Cookson Electronics
A Division of Cookson Group plc

# High Density / Fine Feature Solder Paste Printing

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APEX 2001

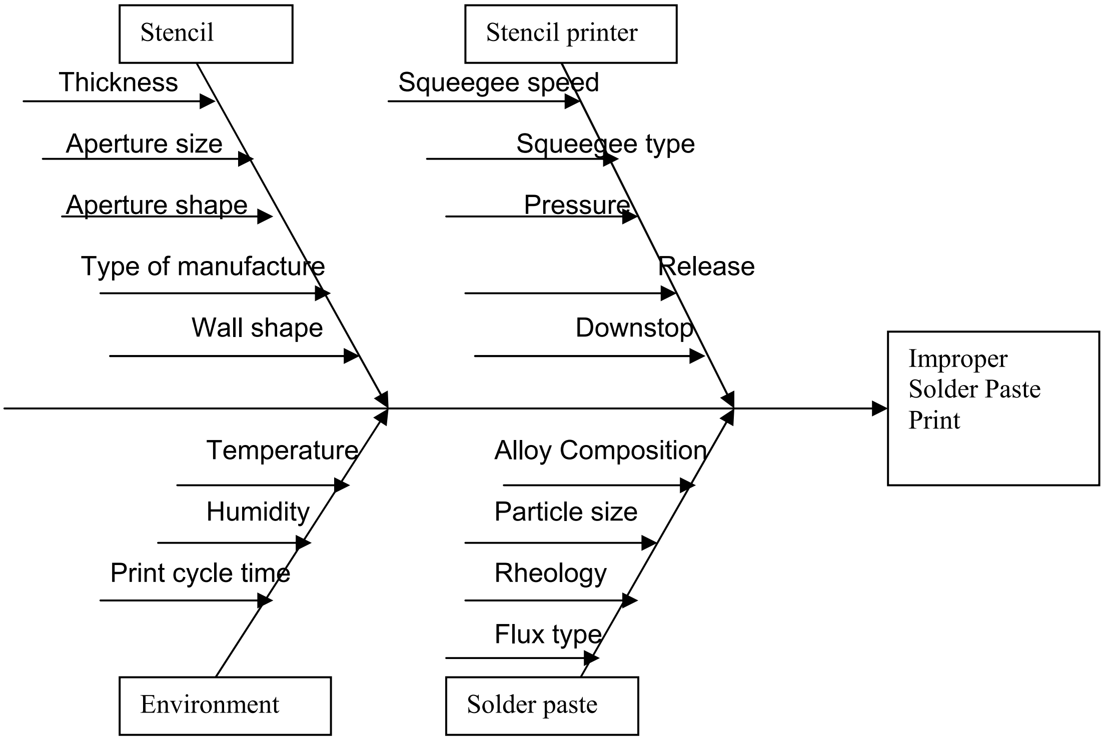
## Abstract

To achieve low PPM defects in solder paste printing of high density and fine feature sizes certain rules must be followed in the original manufacturing design. The stencil printer must be capable of aligning to the substrate but there are six other factors that have to be considered before a consistent print can be achieved. These factors include stencil thickness; aperture size and shape (hole wall aspect ratio) squeegee type and paste particle size. This paper will discuss the parameters that should be optimized to achieve high yields and some possible trade off if you are not willing to incorporate these rules in your manufacturing design.

## Introduction

Solder paste printing in the Surface Mount industry has come a long way in the in the past fifteen years. At first the 50 mil pitch devices were a problem as far as defect rate, now as packages shrink in size and increase in lead count we see the defect rate very high 100 to 200 PPM defect rate on the 20 mill pitch and below while manufacturing sees six sigma quality rates on the larger pitch components. It is well documented that stencil printing contributes to high defect rates for the surface mount assembly process the root cause of the defect may be too complex to ascertain. The paste printing process has four major variables, printer, stencil, substrate and solder paste. From these major factors we can develop a fishbone diagram (figure 1.) which has many contributing factors as to what the root cause was for the print defect.

**Figure 1.**



Solder paste is printed on the printed circuit board to serve as an electro/mechanical and sometimes-thermal connection for the electronic component and pad on the circuit board after reflow. The paste is pushed over the stencil by a squeegee and rolls into the apertures onto the component pad. Once the apertures are filled the squeegee levels the paste to the top of the stencil and moves onto the next area of the stencil to be filled. The forces that adhere the paste to the pad must overcome the same forces that hold the paste to the sidewalls of the stencil. If the forces are not overcome we will have partial release and an insufficient amount of solderpaste on the pad which will result in a poor solder joint at best or open solder as the worst case. The amount of solder paste deposited must contain enough metal and flux to result in a fillet between the component body or lead and the pad on the substrate.

## Experimental details

Five factors were identified as having a high probability of affecting the paste release process. These factors include the shape of stencil aperture, the particle size of solder paste, the squeegee blade type, the size of stencil aperture and the stencil thickness. From the hole shape, hole size and stencil thickness we can determine the hole wall aspect ratio (area of aperture / area of stencil wall) table 1. Additional factors that are important are paste viscosity, print temperature, and humidity. All three factors were kept constant for the experiment.

**Table 1**.

| Stencil Thickness Mills | Aperture size Round Mills | Hole Wall Aspect Ratio | Aperture size Square Mills | Hole Wall Aspect Ratio |
|---|---|---|---|---|
| 4 | 6 | 0.37519 | 6 | 0.375 |
| 4 | 8 | 0.50025 | 8 | 0.500 |
| 4 | 10 | 0.62513 | 10 | 0.625 |
| 5 | 6 | 0.30015 | 6 | 0.3 |
| 5 | 8 | 0.40020 | 8 | 0.4 |
| 5 | 10 | 0.50025 | 10 | 0.5 |
| 6 | 6 | 0.25012 | 6 | 0.25 |
| 6 | 8 | 0.33350 | 8 | 0.33333 |
| 6 | 10 | 0.41687 | 10 | 0.41666 |

The aperture shapes used were square and round. Previous testing resulted in tighter control of the paste deposition with square apertures. With the square shape the volume of paste and spacing between pads can be maximized to minimize the opportunity for bridged deposits. The hole wall aspect ratio for both shapes is for all practical purposes is the same (see table 1). The particle size of the paste was type 3 and type 5. Although there is a cost difference between the two types if the finer particle size results in a lower defect rate a high repair cost should justify the increased paste cost. The squeegee blades chosen for this test were metal and 90 durometer polyethylene. The aperture size used was 6, 8, and 10 thousandths of an inch. The stencil thickness was 4, 5, and 6 thousandths, 5 thousandths being a typical stencil thickness for standard SMT assembly.

The following equipment / materials/settings were used in this experiment:

| | |
|---|---|
| Stencil Printer | Speedline MPM UP 2000 |
| Stencils | IRI Alpha Metals laser cut electropolished |
| Solder Paste | Alpha Metals Omnix 5000 |
| Measurement Equipment | Cyberoptics Cyberscan 200 |
| Temperature/humidity | 74-76 F, 45-50 RH |

| | |
|---|---|
| Print speed | 1”/second |
| Squeegee pressure | 2.0 pounds /inch of squeegee blade |

**Results and Discussion**

**Objective:** The objective of the experiment is to identify which factors have the most influence on solder paste height and if there is a significant difference in stencil print quality per the identified experimental factors.

**Experiment Design $3^2 \times 2^3$ mix level design**

The factors and associated levels for the experiment are as follows:

| | | Levels | | |
|---|---|---|---|---|
| Letters | Factors | 1 | 2 | 3 |
| A | Paste Type | 3 | 5 | |
| B | Stencil Thickness | 4 | 5 | 6 |
| C | Aperture Shape | Round | Square | |
| D | Aperture Size | 6 | 8 | 10 |
| E | Squeegee blade Type | Poly | Metal | |

**Response Parameters**

| Parameters to be Measured | Measurement Equipment |
|---|---|
| 1. Solder Paste Height | Cyberoptics Cyberscan 200 |

The ability for the measurement system to repeatability measure solder paste height was not evaluated.

**Experimental Design chosen for data collection and analysis:**

**Full Factorial design:** A Full Factorial Design was chosen for the experiment. This design will evaluate all main effects for each factor.

**Experimental Design Analysis:** The following section describes the results for the dependent variable (response) solder paste height in mils. The analysis performed is an Analysis of Variance “ANOVA” Model that identifies the amount of experimental error and the significance of the model in accounting for the variability in the experiment. The effect test identifies the factors and interactions that are significant. Effects listed as “most significant” represent the independent process variables that have the greatest influence on a particular treatment response. Once the important factors have been determined, the relationship between the response and the important factors are graphically displayed using main effect plots, and interaction plots.

**Table 2. Response: Solder Paste Height**

| Summary of Fit | |
|---|---|
| RSquare | **0.772357** |
| RSquare Adj | 0.76511 |
| Root Mean Square Error | 1.214266 |
| Mean of Response | 2.604466 |
| Observations (or Sum Wgts) | 2302 |

**Table 3. Analysis of Variance**

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 71 | 11155.703 | 157.123 | 106.5642 |
| Error | 2230 | **3288.003** | 1.474 | Prob>F |
| C Total | 2301 | 14443.706 | | **0.00001** |
| Error sum ratio | | 22.76% | | |

**Table 4. Effect Test**

| Source | Nparm | DF | Sum of Squares | F Ratio | Prob>F |
|---|---|---|---|---|---|
| **Paste type** | 1 | 1 | 195.1093 | 132.3276 | **<.0001** |
| **Stencil Thickness** | 2 | 2 | 426.3207 | 144.5703 | **<.0001** |
| **Paste type*Stencil Thickness** | 2 | 2 | 66.8006 | 22.6529 | **<.0001** |
| **Aperture shape** | 1 | 1 | 97.7232 | 66.2781 | **<.0001** |
| Paste type*Aperture shape | 1 | 1 | 0.0054 | 0.0037 | 0.9518 |
| Stencil Thickne*Aperture shape | 2 | 2 | 1.7002 | 0.5765 | 0.5619 |
| **Paste type*Stencil Thickness*Aperture shape** | 2 | 2 | 18.0915 | 6.1350 | **0.0022** |
| **Aperture Size** | 2 | 2 | 9021.0947 | 3059.158 | **0.0000** |
| **Paste type*Aperture Size** | 2 | 2 | 141.9298 | 48.1300 | **<.0001** |
| **Stencil Thickness*Aperture Size** | 4 | 4 | 331.8285 | 56.2634 | **<.0001** |
| **Paste type*Stencil Thickness*Aperture Size** | 4 | 4 | 81.8305 | 13.8748 | **<.0001** |
| Aperture shape*Aperture Size | 2 | 2 | 3.9450 | 1.3378 | 0.2626 |
| **Paste type*Aperture shape*Aperture Size** | 2 | 2 | 89.5403 | 30.3642 | **<.0001** |
| **Stencil Thickness*Aperture shape*Aperture Size** | 4 | 4 | 77.0117 | 13.0578 | **<.0001** |
| **Paste type*Stencil Thickness*Aperture shape*Aperture Size** | 4 | 4 | 22.9728 | 3.8952 | **0.0037** |
| **Blade type** | 1 | 1 | 92.4923 | 62.7304 | **<.0001** |
| Paste type*Blade type | 1 | 1 | 4.4383 | 3.0102 | 0.0829 |
| Stencil Thickne*Blade type | 2 | 2 | 51.4811 | 17.4579 | **<.0001** |
| **Paste type*Stencil Thickness*Blade type** | 2 | 2 | 11.6023 | 3.9345 | **0.0197** |
| **Aperture shape*Blade type** | 1 | 1 | 7.9238 | 5.3741 | **0.0205** |
| Paste type*Aperture shape*Blade type | 1 | 1 | 0.2559 | 0.1735 | 0.6770 |
| **Stencil Thickness*Aperture shape*Blade type** | 2 | 2 | 9.9735 | 3.3821 | **0.0341** |
| **Paste type*Stencil Thickness*Aperture shape*Blade type** | 2 | 2 | 34.0783 | 11.5564 | **<.0001** |
| **Aperture Size *Blade type** | 2 | 2 | 50.1310 | 17.0000 | **<.0001** |
| **Paste type*Aperture Size*Blade type** | 2 | 2 | 35.2849 | 11.9655 | **<.0001** |
| **Stencil Thickness*Aperture Size*Blade type** | 4 | 4 | 194.0258 | 32.8982 | **<.0001** |
| **Paste type*Stencil Thickness*Aperture Size*Blade type** | 4 | 4 | 32.9376 | 5.5848 | **0.0002** |
| **Aperture shape*Aperture Size*Blade type** | 2 | 2 | 21.8028 | 7.3936 | **0.0006** |
| Paste type*Aperture shape*Aperture Size*Blade type | 2 | 2 | 1.8736 | 0.6354 | 0.5298 |
| Stencil Thickne*Aperture shape*Aperture Size*Blade type | 4 | 4 | 4.2276 | 0.7168 | 0.5804 |
| **Paste type*Stencil Thickness*Aperture shape*Aperture size*Blade type** | 4 | 4 | 22.7092 | 3.8505 | **0.0040** |

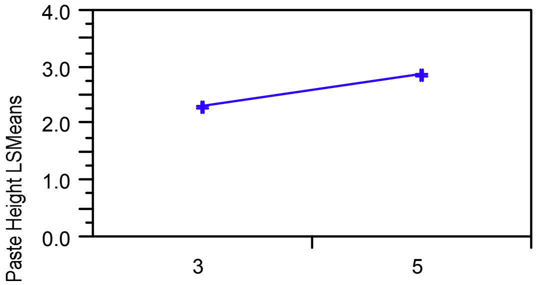
The first item to verify is that the model used is significant. A good fit of the model is a RSquare close to 1 or -1. In Table 2, the RSquare is **0.772357**, which indicates a good fit. The next output to review is found in the Analysis of Variance Table in Table3. The Prob>F or p-value indicates how significant the model is, in other words, do the factors account for the majority of variation in the output? P-values should be .05 or lower to indicate a 95% significance factor. This model is very significant. The P-value is <.00001. This indicates that the factors are accounting for the majority of the variation in the solder paste height for each treatment. The ratio of the error sums of squares and the C Total sums of squares should be no greater than 35%. In this case the error in the model is only **22.76%** in Table 3.

Once we are satisfied that the model is a good fit and is significant, the effects of each of the parameters are analyzed. Again, the Prob>F or P-values indicate how significant each parameter is in the model. P-values of .05 or less are considered 95% significant. Those p-values that are .10 or less are considered 90% significant. The main effects and interactions highlighted in "bold" in table 4 are the significant factors at 95%:

The following plots and corresponding least squares means are presented for each of the significant main effects plots. The plots graphically display the difference in the levels of each factor in reference to solder paste height generated for each level. The Effect Test displays the Prob>F or p-value that corresponds to the p-value found in the effect test in Table 4. The Least Squares Means quantifies the average Solder Paste Height for each level of the factor.

Main Effect Plot: Solder Paste type

Profile Plot



Effect Test

| Sum of Squares | F Ratio | DF | Prob>F |
|---|---|---|---|
| 194.87222 | 112.3343 | 1 | <.0001 |

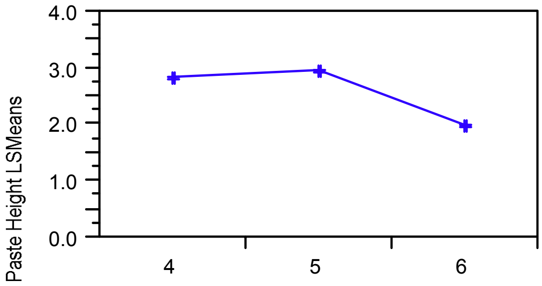
Least Squares Means

| Level | Least Sq Mean | Std Error | Mean |
|---|---|---|---|
| 3 | 2.315118255 | 0.0388224706 | 2.31342 |
| 5 | 2.897024869 | 0.0388224706 | 2.89551 |

The plot graphically displays the difference in the levels of Solder Paste types in reference to the quantity of solder paste height generated for each level. The Effect Test displays the Prob>F or p-value that corresponds to the p-value found in the effect table earlier in the analysis. For solder paste type, the p-value is <.0001. The Least Squares Means quantifies the average solder paste height for each level of solder paste type. Solder Paste type 5 provides the highest paste height to overall stencil thickness.

Main Effect Plot: Stencil Thickness

Profile Plot



Effect Test

| Sum of Squares | F Ratio | DF | Prob>F |
|---|---|---|---|
| 425.88671 | 122.7514 | 2 | <.0001 |

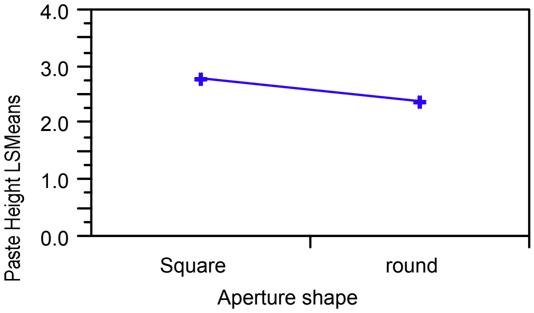
Least Squares Means

| Level | Least Sq Mean | Std Error | Mean |
|---|---|---|---|
| 4 | 2.855376143 | 0.0475896886 | 2.85120 |
| 5 | 2.961770833 | 0.0475267531 | 2.96177 |

| | | | |
|---|---|---|---|
| 6 | 2.001067708 | 0.0475267531 | 2.00107 |

The plot graphically displays the difference in the levels of stencil thickness in reference to the quantity of solder paste height generated for each level. The Effect Test displays the Prob>F or p-value that corresponds to the p-value found in the effect table earlier in the analysis. For stencil thickness, the p-value is <.0001. The Least Squares Means quantifies the average solder paste height for each level of stencil thickness. Stencil thickness of 4 mils and 5 mils provides the highest paste height. There is minimal difference in solder paste height between 4 mil and 5 mil stencil thickness.

Main Effect Plot: Aperture shape Profile Plot



Effect Test

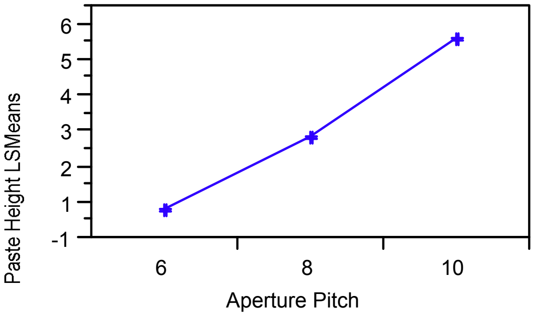
| Sum of Squares | F Ratio | DF | Prob>F |
|---|---|---|---|
| 98.084757 | 56.5411 | 1 | <.0001 |

Least Squares Means

| Level | Least Sq Mean | Std Error | Mean |
|---|---|---|---|
| Square | 2.812491319 | 0.0388054314 | 2.81249 |
| round | 2.399651804 | 0.0388396967 | 2.39608 |

The plot graphically displays the difference in the levels of aperture shape in reference to the quantity of solder paste height generated for each level. The Effect Test displays the Prob>F or p-value that corresponds to the p-value found in the effect table earlier in the analysis. For aperture shape, the p-value is <.0001. The Least Squares Means quantifies the average solder paste height for each level of aperture shape. The square aperture shape provides the highest paste height.

Main Effect Plot: Aperture Size Profile Plot



Effect Test

| Sum of Squares | F Ratio | DF | Prob>F |
|---|---|---|---|
| 9016.8604 | 2598.89 | 2 | 0.00001 |

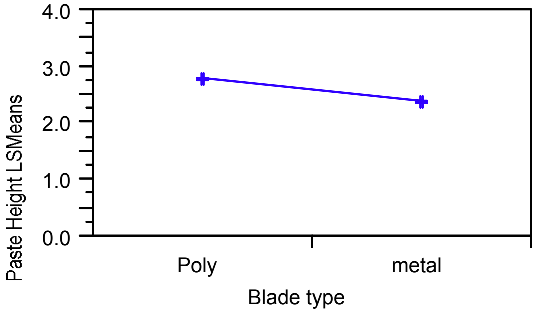
Least Squares Means

| Level | Least Sq Mean | Std Error | Mean |
|---|---|---|---|
| 6 | 0.305651042 | 0.0475267531 | 0.30565 |
| 8 | 2.374296875 | 0.0475267531 | 2.37430 |
| 10 | 5.138266768 | 0.0475896886 | 5.14005 |

The plot graphically displays the difference in the levels of aperture pitch in reference to the quantity of solder paste height generated for each level. The Effect Test displays the Prob>F or p-value that corresponds to the p-value found in the effect table earlier in the analysis. For aperture pitch, the p-value is <.00001. The Least Squares Means quantifies the average solder paste height for each level of aperture pitch. The 10 mil aperture pitch provides the highest paste height.

Main Effect Plot: Blade type

Profile Plot



Effect Test

| Sum of Squares | F Ratio | DF | Prob>F |
|---|---|---|---|
| 92.844016 | 53.5200 | 1 | <.0001 |

Least Squares Means

| Level | Least Sq Mean | Std Error | Mean |
|---|---|---|---|
| Poly | 2.806901042 | 0.0388054314 | 2.80690 |
| metal | 2.405242082 | 0.0388396967 | 2.40168 |

The plot graphically displays the difference in the levels of squeegee blade type in reference to the quantity of solder paste height generated for each level. The Effect Test displays the Prob>F or p-value that corresponds to the p-value found in the effect table earlier in the analysis. For squeegee blade type, the p-value is <.0001. The Least Squares Means quantifies the average solder paste height for each level of squeegee blade type. The Polly squeegee blades provide a higher solder paste height.

The question now becomes what parameters will provide the most consistent printing. Seventy-two different test conditions were evaluated. The paste heights that were 1.5 thousandths higher or 1 thousandth lower than the stencil thicknesses were eliminated. The remainders were tabulated by standard deviation to see variables provided the lowest standard deviation Table5.

**Table 5**

| Paste Type | Stencil Thickness | Aperture Shape | Apert ure | Blade | Std Deviation | Hole Aspect Ratio | Wall |
|---|---|---|---|---|---|---|---|
| 5 | 4 | Square | 10 | Poly | 0.306688 | 0.625 | |
| 3 | 4 | Square | 10 | Poly | 0.332261 | 0.625 | |
| 5 | 4 | Round | 10 | Poly | 0.340631 | 0.62513 | |
| 5 | 5 | Round | 10 | Poly | 0.519384 | 0.50025 | |
| 3 | 4 | Round | 10 | Poly | 0.557065 | 0.62513 | |
| 5 | 4 | Square | 10 | Metal | 0.566629 | 0.625 | |
| 3 | 4 | Square | 10 | Metal | 0.657156 | 0.625 | |
| 3 | 4 | Square | 8 | Poly | 0.683883 | 0.5 | |
| 3 | 4 | Round | 10 | Metal | 0.769666 | 0.62513 | |
| 5 | 5 | Square | 10 | Poly | 0.824016 | 0.5 | |
| 3 | 5 | Square | 10 | Poly | 0.828893 | 0.5 | |
| 5 | 4 | Square | 8 | Poly | 0.916839 | 0.5 | |
| 3 | 5 | Square | 10 | Metal | 1.245902 | 0.5 | |
| 5 | 4 | Round | 10 | Metal | 1.310379 | 0.62513 | |
| 3 | 6 | Square | 10 | Poly | 1.442708 | 0.41666 | |
| 3 | 5 | Round | 10 | Metal | 1.764228 | 0.50025 | |
| 3 | 6 | Square | 10 | Metal | 1.971514 | 0.41666 | |
| 5 | 4 | Round | 8 | Poly | 2.02836 | 0.50025 | |
| 3 | 5 | Round | 10 | Poly | 2.078768 | 0.50025 | |
| 5 | 4 | Square | 8 | metal | 2.205925 | 0.5 | |
| 3 | 6 | Round | 10 | Poly | 2.278927 | 0.41687 | |
| 5 | 6 | Square | 10 | Poly | 2.301192 | 0.41666 | |
| 5 | 6 | Round | 10 | Poly | 2.381772 | 0.41687 | |
| 5 | 5 | Square | 8 | Poly | 2.877031 | 0.4 | |

**Summary:** Based on the analysis results, the following is recommended:
The following factor combinations provide the best print quality and consistent solder paste heights: a stencil aperture at 10 mils with square shapes, stencil thickness of 4, solder paste type 5, and polyethylene blades 90 durometer. If trade offs are to be made the defect rates will increase resulting in higher manufacturing costs repair costs or warranty repairs.

This article was originally published in the Proceedings of APEX January 2001.