A NEW DIMENSION IN STENCIL PRINT OPTIMIZATION

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ABSTRACT

Over the years stencil design has made a transition from traditional art that is based on experience to a modern day scientific approach based on designed experiments, which will deliver optimum print performance. Modern technology puts high demands on the different aspects of stencil design, which has to account for the fine pitch, as well as the large pitch components on board. Moreover, to control paste print volume, an engineer has to choose the best performing aperture geometry, stencil thickness, aperture wall taper, and whether or not to electropolish; not to mention the varied manufacturing techniques, which in most cases dictate the stencil manufacturing costs. This lack of in-depth understanding of the subject motivated our team to investigate the issue with a test matrix comprising all the possible combinations of stencil aperture design and manufacturing processes currently used in the surface mount industry.

The variables evaluated for this study are spread across different materials and manufacturing methods; coupled with innovative aperture geometry covering a wide range of sizes. A designed set of experiments is performed to find the effect of all the identified factors on the response variables.

The resulting knowledge base consists of more than 10,000,000 records of data. The results help clear some of the widely perceived misconceptions regarding stencil design and the different manufacturing processes. These answers give a new dimension to the fundamental understanding of a stencil aperture design and its resulting effect of print performance.

Key words: stencil printing, taper, electropolish, laser-cut, chem-etch, electro-form, transfer efficiency.

BACKGROUND

The stencil design is one of the most important factors that determine yield in an electronic assembly facility. Design of the stencil is dependent on a variety of factors: the printed circuit board component layouts, PCB materials, pad finishes, and the components used; in short the entirety of the PCB design. Other factors, which influence stencil design are the number of apertures, location of the apertures, cost of manufacturing, aperture size, and pitch.

The parameters that are usually specified for a stencil are the stencil material, method of fabrication, stencil foil thickness, aperture shape, size, and orientation. It has been accepted by the industry that tapered aperture walls and electropolishing of the walls aid in release of the solder paste, but no data is available which shows the degree of taper and electropolish that is needed for optimum release of solder paste. The method of stencil fabrication is also an important factor that affects the performance of the stencil printing process. The methods usually used for stencil fabrication are laser cutting, electroforming, and chemical etching. Numerous studies have been done so far to compare the print performance of each of these methods.

But most of these studies have been conducted using different stencils, and the results are therefore affected by different machine settings and environmental conditions. In order to truly compare the print performance of the different manufacturing methods, they have to be printed under the same print conditions ideally with the same print stroke.

The overall objective of this research effort is to evaluate the print performance across stencils with different manufacturing techniques, apertures with different degrees of taper and electropolish, and stencils with different thicknesses and materials. The print performance is measured by the transfer efficiency (ratio of deposited solder paste volume to the measured aperture volume), st. dev./vol. (ratio of standard deviation of the volume of paste deposits to the average paste volume), and the volume of paste deposited on the boards. The experimental results will aid in recommending the best manufacturing technique, along with the combination of taper and electropolish that results in maximum transfer efficiency and least standard deviation, and at the same time maximizing the volume of solder paste deposited on the board for a given aperture design.

FACTORS AFFECTING STENCIL PRINTING

The Ishikawa diagram on the following page lists the different factors affecting the stencil printing operation.

The Ishikawa diagram is a comprehensive list of the different factors affecting the stencil printing operation. A few significant factors are identified as being most significant, and these factors were optimized for each stencil being evaluated. All other factors were maintained constant to eliminate any variability in the data. Print speed and print pressure are identified as the significant factors and are optimized.

TEST VEHICLE

The main purpose of this research effort is to evaluate the relative performance of stencils that have different manufacturing conditions and have unique design characteristics. Figure 2 is a schematic of the stencil layout and has twelve cells, each having a unique degree of taper and degree of electropolish.

The different degrees of taper are denoted by LT, MT, and HT, which stand for low taper, medium taper, and high taper. The different degrees of polish are denoted by NP, LP, MP, and HP, which stand for no polish, low polish, medium polish, and high polish, respectively.

Figure 3 shows the layout of apertures within a cell. Within a cell there are five geometries: circles, squares, rectangles, oblongs, and homebase. The length to width ratio on the rectangle and oblong apertures is 5:1.

In addition to the different geometries, there are eight different size combinations aligned in two orientations (horizontal and vertical) to study the effect on rectangle and oblong apertures. The total number of apertures in a stencil is 9408. It is beyond the scope of this paper to cover all the combinations. This paper will therefore focus on sizes from 12 to 25 mils for the circular and square geometry.

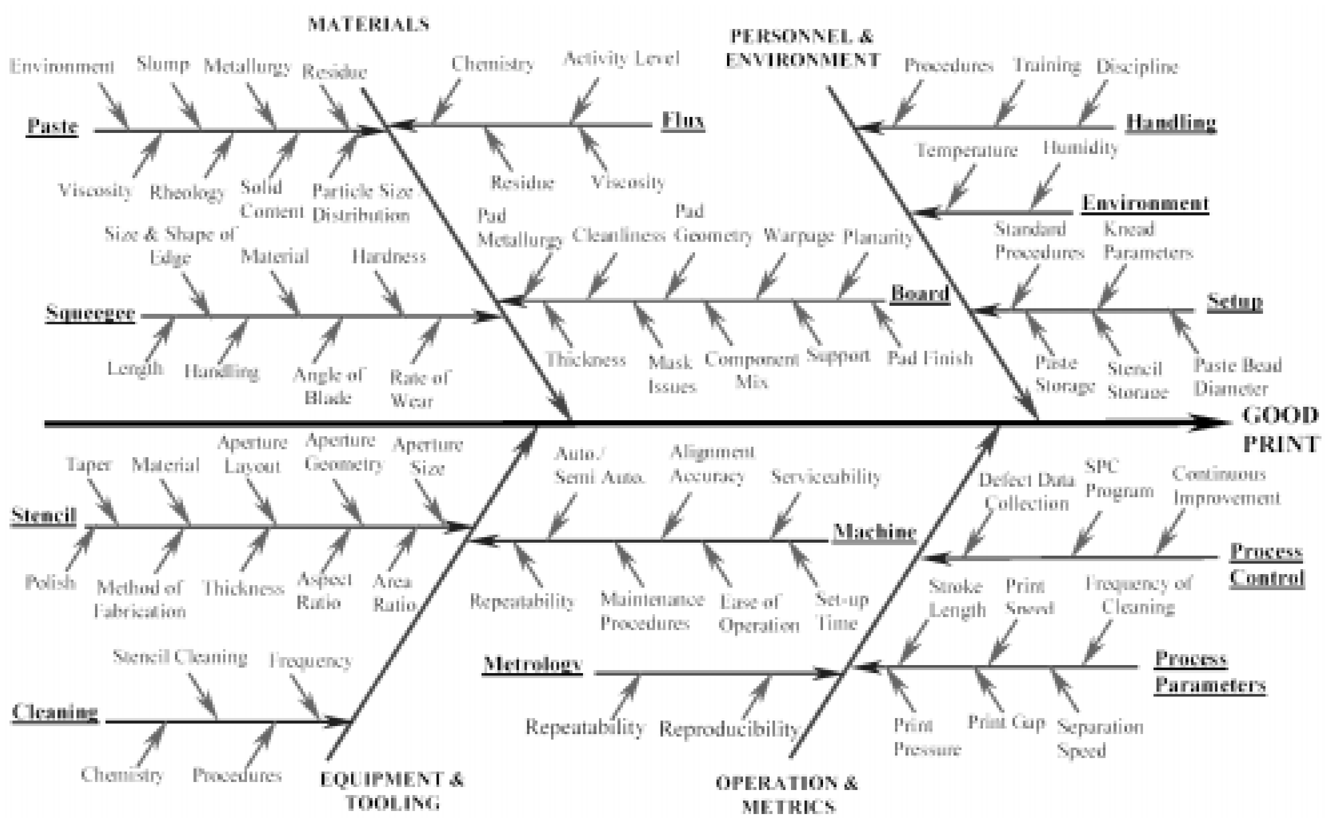

Figure 1: Fishbone-stencil printing factors.

	NP	LP	MP	HP
LT	A	B	C	D
MT	E	F	G	H
HT	I	J	K	L

Figure 2: Layout of cells in the stencil.

Chem-Etch Stencils

The chem-etch process uses a ferric chloride bath to etch the apertures in the stainless steel foil. The process first entails the production of photo-tools or photographic positives of the required stencil image. These photo-tools, one each for top and bottom, are carefully aligned over a stainless steel plate covered with a photo-imageable resist, which is then exposed and developed. The developed plate is then fed through the etcher for a set number of passes; this is a function of plate thickness. During this process, etching proceeds in the horizontal direction in addition to the vertical direction, which is called undercutting. This leads to slightly oversized apertures. This increase in aperture size due to undercutting has to be accounted for during the initial imaging phase. Most chem-etch stencils have an hourglass profile due to double-sided etching.

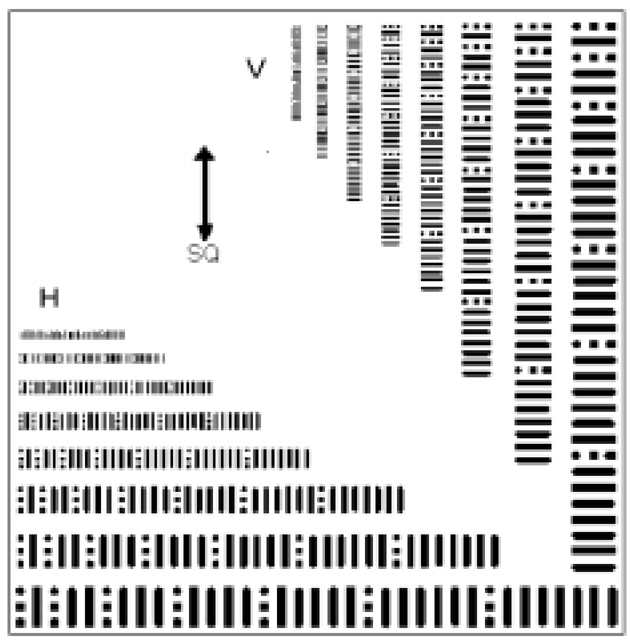

Figure 3: Layout of apertures in a cell.

Laser-Cut Stencils

The laser cutting process is also a subtractive process just like the chem-etch process, the only difference being a laser beam is used to form apertures instead of a chemical bath. The inherent advantages of this process lie in its ability to form very fine aperture sizes with consistent accuracy. Aperture holes are formed one at a time, thereby resulting in higher manufacturing costs which finally depends on the number of apertures in the stencil.

E-Form Stencils

The main difference between E-form and the previously mentioned processes is that the E-form process is an additive process. In this process, nickel is deposited on a copper mandrel to build the apertures. A photosensitive dry film is laminated on the copper foil. This is polymerized by the UV light through a photomask of the stencil pattern.

After developing, a negative image is created on the mandrel where only the apertures on the stencil remain covered by the photoresist. The stencil is developed by growing nickel plating around the photoresist. The photoresist is then removed after the desired thickness is achieved. This process is one of the more expensive stencil manufacturing processes and is best suited for very small aperture sizes and fine pitches.

EQUIPMENT, CONSUMABLES, & OTHER FACTORS

Equipment: MPM UP 3000
Solder Paste: Type 3 paste
Squeegee: Metal squeegee (10 inch wide)
Board: Bare solder mask covered board
Snap-off distance: -0.005"
Snap-off speed: 8 mils/sec
Direction of squeegee stroke: Forward
Voyager 18 x 24: Optical measuring instrument for characterizing stencil aperture openings.
GSI 8200: To measure solder paste deposits on boards.
Mitutoyo deep throat micrometer: Stencil thickness measurement.

EXPERIMENTAL PROCEDURE

The following flowchart outlines the sequence of steps for the experimental procedure.

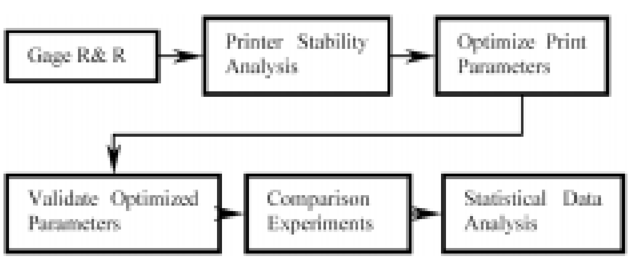

Figure 4: Flowchart of experimental procedure.

Prior to conducting the experiments, stability studies are conducted on all process measurement equipment, and measurement system analysis is conducted for all gauges used for measurement. These studies are necessary to find out all sources and magnitude of variation due to machine characteristics. The results from the above experiments are documented in "CE-PDG internal document 0137-TR001" and are not covered in this report.

Stencil Printing Optimization

The main objective of this experiment is to optimize the stencil printing parameters. Design of experiments has proven to be very beneficial in process optimization and improvement. In process development using design of experiments, the first step is to identify the important independent factors affecting the process. Screening experiments are performed for this purpose. Fractional factorial or Taguchi designs can be used in screening experiments.

Once the significant factors are identified, the next step is to design a full factorial experiment. The optimum result might be to hit a target and then minimize or maximize the response. In case of volume, the response is maximized, whereas in case of standard deviation it is minimized. Response surface designs are used for this purpose.

In this research, the print pressure and print speed are identified as optimal parameters and optimized at a separation speed of 8 mils/sec.

The section below explains the response surface methodology for optimization.

Response Surface Methodology

Response surface methodology (RSM) is a method in which a plot of the different factors (at their different levels) can be used to help determine the optimal level settings with respect to the output. As in our case, many factors have predetermined settings; for example, the paste type is fixed, the environmental operating conditions (temperature and humidity) are fixed, etc.

Furthermore, we have identified pressure and print speed as the two factors that are most significant, and the goal is to determine which levels of these factor combinations should be selected to optimize the response. This is performed with the use of an RSM plot. The RSM plot consisting of two factors of interest is a 3-dimensional plot of the expected response (plotted in the Z axis) according to the different levels of the factors.

Experimental Design

Typical response surface designs are central composite design (CCD) and Box Behnken. A CCD is the most effective experimental design for sequential experimentation. Blocked or unblocked CCDs can be created. CCD consists of 2K (K is the number of factors) factorial or "cube" points, axial points (also known as star points), and center points. A CCD is used for the optimization of the print speed and print pressure.

The design is blocked by squeegee stroke direction to eliminate variation arising from differences in the direction of print stroke, and also to eliminate the potential variation caused by using two different squeegees.

Circles with 12, 16, 20 and 25 mils are included in the optimization experiments. Square geometries are not included in the optimization because, for a given size, circles and harder to print than squares, and it is expected that the optimized parameters for circles would work for squares.

A sub-optimal target of 95% of the theoretical aperture volume is chosen for all geometries. This target is not possible to achieve for the 12 and 16 mil circles due to area ratio restrictions, but the general idea is to maximize the volume deposited for the smaller apertures. The delta volume and standard deviation is used for deciding on the optimal parameters. The variable factors and associated levels for the optimization experiment are as follows:

Factors	Low	Levels Middle	High
Squeegee Speed (inches/sec)	1	3	6
Squeegee Force (lbs)	15	22.5	30

Table 1: Factors/levels for print optimization.

To detect a 1.5σ shift in the mean and a 0.05 β missed detection rate, two replicates of the experiment are performed. The total number of boards is 28. Runs are blocked by squeegee stroke and are randomized within replicates.

The following table shows the different levels of speed and pressure used for the optimization experiments.

Std Order	Run Order	Blocks	Force (lbs)	Speed (in/sec)
3	1	1	17.2	5.3
6	2	1	22.5	3.5
4	3	1	27.8	5.3
7	4	1	22.5	3.5
2	5	1	27.8	1.7
5	6	1	22.5	3.5
1	7	1	17.2	1.7
11	8	2	22.5	6
14	9	2	22.5	3.5
12	10	2	22.5	3.5
8	11	2	15	3.5
9	12	2	30	3.5
10	13	2	22.5	1
13	14	2	22.5	3.5

Table 2: Run order for print optimization.

OPTIMIZATION RESULTS

The following response curves show the trends for the 12 mil circles. From the response curves we see that a high speed and high force result in high volume of paste deposited, and at the same time it has a low standard deviation. Similar curves are plotted for 16, 20, and 25 mil circles. The optimal parameters for the 5 mil thick stencil are a pressure of 22.5 lbs and a speed of 5 in/sec. The main criteria for selecting optimal parameters are to maximize paste volume transfer, to minimize standard deviation, and to operate in the flattest part of the curve. More weightage is given to the smaller apertures due to tighter area and aspect ratios. (More response curves for the other aperture sizes are provided in the appendix of the conference article featured on-line in the smta.org Knowledge Base.)

VALIDATION EXPERIMENTS

Validation experiments are necessary to verify the volumes predicted by the responses generated by the CCD. Validation of the optimized print parameters is performed by printing 30 boards in each print direction. The number 30 is chosen, as it gives a sample size large enough to perform sound statistical analysis. The procedure followed for the validation is similar to the optimization experiment.

Figure 6 shows the comparison of the predicted and actual transfer efficiency and predicted and actual paste volume standard deviation, respectively. The two graphs show agreement between the predicted and actual transfer efficiencies and standard deviation for all geometries, and thus validate the optimized print parameters.

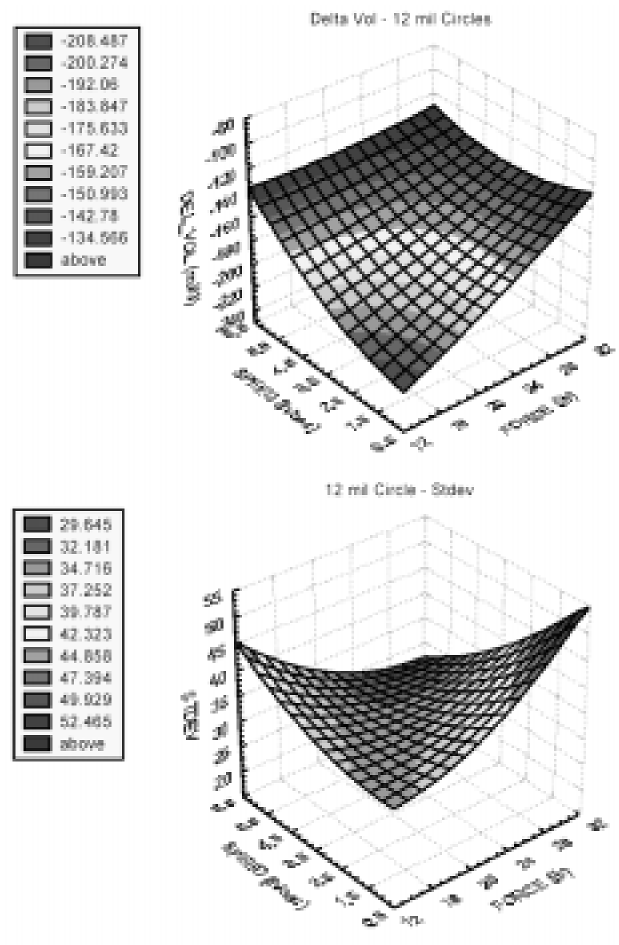

Figure 5: Response curves for 12 mil circles.

PRINT COMPARISON EXPERIMENTS

The optimized parameters were used for comparison studies. Thirty boards are printed for each direction of squeegee stroke. The performance measures chosen for this study are transfer efficiency and the ratio of standard deviation to mean solder paste volume. Multiple comparisons using Tukey's test followed by t test is used to perform data analysis.

Transfer efficiency is calculated by dividing the ratio of deposited solder paste volume by the measured aperture volume. It is desirable to have high transfer efficiency in the print process. The aperture volume is calculated using squeegee and board side measurements recorded by the Voyager and using thickness measurements recorded by the deep throat micrometer.

Standard deviation / Volume is the ratio of the standard deviation of volumes of the paste deposits to the mean volume of the deposits and is expressed as a percent. This response addresses the variability in the printing process.

Multiple Comparison & Paired -t test

Tukey's test is used to perform the multiple comparison of different cells. (Shown in the appendix of the conference article featured on-line in the smta.org Knowledge Base is an example of a multiple comparison test using Tukey's method for transfer efficiency for mil circles for the laser cut stencil.)

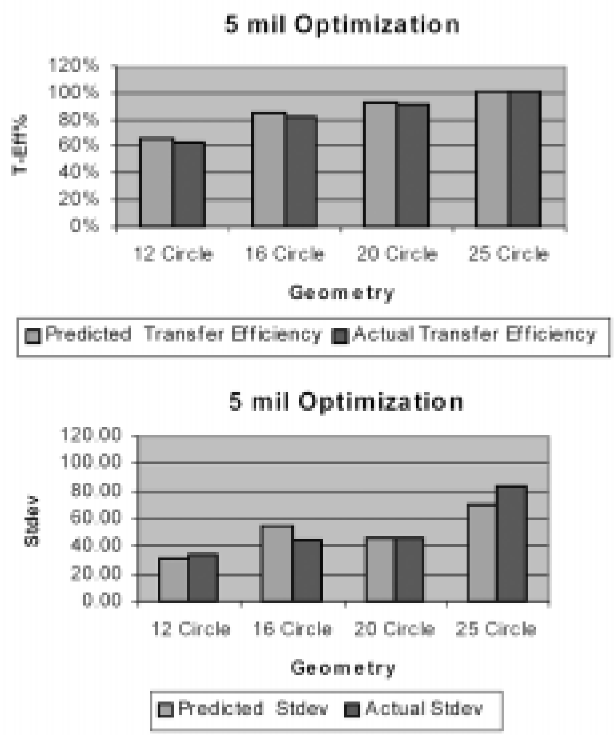

Figure 6: Validation of optimized parameters.

Paired -t test is performed to determine if or not the best and the worst performing cells are statistically different from each other. (An illustration of the same is provided in the appendix of the conference article in the smta.org Knowledge Base.)

RESULTS & DISCUSSION

This section focuses on the effect of taper and electropolish and compares the performance of different manufacturing techniques. Also, comparisons between circular and square geometries are provided.

The following thickness measurements (Figure 7) were recorded for the cells subjected to different electropolish conditions. Stencil thickness measurements are carried out to calculate the actual aperture volume and to determine the variation in thickness caused due to different electropolishing conditions.

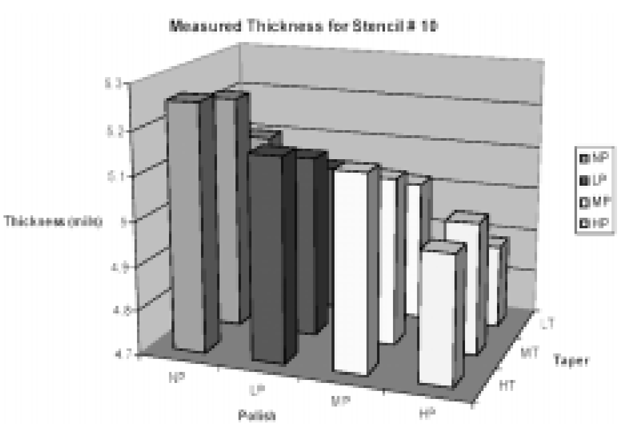

Figure 7: Thickness variation with increased electropolish.

The graph in Figure 7 shows reduced stencil thickness for cells with high electropolish. The higher the degree of electropolish, the lesser the thickness. The reduced stencil thickness results in an increase in area ratio and aspect ratio.

Results

Figure 8 shows the best and the worst performing cells for the 5 mil thick stencil for each of the response variables considered: viz., volume of paste, release efficiency, and st. dev./vol. It is seen from the plot that cells H and L are statistically the best performing cells, and cell A performs the worst for each of the three response variables. Cells H and L have a high degree of electropolish, and medium and high taper, respectively. Cell A has a low degree of wall taper and no electropolish.

A	B	C	D
284.77	307.67	318.91	334.57
E	F	G	H
340.09	339.18	353.56	394.27
I	J	K	L
379.00	368.76	362.17	399.63

A	B	C	D
53.91	57.55	58.61	63.11
E	F	G	H
62.44	62.3	64.36	68.5
I	J	K	L
65.27	66.84	62.54	67.7

A	B	C	D
24.67	17.82	16.21	15.07
E	F	G	H
11.9	12.94	13.08	10.31
I	J	K	L
11.08	12.38	11.95	9.22

Figure 8: Volume, transfer eff. & st. dev. / volume for 5 mil thick laser-cut stencil. (Please note apertures of Cell D are Chemically etched.)

Effect of Taper

The following plots show the effect of degree of taper on circular apertures of all sizes.

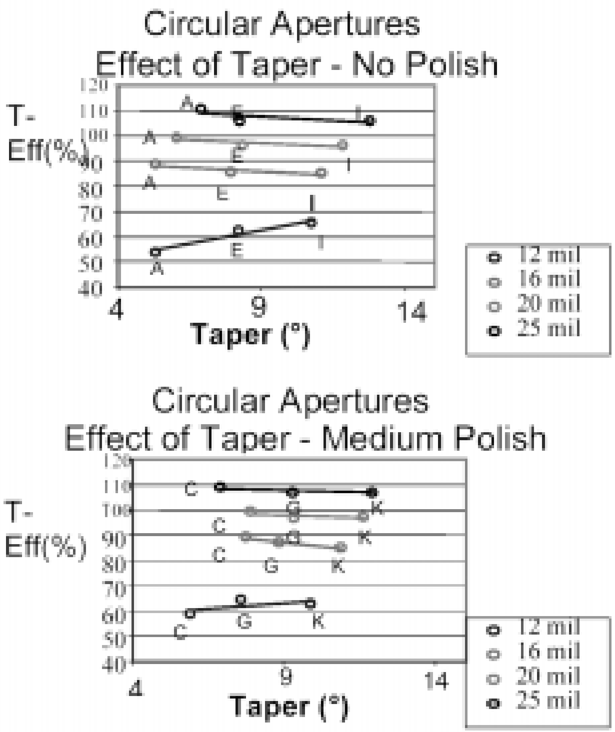

Figure 9: Effect of taper on transfer efficiency.

The graphs above clearly indicate the effect of taper for the 5 mil thick stencil. It is seen that for smaller apertures the increase in taper increases transfer efficiency, whereas for larger apertures (16 mil and above) taper does not have as much of an effect as it has for the smaller apertures. For larger apertures, cells with less degree of wall taper show higher transfer efficiency. The above trend is consistent with the square geometry.

Effect of Electropolish

The degree of electropolish certainly effects the release characteristics of the stencil aperture. Electropolish is usually provided to smoothen the surface finish of the aperture walls. This reduces the overall surface area of the aperture walls that comes in contact with the solder paste, thereby enhancing paste release. Also, in addition to smoothening the wall finish, the polishing slightly reduces the overall thickness of the stencils, thereby increasing the area ratio and aspect ratio of an aperture.

Wipe Frequency

The wipe frequency is determined by the clogging of the stencil, which is indicated by a drastic drop in the transfer efficiency and/or rise in the standard deviation / mean volume. The objective of this experiment is to determine the wipe frequency for the 5 mil thick stencils, in other words, the number of boards that can be printed before it affects print quality. The optimized print parameters were used to print 100 boards. Stencil underside wiping is not used between prints.

The following plots (Figure 10) show the transfer efficiency and standard deviation / mean volume for 10 mil circles and 12 mil circles.

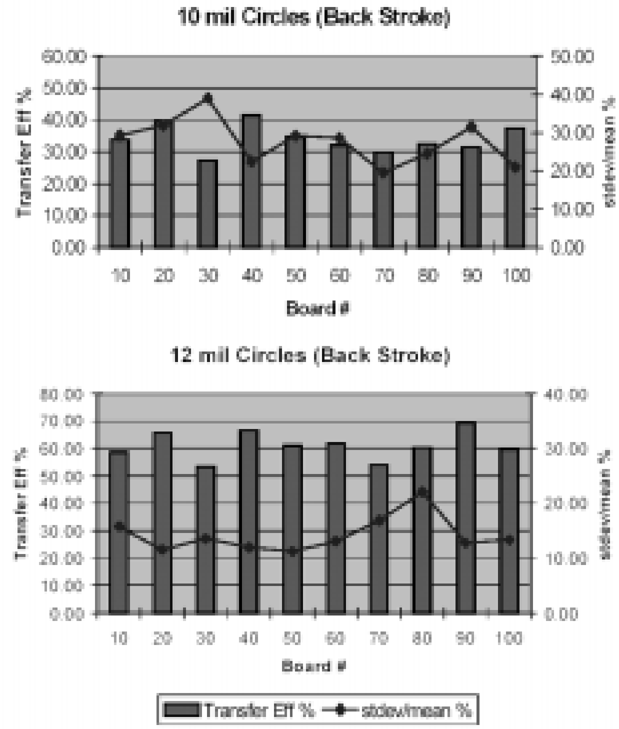

Figure 10: Effect of boards printed without wiping.

From the plots above it is seen that there was no significant drop in transfer efficiency and no increase in st. dev. / mean volume for about 100 boards.

Comparison Between Squares and Circles

The figure below shows the effect of circular and square geometry with respect to transfer efficiency for 12 mil aperture openings.

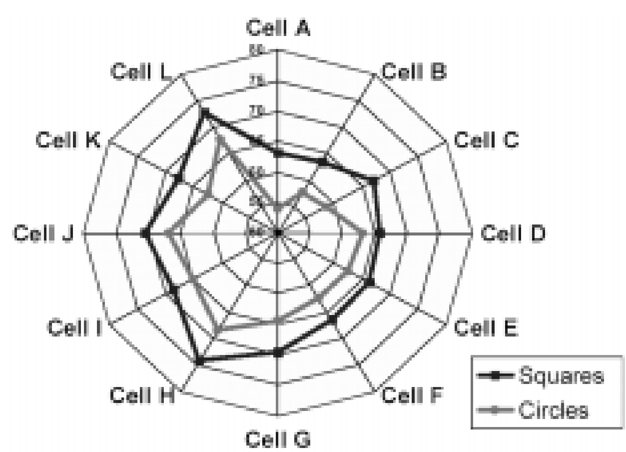

Figure 11: Comparison between circles and squares.

It is seen that for a given size, the square geometry performs better than the circular geometry for all the sizes considered in this study. The better performance of the square apertures could be attributed to higher initial design volume of the aperture.

Comparison between Different Manufacturing Techniques

For comparing the different stencil manufacturing techniques, the best performing cell is chosen from each stencil. The following plot shows the comparison between the manufacturing techniques with the absolute volume of solder paste as the response variable.

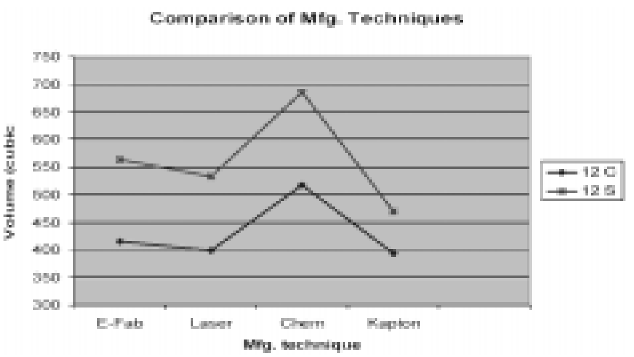

Figure 12: Comparison of manufacturing techniques.

Figure 12 shows the relative performance of different manufacturing techniques. It is seen that chem-etch stencil deposits more volume, however this could be due to overetching of the aperture walls, which is inherent to any chemetch process. Amongst the other stencils, the E-form stencil performs better than the laser-cut stencil. This trend is consistent for the larger apertures, as well. No significant benefit is observed for the polyimide stencil.

CONCLUSIONS & RECOMMENDATIONS

The results from the print optimization study emphasize the importance of aperture design on the final outcome of the stencil printing process.

Aperture wall taper has a positive effect on the transfer efficiency, and at the same time it helps in reducing the standard deviation. A difference of 0.8 to 1.1 mils between the board side and squeegee side diameter of an aperture is found to result in optimum paste release.

The benefits of high taper are consistent across different aperture sizes and geometries. For fine pitch, small apertures, we have to be careful not to increase the taper so much that an increase in transfer efficiency might be offset by a reduced amount of paste deposited on the board.

The degree of electropolish helps to have a better aperture wall finish, which further enhances paste release efficiency.

For a given size and area ratio, the square geometries have better paste transfer efficiency, low standard deviation, and higher volume of paste deposited than the circular apertures.

E-form stencils perform better than laser-cut stencils; the better performance of chem-etch stencils could be due to over etching of aperture walls.

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BIOGRAPHY

Ian Fleck was the global business development manager, Cookson Electronics for Alpha Stencil and Printing Plate Group, prior to heading up stencil sales for North and South America. He was born and educated in Scotland and employed mainly in the printing and electronics industries before coming to the United States.

Ian has fifteen years of combined employment experience in Great Britain with The British Printing Corporation and chemical giant DuPont de Nemours, where he offered knowledge of the new communication technologies to be used by industries in the future. He also has three years of experience running his own business, selling products to the surface mount industry in the UK, which made the switch to stencil product management in the US much easier.

In 1992 Ian Fleck joined Alpha USA as product manager to introduce laser cutting processes for making surface mount stencils. After establishing Alpha as the world's number one supplier of stencils, he became a regional sales manager in 1996 for all Alpha products in the US before returning to the Alpha Stencil Group in June of 2001.

Prashant Chouta is a project manager at Cookson Electronics Process Technology located in Foxborough, MA. He is currently involved in advanced research projects providing process engineering solutions for the various sectors of Cookson Electronics and its customers.

He has led teams that are focused on providing key technical solutions and is currently the project chair for NEMI Optoelectronic Soldering Automation Project. Prior to that he served as a consultant with the consulting group of Speedline Global Services Group, where he was involved in process improvement programs and SMT certification program for process engineers.

He has contributed towards numerous technical publications and textbooks. He holds a B.E. in mechanical engineering from Maharashtra Institute of Technology, Pune, and a M.S. in industrial engineering from Binghamton University, NY, with a special focus on electronics packaging.

APPENDIX

Optimization Results

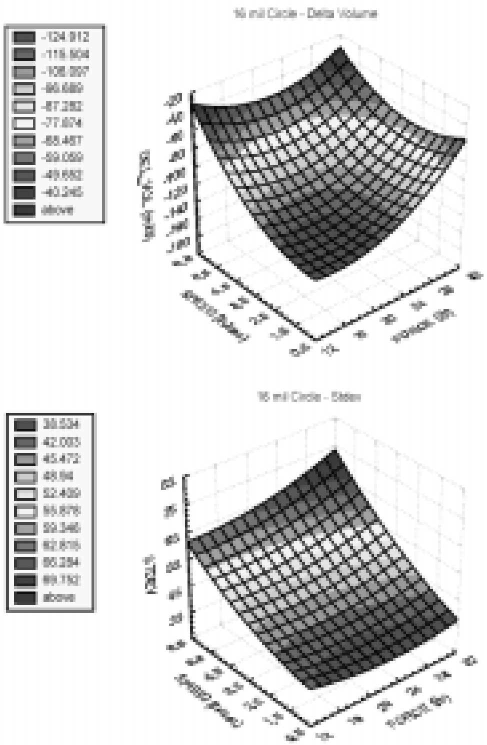

Figure 13: Optimization results for 16 mil circles.

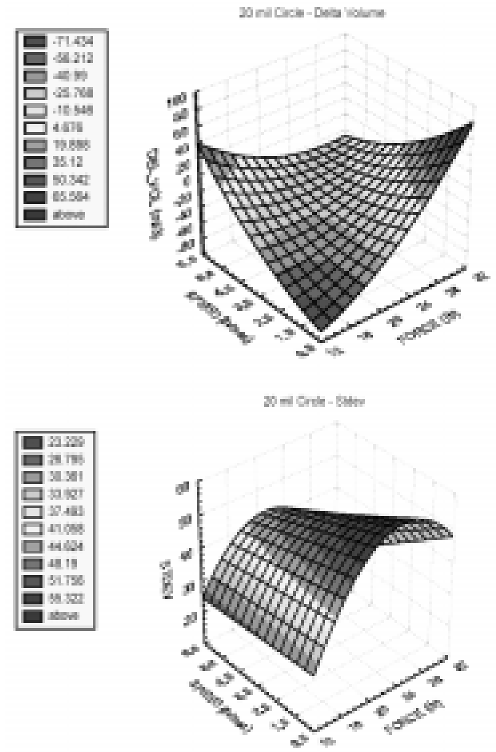

Figure 14: Optimization results for 20 mil circles.

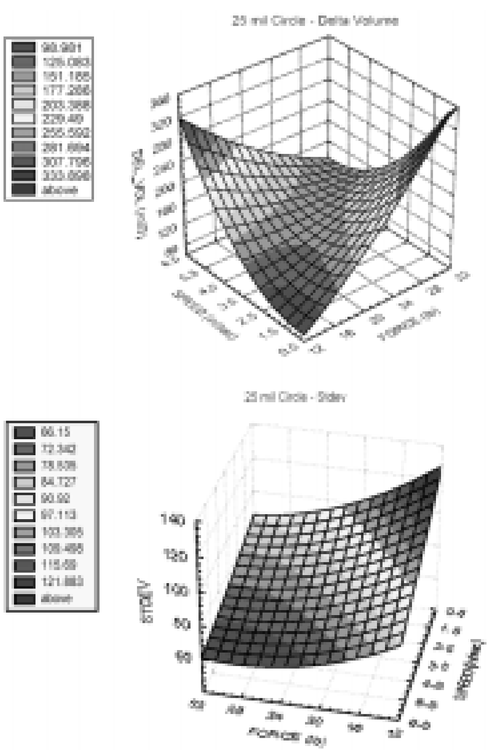

Figure 15: Optimization results for 25 mil circles.

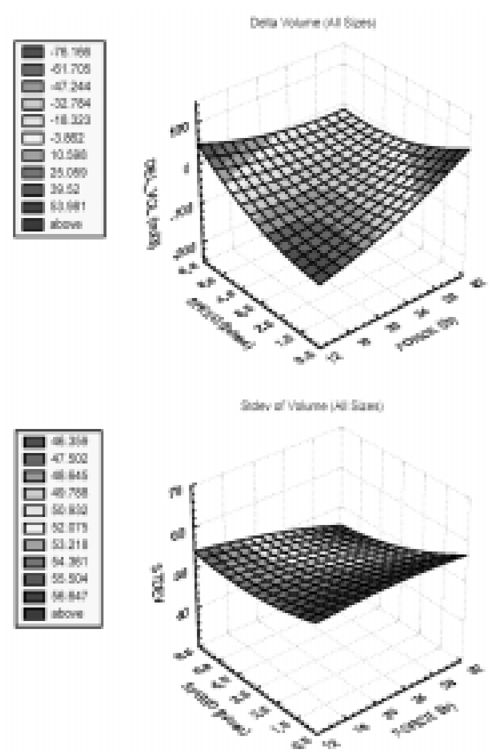

Figure 16: Optimization results for all sizes combined.

Multiple Comparison & Paired -t Test

Tukey's test is used to perform multiple comparisons of different cells. Shown below is an example of a multiple comparison test using Tukey's method for transfer efficiency for 12 mil circles.

The cell with the maximum transfer efficiency is determined from the data below. Cell H has the highest mean, and hence it is the best performing cell. However, it is necessary to determine if cell H is statistically the best. This is done by using the confidence intervals for the cells shown below. The mean transfer efficiency over 30 boards is compared for each cell.

Analysis of 12 mil circles, 5 mil thick stencil , forward stroke

```
Source   DF    SS       MS     F      P
Cell ID  11    6181.7   562.0  10.84  0.000
Error    348   18047.1  51.9
Total    359   24228.8
                        Individual 95% CIs For Mean
                        Based on Pooled St. Dev.

Level    N     Mean     StDev   -----+---------+---------+---------+-
Cell_A   30    53.912   8.080  (---*---)
Cell_B   30    57.553   10.326     (---*---)
Cell_C   30    58.613   8.901       (----*---)
Cell_D   30    63.116   5.783                 (---*----)
Cell_E   30    62.441   5.731               (---*---)
Cell_F   30    62.309   8.054               (---*---)
Cell_G   30    64.360   7.623                   (---*----)
Cell_H   30    68.509   4.803                         (---*---)
Cell_I   30    65.273   7.250                   (----*---)
Cell_J   30    66.840   7.155                      (---*----)
Cell_K   30    62.549   6.194                (---*----)
Cell_L   30    67.700   4.092                       (---*---)
                                -----+---------+---------+---------+-
Pooled StDev = 7.201              54.0      60.0      66.0      72.0
```

Tukey's pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.00120

Critical value = 4.62
Intervals for (column level mean) - (row level mean)

The cells are compared with other cells, and a confidence interval is generated for each comparison. Consider the comparison of cell H and cell L. The confidence interval goes from a negative number (-5.266) to a positive number (6.883), and thus includes zero, and hence they are not statistically different according to Tukey's test. A paired -test is performed to determine statistically the difference between cells.

Paired -t Test

Paired -t test is performed on cells that have zero in their confidence intervals. For example, cell H is compared to all the other cells whose confidence interval contains zero. Similar analysis is performed for the worst cell, but in this case the cell with the least transfer efficiency is considered.

In the paired -t test every board for a cell is compared to the board for the other cell. The difference between two cells is calculated. If the confidence interval for the combination again contains zero, and the p-value is greater than 0.05, then the cells are not statistically different. (Results are then entered into tables similar to Figure 8. The following is an illustration of paired -t test for transfer efficiency. Similar analysis is performed for volume and st. dev./vol.).

	Cell A	**Cell B**	**Cell C**	**Cell D**	**Cell E**	**Cell F**	**Cell G**	**Cell H**	**Cell I**	**Cell J**	**Cell K**
Cell B	-9.715 2.434										
Cell C	-10.776 1.373	-7.135 5.014									
Cell D	-15.279 -3.13	-11.638 0.511	-10.577 1.572								
Cell E	-14.604 -2.455	-10.963 1.185	-9.902 2.246	-5.4 6.749							
Cell F	-14.472 -2.323	-10.831 1.318	-9.77 2.378	-5.267 6.881	-5.942 6.206						
Cell G	-16.523 -4.374	-12.882 -0.733	-11.821 0.327	-7.318 4.83	-7.993 4.156	-8.125 4.023					
Cell H	-20.671 -8.523	-17.031 -4.882	-15.97 -3.821	-11.467 0.681	-12.142 0.007	-12.274 -0.125	-10.223 1.925				
Cell I	-17.435 -5.287	-13.795 -1.646	-12.734 -0.585	-8.231 3.917	-8.906 3.243	-9.038 3.111	-6.987 5.161	-2.838 9.31			
Cell J	-19.002 -6.854	-15.362 -3.213	-14.301 -2.152	-9.798 2.35	-10.473 1.676	-10.605 1.543	-8.554 3.594	-4.405 7.743	-7.641 4.507		
Cell K	-14.712 -2.563	-11.071 1.078	-10.01 2.138	-5.507 6.641	-6.182 5.966	-6.314 5.834	-4.263 7.885	-0.114 12.034	-3.351 8.798	-1.783 10.365	
Cell L	-19.863 -7.714	-16.222 -4.073	-15.161 -3.013	-10.658 1.49	-11.333 0.815	-11.465 0.683	-9.414 2.734	-5.266 6.883	-8.502 3.647	-6.934 5.214	-11.225 0.923

Table 3: Confidence intervals for different cells.

Shown below are the paired -t test for the best cell for T-Eff for 12 mil circles.

Paired T for Cell D - Cell H

	N	Mean	Stdev	SE Mean
Cell D	30	63.12	5.78	1.06
Cell H	30	68.51	4.80	0.88
Difference	30	-5.393	5.209	0.951

95% CI for mean difference: (-7.338, -3.448)
T-Test of mean difference = 0 (vs not = 0): T-Value = -5.67, P-Value = 0.000

Paired T for Cell E - Cell H

	N	Mean	StDev	SE Mean
Cell E	30	62.44	5.73	1.05
Cell H	30	68.51	4.80	0.88
Difference	30	-6.068	4.563	0.833

95% CI for mean difference: (-7.771, -4.364)
T-Test of mean difference = 0 (vs not = 0): T-Value = -7.28, P-Value = 0.000

Paired T for Cell G - Cell H

	N	Mean	StDev	SE Mean
Cell G	30	64.36	7.62	1.39
Cell H	30	68.51	4.80	0.88
Difference	30	-4.149	5.245	0.958

95% CI for mean difference: (-6.107, -2.190)
T-Test of mean difference = 0 (vs not = 0): T-Value = -4.33, P-Value = 0.000

Paired T for Cell I - Cell H

	N	Mean	StDev	SE Mean
Cell I	30	65.27	7.25	1.32
Cell H	30	68.51	4.80	0.88
Difference	30	-3.24	6.23	1.14

95% CI for mean difference: (-5.56, -0.91)
T-Test of mean difference = 0 (vs not = 0): T-Value = -2.85, P-Value = 0.008

Paired T for Cell J - Cell H

	N	Mean	StDev	SE Mean
Cell J	30	66.84	7.15	1.31
Cell H	30	68.51	4.80	0.88
Difference	30	-1.67	6.71	1.22

95% CI for mean difference: (-4.17, 0.84)
T-Test of mean difference = 0 (vs not = 0): T-Value = -1.36, P-Value = 0.184

Paired T for Cell K - Cell H

	N	Mean	StDev	SE Mean
Cell K	30	62.55	6.19	1.13
Cell H	30	68.51	4.80	0.88
Difference	30	-5.960	5.185	0.947

95% CI for mean difference: (-7.896, -4.024)
T-Test of mean difference = 0 (vs not = 0): T-Value = -6.30, P-Value = 0.000

Paired T for Cell L - Cell H

	N	Mean	StDev	SE Mean
Cell L	30	67.700	4.092	0.747
Cell H	30	68.509	4.803	0.877
Difference	30	-0.809	3.696	0.675

95% CI for mean difference: (-2.189, 0.571)
T-Test of mean difference = 0 (vs not = 0): T-Value = -1.20, P-Value = 0.240

Cells H, J, and L are not statistically different and classify as best Cells for transfer efficiency.