

An Investigation into Printing Miniaturised Devices for the Automotive and Industrial Manufacturing Sectors

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Abstract

The electronics market is divided into many segments each having its own challenges; but one theme that connects the electronics community together is a need for higher yield with lower costs. Or simply the manufacturing process needs to become ever efficient.

Within the consumer sector miniaturisation is the watch-word and all eyes are on the 0.3mm CSP and metric 03015 components. Both of these devices will pose serious heterogeneous questions for High Volume Manufactures, especially if the current stencil thickness of 100 microns is required for standard technology.

The Automotive and Industrial electronics sector which are not normally brushed with the challenges of miniaturisation have started to become connected to this demanding world. The reason for this is not through the consumer driver of increased functionality, but one of pure supply and demand economics. The demands for large foot print devices are decreasing therefore the unit price and scarcity is increasing; whereas smaller foot print devices are increasing in demand and availability and as a consequence the unit price and scarcity is reducing. For this reason Automotive and Industrial electronic manufacturers are now faced with implementing fine pitch devices due to availability and cost.

The Automotive and Industrial electronics sector have several large obstructions when engaging with miniaturised devices: - the addition of large devices on the same product, harsh environmental concerns and safety/reliability demands. All of these issues require a highly capable heterogeneous solder paste printing process.

This paper investigates a solution the Automotive and Industrial electronics community can implement to ensure a high yield print process in which fine pitch footprint devices can be printed alongside traditional larger footprint devices.

Introduction

Within the Automotive sector a transition from mechanical systems to electronic assemblies continues to transform the automotive landscape¹. Automotive electronics currently represents one of the higher semiconductor growth segments with a CAGR of 6.8% (2012-2017)² According to a leading Semicon supplier, todays electronics system account for more than one-third of the total cost of a new vehicle. The main drivers of this growth are safety, connectivity, efficiency and comfort. In addition to today's growth within the automotive sector, hybrid and electric vehicles are forecasted to integrate significant electronic content in automobiles³.

Due to component availability and cost the Automotive and Industrial sectors are now faced with the challenge of implementing 0.4mm CSP devices into the manufacturing process. The printing techniques for the 0.4mm CSP device have been covered in many past technical papers. However these investigations and recommendations have been focused on the three C's (Consumer, Communication and Computing Sectors) which benefit from the use of 100 um stencil architectures. The Automotive and Industrial sector tend to deliver products which contain larger footprint devices therefore requiring greater volumes of solder. To achieve the increased solder volume the Automotive and Industrial sectors tend to use 127um stencil foils.

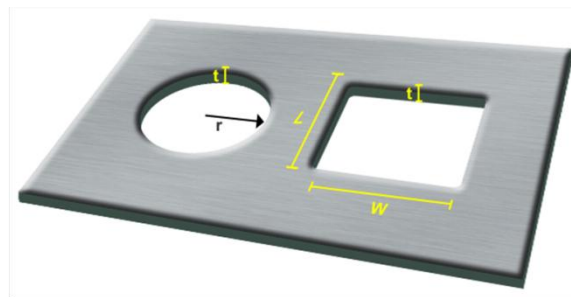
The dilemma that a slightly thicker stencil presents is one of Area Ratio. The Area ratio calculation in its simplest form is a ratio between the Aperture opening area and Aperture wall surface. Figure 1 illustrates the calculation for both circles and squares.

The factors that make up an aperture - Stencil thickness, aperture diameter, width and length all influence the resultant Area Ratio. If we take two examples we can observe the effects; a stencil of 100 microns and a circular aperture of 240micron would result in an Area Ratio of 0.6; by changing the diameter to 20um the Area ratio becomes 0.5. Needless to say the act of calculating Area Ratio simply allows the Engineer to quickly register an apertures dimension and produce an Area Ratio integer. The significance of this value is correlated to the transfer efficiency or “how much solder paste is expected to release from the aperture”.

To aid the process engineer, IPC have produced a stencil guideline, IPC 7525B⁴, which recommends that aperture area ratios should be kept within a range of 0.5 -0.66 (material set dependant) to ensure a minimum 70-75% transfer efficiency and therefore an acceptable stencil printing process.

Figure 2 illustrates the “Historical” transfer efficiency curves which have been the accepted point of reference, as can be seen the transfer efficiency of 70% falls off after Area Ratios of 0.66.

During recent years the solder paste, stencil and capital equipment suppliers have invested resources into extending the process window thus allowing smaller Area Ratio apertures to achieve the required minimum 70-75% transfer efficiency. These incremental developments are illustrated within Figure 2 (today curve); with careful selection of material sets and process setup the smallest Area Ratio which can achieve 70-75% transfer efficiency has been extended to 0.5.



$$\text{Area Ratio (Rect)} = \frac{\text{Aperture Open Area (L x W)}}{\text{Aperture Wall Surface Area } 2t(L+W)}$$

$$\text{Area Ratio (Circle)} = \frac{\text{Aperture Open Area } (\pi r^2)}{\text{Aperture Wall Surface Area } (2 \pi r)t}$$

Figure 1 - Area Ratio Calculation

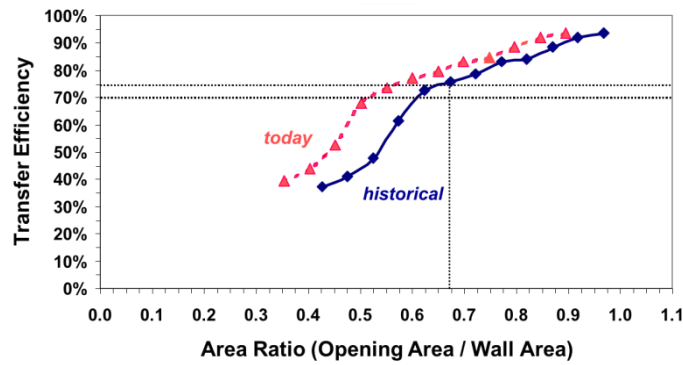


Figure 2 - Transfer Efficiency curves (Historical and Today)

Dilemma

To illustrate the dilemma the Automotive and Industrial sector are facing the aperture range associated with the 0.4mm CSP device and calculated Area Ratios for both 100um and 127um stencil foil thicknesses are shown in Table 1.

Table 1 - Area Ratio values

Aperture Size	100um Stencil Thickness	127um Stencil Thickness
200um aperture Diameter	0.50	0.39
225um aperture Diameter	0.56	0.44

Although today's leading edge print process can achieve Area Ratios of 0.5, it is clear to see the 0.4mm CSP aperture range when combined with 127um stencil thicknesses falls outside today's capability.

Proposal

Within the three C's sector, innovative solutions such as Nano coatings⁵⁻⁶, stencil manufacturing techniques, stencil finish⁷⁻⁸ and ultrasonic squeegees⁹⁻¹⁰ have been investigated to break through the 0.5 Area Ratio barrier. From these documented innovations the ultrasonic squeegee has shown the most capability therefore this device will be used throughout this investigation to establish if apertures ranging from 200um to 225um with associated Area Ratios of 0.39 to 0.44 can be printed.

Test Vehicle

The test vehicle used through the investigation is shown in Figure 3. This substrate contains standard device layouts which follow IPC recommendations. The outer dimensions are 150mm x 150mm with a thickness of 1mm. The substrate is fabricated from FR4 and all pads are none solder mask defined (NSMD).

The two 0.4mm CSP were used to measure the success of the investigation. The land dimensions follow the IPC recommendations. The aperture designs used for the investigation are shown in Figure 4. The associated Area Ratios are calculated assuming the stencil thickness is 127um, as can be seen the two designs are way below the currently 0.5 limit.

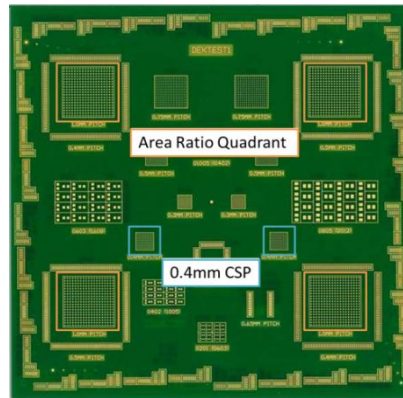
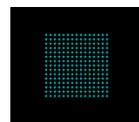
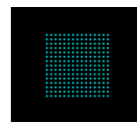


Figure 3 - Test Vehicle



Aperture: 0.200mm circle
Area Ratio: 0.394



Aperture: 0.225mm circle
Area Ratio: 0.443

Figure 4- Aperture designs

SIPOC

Figure 5 shows the SIPOC used throughout this investigation

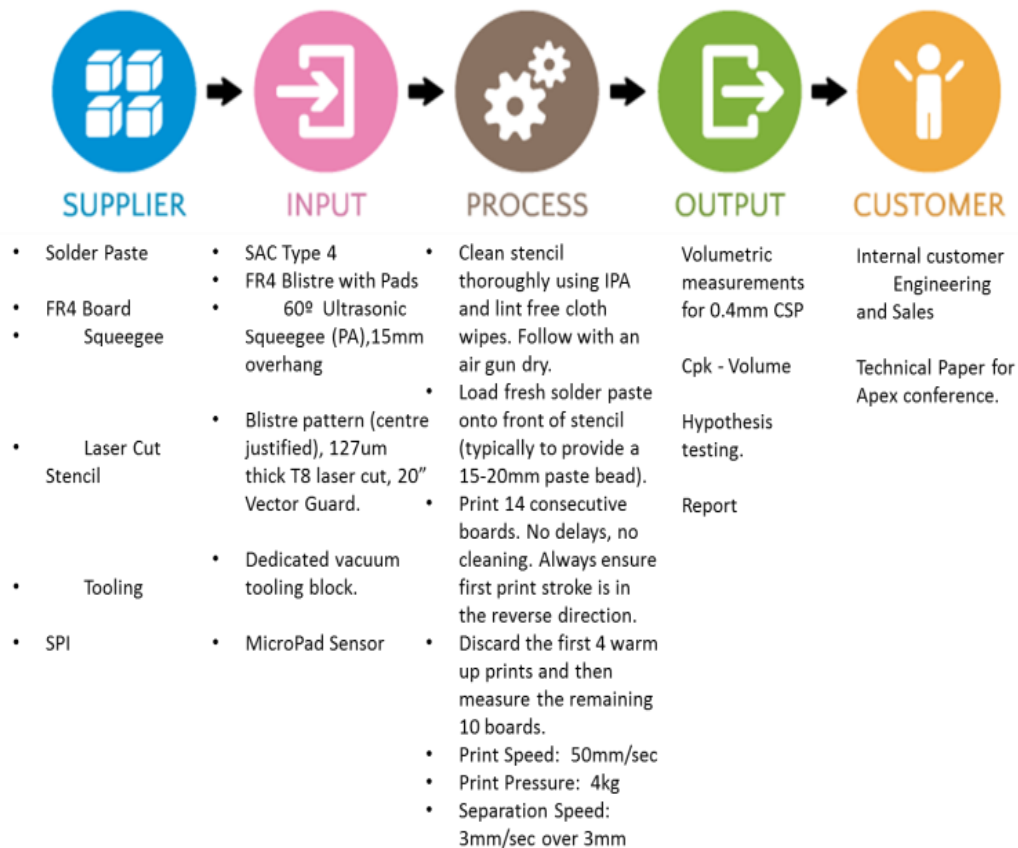


Figure 5 - SIPOC

Measurement tool

The measurement tool used through the investigation was a production Solder Paste Inspection (SPI) machine with a micro-pad sensor. The measurement tool was setup to record solder paste height, area and volume for each printed deposit. The following section outlines the Gage R&R performed on the SPI tool to ensure that the precision errors were acceptable.

Gage R&R

The Gage R&R test program comprised of a printed substrate which was allowed to dry to ensure stability. This substrate was used for all Gage R&R trials. The Gage R&R test plan is outlined in table 2, each trial included six inspection cycles. Aperture sizes of 175,200 and 225um were measured to understand the precision of the SPI machine. The design of the Gage R&R provides the study with 36 parts for each run which generates 108 data points. The results of the Gage R&R are shown in Table 3 and Figure 6.

Table 2 - Gage Test Plan

Run Number	Observation
Run 1	Straight Run
Run 2	Machine left for 2 hours before run
Run 3	Machine power cycled and reset before run

The Anova table shown in Table 3 and Figure 6 shows the P value for “Run” is greater than 0.05 (alpha level 95%) indicating that this factor has no effect on the Gage R&R. Therefore the only source that has an effect on the Gage R&R study is location. The % study variation figures for total Gage R&R, repeatability and reproducibility were below 10%, indicating the measurement tool has an acceptability rating of “Excellent”; therefore this tool was used with confidence throughout the investigation.

Table 3 - Gage R&R ANOVA

Results for: Gauge R&R 175-225 Volume					
Gage R&R Study - ANOVA Method					
Two-Way ANOVA Table With Interaction					
Source	DF	SS	MS	F	P
Location	2	1.26235E+13	6.31176E+12	3750.02	0.000
Run	2	1.36069E+10	6.80343E+09	4.04	0.110
Location * Run	4	6.73251E+09	1.68313E+09	0.58	0.680
Repeatability	45	1.31070E+11	2.91267E+09		
Total	53	1.27749E+13			
Alpha to remove interaction term = 0.25					
Two-Way ANOVA Table Without Interaction					
Source	DF	SS	MS	F	P
Location	2	1.26235E+13	6.31176E+12	2244.34	0.000
Run	2	1.36069E+10	6.80343E+09	2.42	0.100
Repeatability	49	1.37803E+11	2.81230E+09		
Total	53	1.27749E+13			
Gage R&R					
Source	StdDev (SD)	Study Var (5.15 * SD)	%Study Var (%SV)		
Total Gage R&R	55082	283672	9.26		
Repeatability	53031	273110	8.92		
Reproducibility	14891	76686	2.50		
Run	14891	76686	2.50		
Part-To-Part	592028	3048944	99.57		
Total Variation	594585	3062112	100.00		
Number of Distinct Categories = 15					

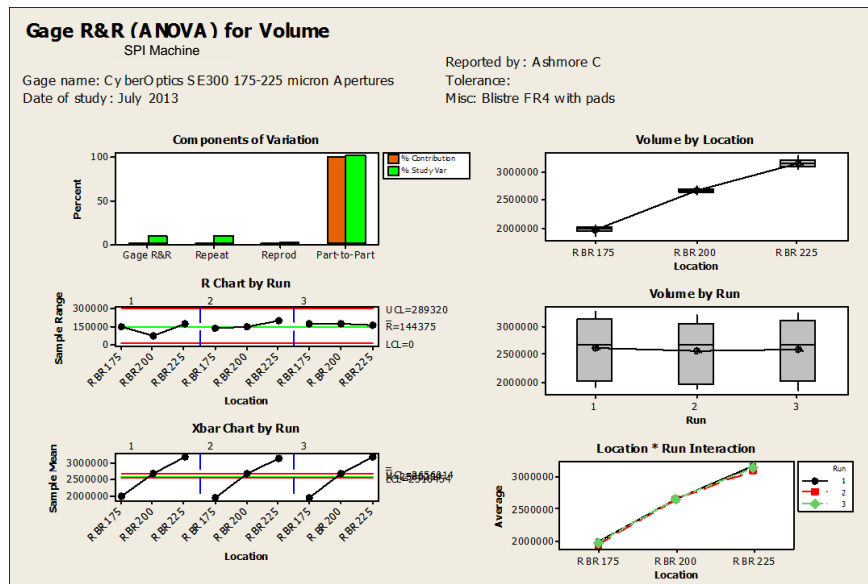


Figure 6 - Gage R&R ANOVA

Baseline Results

Although the Area Ratio calculations and historical references predict failure for the 200 and 225um aperture designs, the next stage is to test and benchmark the predicted output. The setups for these tests are outlined in the SIPOC.

The process capability for this benchmarking activity and subsequent test will be measured against transfer efficiency (TE). Transfer Efficiency is the ratio between the measured volume and the theoretical volume. Note due to legacy the results are reported in a decimalised percentage (i.e. 0.5 = 50%). A Cp and Cpk index of 1.33 or greater is required to verify a stable process output.

Figure 7 and 8 shows the process output achieved from the 200um aperture design (Area Ratio = 0.394) with a standard print process setup. As can be seen the 200um apertures process capability analysis indicates the process has a relatively low standard deviation (13%) but a mean volume of only 36%, producing a Cp of 1.1 and a Cpk of -0.67; indicating that the process is not capable.

Figure 9 and 10 show the process output achieved from the 225um aperture design (Area Ratio = 0.443) with a standard print process setup. As can be seen the 225um aperture process capability analysis indicates the process has a relatively high standard deviation (31%) with a mean volume of only 59%, producing a Cp of 0.45 and a Cpk of -0.01; indicating that the process is not capable.

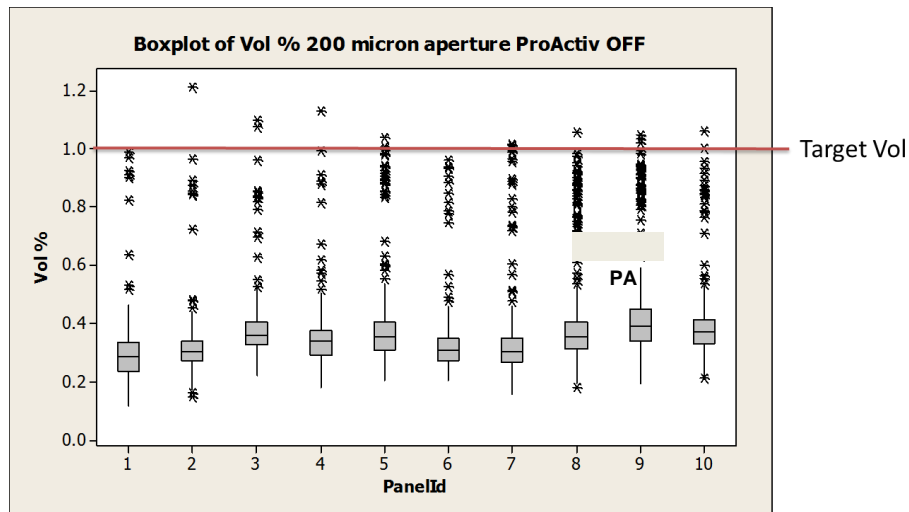


Figure 7 - Boxplot 200um Aperture Diameter Standard Process - Ultrasonic Off

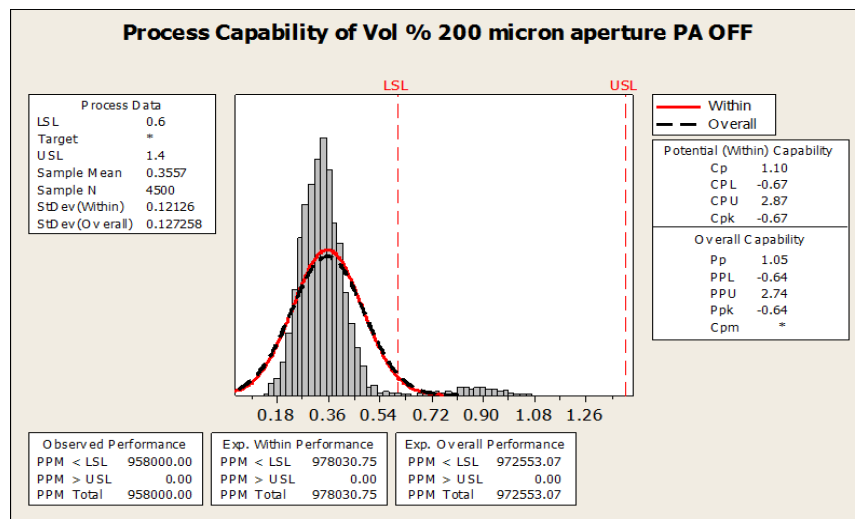


Figure 8 - Process Capability 200um Aperture Diameter Standard Process- Ultrasonic Off

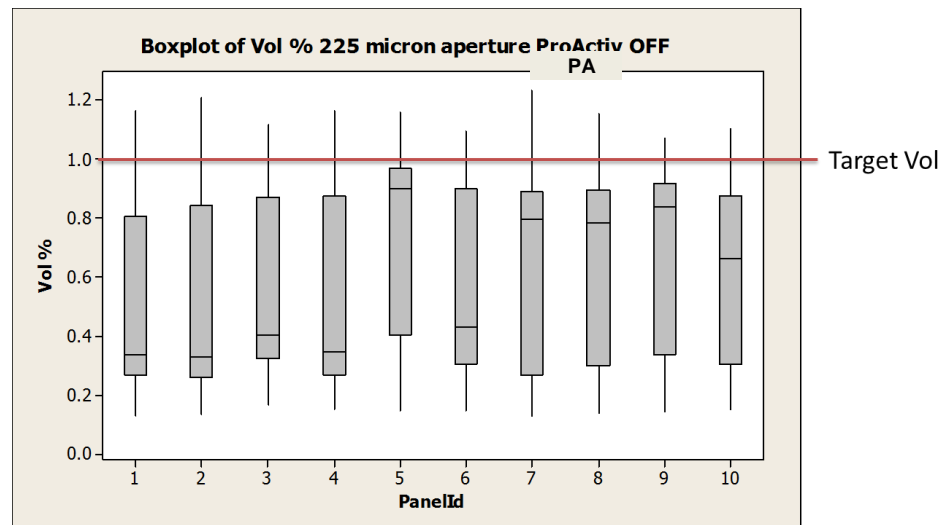


Figure 9 - Boxplot 225um Aperture Diameter Standard Process- Ultrasonic Off

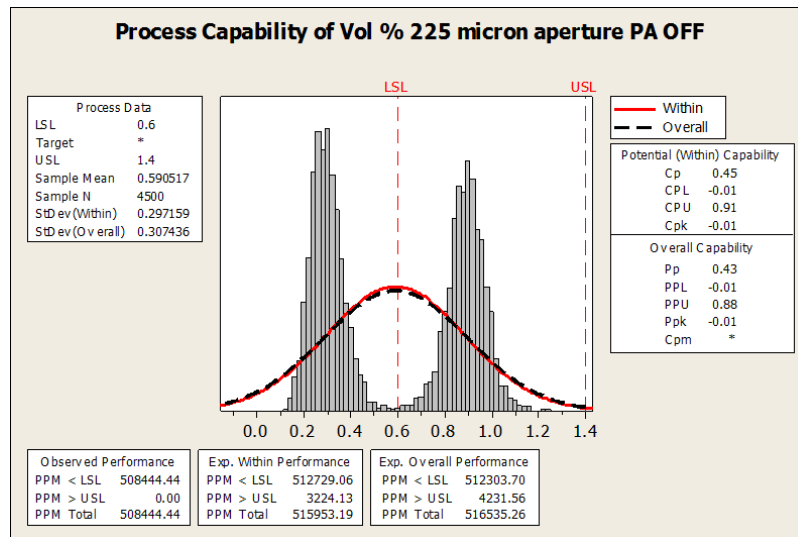


Figure 10 - Process Capability 225um Aperture Diameter Standard Process- Ultrasonic Off

Benchmark conclusions

The results from the baseline show that both aperture sizes deliver a process which falls outside the target Cp/Cpk. The 200 micron aperture produces an output which has a low standard deviation (13%) but only manages a mean output of 36% volume. The 225 shows a tendency to improve the volumetric output but the histogram shows that a bimodal output is present indicating poor process stability.

Both experiments have failed to produce a satisfactory process and have therefore matched the predicted outcome of the Area Ratio model.

Design of Experiment (DoE)

As concluded from the benchmark analysis, the aperture range which is required to print 0.4mm CSP devices is not capable with a standard process setup. A DoE technique will be employed to determine the effect and interaction of both aperture size and squeegee type. The factors to be included are aperture size and squeegee type. The 2 level full factorial experiment is illustrated in Table 4, each experiment is to be replicated 10 times. The DoE was conducted under the conditions outlined in the SIPOC.

Table 4 - Design of experiment

	Level 1	Level -1
Aperture Size	225	200
Squeegee Type	Ultrasonic (PA)	Standard

Analysis

Figure 11 outlines the design of experiment ANOVA table. As can be seen the P values of the terms are 0, this indicates that that all terms are significant and the R-Sq. value of 97.03% indicates that the majority of the resultant output is explained by the experiment.

Estimated Effects and Coefficients for Cpk TE (coded units)

Effect	Coef	SE Coef	T	P	
Constant	0.3403	0.02627	12.96	0.000	
ProActiv	1.4099	0.7049	0.02627	26.84	0.000
Aperture Size	1.0629	0.5315	0.02627	20.23	0.000
ProActiv*Aperture Size	0.3575	0.1787	0.02627	6.80	0.000

PA 56119 PRESS = 1.22647
PA = 97.03% R-Sq(pred) = 96.33% R-Sq(adj) = 96.78%

Analysis of Variance for Cpk TE (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	31.1754	31.1754	15.5877	564.86	0.000
ProActiv	1	19.8768	19.8768	19.8768	720.29	0.000
Aperture Size	1	11.2986	11.2986	11.2986	409.44	0.000
2-Way Interactions	1	1.2777	1.2777	1.2777	46.30	0.000
ProActiv*Aperture Size	1	1.2777	1.2777	1.2777	46.30	0.000
Residual Error	36	0.9934	0.9934	0.0276		
Pure Error	36	0.9934	0.9934	0.0276		
Total	39	33.4465				

Estimated Coefficients for Cpk TE using data in uncoded units

Term	Coef
Constant	-8.69480
ProActiv	-2.33340
Aperture Size	0.0425180
ProActiv*Aperture Size	0.0142980

Figure 11 - Design of Experiment ANOVA

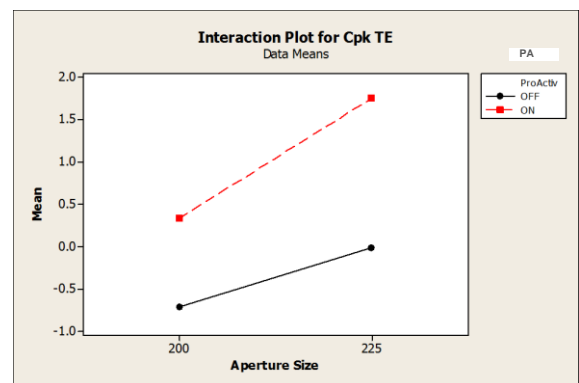
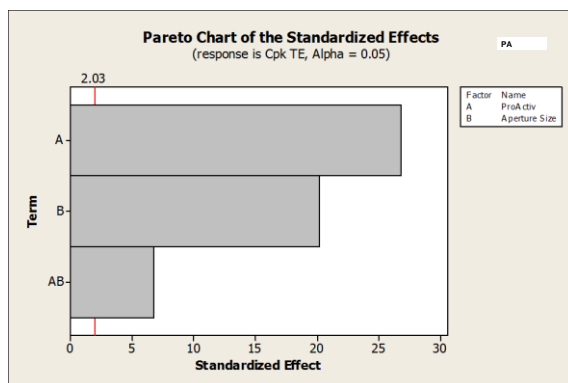
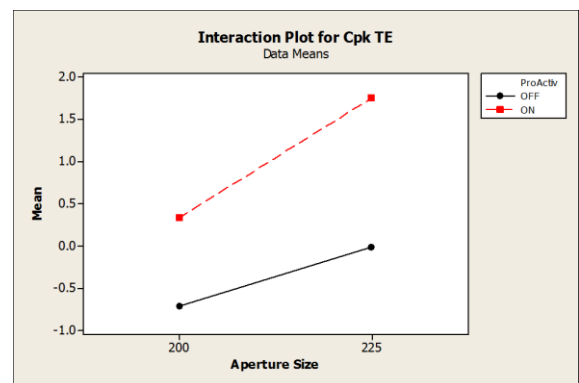
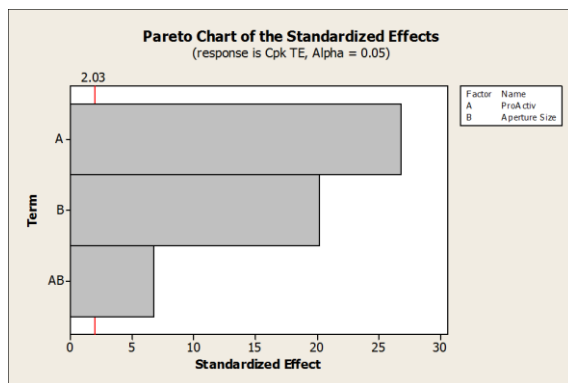


Figure 12 – DoE Pareto Chart

Figure 13 DoE Interaction Plot

Figure 12 clearly shows the impact of both factors; the pereto chart indicates all features are important, with the ultrasonic squeegee (factor A) the most significant. Figure 13 illustrates the interaction plot, the graph show that even with the ultrasonic squeegee active the 200um aperture is not meeting the minimum 1.33 Cpk value therefore this aperture will be discounted from the subsequent analysis.

To better understand the impact of both factors the coefficients derived from the ANOVA (table 3), can be used to model the process; figure 14 illustrates the derived mathematical model.

$$C1*PA + C2 \text{ Aperture Size} + C3 (PA \times \text{Aperture Size}) + \text{Constant} = \text{Transfer Efficiency Cpk}$$

Figure 14 – Mathematical Model

This model can also be used to ascertain the effect on the process output as incremental changes are made to the aperture size, thus allowing the smallest capable aperture size to be discovered.

The software optimizer tool uses the mathematical model outlined in Figure 14 to graphically represent the changes in process output as the factors are modified. Figure 15 to 17 illustrate the output of this analysis.

Figure 15 illustrates that with the ultrasonic squeegee OFF; the composite desirability yields a value of 0, thus indicating that no solution is possible independent of aperture size. Figure 16 illustrates that the model predicts the smallest aperture in which a Cpk of 1.33 is achievable is 217.5um whereas Figure 17 illustrates that the model predicts the 225um aperture produces a Cpk value of 1.76.

Apertures larger than 225um are outside the experimental space and therefore are not covered in this analysis. From an experienced based view point larger apertures will tend to print much easier due to the larger corresponding Area Ratio; however as the aperture size increases the interspace between the deposits decrease. This decrease in interspace will tend to generate wet bridging between adjacent deposits, as a result apertures 225um or less are recommended for a high volume manufacturing 0.4mm pitch CSP assembly process.

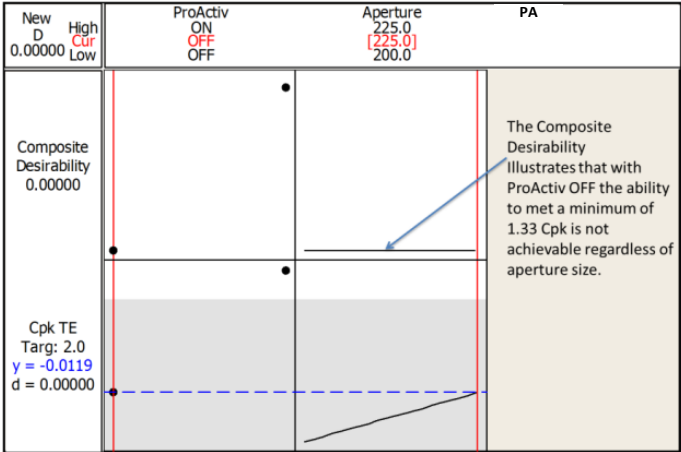
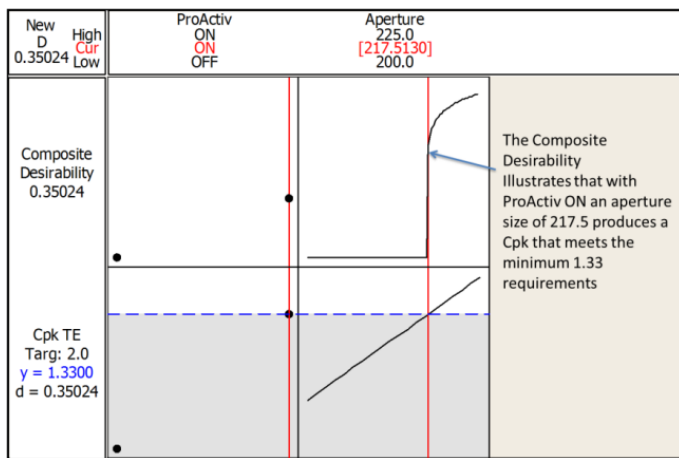


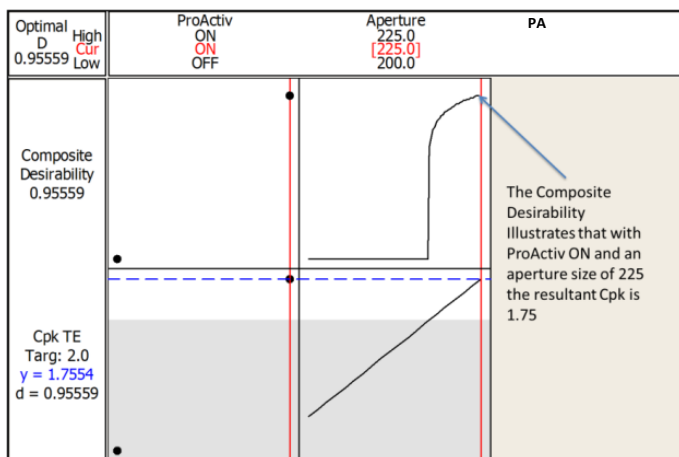
Figure 15 - Predicted Cpk with no ultrasonic squeegee

PA



PA

Figure 16 - Predicted minimum aperture size with ultrasonic squeegee



PA

Figure 17 - Predicted Cpk with largest aperture size with ultrasonic squeegee

Further Statistical Testing

To complete the statistical analysis, the following section will investigate the 225um aperture to establish if any statistical difference in transfer efficiency between ultrasonic and standard squeegee exists.

Figure 18 and 19 show the non-normal distribution curves of the data therefore the moods medium test and test for equal variance will be employed to perform the null hypothesis testing.

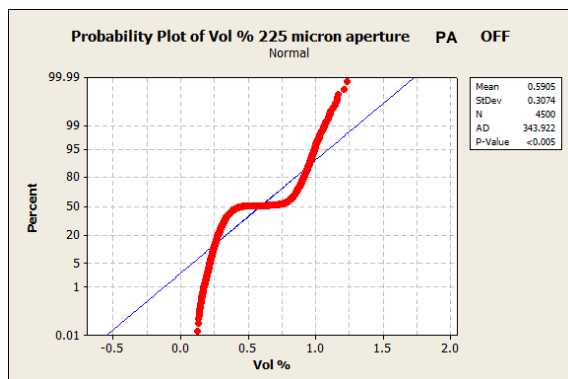


Figure 18 – Probability Plot 225um Ultrasonic OFF

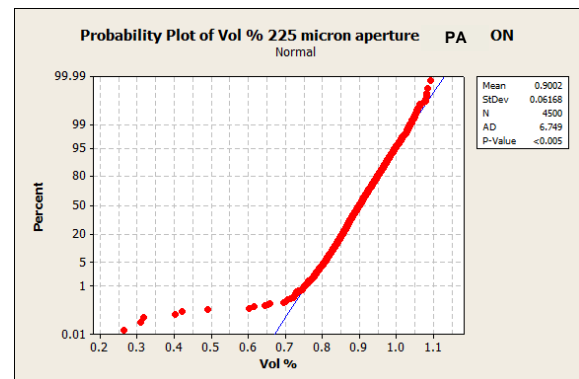


Figure 19 – Probability Plot 225um Ultrasonic ON

Figure 20 illustrates the results from the Moods Medians. The results show a P value of 0, indicating that within a confidence level of 95% the medians are different. The Confidence Intervals (with 95% confidence) indicate that the transfer efficiency from an ultrasonic squeegee is improved between 25.8 and 46.8% with respect to a standard squeegee.

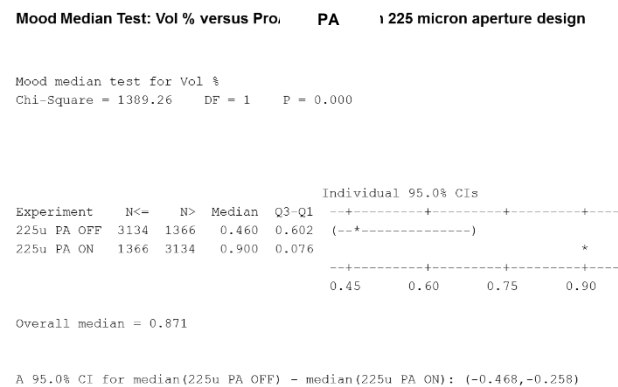


Figure 20 - Moods Median Test 225um aperture

Figure 21 shows the results from the test for equal variance, these results illustrate the standard deviation of each data set. As can be seen the Levene's test shows a value of zero, indicating that within the two subsets the standard deviations are different. The Bonferroni confidence intervals indicated that the Ultrasonic Squeegee ON data set produces the lowest Standard Deviation.

The Moods Median and Test for equal variance analysis shows that for the 255um aperture there is a positive transformation in transfer efficiency between the standard and ultrasonic squeegee system.

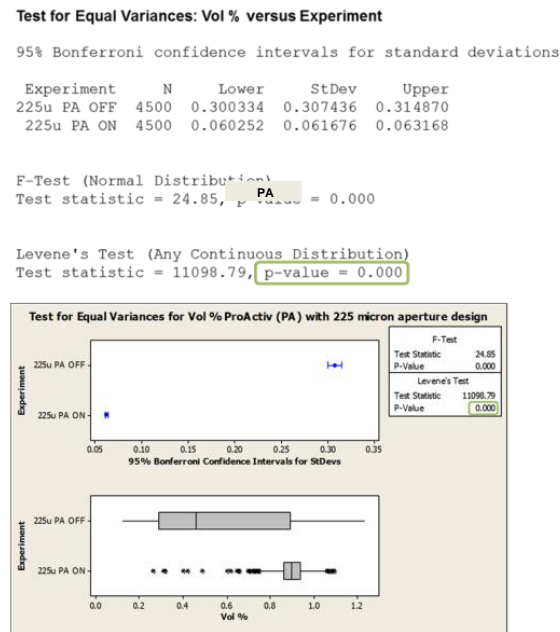


Figure 21 - Test for equal variance 225um aperture

Confirmation Run

From the design of experiments and statistical testing, the 225um aperture with ultrasonic squeegee demonstrated a capable process. The following section shows a confirmation run which uses the 225um aperture and ultrasonic squeegee in order to verify the finding. The confirmation run included a rebuild of the experiment setup as outlines in Figure 5.

Figure 22 illustrates the process output from the confirmation run. The resultant Cp/Cpk values are 2.31 and 1.73; both these values are greater than the minimum required 1.33. This verifies the 225um with ultrasonic squeegee is capable of printing 0.4mm CSP devices alongside 127um stencil foils and other standard material sets used within the solder paste printing process.

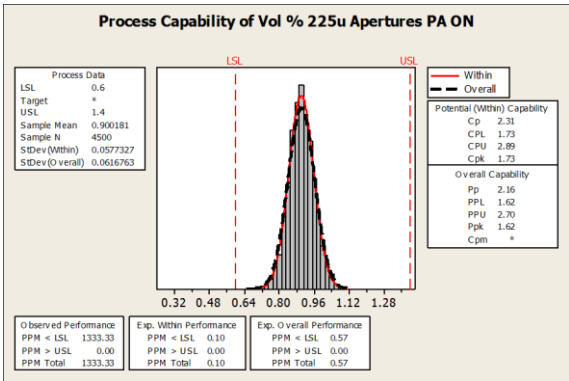


Figure 22 – Rerun process capability

Heterogeneous View

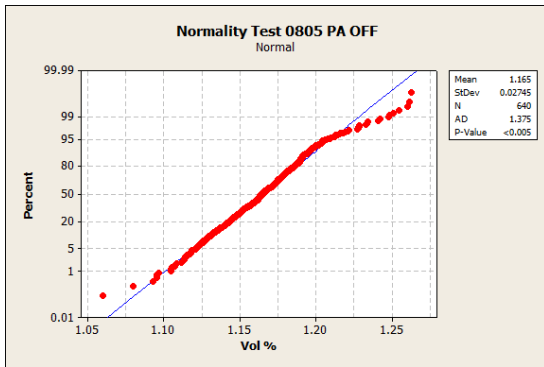
The testing so far has exclusively been focused on implementing 0.4mm CSP technology for the 127um stencil user. Obviously for any solder paste printing solution to be accepted; its capability needs to cover a full range of size and shaped deposits. The following section will investigate the proposed 0.4mm CSP ultrasonic solution and the impact to a heterogeneous process.

The components to be included in this heterogeneous study are 0805 and 0.4mm Quad Flat Packs (QFP), aperture dimensions are outlines in table 5. The process setup followed the SIPOC outlined in Figure 5 with the exception of the heterogeneous devices.

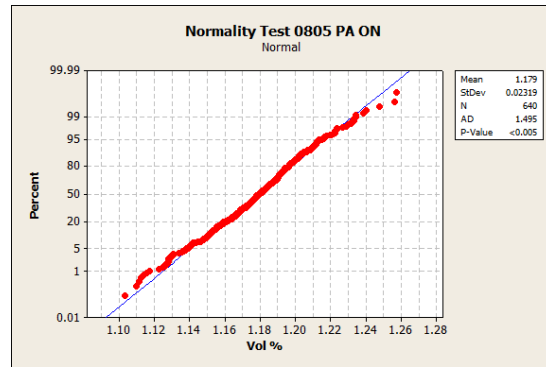
Table 5 - Aperture size for heterogeneous study

	0805	0.4mm QFP
Width (um)	1400	170
Length (um)	1100	1570

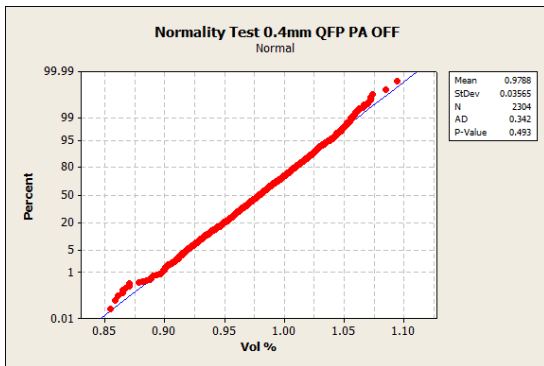
Figure 23 to 26 illustrate the normality testing of the 0805 and 0.4mm QFP with and without the ultrasonic squeegee solution. As can be seen the P values from the normality tests are less than 0.05, except for 0.4mm QFP Ultrasonic OFF (Figure 25), for the sake of symmetry all datasets to be declared non-normally distributed.



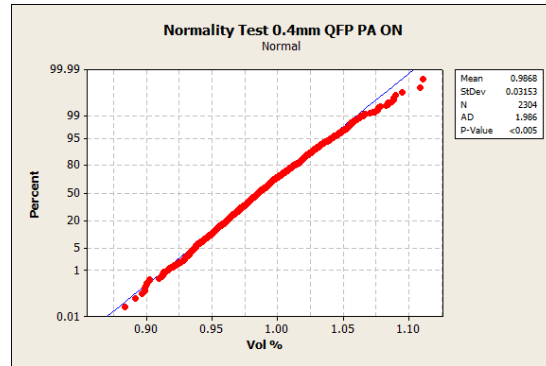
**Figure 23 – Normality Test 0805
Standard Squeegee**



**Figure 24 – Normality Test 0805
Ultrasonic Squeegee**



**Figure 25 – Normality Test 0.4mm QFP
Standard Squeegee**



**Figure 26 – Normality Test 0.4mm QFP
Ultrasonic Squeegee**

To understand if the ultrasonic squeegee yields an impact on the heterogeneous aspect of solder paste printing the data will be analysed using a Moods Median, Test for Equal Variance and Process Capability study.

Figure 27 to 30 illustrate the analysis of the 0805 and 0.4mm QFP devices. The Moods Median analysis displays a P value of zero for both the 0805 and 0.4m QFP device types. This indicates that with 95% confidence the medians of the subgroups (ultrasonic squeegee ON/OFF) are dissimilar. The test for equal variance displays a P value (Levene's Test) of zero for both the 0805 and 0.4mm QFP package types. Therefore indicating that with 95% confidence the variation (standard deviation) of the subgroups (ultrasonic squeegee ON/OFF) are dissimilar.

The following analysis investigates and answers if the differences between the subsets affect the process output.

Results for: Moods Median Test 0805

Mood Median Test: Vol % versus Experiment

Mood median test for Vol %
Chi-Square = 84.05 DF = 1 P = 0.000

Experiment	N<=	N>	Median	Q3-Q1
PA OFF	402	238	1.1647	0.0338
PA ON	238	402	1.1795	0.0276

Individual 95.0% CIs
-----+-----
(--*--)
-----+-----
(--*--)

Overall median = 1.1733

A 95.0% CI for median(PA OFF) - median(PA ON): (-0.0180,-0.0120)

**Figure 27 Moods Median Test
0805**

Results for: Moods Median Test 0.4mm QFP

Mood Median Test: Vol % versus Experiment

Mood median test for Vol %
Chi-Square = 817.78 DF = 1 P = 0.000

Experiment	N<=	N>	Median	Q3-Q1
PA OFF	1472	832	0.979	0.048
PA ON	0	640	1.179	0.028

Individual 95.0% CIs
-----+-----
-----+-----
(*)

Overall median = 0.992

A 95.0% CI for median(PA OFF) - median(PA ON): (-0.203,-0.198)

**Figure 28 Moods Median Test
0.4mm QFP**

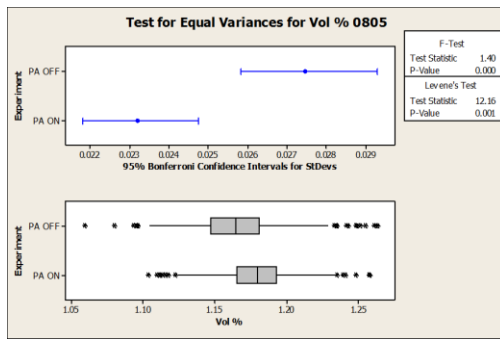


Figure 29 Test for equal variance 0805

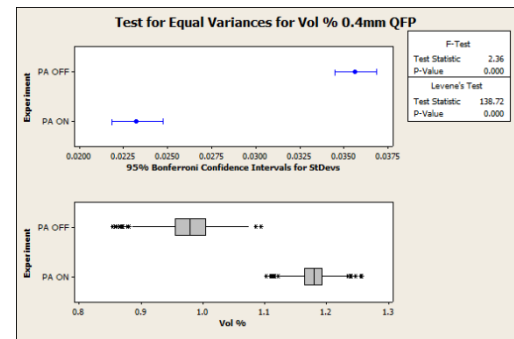


Figure 30 Test for equal variance 0.4mm QFP

Figure 30 to 33 illustrate the process capability output for the 0805 and 0.4mm QFP packages. Each package type is analysed under the condition of ultrasonic squeegee ON/OFF.

The process capability curves shown in Figure 30 and 32 show the output from a standard system (ultrasonic squeegee OFF). The results show both devices to be within the required ≥ 1.33 Cpk value, this is an expected outcome as both devices are representative of “todays” standard assembly processes

The process capability curves shown in Figure 31 and 33 show the output from an ultrasonic activated squeegee system. As can be seen, the Cpk index value is greater when the ultrasonic condition is ON; indicating that the addition of an ultrasonic device has process capability benefits to the larger footprint devices. For reference the results for both conditions are presented in Table 6.

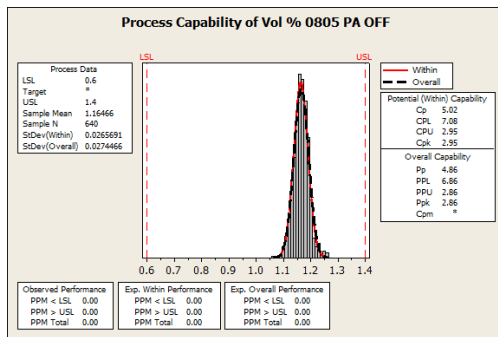


Fig 30 – Process Capability 0805
Standard Squeegee

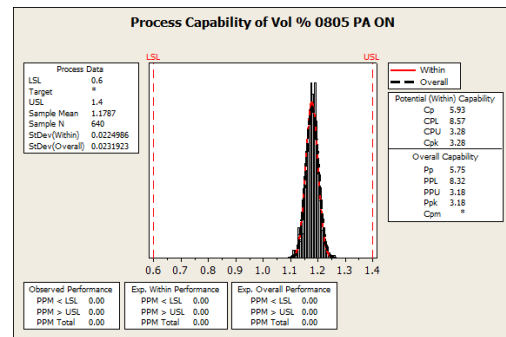


Fig 31 – Process Capability 0805
Ultrasonic Squeegee

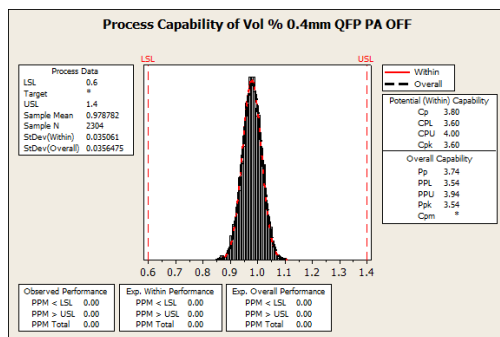


Fig 32 – Process Capability 0.4mm QFP
Standard Squeegee

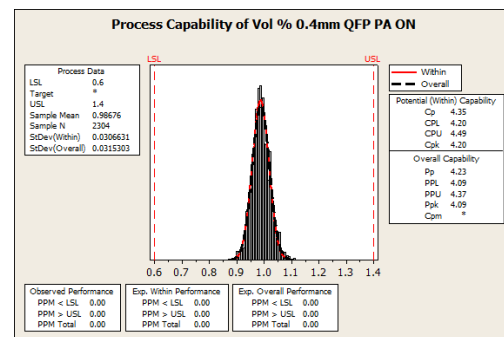


Fig 33 – Process Capability 0.4mm QFP
Ultrasonic Squeegee

Table 6 – Cpk values for 0805 and 0.4mm QFP

	0805 Cpk	0.4mm QFP Cpk
Ultrasonic Squeegee OFF	2.095	3.6
Ultrasonic Squeegee ON	3.28	4.2

Conclusions

The purpose of this paper was to answer the question, “Can 0.4mm CSP devices be printed within an Automotive and Industrial assembly environment”? As considered throughout this paper, the issues of printing 0.4mm CSP compatible apertures through the established 127um stencil foil thickness leads to an infringement of industry recognised Area Ratio rules. Therefore this investigation focused around the possibility of breaking these established Area Ratios with no detrimental effect on standard depositions.

The findings from this investigation are listed below:

- The results from this investigation demonstrated the ultrasonic squeegees ability to extend the print process window to include Area Ratios ≥ 0.45 . This allows 225um apertures to be printed using 127um stencil foils.
- The analysis has demonstrated the 200um diameter apertures were outside the ultrasonic squeegees capability. Therefore the ability to print Area Ratio's below 0.4 is still an unknown.
- The ability to print 225um diameter apertures using 127um foil thicknesses gives the Automotive and Industrial sector the possibility of printing solder paste deposits for the 0.4mm CSP.
- The inclusion of an ultrasonic squeegee does not adversely affect the paste deposition of larger footprint devices

Therefore the ability to print 0.4mm CSP compatible apertures using incumbent material sets is possible when ultrasonic squeegee technology is employed.

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