Investigating the Influence of Corner Radius within Rectangular Aperture Designs

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Abstract
The mobile and consumer market is the driving force of the electronics assembly sector,this sector historically has been associated with early adopters of leading edge surface mount technology (SMT). The main driver for adopting state of art SMT is the consumers demand for greater user functionality. Meeting this demand requires integrating more into less, or to give its correct term – Miniaturization.

The assembly community has become used to the introduction of new smaller feature sized devices. The next device that will drive this next round of miniaturization is the Metric 0201(M0201). This passive device will measure 250um x 125um and offer a 60% reduction in real-estate to its predecessor. The M0201 will be used in both Systems in Package (S.I.P) and consumer electronic applications.

The implementation of the M0201 within the S.I.P application will result in a homogeneous solder paste solution, as a consequence the stencil thickness can be chosen to ensure aperture area ratios are well within the IPC recommendations. However, the implementation of the M0201 device within the mobile and consumer sector will result in a heterogeneous solder paste solution. Within this heterogeneous environment the stencil thickness will be comprised due to the volumetric requirements presented by the mixed technology application. The combination of sub 150um apertures and standard stencil thickness will lead to area ratios falling below the IPC recommendations.

Previous research into printing challenging area ratios has focused on an improved method of filling the apertures through the utilization of ultrasonic squeegees and novel stencil coatings. Although the filling process is a major element to the printing process, the release of the aperture is equally as important to delivering a repeatable solder paste deposit. From a release point of view, an aperture is the structure that forms and molds the solder paste deposit. It is also from this aperture that the deposit has to release from.

The incumbent aperture design for passive chip devices has been a regular polygon (rectangle) design, one that traces the outline of the device land. Within this study the inclusion of a radius within rectangular aperture geometries will be investigated. The influence of a radius will be measured against the resultant volumetric Cp/Cpk values. The study will include three aperture designs that are compatible with the next generation devices, each aperture design will include six radii profiles.

The findings from this investigation will show if any process improvements can be associated with the inclusion of a radius within a regular rectangular aperture design.

Introduction
The electronic assemblies being used in today's mobile devices are pushing the boundaries of what is possible to manufacture at high volumes, low cost and high yields – and it is not going to get any easier.
Passive devices are gearing up for yet another format change, the next generation package sizes which are being touted are Metric 03015 (300um x 150um) and an even smaller package, Metric 0201 (200um x 100um).

The inclusion of these devices alongside traditional surface mount package types, such as Connectors, TANT's, M1005, is starting to raise questions of how to print such devices in one heterogeneous process. Solutions such as stepped stencils and a two print process have been muted but these solutions raise concerns on both the yield and cost aspect of manufacture.
The largest roadblock to just printing aperture geometries with one single thickness of stencil is the Area Ratio (AR) rule; the current limit for high volume, high yield printing is an AR of 0.5.

The latest development tool for breaking past the 0.5 area ratio limit is an ultrasonic squeegee system [1]. In this system, the squeegee assembly contains ultrasonic transducers within its body to assist the deposition process during a print stroke. Previous studies indicate that the technique can enhance the print process with stencil aperture area ratios down to 0.4 [2, 3]. The ultrasonic squeegee technology increases the action of shear thinning the solder paste material thus allowing the solder paste to flow and fill small apertures more efficiently that passive squeegees [4,5].

However the aperture of a stencil printing process has a large impact on the resultant repeatability and accuracy of the associated solder paste deposit, therefore the importance of the apertures composition is paramount. In the past the research team has investigated fabrication methods; metal alloys, coatings and the impact of aspect ratio to better understand how to provide the most accurate and repeatable print process. The next element to be investigated is the impact of a corner radius within a regular rectangular aperture design. The impact of rounding the corner of a rectangular aperture to create a distal end will be investigated. The hypothesis of including a radius to the rectangular aperture is the solder paste will not adhere to the aperture corner therefore improving the repeatability of the solder paste release.

Area Ratio.

Stencil printing performance has historically been characterized by the well-known correlation between stencil aperture dimensions and the corresponding solder paste transfer that is predictable. The stability of this relationship has allowed the standardization of stencil design guidelines published by IPC [6].

The definition of aperture Area Ratio (AR) is straight-forward – it is simply the ratio between the surface area of an aperture opening to the surface area of the aperture wall, represented by the following equation (Figure 1).

$$AR = \frac{\text{Aperture Open Area}}{\text{Aperture Wall Area}}$$

Figure 1 - Area Ratio Formula

If the adhesion of solder paste on the aperture wall surface area exceeds that of the aperture opening then the solder paste will want to adhere to the aperture wall more than the pad, resulting in an aperture which will exhibit blockage and therefore an incomplete solder paste deposit. Equally if the adhesion of solder paste on the aperture opening pad contact surface area is greater, then the solder paste willfavour adhesionto the pad rather than the aperture wall, leading to a more complete printed deposit. Figure 2 illustrates the concept of how area ratio influences solder paste transfer.

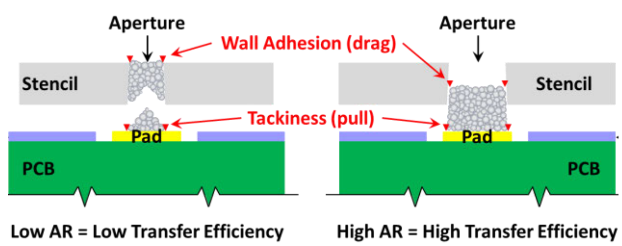

Figure 2 - Area Ratio influence on solder paste transfer efficiency.

Therefore, it is known that as the stencil aperture area ratio decreases then the chances of successful printing with full deposits becomesless likely.

A typical paste transfer efficiency curve representative of where the industry is today is shown in Figure 3 alongside a historical curve from around 20 years ago. The positive shift in transfer efficiency capabilities can be attributed to several factors including improvements in solder paste materials, stencil manufacturing techniques together with better understanding of equipment set up and process parameters [7, 8, 9, 10, 11].

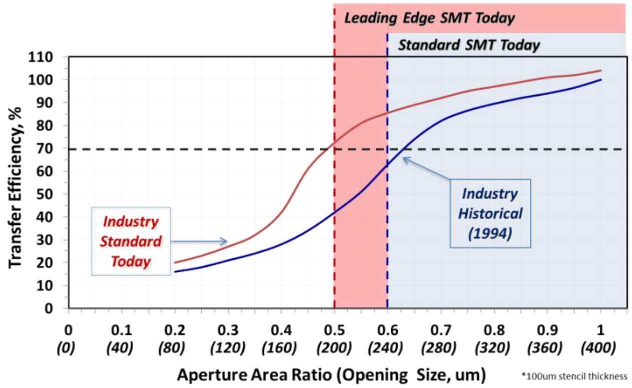

Figure 3 Today's leading-edge solder paste transfer efficiency capabilities compared to 1994.

Metric 0201 Requirements

Moving forward, it is clear that there is a very real requirement for print process capabilities down to aperture area ratios of 0.4 to address imminent roadmap challenges.

Whilst the industry continues to invest in various material improvements, we have been investigating the benefits of an ultrasonic squeegee system to fulfil this requirement. In this system, the squeegee assembly contains ultrasonic transducers within its body to assist the deposition process during a print stroke. Previous studies [1, 2, 3] indicate that the technique can enhance the print process with stencil aperture area ratios down to 0.40 as shown in Figure 4.

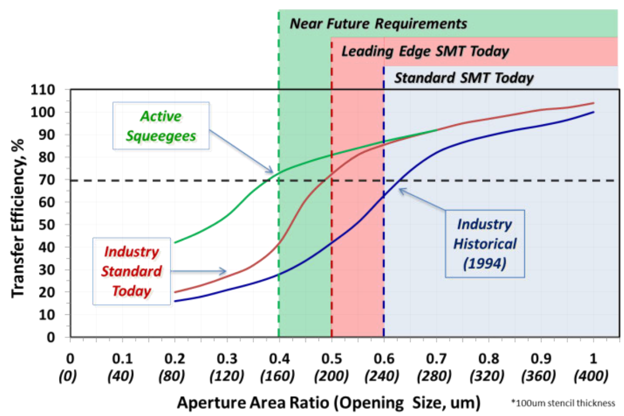

Figure 4 - Near future solder paste transfer efficiency requirements.

Corner Radius Percentage

The corner radius percentage is derived from the percentage of the rectangular aperture which has been transformed to a radius (Figure 5). Within this investigation each aperture design will have six radii treatments applied.

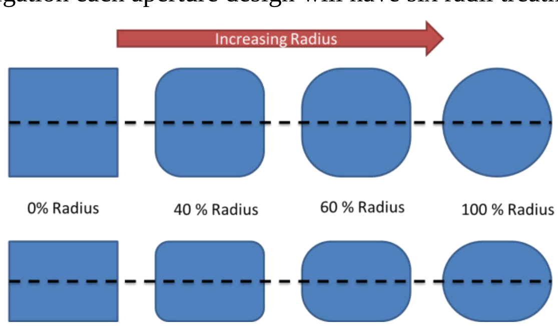

Figure 5 – Corner Radius Percentage

Experimental

Objective

The objective of this investigation is to discover if applying acorner radius into an aperture has an impact on the process output. The transfer efficiency of the individual aperture designs will be reported, analysed and conclusions drawn.

SIPOC

The SIPOC Diagram in Figure 6 identifies the relevant elements used throughout the investigation.

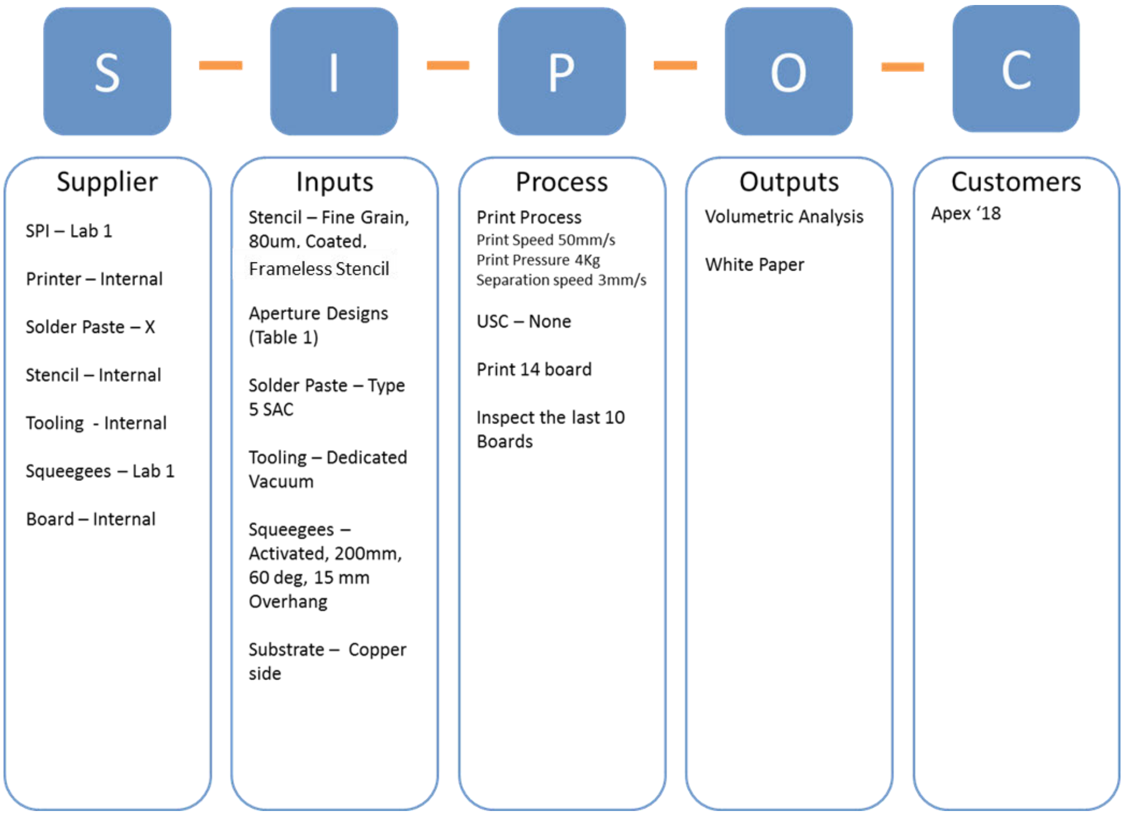

Figure 6. SIPOC Overview

Stencil Design

Table 1 illustrates the stencil dimensions used throughout the investigation. The stencil thickness was 80um and the fabrication technique was laser cut with no coating. The area ratios of all the aperture designs were 0.4.

Table 1. Stencil Dimensions

Aperture Dimensions (um)	Radius (%, um)					
	0% um	20% um	40% um	60% um	80% um	100% um
128 x 128	0	12.8	25.6	38.4	51.2	64
142 x 118	0	11.8	23.6	35.4	47.2	59
154 x 110	0	11	22	33	55	55

The stencil designs were laid out as shown in Figure 7. The 5 x 6 array was step and repeated 41 times to create the grouping shown in Figure 8. This grouping was then duplicated and used to populate the printing test vehicle board (Figure 8). The final aperture layout provides 82 replicates for each aperture design which are evenly positioned across two large open copper surfaces.

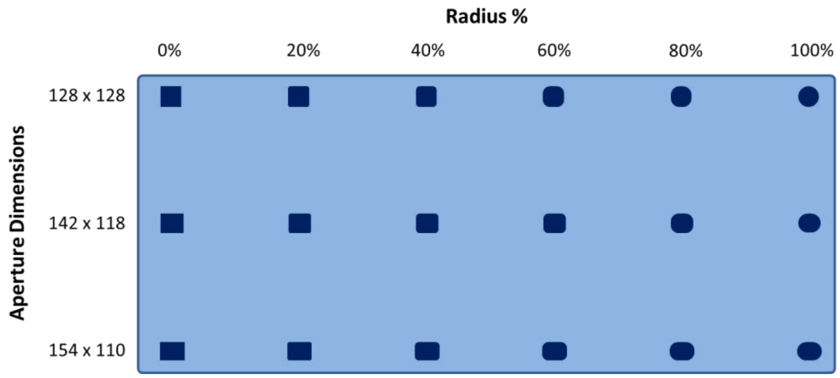

Figure 7 - Aperture Layout

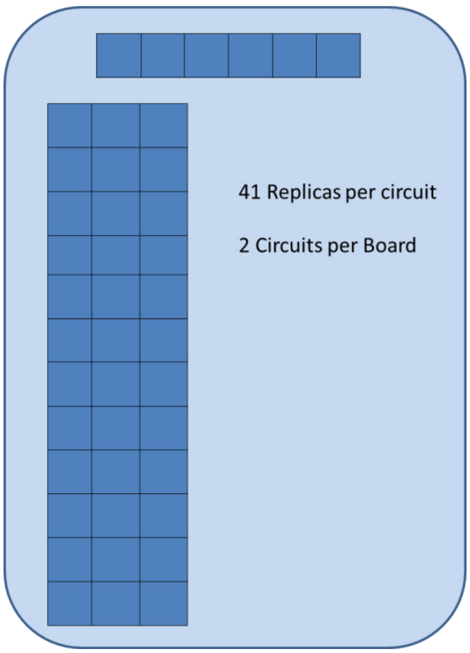

Figure 8 - Aperture Replicas

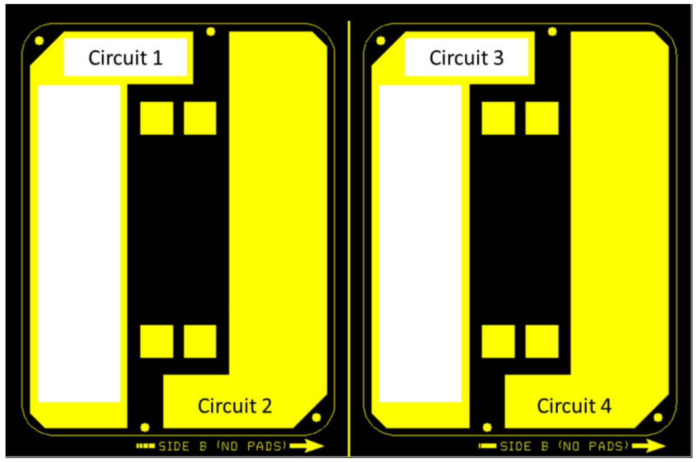

Figure 9.Locations (white) of Test Print Apertures

Discussion

The Cp and Cpk index will be used to assess the output from the experiment.The formulas are shown in Figure 9a and 9b. The process bandwidth used to calculate the Cp/Cpk index was +/- 40%, atarget of ≥1.33 (4 sigma) was applied to the analysis.

$$Cp = \frac{USL - LSL}{6 \times Sigma}$$

Figure 9a. Cp Formula

$$Cpk = \min\left[\frac{USL-\mu,\ \mu-LSL}{3\sigma}\right]$$

Figure 9b. Cpk Formula

Results

The graphical and statistical analysis will investigate if a relationship between the process output and the inclusion of a radius exists. For the purpose of statistical analysis the data has been grouped into aperture size and radius. The Cp/Cpk analysis includes the aperture data for the 10 board run.

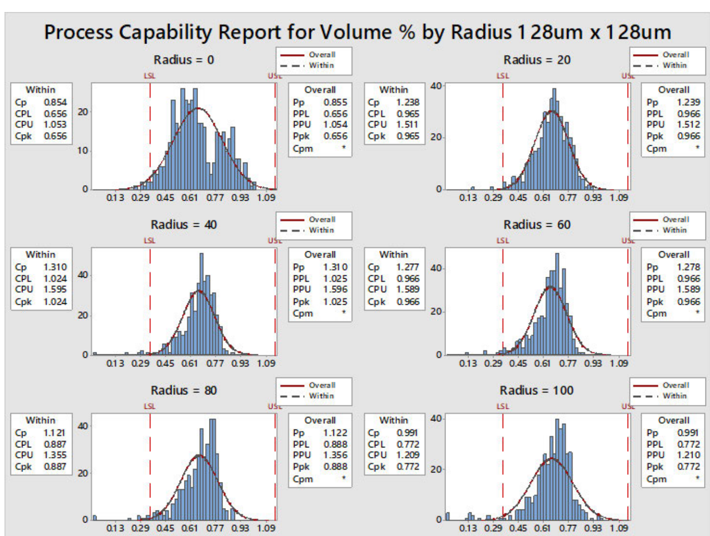

Figure 10. Process Capability Volume % by Radius - 128um x 128um

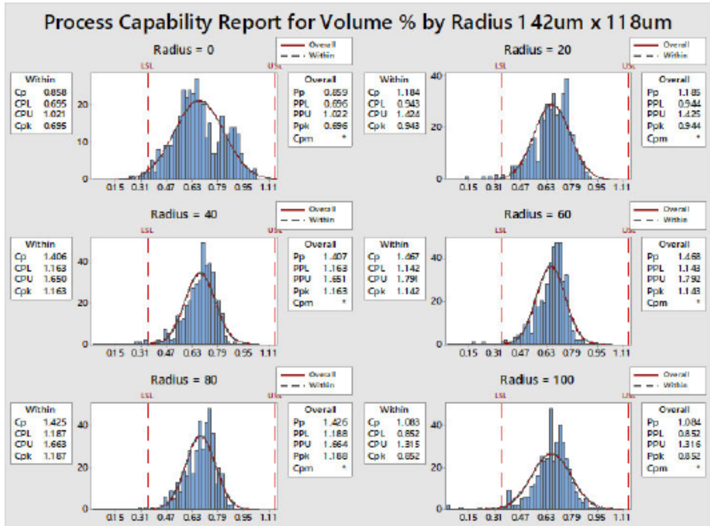

Figure 11. Process Capability Volume % by Radius - 142um x 118um

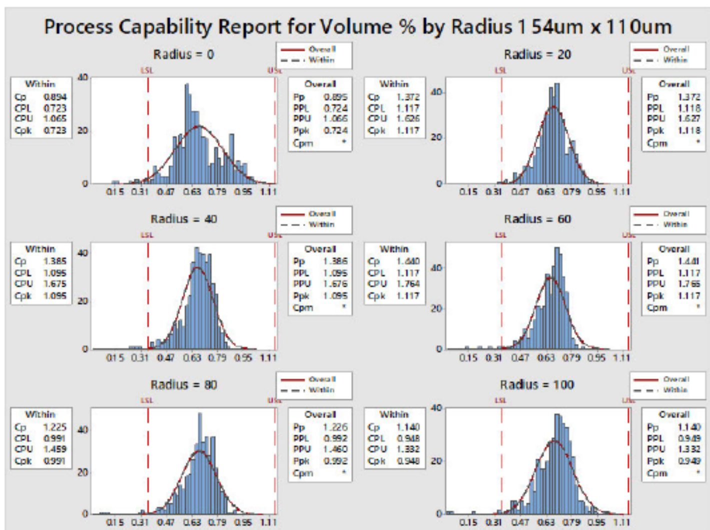

Figure 12. Process Capability Volume % by Radius - 154um x 110um

Table 2. 128um x 128um Aperture design – Descriptive Statistics

Radius	LSL	Target	USL	Sample Mean	StDev(Within)	Cp	Cpk
0	0.35	0.7	1.15	0.66	0.156	0.85	0.66
20	0.35	0.7	1.15	0.66	0.108	1.24	0.97
40	0.35	0.7	1.15	0.66	0.102	1.31	1.02
60	0.35	0.7	1.15	0.65	0.104	1.28	0.97
80	0.35	0.7	1.15	0.67	0.119	1.12	0.89
100	0.35	0.7	1.15	0.66	0.135	0.99	0.77

Table 3. 142um x 118um Aperture design – Descriptive Statistics

Radius	LSL	Target	USL	Sample Mean	StDev(Within)	Cp	Cpk
0	0.35	0.7	1.15	0.67	0.155	0.86	0.70
20	0.35	0.7	1.15	0.67	0.113	1.18	0.94
40	0.35	0.7	1.15	0.68	0.095	1.41	1.16
60	0.35	0.7	1.15	0.66	0.091	1.47	1.14
80	0.35	0.7	1.15	0.68	0.094	1.43	1.19
100	0.35	0.7	1.15	0.66	0.123	1.08	0.85

Table 4. 154um x 110um Aperture design – Descriptive Statistics

Radius	LSL	Target	USL	Sample Mean	StDev(Within)	Cp	Cpk
0	0.35	0.7	1.15	0.67	0.149	0.89	0.72
20	0.35	0.7	1.15	0.68	0.097	1.37	1.12
40	0.35	0.7	1.15	0.67	0.096	1.39	1.10
60	0.35	0.7	1.15	0.66	0.093	1.44	1.12
80	0.35	0.7	1.15	0.67	0.109	1.23	0.99
100	0.35	0.7	1.15	0.68	0.117	1.14	0.95

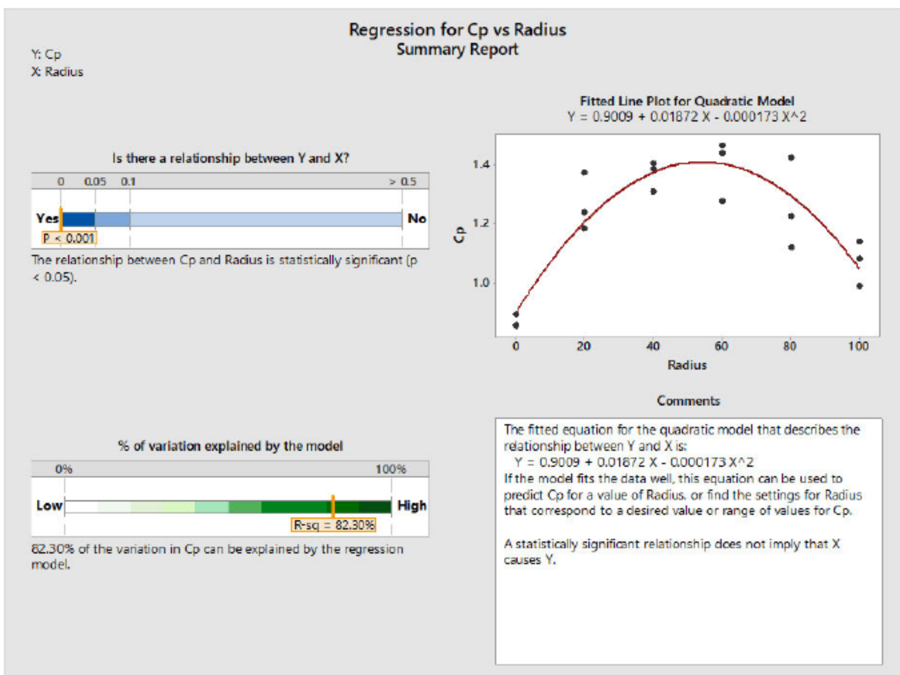

Figure 13. Regression Analysis for Cp vs Radius

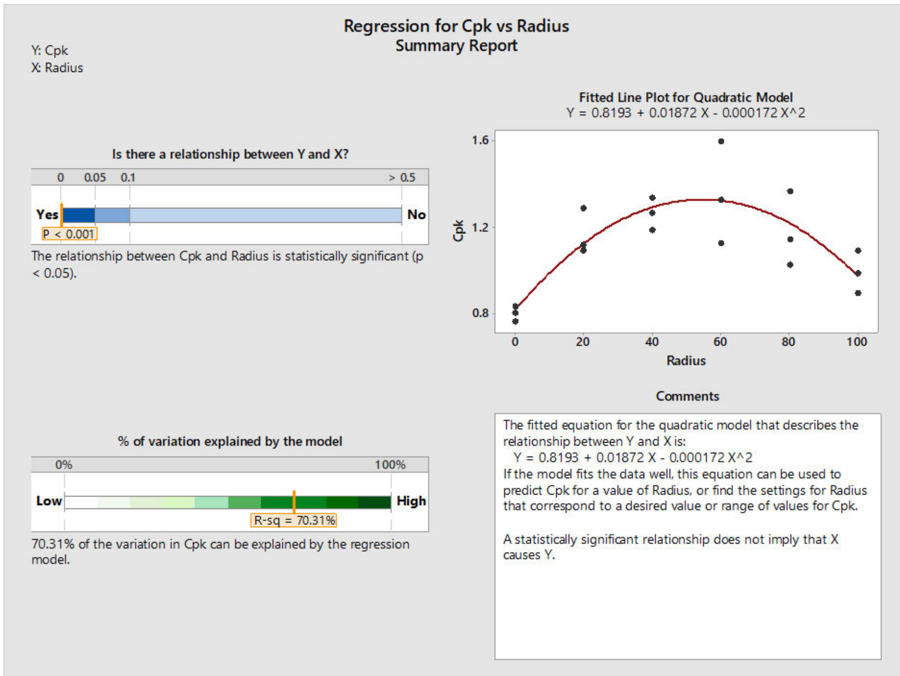

Figure 14. Regression Analysis for Cpk vs Radius

Discussion and Conclusions

From the investigation, we can observe the influence of applying an aperture radius with respect to the process output. The process capability graphs (Figures 10 to 12) show a variation in process capability as the applied aperture radius is varied. The analysis will start with the smallest volumetric aperture (128um x 128um) and work towards the largest volumetric aperture size 154um x 110um.

Figure 10 illustrates the capability graph for the 128um x 128um aperture; thegraph shows that with zero applied radii the aperture produces a result that exhibits a bimodal effect. This indicates that the process has in fact two subsets, reflecting the presence of two different processes being "mixed" within one aperture design. The resultant Cp value from this aperture design is 0.8; a Cp result below 1.33 indicates a process that is not stable or capable of producing a durable printing process.As the value of the applied radius is increased to 20% the data becomes more normal with the standard deviation dramatically decreasing and a corresponding increase in Cp (Table 2). This improvement in process capability tracks the increase in applied radius until a value of 80% is reached, after this point the process capability starts to decrease (Table 2).

The previously cited trend was also observed with the two additional aperture designs included within this investigation after 60% radius. The results from the 142um x 118um aperture designs are illustrated within Figure 11, the tabulated results are shown inTable 3. From the results it can be seen that a maximum Cp of 1.47 was achieved with an applied radius of 60%.The 154um x 110um aperture follows the trend with the 60% applied radius providing the maximum process capability, illustrated within Figure 12 and Table 4.

From the results we can see that the Cpk values for all treatments have not met the 1.33 target. The reason for the failing is due to the mean volume of the deposits been lower than the target (70%). For future work the mean volume would be increased with process optimisation.

Figure 13 shows the three aperture designs regressed against the resultant Cp and percentage of corner radius. The regression analysis supports the non-linearobservation gained from the Cp results. The fitted line response of applied aperture radii for all three aperture designs with respect to the resultant Cp is a quadratic model.The R^2 value for the model is 82 indicating that 82 percentage of the model can be explained by the mathematical equation. The P value for the model is less than 0.05 indicating that there is a strong relationship between the applied aperture radii and resultant Cp value.

The quadratic contour of the graph within Figure 13 shows how the Cp peaks as the percentage of corner radius achieves a value between 40 and 60%.

Figure 14 shows the three aperture designs regressed against the resultant Cpk and percentage of corner radius. . The R^2 value for the model is 70 indicating that 70 percentage of the model can be explained by the mathematical equation. The P value for the model is less than 0.05 indicating that there is a strong relationship between the applied aperture radii and resultant Cpk value. As with the previous regression analysis the resultant response is quadratic with a peak Cpk value occurring between corner radius values of 40 to 60%.

This investigation was commissioned to determine if applying acorner radius into a rectangular aperture has an impact on the print efficiency.The result has proven that the inclusion of a corner radius does impact the process capability although the effect is not a linear response. The results have shown that a value of 40 to 60percent corner radius produces the highest Cp and Cpk values.

Therefore to conclude; when implementing a challenging area ratio printing process that requires a rectangular aperture the inclusion of a 40-60 percentagecorner radius will improve the process repeatability and accuracy.

References

1. C. Ashmore, M. Whitmore, “New Developments in Broadband Printing Techniques,” Proceedings of SMTA International, Orlando, FL, October 2010.

2. M. Whitmore, C. Ashmore, “The Development of New SMT Printing Techniques for Mixed Technology (Heterogeneous) Assembly,” 34th International Electronic Manufacturing Conference, Melaka, Malaysia, November 2010.

3. M. Whitmore, C. Ashmore, “The Next Big Challenge For Stencil Printing – Sub 0.5 Area Ratio Apertures,” Proceedings of SMTA International, Chicago, IL, October 2015.

4 M. Whitmore, J. Schake, “Factors Affecting Stencil Aperture Design for the Next Generation Ultra-Fine Pitch Printing”, Proceedings of SMTA ICSR, Toronto, ON May 2013.

5 J. Schake, M. Whitmore, C. Ashmore, “Stencil Aperture Design Guidelines for 0.3CSP Ultra Fine Pitch Printing,” Proceedings of SMTA International, Fort Worth, TX, October 2013.

6. Stencil Design Guidelines, IPC-7525B,October 2011.

7. C. Ashmore, M. Whitmore, S. Clasper, “Optimising the Print Process for Mixed Technology,” Proceedings of SMTA International, San Diego, CA, October 2009.

8 R. Dervaes, J. Poulos, S. Williams, “Conquering SMT Stencil Printing Challenges with Today’s Miniature Components”, Proceedings of IPC APEX Expo, Las Vegas, NV, April 2009.

9. W.Coleman, M. Burgess, “Stencil Performance Comparison / AMTX Electroform versus Laser-Cut Electroform Nickel Foil, Proceedings of SMTA International, Chicago, IL, October, 2006.

10. R. Mohanty, “What’s in a Squeegee Blade?” Circuits Assembly, May 2009.

11. M, Rösch, J. Franke, C. Läntzsch, “Characteristics and Potentials of Nano-Coated Stencils for Stencil Printing Optimization, Proceedings of SMTA International, Orlando, FL, October 2010.

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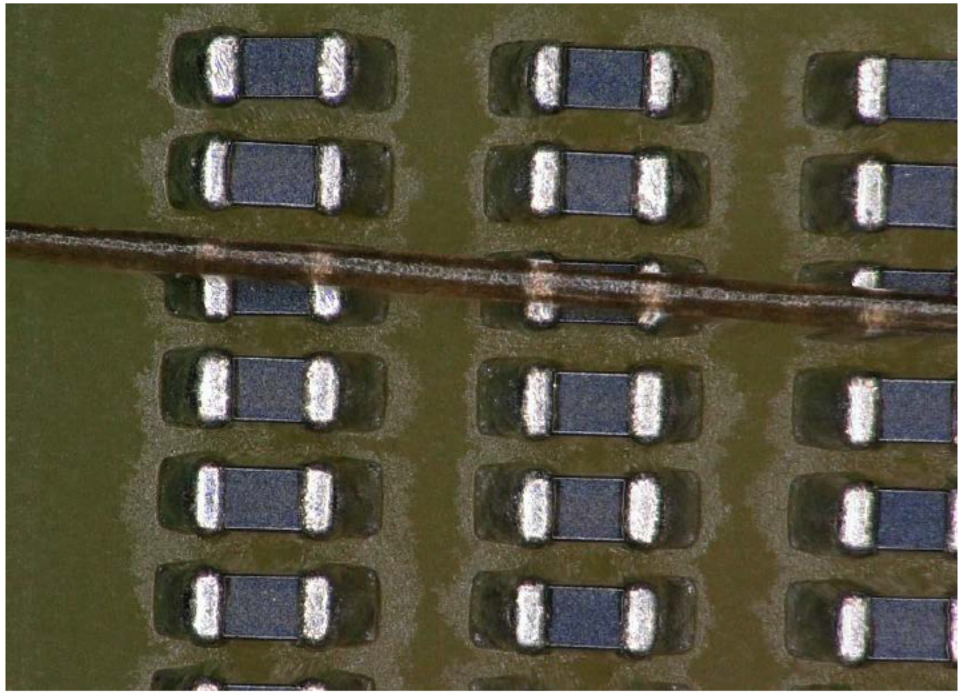
Introduction

- The next generation passive devices - Metric 03015 and 0201.
- Heterogeneous questions starting to be raised.
- Current limit for Area Ratio is 0.5.
- Ultrasonic Squeegee Technology aids the heterogeneous requirements - Minimum Area Ratio to 0.4
- Can the inclusion of a corner radius aid with solder paste release from challenging Area Ratio apertures ?

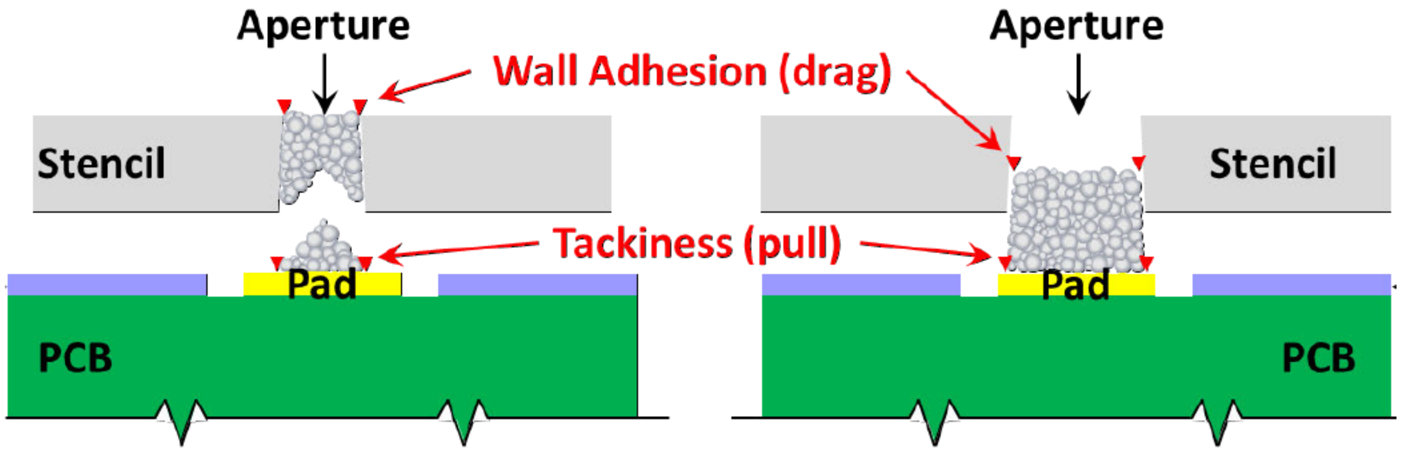
How small ?!?



Metric 0201 = 250um x 125um

Human Hair = 80um

Area Ratio

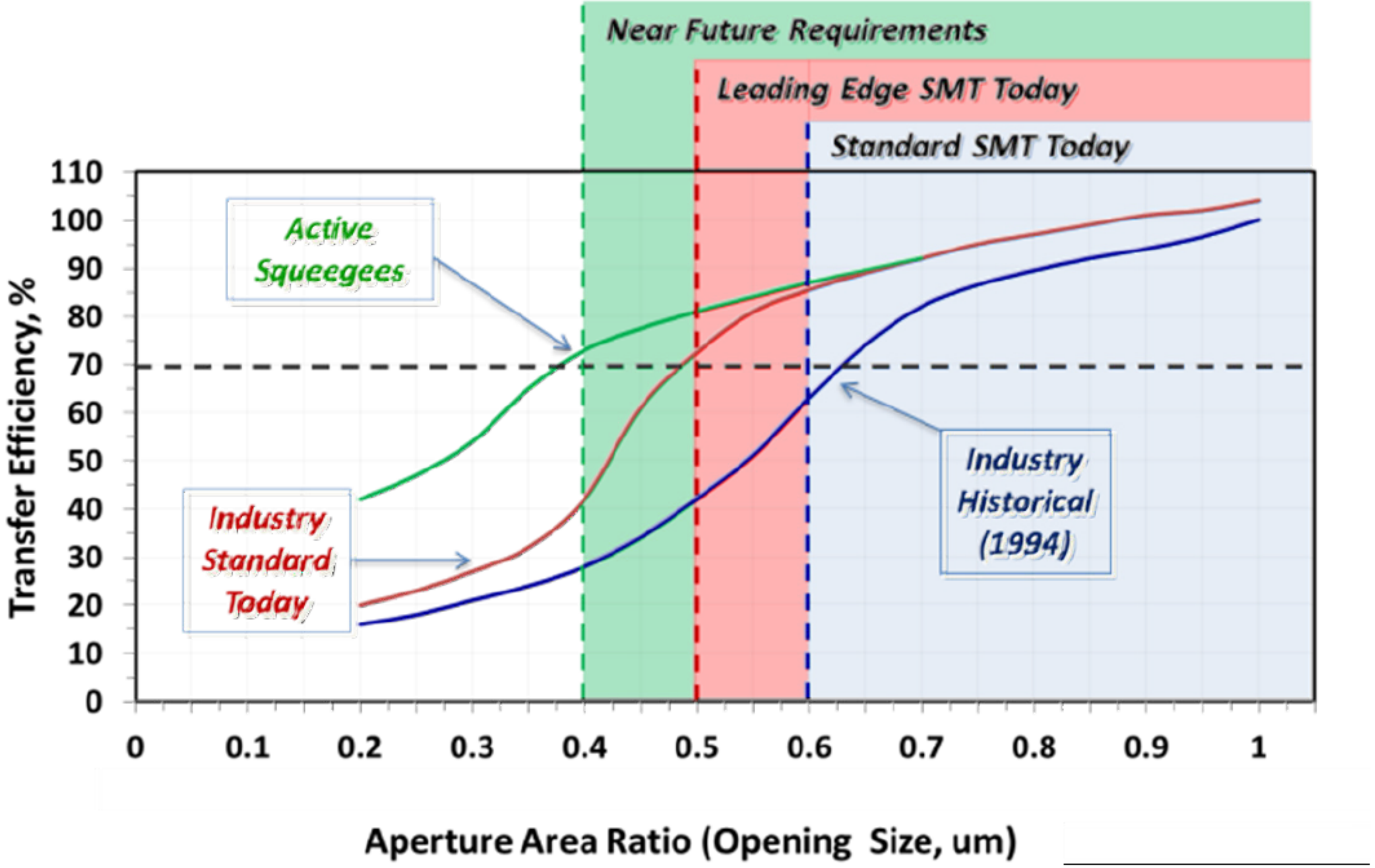


Low AR = Low Transfer Efficiency

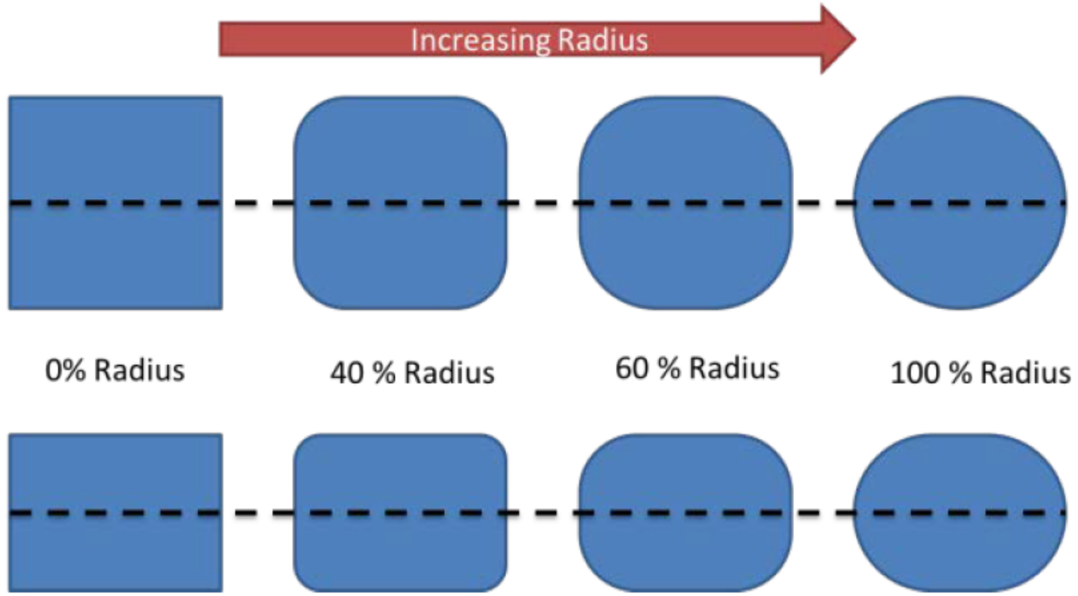
High AR = High Transfer Efficiency

$$\text{Area Ratio} = \frac{\text{Aperture Open Area}}{\text{Wall Surface Area}}$$

Metric 0201 Requirements



Corner Radius Percentage



Experiment

Objective :

The objective of this investigation is to discover if applying a corner radius into an aperture has an impact on the process output.

The transfer efficiency of the individual aperture designs will be reported, analysed and conclusions drawn.

SIPOC

S – I – P – O – C

Supplier

- SPI – Lab 1
- Printer – Internal
- Solder Paste – X
- Stencil – Internal
- Tooling - Internal
- Squeegees – Lab 1
- Board – Internal

Inputs

- Stencil – Fine Grain, 80um. Coated.
- Frameless Stencil
- Aperture Designs (Table 1)
- Solder Paste – Type 5 SAC
- Tooling – Dedicated Vacuum
- Squeegees – Activated, 200mm, 60 deg, 15 mm Overhang
- Substrate – Copper side

Process

- Print Process
  - Print Speed 50mm/s
  - Print Pressure 4Kg
  - Separation speed 3mm/s
- USC – None
- Print 14 board
- Inspect the last 10 Boards

Outputs

- Volumetric Analysis
- White Paper

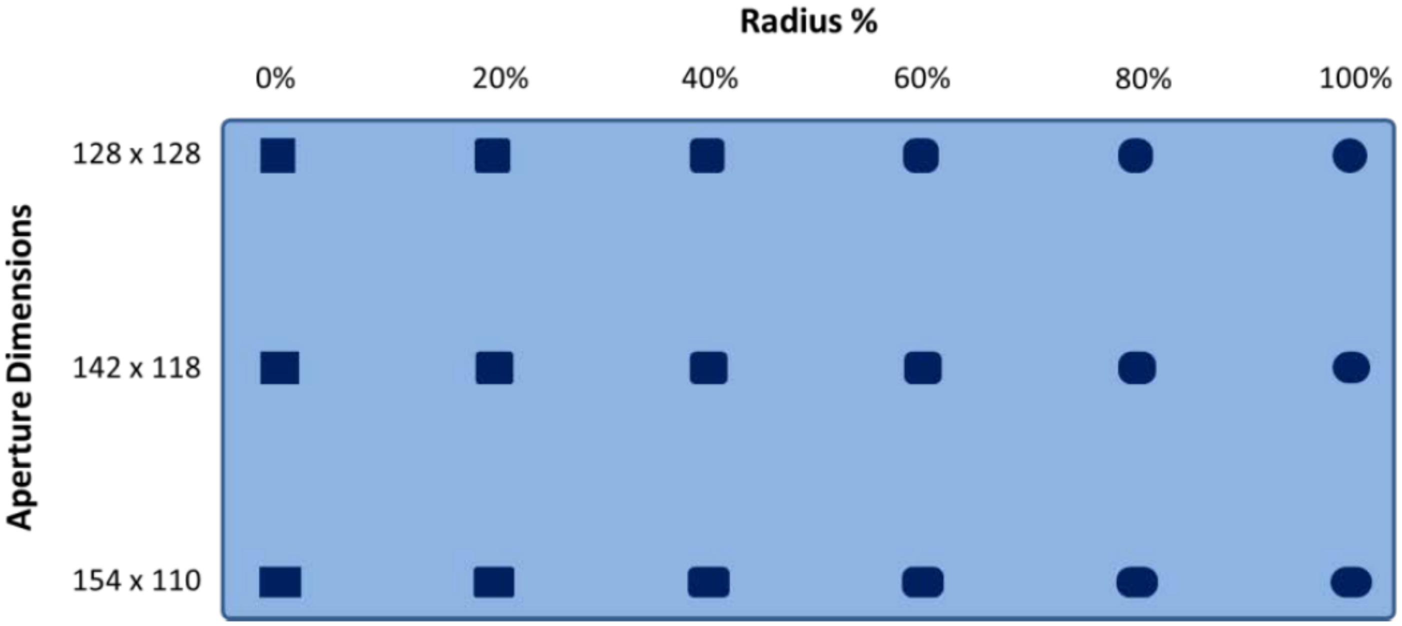
Customers

- Apex '18

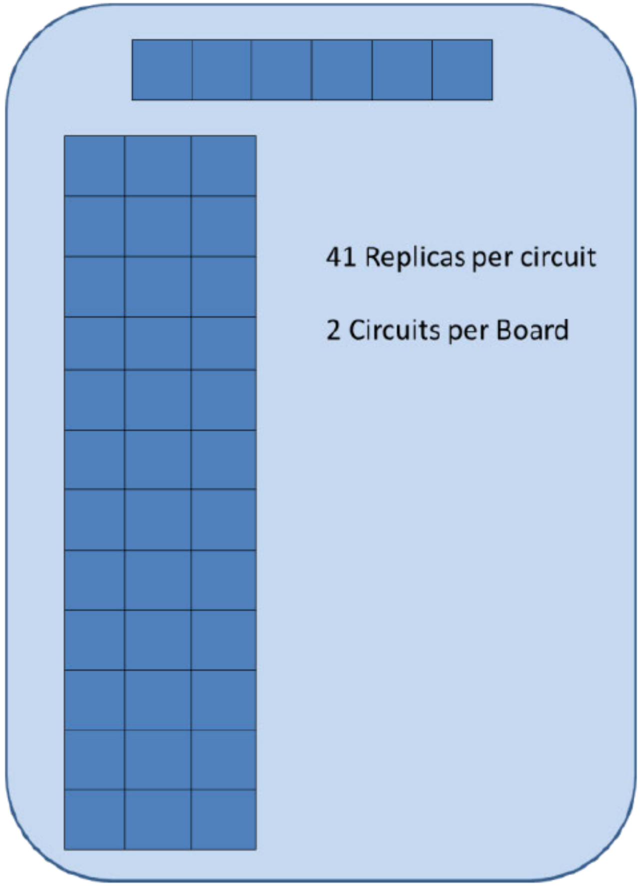
Stencil Design – 80um Laser Cut S.S

All Aperture Design = Area Ratio 0.4

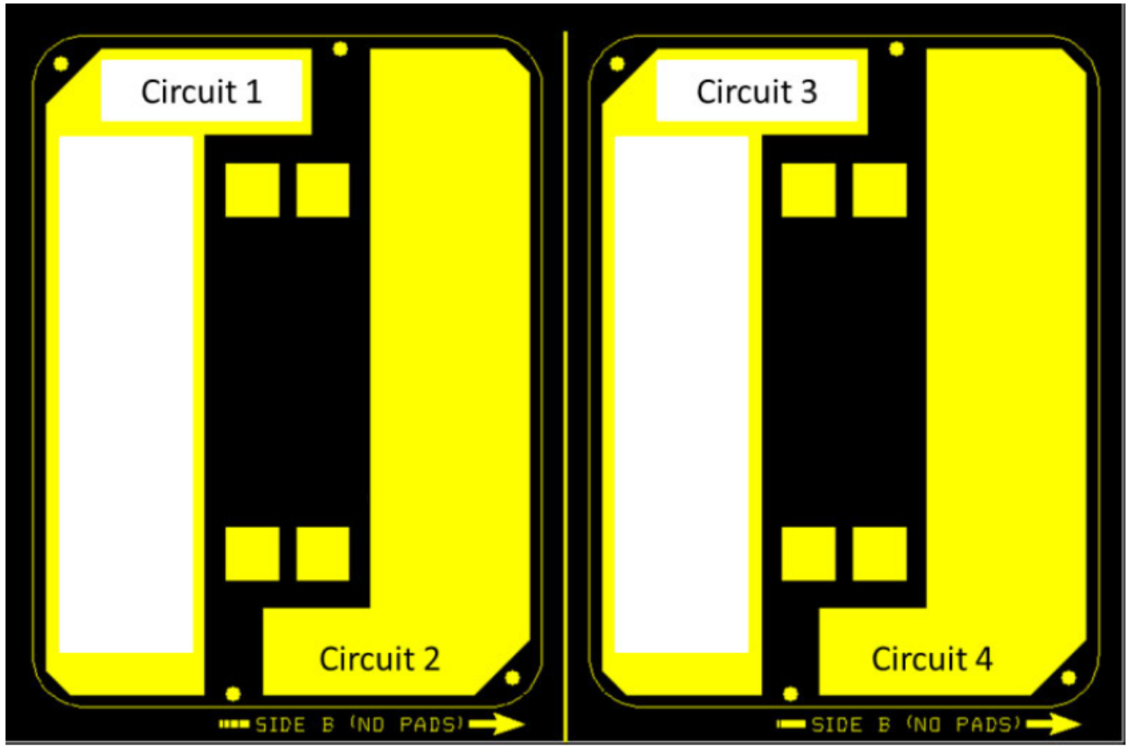
Aperture Dimensions (um)	Radius (%, um)					
	0% um	20% um	40% um	60% um	80% um	100% Um
128 x 128	0	12.8	25.6	38.4	51.2	64
142 x 118	0	11.8	23.6	35.4	47.2	59
154 x 110	0	11	22	33	55	55



Stencil Layout



Board Layout



Analysis

$$Cp = \frac{USL - LSL}{6\sigma}$$

$$Cpk = Min\left(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right)$$

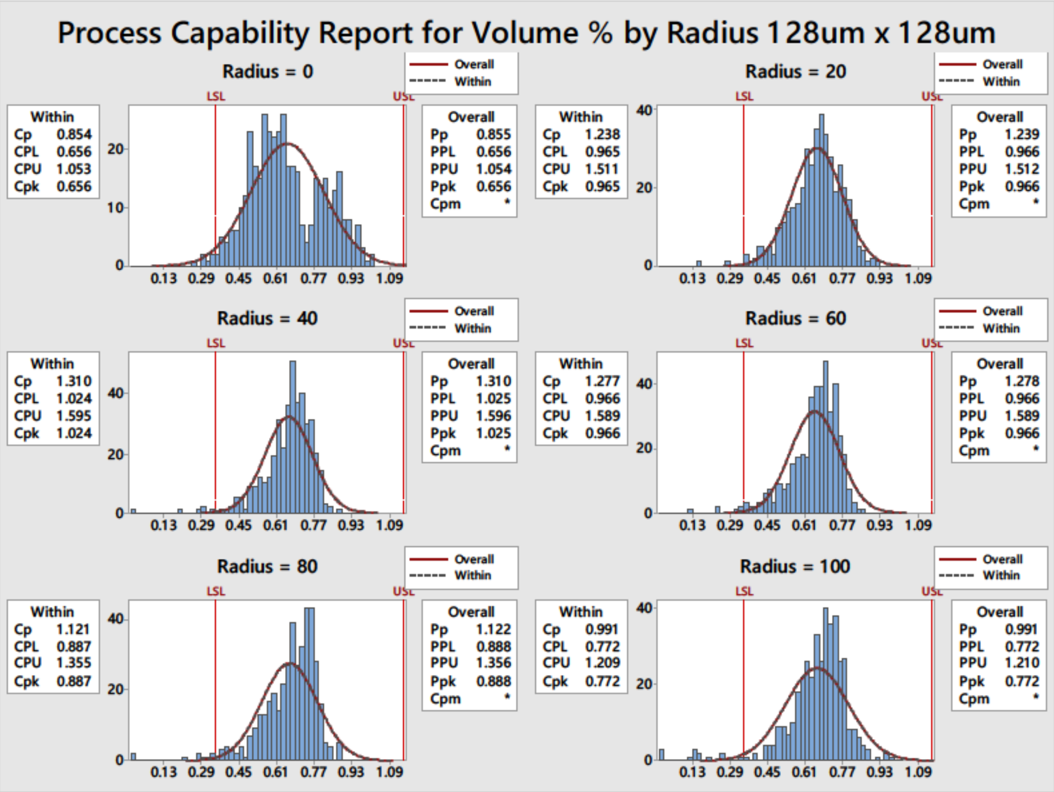
The process bandwidth used to calculate the Cp/Cpk index was +/- 40%, a target of ≥1.33 (4 sigma) was applied to the analysis.

Results

- Process Capability Volume % by Radius (Cp, Cpk)
- Regression Analysis for Cp and Cpk

Volumetric results presented in decimalised percentage

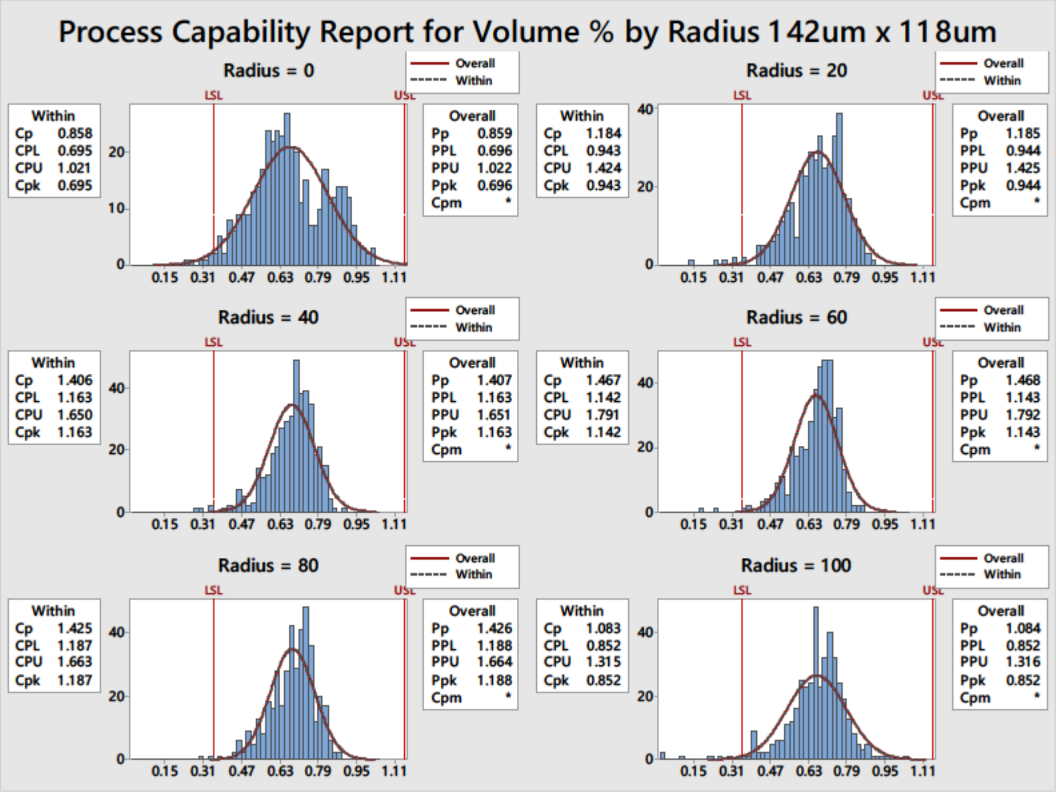
Process Capability Volume % by Radius - 128um x 128um



Radius	LSL	Target	USL	Sample Mean	StDev(Within)	Cp	Cpk
0	0.35	0.7	1.15	0.66	0.156	0.85	0.66
20	0.35	0.7	1.15	0.66	0.108	1.24	0.97
40	0.35	0.7	1.15	0.66	0.102	1.31	1.02
60	0.35	0.7	1.15	0.65	0.104	1.28	0.97
80	0.35	0.7	1.15	0.67	0.119	1.12	0.89
100	0.35	0.7	1.15	0.66	0.135	0.99	0.77

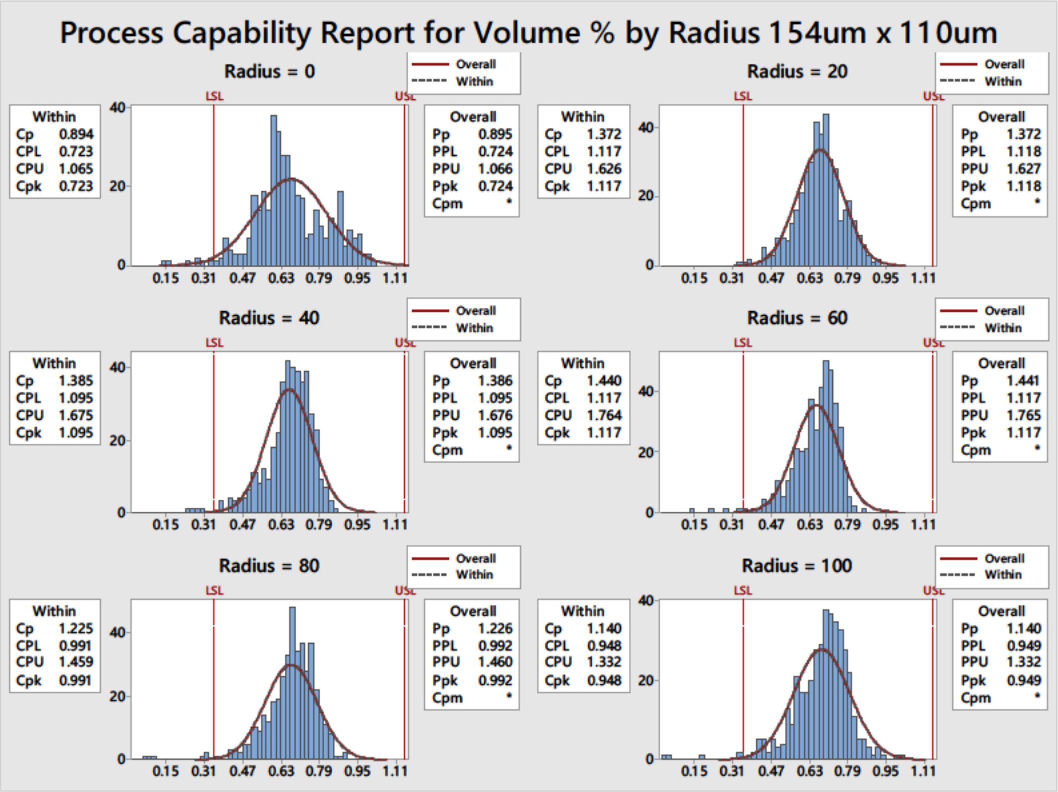
SUCCEED AT THE VELOCITY OF TECHNOLOGY

Process Capability Volume % by Radius - 142um x 118um



Radius	LSL	Target	USL	Sample Mean	StDev(Within)	Cp	Cpk
0	0.35	0.7	1.15	0.67	0.155	0.86	0.70
20	0.35	0.7	1.15	0.67	0.113	1.18	0.94
40	0.35	0.7	1.15	0.68	0.095	1.41	1.16
60	0.35	0.7	1.15	0.66	0.091	1.47	1.14
80	0.35	0.7	1.15	0.68	0.094	1.43	1.19
100	0.35	0.7	1.15	0.66	0.123	1.08	0.85

Process Capability Volume % by Radius - 154um x 110um



Radius	LSL	Target	USL	Sample Mean	StDev(Within)	Cp	Cpk
0	0.35	0.7	1.15	0.67	0.149	0.89	0.72
20	0.35	0.7	1.15	0.68	0.097	1.37	1.12
40	0.35	0.7	1.15	0.67	0.096	1.39	1.10
60	0.35	0.7	1.15	0.66	0.093	1.44	1.12
80	0.35	0.7	1.15	0.67	0.109	1.23	0.99
100	0.35	0.7	1.15	0.68	0.117	1.14	0.95

Regression Analysis for Cp vs Radius

Regression for Cp vs Radius
Summary Report

Y: Cp
X: Radius

Is there a relationship between Y and X?

0 | 0.05 | 0.1 | > 0.5

Yes — No

P < 0.001

The relationship between Cp and Radius is statistically significant ($p < 0.05$).

% of variation explained by the model

0% | 100%

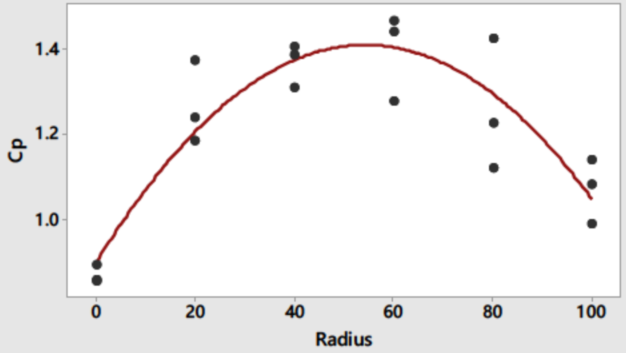
Low — High

R-sq = 82.30%

82.30% of the variation in Cp can be explained by the regression model.

Fitted Line Plot for Quadratic Model

Y = 0.9009 + 0.01872 X - 0.000173 X^2



Comments

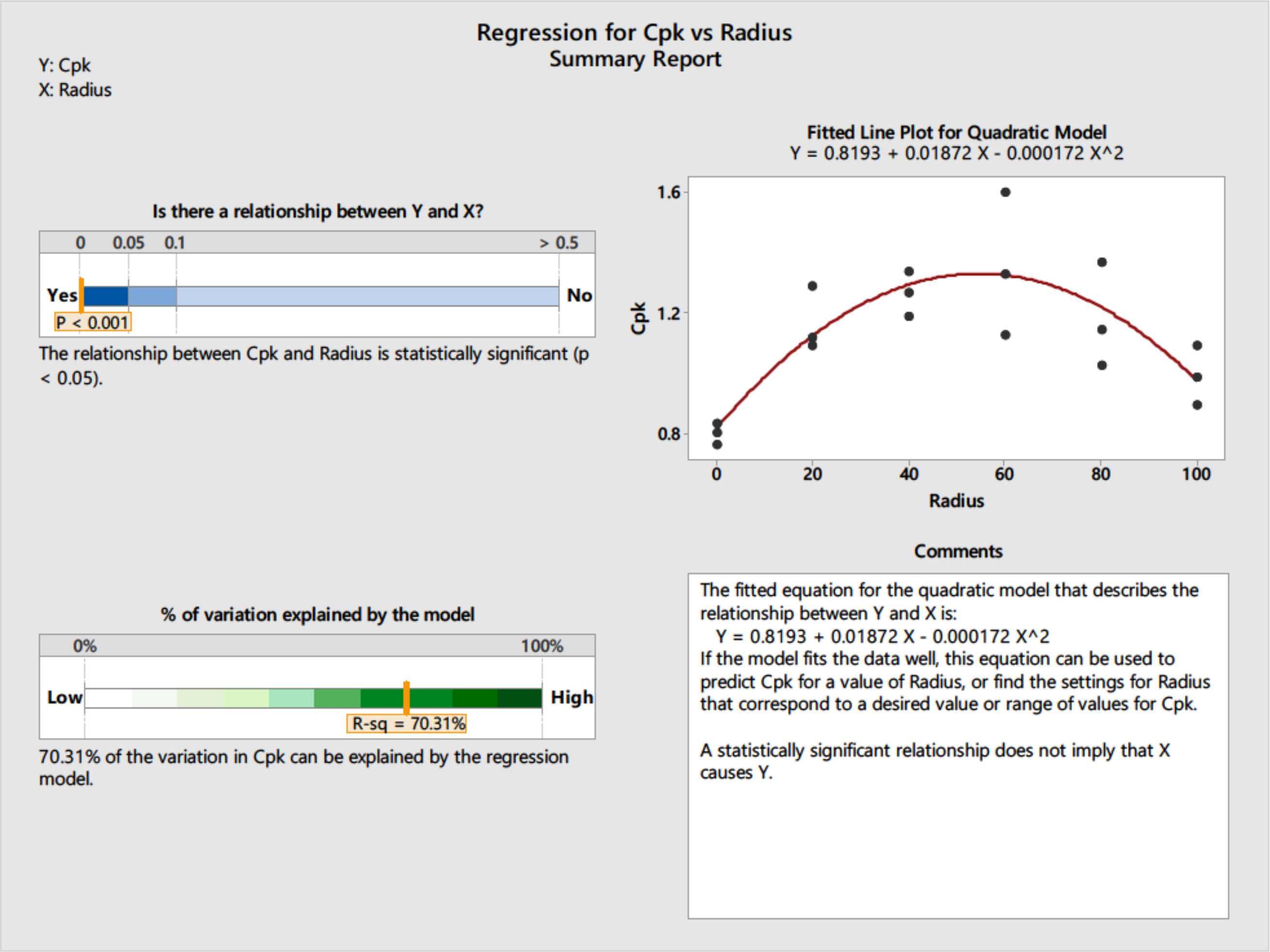
The fitted equation for the quadratic model that describes the relationship between Y and X is:

Y = 0.9009 + 0.01872 X - 0.000173 X^2

If the model fits the data well, this equation can be used to predict Cp for a value of Radius, or find the settings for Radius that correspond to a desired value or range of values for Cp.

A statistically significant relationship does not imply that X causes Y.

Regression Analysis for Cpk vs Radius



Discussion and Conclusions

An Aperture Design with zero radius produces a bimodal histogram – resulting in low process capability

The regression analysis illustrates the impact of applying a radius within an aperture. The response is quadratic in shape. The optimum output occurs when the radius is equal to 50%.