Investigating 0201 Printing Issues and Stencil Design

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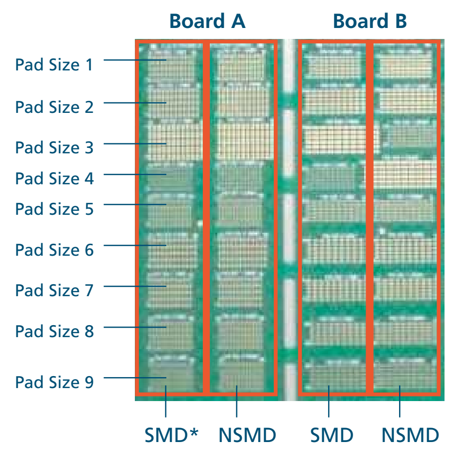
Experimental results on printer settings, stencil design and stencil technology for 0201s.

Many of today's consumer electronic products require miniaturization of components and high-density assembly on printed circuit boards (PCBs). With these demands, 0201 packages have become an interesting topic to study in electronics manufacturing.

To investigate PCB design and assembly processes on 0201 packages, a 0201 test vehicle was designed that included important design factors such as pad size, pad shape, solder-mask-defined pads vs. non-solder-mask-defined pads, and spacing between components. Nine types of pad designs with different pad sizes and shapes for 0201 packages were tested. Following are the results from experiments designed to understand printing issues, such as printer settings, stencil design and stencil technology.

Test Vehicle

A test vehicle (Figure 1), a six-layer FR-4 board with a nickel/gold pad finish, was designed for the 0201 process evaluation. The test vehicle had four boards in a panel, with outside dimensions of 3.5 in. x 1.4 in. for the board and 5 in. x 7 in. for the panel. Boards A and B had a total of 36 groups of 0201s. The 18 groups of 0201s on board A had a vertical orientation, and the 18 groups of 0201s on board B had a horizontal orientation. Sixty 0201s were designed in each group. Within these 60 0201s, 30 0201 pads had via in pad and the other 30 0201 pads did not have via in pad. Nine types of pad designs were used: four with rectangular shape, two with round shape and three with home-based shape, with different dimensions.



** SMD refers to solder-mask-defined pad, and NSMD refers to non-solder-mask-defined pad.*

FIGURE 1: A picture of the topside of board A and board B on the 0201 test vehicle. The orientation of 0201s on board A is vertical and horizontal on board B.

Stencils

Two stencil technologies were tested in the experiment: laser-cut-with-polish and electroform. The aperture shape was the same as the pad shape, while the ratio of aperture to pad size was 120%, 100% and 80%. Table 1 shows the area ratio of the apertures on each type of opening, with 5 mil stencil thickness.

Solder paste

The solder paste used in this work was a eutectic (63Sn/37Pb), no-clean solder paste with particle size type 3 and type 4.

Printer Optimization

For printer optimization, three parameters with the values of low, medium and high were identified based on experience and recommendations from the solder paste vendor and the printer vendor. By using the Box-Baken Design of Experiments (DOE) Method, a total of 13 sets of parameters were designed for this experiment. The printer settings are provided in Table 2. The laser-cut with polish stencil and a no-clean type 4 solder paste were used for this test

The solder paste height measurement data were analyzed, with the data obtained from the solder-mask-defined pads and the non-solder-mask-defined pads analyzed separately. In addition, based on experience, if the area ratio is lower

Pad	--------- Area Ratio ---------		
	120%	100%	80%
Pad Size 1	0.58	0.53	0.47
Pad Size 2	0.67	0.61	0.55
Pad Size 3	0.94	0.86	0.77
Pad Size 4	0.40	0.37	0.33
Pad Size 5	0.65	0.59	0.53
Pad Size 6	0.86	0.79	0.70
Pad Size 7	0.75	0.68	0.61
Pad Size 8	0.71	0.65	0.58
Pad Size 9	0.68	0.62	0.55

TABLE 1: Area ratio calculated based on stencil aperture openings.

1	H	M	L	1.36	0.97
2	M	H	H	1.32	1.32
3	H	L	M	1.12	1.04
4	L	M	L	1.90	1.10
5	M	H	L	1.68	1.16
6	H	M	H	1.24	1.16
7	M	L	H	1.12	0.8
8	M	M	M	1.60	1.05
9	M	L	L	1.44	0.98
10	H	H	M	1.24	1.03
11	L	H	M	0.79	1.28
12	L	M	H	1.01	1.64
13	L	L	M	1.45	1.35

TABLE 2: Printing DOE and C_{PK} data for solder paste height.

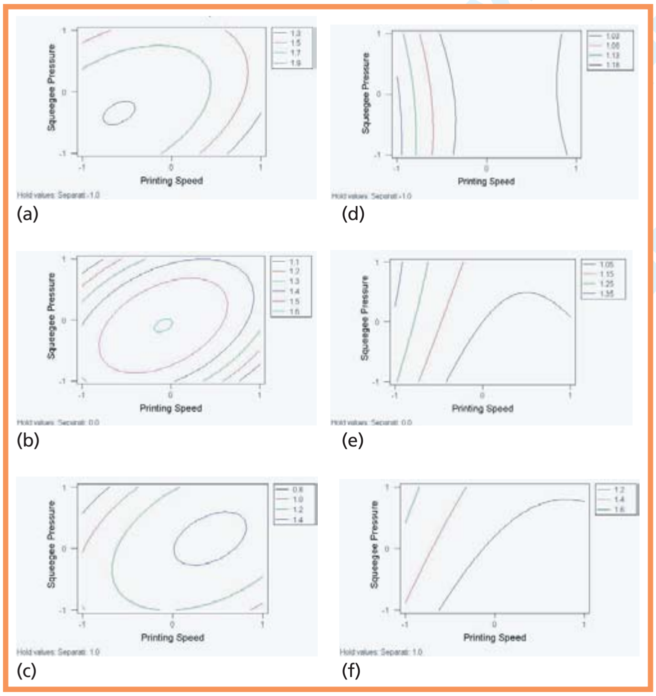
Plot	Pad Definition	Separation Speed	Printing Speed	Squeegee Pressure	Highest CpK
figure 7 (a)	SMD*	L	L to M	L to M	1.90
figure 7 (b)	SMD	M	M	M	1.80
figure 7 (c)	SMD	H	M-H	M	1.40
figure 7 (d)	NSMD	L	L	L to M	1.18
figure 7 (e)	NSMD	M	L	H	1.37
figure 7 (f)	NSMD	H	L	H	1.60

** SMD refers to solder-mask-defined pad, and NSMD refers to non-solder-mask-defined pad.*

TABLE 3: Recommendation from DOE analysis.

than 0.5, poor printing quality is expected. Therefore, when performing the C_{PK} calculation, the data obtained from the apertures with an area ratio lower than 0.5 were not included in the data analysis.

The calculated C_{PK} for each set of parameter settings is provided in Table 2. For the calculation on the solder-mask-defined pads, the specification used was 4 mils to 6 mils, while, on the non-solder-mask-defined pads, the specification utilized was 4.5 mils to 6.5 mils. Different solder paste height specification was employed in the calculation because an average of 0.5 mil of solder paste height difference between the solder-mask-defined pads and the non-solder-mask-defined pads was observed during the solder paste height analysis.



(a) (d)

(b) (e)

(c) (f)

FIGURE 2: Contour analysis on printer setting optimization. The analysis conditions are listed as the following:
a) on solder-mask-defined pads when separation speed at low
b) on solder-mask-defined pads when separation speed at medium
c) on solder-mask-defined pads when separation speed at high
d) on non-solder-mask-defined pads when separation speed at low
e) on non-solder-mask-defined pads when separation speed at medium
f) on non-solder-mask-defined pads when separation speed at high.

Based on the C_{PK} data in Table 2, the best four printer settings for solder-mask-defined pads were Run #4, #5, #8 and #13, while the best four printer settings for non-solder-mask-defined pads were Run #12, #13, #2 and #11. Comparing the above printer settings, Run#13 is the optimized printer setting for both types of pads.

DOE Analysis

The C_{PK} data in Table 2 were used as a response in the Box-Baken DOE analysis. Contour plots for three printer parameters—printing speed, squeegee pressure and separation speed—on both solder-mask-defined and non-solder-mask-defined pads are presented in Figure 2. The recommendations from each of the contours are listed in Table 3.

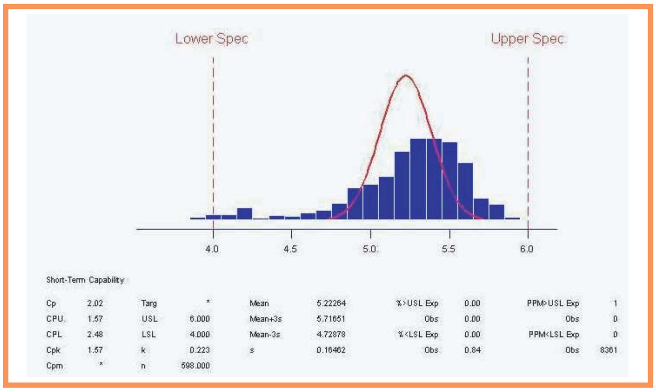
For solder-mask-defined pads, the separation speed does not influence the C_{PK} of solder paste height significantly. The recommendation for printer settings for these pads is to use medium printing speed and medium squeegee pressure.

For non-solder-mask-defined pads, the printing speed used in the printer should always be slow, while the squeegee pressure will depend on the separation speed. When the separation speed is low, the squeegee pressure should be low to medium; when the separation speed utilized is medium to high, the squeegee pressure used should be high.

However, when low separation speed was used for non-solder-mask-defined pads, the C_{PK} of the solder paste height was only 1.18; therefore, for a board with both types of pads, separation speed of medium to high is recommended. Considering that non-solder-mask-defined pads have lower solder paste height C_{PK} than solder-mask-defined pads, low printing speed and high squeegee pressure are recommended.

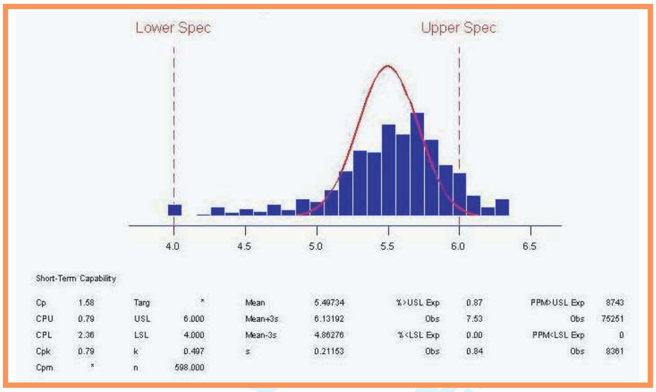
Solder Paste Height

Figures 3 and 4 illustrate the 0.5 mil difference between both types of pads for different area ratios. The solder paste height on non-solder-mask-defined pads is lower than that of solder-mask-defined pads when the area ratio is below 0.53. With the area ratio increase, the solder paste height on non-solder-mask-defined pads becomes higher than that of solder-mask-defined pads.



Cp	2.02	Targ	*	Mean	5.22264	%>USL Exp	0.00	PPM>USL Exp	1
CPU	1.57	USL	6.000	Mean+3s	5.71651	Obs	0.00	Obs	0
CPL	2.48	LSL	4.000	Mean-3s	4.72878	%<LSL Exp	0.00	PPM<LSL Exp	0
Cpk	1.57	k	0.223	s	0.16462	Obs	0.84	Obs	8361
Cpm	*	n	598.000						

FIGURE 3: Solder paste height distribution on data obtained from solder-mask-defined pads.



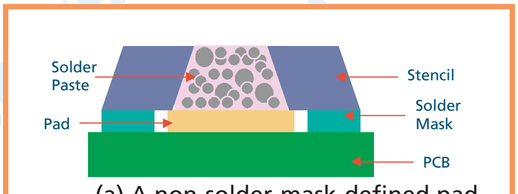
Cp	1.58	Targ	*	Mean	5.49734	%>USL Exp	0.87	PPM>USL Exp	8743
CPU	0.79	USL	6.000	Mean+3s	6.13192	Obs	7.53	Obs	75251
CPL	2.36	LSL	4.000	Mean-3s	4.86276	%<LSL Exp	0.00	PPM<LSL Exp	0
Cpk	0.79	k	0.497	s	0.21153	Obs	0.84	Obs	8361
Cpm	*	n	598.000						

FIGURE 4: Solder paste height distribution on data obtained from non-solder-mask-defined pads.

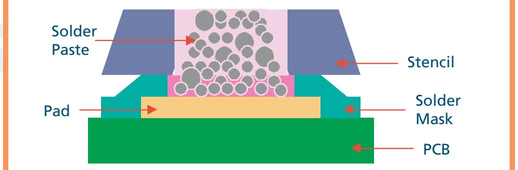
For solder paste volume comparison between both types of pads, the data show that, when the area ratio is lower than 0.53, the solder paste volume on non-solder-mask-defined pads is lower than on solder-mask-defined pads. However, when the area ratio is higher than 0.53, the ratio between solder paste volume on both types of pads ranges from 70% to 107%, and most of the data are between 80% and 100%.

These data indicate that, although the solder paste height on non-solder-mask-defined pads is higher than on solder-mask-defined pads, the solder paste volume on the former is lower than on the latter. Because the same aperture opening was used on both types of pads, the solder paste height difference is not a stencil-related issue. The phenomena could be explained as different solder paste behavior when separating a stencil from different types of printed pads.

Figure 5 shows a simple structure of both types of pads printed. As can be seen, since solder mask is underneath the stencil, more solder paste was printed on a solder-mask-defined pad than on a non-solder-mask-defined pad; therefore, solder paste volume on a solder-mask-defined pad is higher than on a non-solder-mask-defined pad.



(a) A non-solder-mask-defined pad



(b) A solder-mask-defined pad

FIGURE 5: Structure of pads with different solder mask definition method.

Also, due to the existence of the solder mask, two parts of solder paste are above a solder-mask-defined pad. The first part is the solder paste surrounded by the solder mask, which is attached to the pad; the second is the part of the solder paste surrounded by the metal stencil. While on a non-solder-mask-defined pad, only the second part of solder paste exists. The solder paste height difference is due to the existence of the first part of solder paste.

When removing a stencil from a printed solder-mask-defined pad, the behaviors of the two parts of solder paste are different. The part of the solder paste surrounded by a solder mask will stay on the pad because of the adhesion between the pad and the solder paste. However, the part of the solder paste surrounded by a metal stencil will be pulled up due to adhesion between the solder paste and the aperture wall.

When removing a stencil from a printed non-solder-mask-defined pad, only the center part of solder paste adheres to the pad because the outside paste particles will be pulled by the stencil. Therefore, the solder paste printed on a solder-mask-defined pad holds its shape better than on a non-solder-mask-defined pad.

By using optical solder paste measurement equipment, a sample of the solder paste height and volume was taken, and the results were consistent with that obtained from the three-dimensional (3-D) laser solder paste measurement machine. Optical pictures and 3-D contour graphs taken from pad size 3 on both types of pads are provided in Figure 6. Although the contour graphs indicate a 0.5 mil height difference between the types of pads, the optical pictures indicate no significant difference in shape between the solder paste on both types of pads.

Stencil Technology

An experiment was designed to compare the solder printer behavior with different stencil technologies such as electroform and laser-cut with polish and different solder paste particle sizes such as type 3 and 4.

Stencil Inspection

The difference between the designed aperture and actual aperture dimensions, ΔD, was calculated after measurement. The ΔD on the electroform stencil is between 0 and 1.1 mil, whereas the ΔD on the laser-cut-with-polish stencil is between -1.7 mils and +2.1 mils. Therefore, the quality of the laser-cut-with-polish stencil is not as good as the electroform stencil.

Based on the data of the aperture opening, solder paste volume was calculated for each type of aperture. The percentage of volume difference between the actual and designed aperture vol-

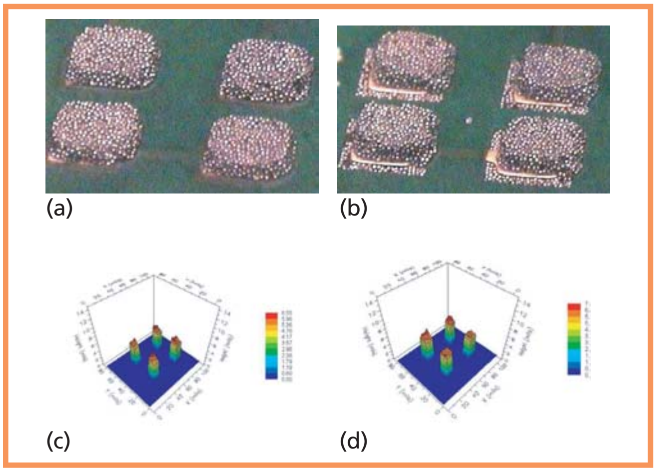


FIGURE 6:

a) A picture taken from pad size 3 with solder-mask-defined pad and 120% aperture opening on stencil.
b) A picture taken from pad size 3 with non-solder-mask-defined pad and 120% aperture opening on stencil.
c) A 3-D picture with measurement from the same location at (a).
d) A 3-D picture with measurement from the same location at (b).

ume on both types of stencils was also calculated and presented in Figure 7. The percentage of volume difference between the actual and designed aperture volume on the electroform stencil

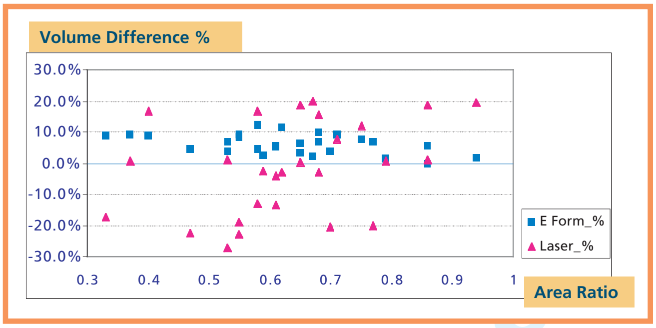
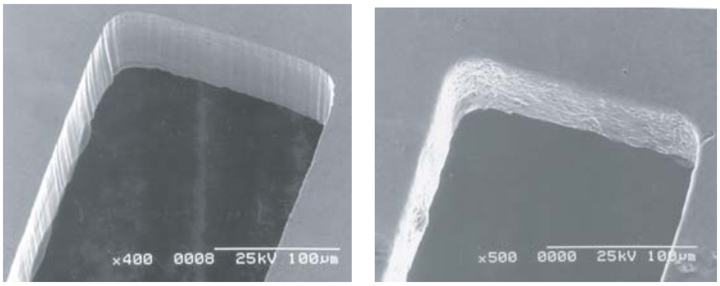


FIGURE 7: The percentage of volume difference between the actual and designed aperture volume on the electroform stencil and the laser-cut-with-polish stencil, versus the area ratio.

is in the range of 0 to 12%, while, on the laser-cut-with-polish stencil, the range is –30% to +20%.

Two stencil coupons were obtained from the stencil vendors to verify the stencil quality. The stencil thickness was measured, and the results met the design requirement. The two pictures (Figure 8) taken with a scanning electron microscope (SEM) illustrate that the aperture wall in the electroform stencil is smoother than in the laser-cut-with-polish stencil. This difference may lead to different solder paste releasing behaviors.

The data obtained from both types of stencils indicate that the electroform stencil has a better quality than the laser-cut stencil.



(a) Electroform stencil (b) Laser-cut with polish stencil

FIGURE 8: SEM pictures taken from the electroform and laser-cut-with-polish stencils.

For electroform stencils, from the stencil manufacturing point of view, the spacing between two adjacent apertures must be larger than the thickness of the stencil. A minimum spacing between two apertures on a 4 mil thick stencil is 4 mils and 5 mils on a 5 mil thick stencil. However, on a laser-cut stencil, 4 mil spacing can be manufactured for a 4 mil, 5 mil or 6 mil thick stencil. Therefore, the stencil manufacturing capability is another concern when making a stencil.

Solder Paste Release and Stencil Technology

Printer setting #13 in Table 2 was utilized in this experiment. During printing, two boards were printed for each test condition. After printing, the solder paste height and volume and their standard deviation were collected by using 3-D laser measurement equipment. The solder paste release behaviors with different stencils were compared based on the solder paste volume.

For area ratios of 0.47 to 0.55, the electroform stencil delivers about 20% more solder paste volume than the laser-cut-with-polish stencil. Therefore, an electroform stencil is recommended if the area ratio is lower than 0.55.

For both electroform and laser-cut-with-polish stencils, only when an area ratio is 0.58 or beyond will it release over 60% of the designed solder paste volume. The releasing percentage rises when the area ratio increases. The trend shows that, when area ratio equals 1.0, the solder paste release reaches 100% for both types of stencils.

Solder Paste Release: Particle Size

The solder paste release behavior with different particle sizes on different stencils was studied for rectangular, round and home-based pads, respectively. The solder paste volume release percentage was calculated by dividing the actual solder paste volume with the actual aperture volume on the stencil.

On the rectangular pad, for the electroform stencil, the type 4 solder paste releases better than the type 3 paste by about 9% in solder paste volume. However, for the laser-cut-with-polish stencil on rectangular pads, the two types of solder paste exhibited similar releasing behaviors in terms of the solder paste volume.

On the round pad for electroform stencil, the type 4 solder paste releases about 13% more volume than the type 3 solder paste. For the laser-cut-with-polish stencil, the two types of solder paste exhibited similar release behaviors in terms of solder paste volume. The solder paste volume release percentage obtained at the area ratio of 0.65 is higher than at the area ratio of 0.68. At the location for area ratio 0.65, the actual aperture opening is larger than design; at the location for area ratio 0.68, the actual aperture opening is smaller than design. Therefore, the actual area ratios for these two locations are different from the theoretical values.

On the home-based pad, the solder paste type does not show significant impact on the solder paste release on both types of stencils.

Solder Paste Release: Non vs. Solder-Mask-Defined Pads

Both solder-mask-defined and non-solder-mask-defined pads have shown similar results in terms of solder paste release behavior, with both types of stencils and both types of solder paste. However, the overall solder paste volume on solder-mask-defined pads is about 20% higher than that on non-solder-mask-defined pads, regardless of the solder paste type and stencil technology.

For the type 3 solder paste, the solder paste release percentage on the solder-mask-defined pads is about 20% higher than on the non-solder-mask-defined pads; for the type 4 solder paste, solder paste release percentage on the solder-mask-defined pads is also about 20% higher than on the non-solder-mask-defined pads. On non-solder-mask-defined pads, the solder paste release percentage for the type 4 solder paste on apertures with area ratios larger than 0.65 is above 60%; for the type 3 solder paste, the solder paste release percentage is only about 50%.

Conclusions

For 0201 packages the electroform stencil exhibits about 20% higher solder paste release than the laser-cut-with-polish stencil when the area ratio ranges from 0.47 to 0.55. This result is because the aperture wall in an electroform stencil is smoother than a laser-cut-with-polish stencil. Therefore, the electroform stencil is recommended if the stencil aperture area ratio is lower than 0.55.

If an electroform stencil is used on rectangular pads, the type 4 solder paste delivers about 9% more solder paste than the type 3 solder paste; on round pads, the type 4 solder paste delivers about 13% more solder paste than the type 3 solder paste. However, if a laser-cut-with-polish stencil is used, the solder paste particle size is not a significant factor, regardless of the pad shape. ■

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