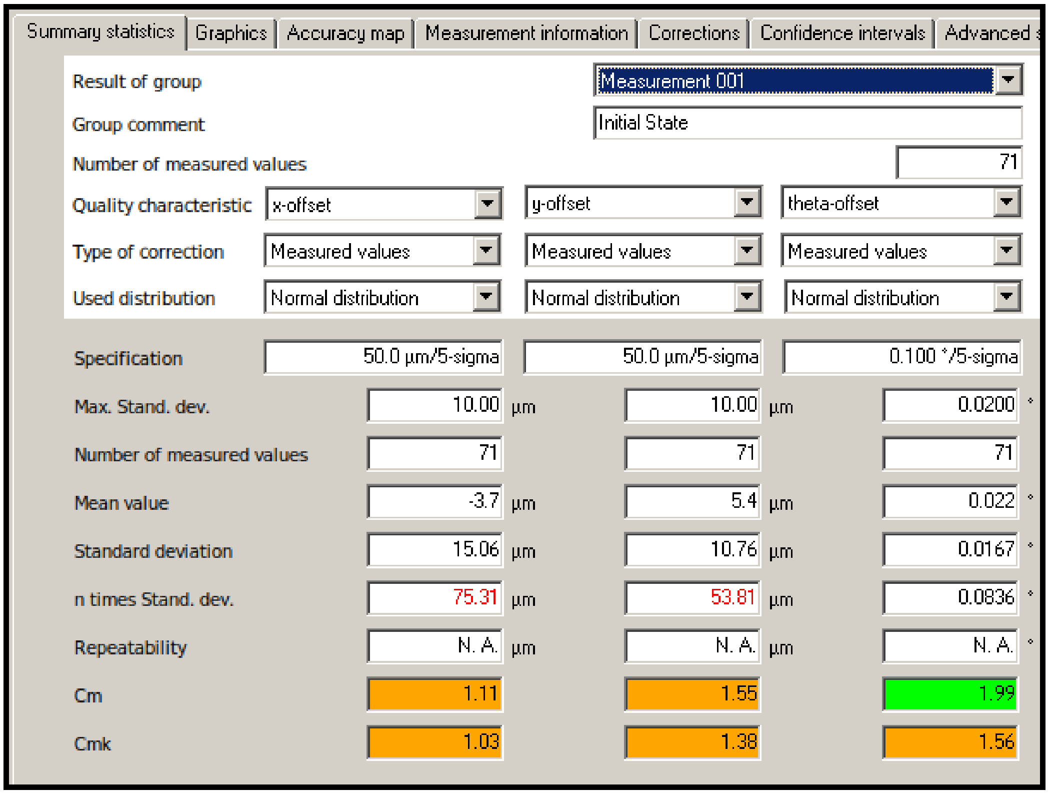
Figure 16 - Squeegee Force measurement tool

Data Collection and Analysis:
Typically, 50 runs are completed for a full test at each specific force setpoint, this breaks down to 25 measurements per stroke direction. If the protocol requires more than just one test, it is good practice to test the system operation with different increasing setpoint levels to make sure the squeegee printing force control system works for all intended force ranges that might be used in production. The software tool is connected to the hardware for a seamless and automatic collection of the force-time curves for the whole test and more importantly the individual print strokes.

Results and Conclusion:
Figure 16 and Figure 17 show the before and after, respectively, of measured results while diagnosing and repairing a closed-loop encoder hardware failure. This is an automated system intended to work and control the squeegee force system with feedback, but what is monitoring the control system? If this had not been measured with an external device, how long would it have continued? What contribution of defects would have been traced back to its failure? And, just one stroke direction - means every other printed board through the machine had questionable print quality. Goal as stated early on in abstract - if you don't measure, you don't know.

Placement Machine Accuracy Evaluation

Problem Introduction:
Brand new line with brand new placement equipment installed in that line with OEM standard calibrations performed so production could start. Before production begins, equipment user performs independent capability tests to validate equipment performance according to OEM specifications. Initial measurements are performed using glass board and glass components with a standard layout. Equipment FAILS specification as indicated with the orange fields in Figure 17. Linear trends are found in the X and Y axes after successful calibration and internal capability measurement test provided by OEM tools. How can the equipment be failing as a brand-new machine, with fresh calibrations, and a self-checking internal capability test that yields passing results? Let's see!



Result of group	Measurement 001		
Group comment	Initial State		
Number of measured values	71		
Quality characteristic	x-offset	y-offset	theta-offset
Type of correction	Measured values	Measured values	Measured values
Used distribution	Normal distribution	Normal distribution	Normal distribution
Specification	50.0 µm/5-sigma	50.0 µm/5-sigma	0.100 °/5-sigma
Max. Stand. dev.	10.00 µm	10.00 µm	0.0200 °
Number of measured values	71	71	71
Mean value	-3.7 µm	5.4 µm	0.022 °
Standard deviation	15.06 µm	10.76 µm	0.0167 °
n times Stand. dev.	75.31 µm	53.81 µm	0.0836 °
Repeatability	N. A. µm	N. A. µm	N. A. °
Cm	1.11	1.55	1.99
Cmk	1.03	1.38	1.56

Figure 17 - Initial Failing Results of Newly Calibrated Machine

Evaluation Methodology:
Utilize an independent measurement tool that has acceptable measurement uncertainty and documentation tracing its calibration. In this case a system with the statement of measurement uncertainty performance shown in Figure 18 was used.

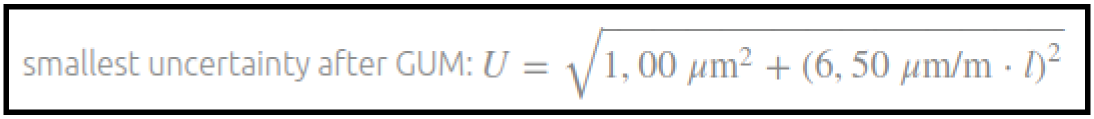

smallest uncertainty after GUM: $U = \sqrt{1,00\ \mu\mathrm{m}^2 + (6,50\ \mu\mathrm{m/m} \cdot l)^2}$

Figure 18 - Independent Measurement Tool's Measurement Uncertainty Claim

The measurement tool combined with a calibrated glass measurement board and calibrated glass measurement components are necessary to setup and complete a statistically significant number of measurements to fully test the configuration of the placement machine as it will be used in production. The machine is configured with a 3-nozzle head capable to place large leaded devices. A TQFP100 glass component is used to replace any leaded production devices for the test. Using the calibrated measurement tools, a series of placements and subsequent measurements are completed to diagnose the failing condition with step by step trial and error to finally resolve the issue. The OEM specification for pass/fail results checking is XY +/-50µm Theta 0.1 degrees @5-sigma.

Test Setup and Preparation:
A framed glass measurement board with dimensions of 340mm (13.38in) x 240mm (9.45in) x 5mm (0.197in) with 1.6mm (0.063in) edge thickness is used for the capability test. The TQFP100 is a glass component in a electrostatic discharge (ESD) plastic body with dimensions of 19.5mm (0.767in) x 19.5mm (0.767in) x 2mm (0.079in) thick on edges and 1.4mm (0.055in) thick in the nozzle pick up area. A software program that logs the configuration and technical information about the machine to be tested is used to create a placement layout file. The layout file is converted to a computer aided design (CAD) file with component centroid locations which will be used to create a placement program for the test. A representation of the layout file according to placement angles that are considered is shown in Figure 19. As well, a representation of the layout according to placement head distribution is seen in Figure 20. These two files overlay on each other and create a mixed distribution of head and angle associations for the accuracy map that will later be built and color coded with measured offsets. Once a program is created for the placement machine, the capability test is ready to be run.

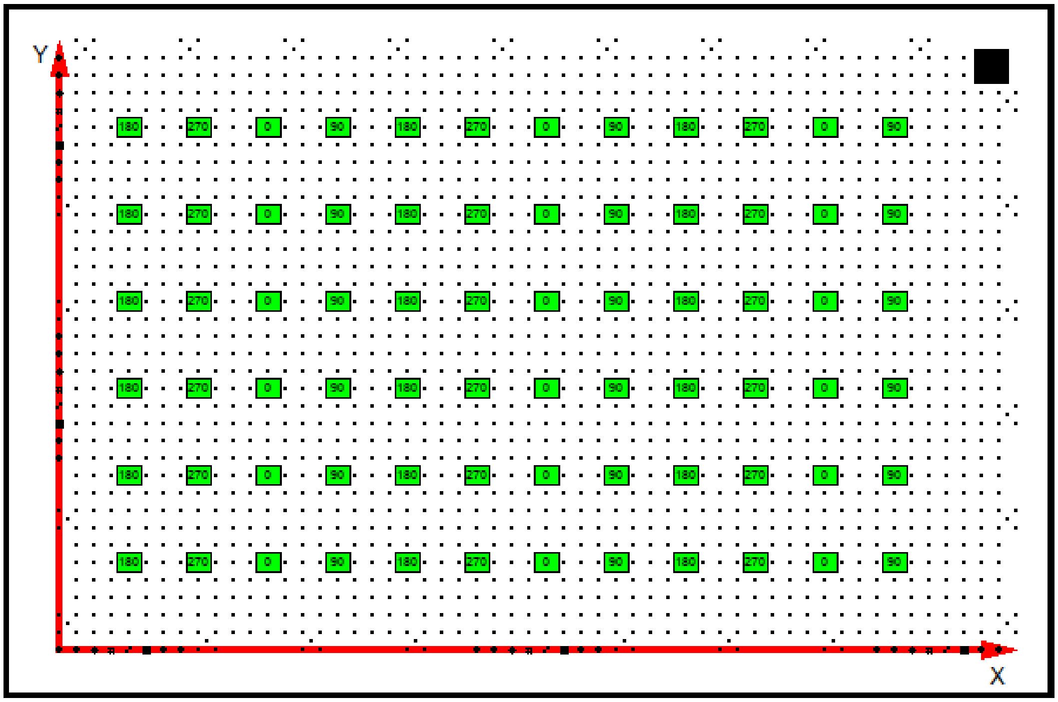


Figure 19 - Placement Layout File with Distribution of Placement Angles

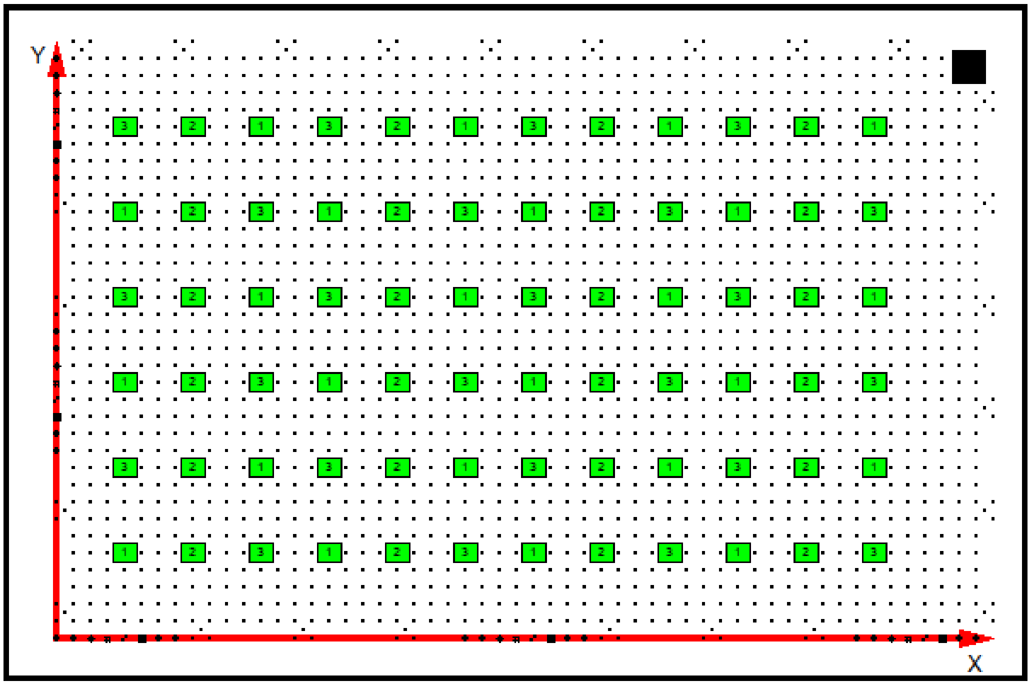


Figure 20 - Placement Layout File with Distribution of Placement Heads

Data Collection and Analysis:
Measurement 001 is the initial measurement after OEM calibrations and internal checks. Figure 21 shows an XY Plot of placements grouped by placement angle. The 5-sigma ellipse is the best fit curve to represent the data set for each angle. The legend details colors according to placement angle. With vertical and horizontal red lines depicting the lower and upper specification limits, any time a 5-sigma ellipse crosses outside the specification limits, it spells failing trouble. Figure 22 shows the similar XY Plot with data grouped by placement head/nozzle.

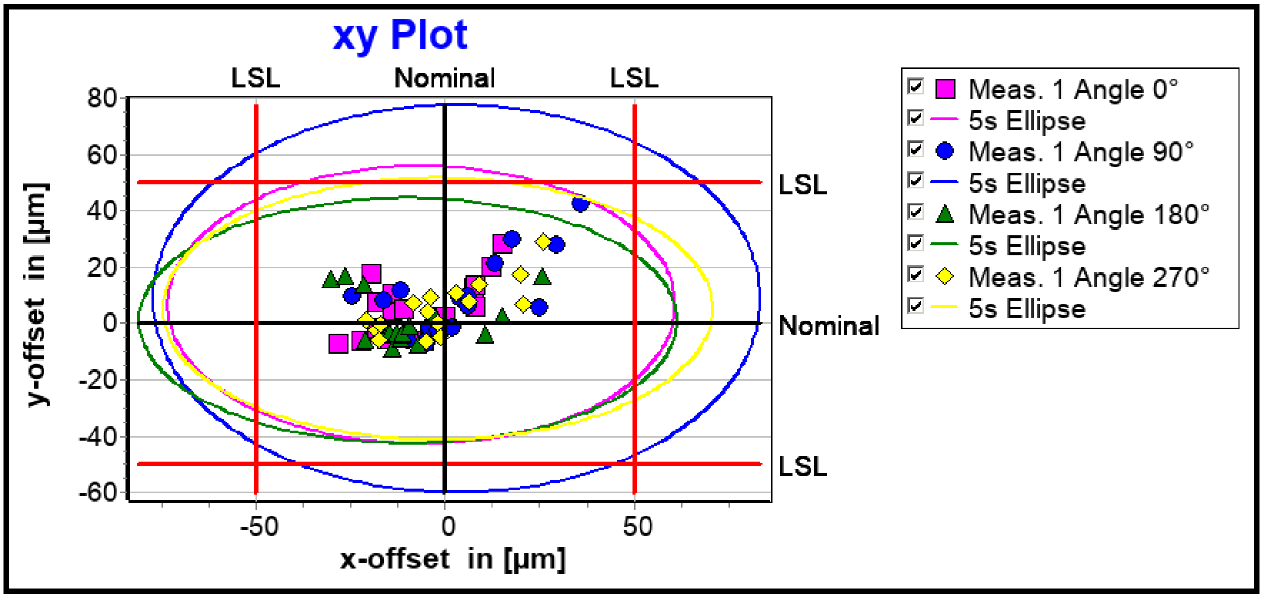


Figure 21 - Initial Measurement 1 XY Plot for all Placement Angles

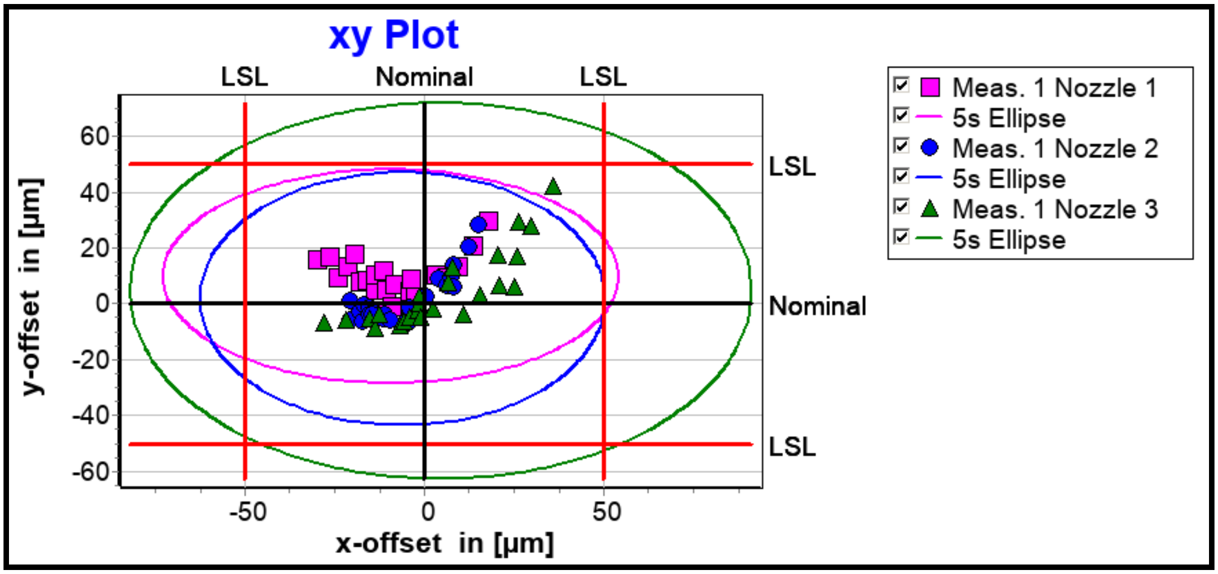
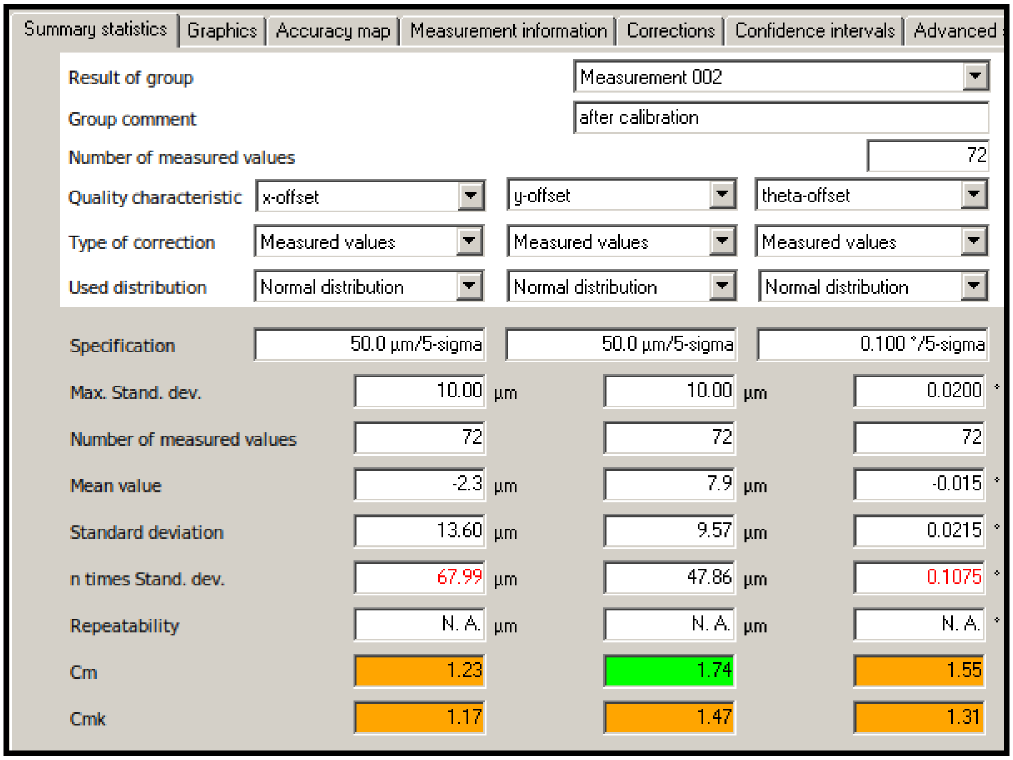


Figure 22 - Initial Measurement 1 XY Plot for all Placement Heads/Nozzles

The first step after the initial failing results was to calibrate the machine using the OEM tools. This also included special calibration components provided by the OEM. After the calibration, the OEM tools documented capability (C_m) values of 5+ for X-axis and 3+ for Y-axis. Measurement 002 results in Figure 23 shows very slight improvement in standard deviation from initial values but results are still failing.

More diagnostics shows there is a linear trend in the X-axis of 161ppm (means 16.1µm of offset shift for every 100mm of X gantry movement). This trend is shown in Figure 24. As well, the Y axis trend is less significant but still present after OEM calibration. The linear trend in Y-axis is 70ppm (means 7.0µm of offset shift for every 100mm of Y gantry travel. This trend is referenced in Figure 25.



Result of group: Measurement 002

Group comment: after calibration

Number of measured values: 72

Quality characteristic	x-offset	y-offset	theta-offset
Type of correction	Measured values	Measured values	Measured values
Used distribution	Normal distribution	Normal distribution	Normal distribution
Specification	50.0 µm/5-sigma	50.0 µm/5-sigma	0.100 °/5-sigma
Max. Stand. dev.	10.00 µm	10.00 µm	0.0200 °
Number of measured values	72	72	72
Mean value	-2.3 µm	7.9 µm	-0.015 °
Standard deviation	13.60 µm	9.57 µm	0.0215 °
n times Stand. dev.	67.99 µm	47.86 µm	0.1075 °
Repeatability	N. A. µm	N. A. µm	N. A. °
Cm	1.23	1.74	1.55
Cmk	1.17	1.47	1.31

Figure 23 - Capability Results after OEM Calibration using OEM Tools M002

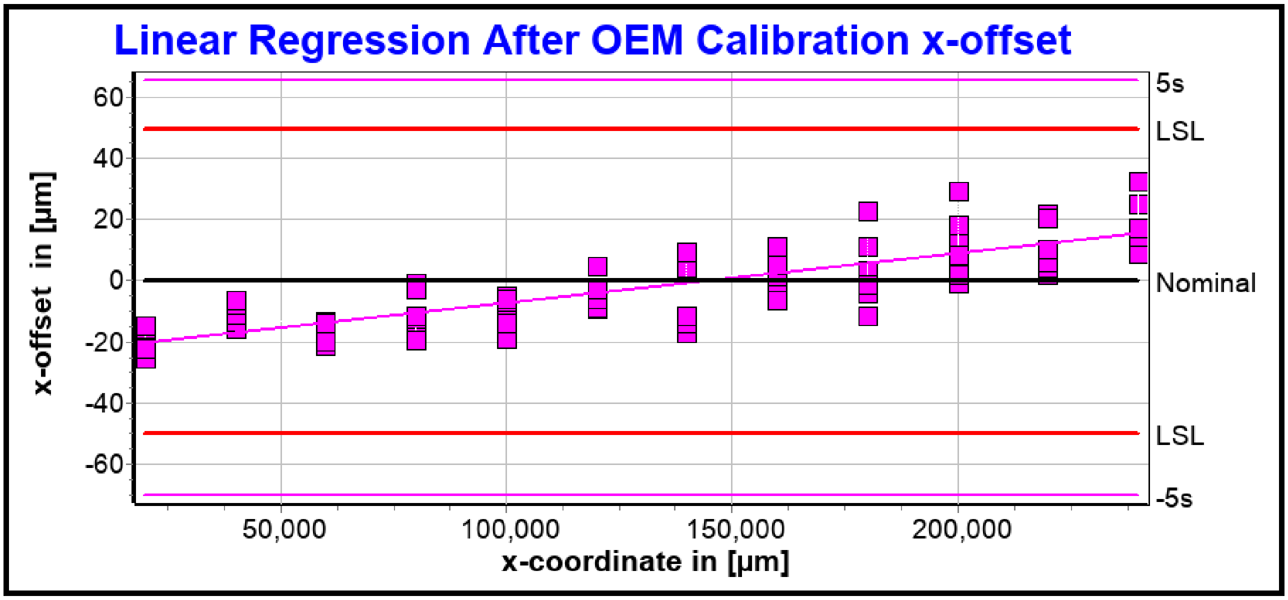


Figure 24 - Linear Regression in X-axis After OEM Calibration M002

The next diagnostic trial confirmed in Measurement 003 was to run the OEM mapping on the placement machine. This required a large calibrated glass plate to be setup in the machine for executing the OEM mapping calibration.

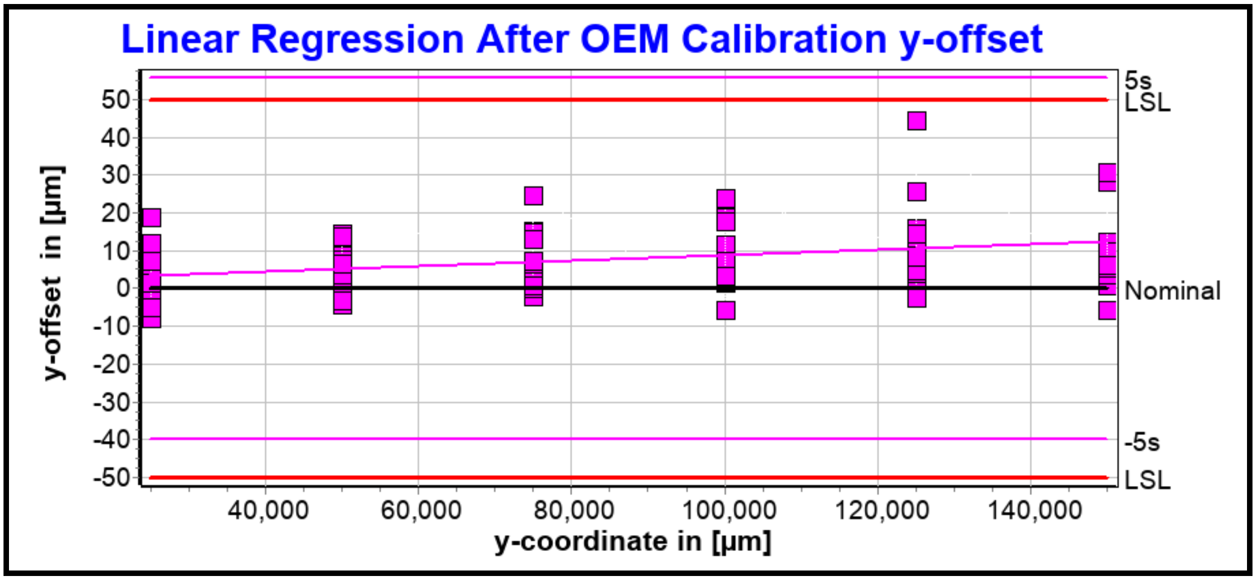
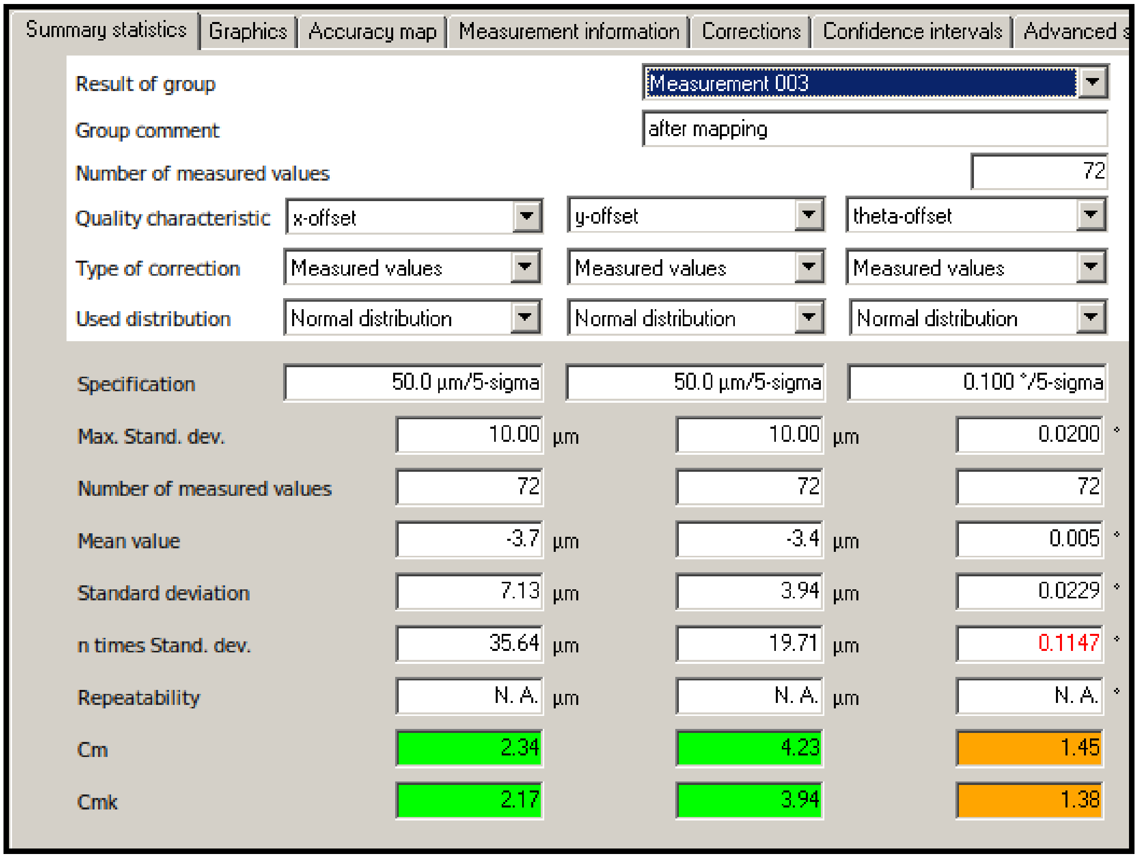


Figure 25 - Linear Regression Result in Y-axis After OEM Calibration M002



Result of group: Measurement 003

Group comment: after mapping

Number of measured values: 72

Quality characteristic	x-offset		y-offset		theta-offset	
Type of correction	Measured values		Measured values		Measured values	
Used distribution	Normal distribution		Normal distribution		Normal distribution	
Specification	50.0 µm/5-sigma		50.0 µm/5-sigma		0.100 °/5-sigma	
Max. Stand. dev.	10.00	µm	10.00	µm	0.0200	°
Number of measured values	72		72		72	
Mean value	-3.7	µm	-3.4	µm	0.005	°
Standard deviation	7.13	µm	3.94	µm	0.0229	°
n times Stand. dev.	35.64	µm	19.71	µm	0.1147	°
Repeatability	N. A.	µm	N. A.	µm	N. A.	°
Cm	2.34		4.23		1.45	
Cmk	2.17		3.94		1.38	

Figure 26 - Capability Results after OEM Mapping Calibration M003

The results of the OEM mapping in X-axis improved the linear trend significantly as can be seen in Figure 27. The regression improved from 161ppm to 52ppm, means 5.2µm of X offset for every 100mm of X gantry travel. The Y regression improved from 70ppm to -13ppm, means -1.3µm of Y offset for every 100mm of Y gantry travel. The internal OEM calibration did not fare so well after the mapping and was showing internal C_m values of 0.6 for both X and Y.

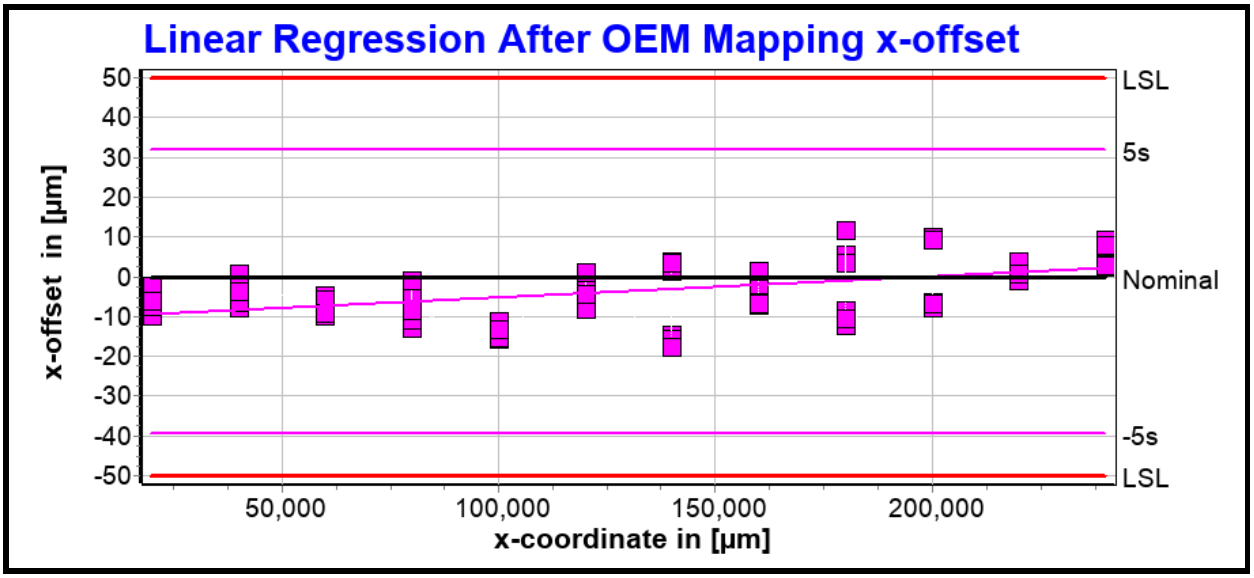


Figure 27 - Linear Regression Result in X-axis After OEM Mapping M003

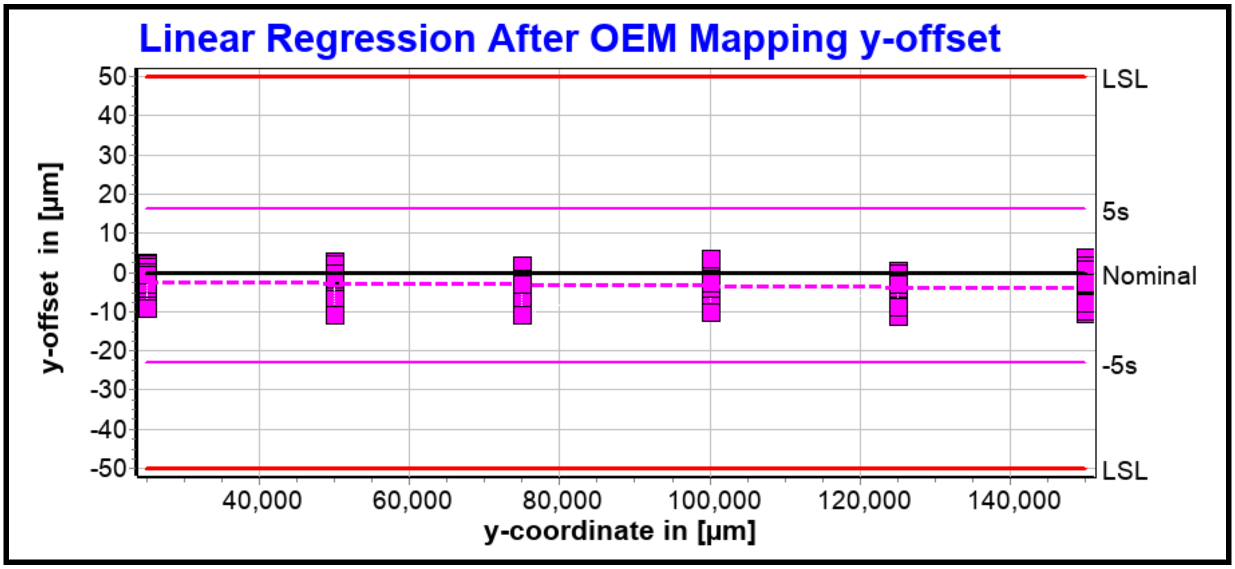
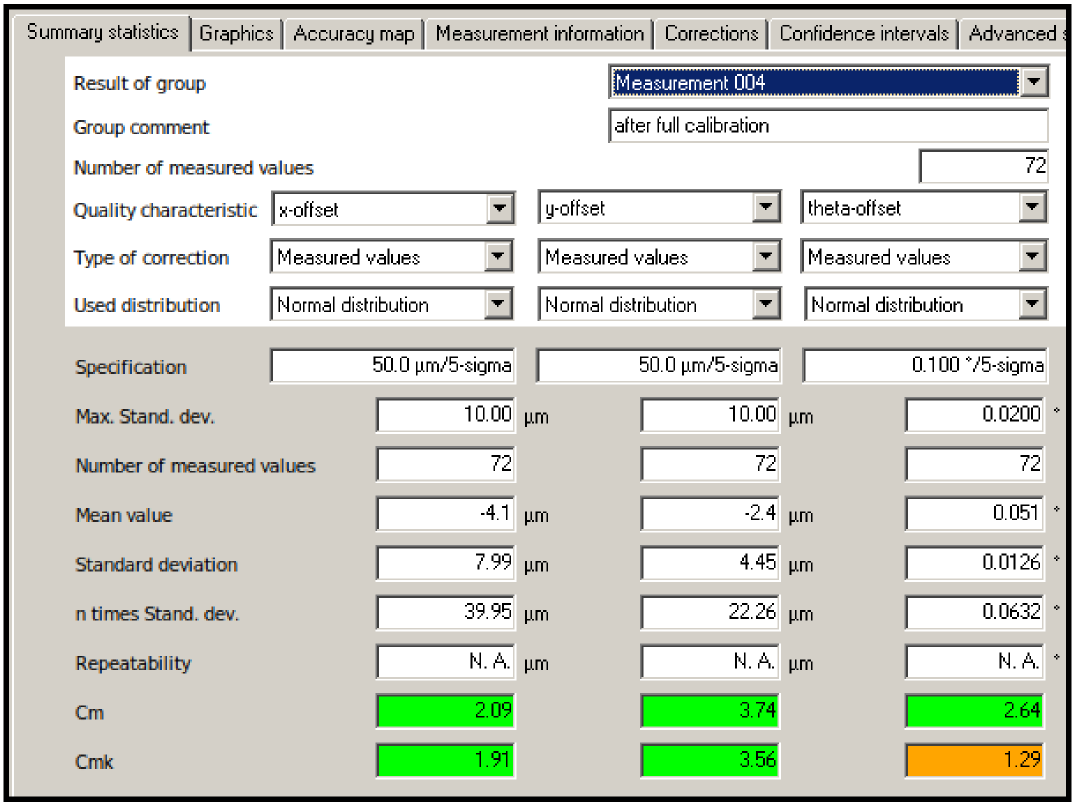


Figure 28 - Linear Regression Result in Y-axis After OEM Mapping M003

Measurement 004 results shown in Figure 29 are after a full and complete set of OEM calibrations. The only remaining questionable result is theta axis which shows a stable offset that can be adjusted into the machine parameters. The theta offset shift after the calibrations is seen in Figure 30. An adjustment of theta offset of -0.05 degrees was manually applied in the appropriate offset field.



Result of group: Measurement 004

Group comment: after full calibration

Number of measured values: 72

Quality characteristic	x-offset	y-offset	theta-offset
Type of correction	Measured values	Measured values	Measured values
Used distribution	Normal distribution	Normal distribution	Normal distribution
Specification	50.0 µm/5-sigma	50.0 µm/5-sigma	0.100 °/5-sigma
Max. Stand. dev.	10.00 µm	10.00 µm	0.0200 °
Number of measured values	72	72	72
Mean value	-4.1 µm	-2.4 µm	0.051 °
Standard deviation	7.99 µm	4.45 µm	0.0126 °
n times Stand. dev.	39.95 µm	22.26 µm	0.0632 °
Repeatability	N. A. µm	N. A. µm	N. A. °
Cm	🟩 2.09	🟩 3.74	🟩 2.64
Cmk	🟩 1.91	🟩 3.56	🟧 1.29

Figure 29 - Summary Results after Full & Complete OEM Calibrations M004

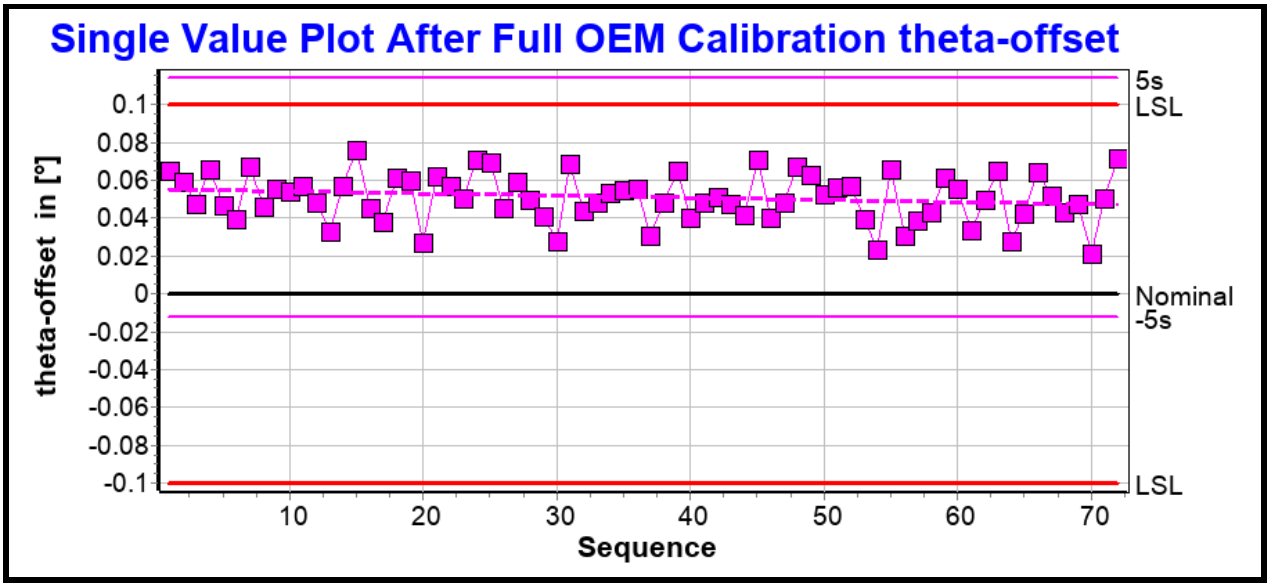
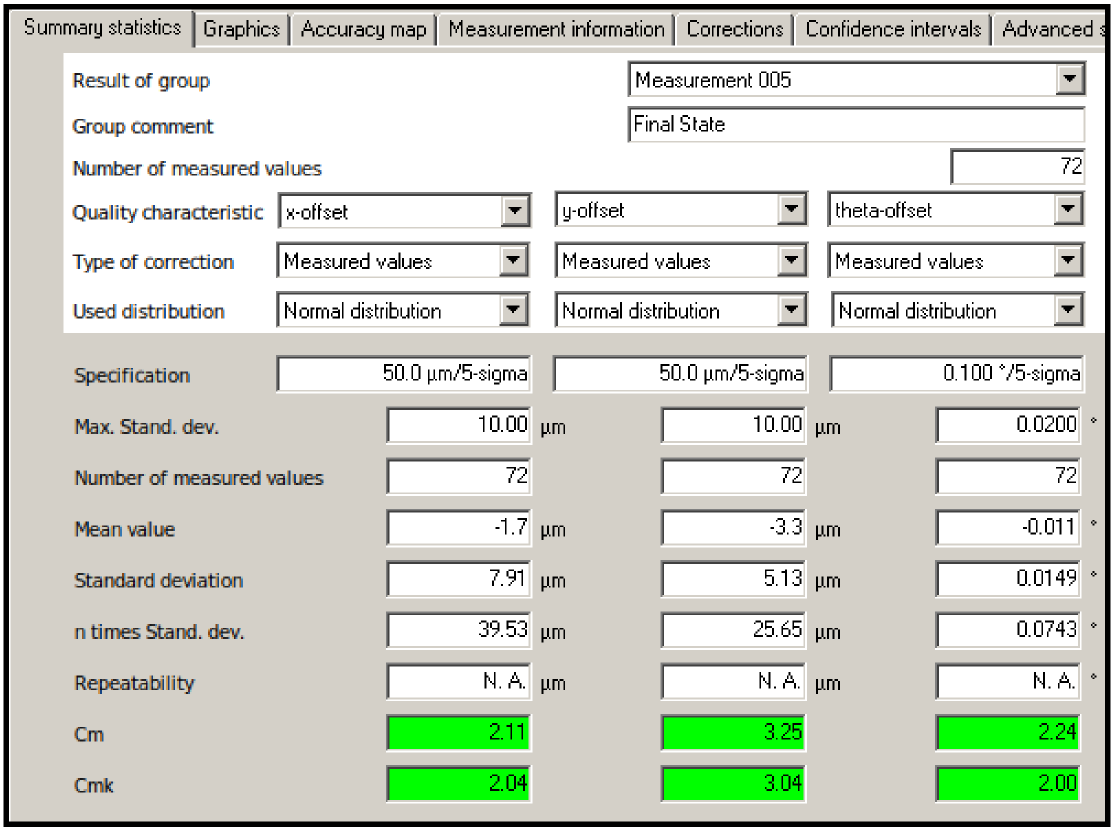


Figure 30 - Single Value Plot Theta After Full & Complete OEM Calibrations M004

Results and Conclusion:

The final results are brought back to within the OEM specifications and are confirmed in Figure 31 and Figure 32. After five (5) diagnostic trials with the machine and follow on measurements to confirm the capability state of the machine after each change, the performance is back on track until the next validation interval. Measurement 001 linear regression showed 17.3µm of X offset per 100mm of gantry travel in X. The glass board itself is 300mm wide, which means over the width of the glass measurement area the results experienced approximately 52µm (0.002in) of X offset. Certainly, the trend was enough to cause high standard deviation and fail the machine specification. Likely, depending on the complexity of product run through the machine, the trend could cause placement related defects. With an OEM system of monitoring checks stating all is well… how can the user be certain the machine is in the best possible accuracy condition? Clearly there is room for improvement and a need to continue independent validation exercises to be certain the wool isn't obstructing the users vision for the best performance required for SMT manufacturing quality.



Result of group: Measurement 005

Group comment: Final State

Number of measured values: 72

Quality characteristic	x-offset	y-offset	theta-offset
Type of correction	Measured values	Measured values	Measured values
Used distribution	Normal distribution	Normal distribution	Normal distribution
Specification	50.0 µm/5-sigma	50.0 µm/5-sigma	0.100 °/5-sigma
Max. Stand. dev.	10.00 µm	10.00 µm	0.0200 °
Number of measured values	72	72	72
Mean value	-1.7 µm	-3.3 µm	-0.011 °
Standard deviation	7.91 µm	5.13 µm	0.0149 °
n times Stand. dev.	39.53 µm	25.65 µm	0.0743 °
Repeatability	N. A. µm	N. A. µm	N. A. °
Cm	2.11	3.25	2.24
Cmk	2.04	3.04	2.00

Figure 31 - Final Results After Full Calibrations and Theta Offset Adjustment M005

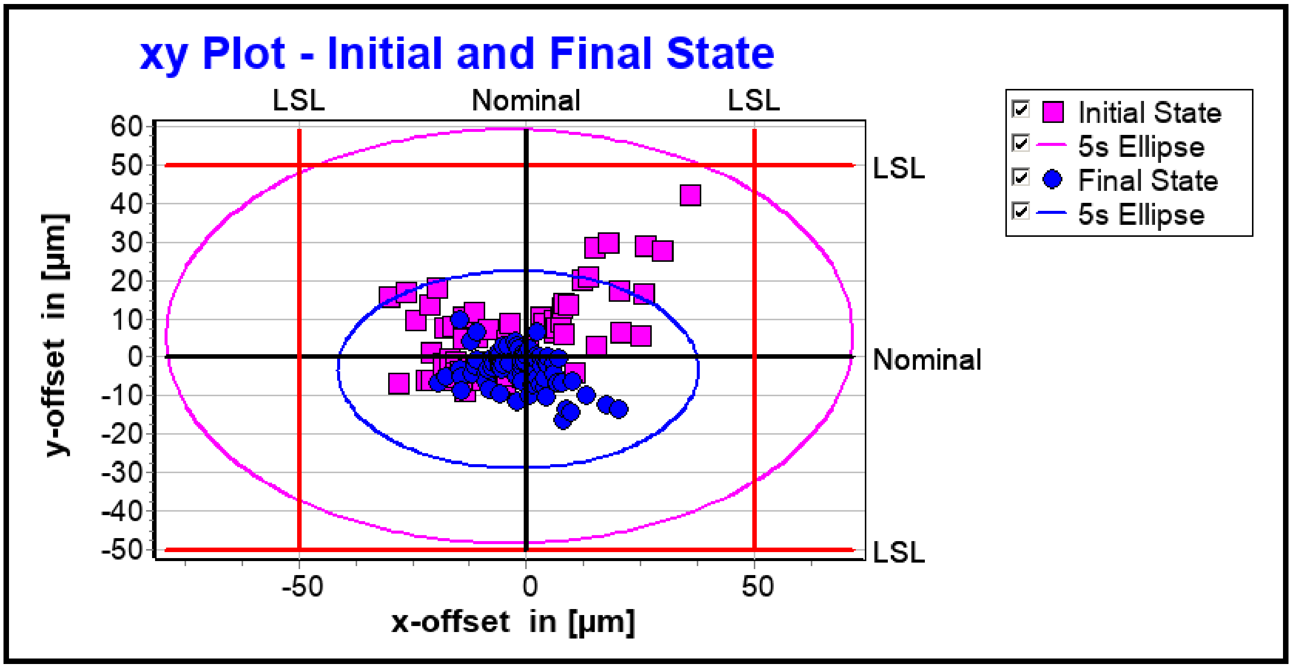


Figure 32 - Final XY Plot Results After Full Calibrations and Theta Offset Adjustment M005

Placement Machine Z-Force Evaluation:

Problem Introduction:
Placement Z-Force is a test method for measuring Z-directional forces on chip components as they are placed in normal production conditions. The example that will discuss this is a manufacturer that is complaining about missing springs placed in SMT product. There are no reported XY issues.

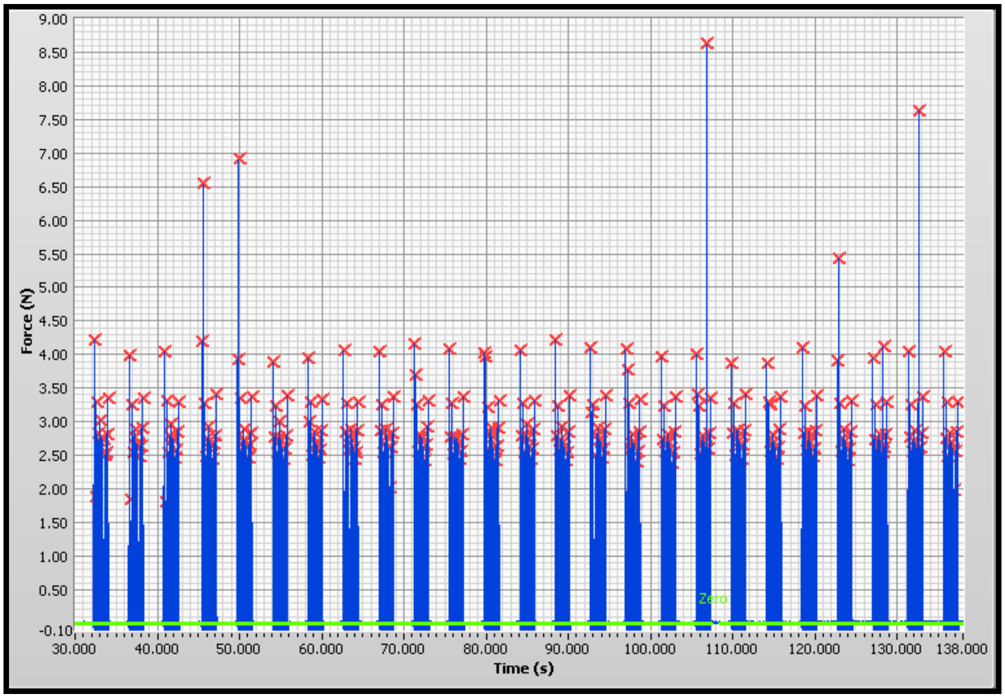


Figure 33 - Initial Force Measurement Sequence

Evaluation Methodology:
Need to use a measurement such as one like seen in Figure 34. A tool to be used under normal production conditions that is maintained in a regular calibration interval. Measurement directly in placement area, and handling and programming like a real PCB. The tool used in this diagnostic series has a Measurement frequency: 10 – 50.000 Hz and has a suitable measurement uncertainty (U): ±0.03 N. The test uses production components for the test. The force time plot shown in Figure 35 is a typical example.

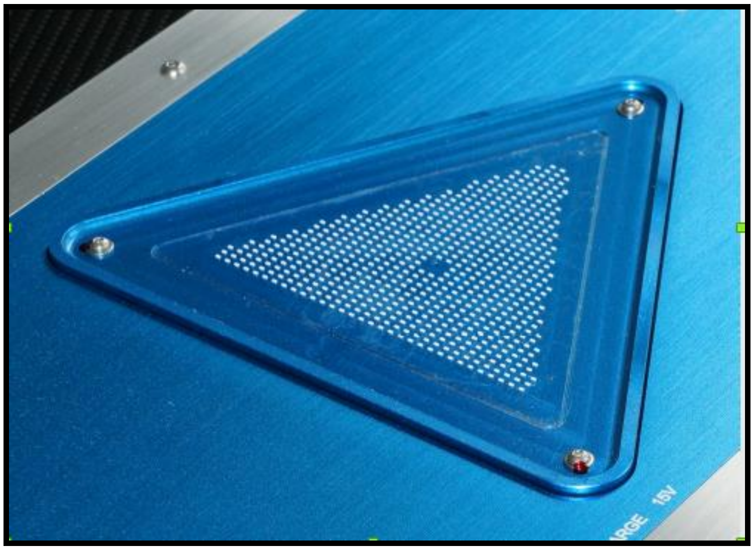


Figure 34 - Placement Z-Force Tool

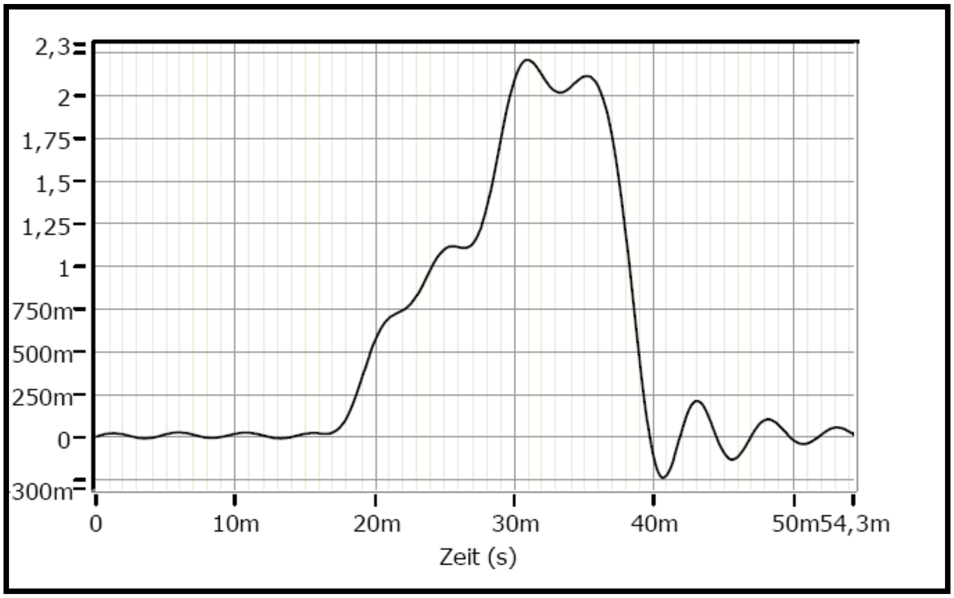


Figure 35 - Force-Time Plot Example

Test Setup and Preparation:
Supplier specs: 3.5N +/- 0.5N @ 4 Sigma.
Single head with 12 nozzles.

Data Collection and Analysis:
One nozzle shows outliers up to 8.5N in Figure 36. The force over time plot is suspect in duration and shape which points to mechanical problems. The solution was to replace the placement head and try a final measurement.

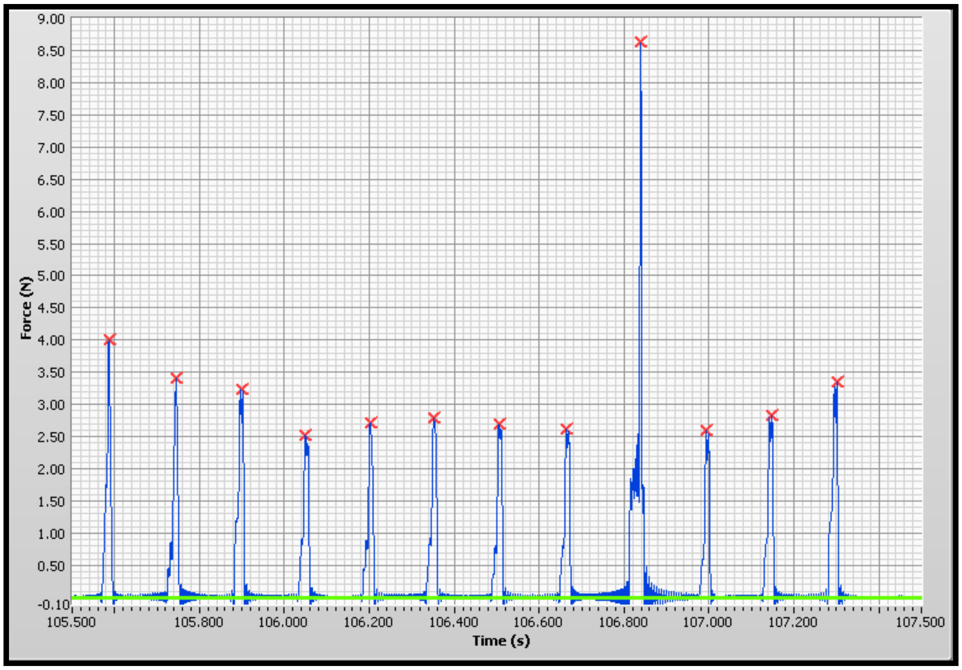


Figure 36 - Force Time Plot Sequence with Error

Results and Conclusion:
The measurement of Z-force in a production environment allows the ability to see what's happening more slowly and clearly with curves when placement speeds are too fast for the naked eye. The trials concluded with replacing a placement head and running another sequence which is shown in Figure 37. The quality of production issues are increased with more advanced measurement tools where they are needed to make measurement easier.

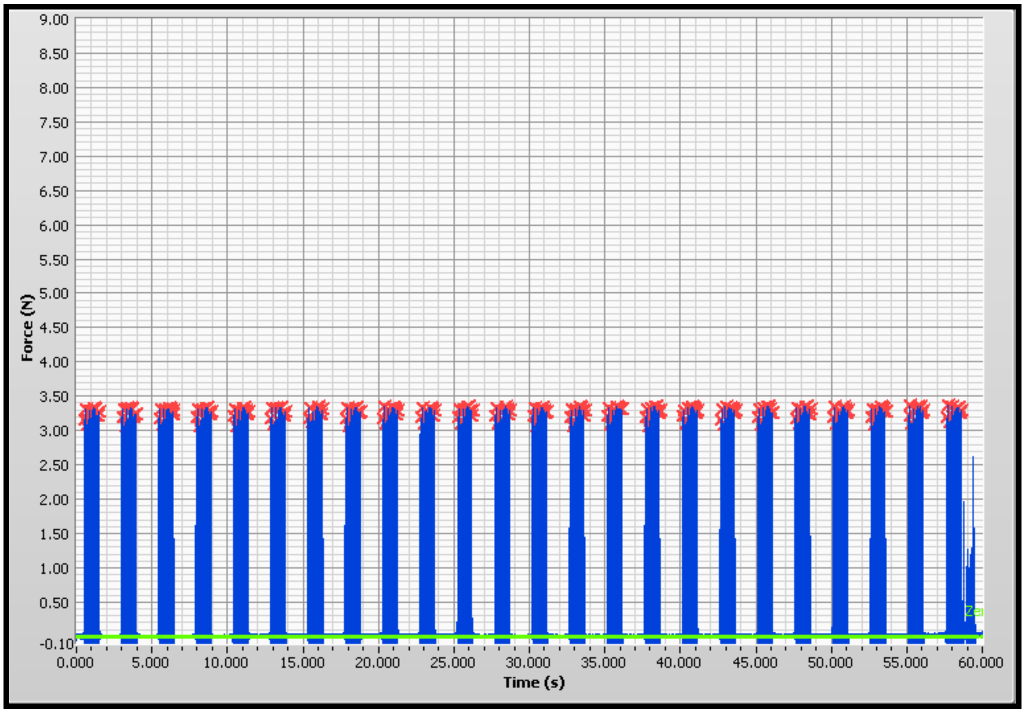


Figure 37 - Force Time Plot in Final State

Summary

The effects of regular capability measurement in every process step is critical to improving manufacturing quality of printed circuit boards. With the complexity of today's products and the ever-challenging size reduction. Better measurement methods are required to understand where defects come from and be able to move to the next level of improvement.

The intrinsic benefits are numerous, and the productivity gains have a penetrating effect on profitability which is what drives the need for improvement.