Stencil Design and Performance for Flip Chip/Wafer Bumping

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Abstract
There has been much recent interest in printing solder paste onto UBM pads of a wafer. Usually the wafer pad is overprinted using a stencil aperture that is larger than the wafer pad. This permits optimum bump height after reflow. There is also interest in printing solder paste onto flip chip pad sites on a substrate such as Fr4 or Ceramic.

This paper will examine stencil aperture designs for bumping applications. The test substrate contains 2 groups of pads; Group 1 has 4 mil (100-micron) pads on 10 mil (250-micron pitch), Group 2 has 4 mil (100 micron) on 14 mil (350-micron pitch). Group 1 is divided into 5 sectors of 400 sites per section. The stencil has 5 different aperture sizes for Group 1 ranging from 5.5 mil (140 micron) to 7.5 mil (190 micron). Group 2 has aperture sizes ranging from 8 mil (200 micron) to 12 mil (300 micron). AMTX Electroformed Stencils 1.5 mil (38 micron), 2.0 mil (50 micron) and 2.5 mil (63 micron) thick are used to print the Group 1 and Group 2 apertures. Bump height after reflow will be reported for each Group and compared to theoretical Bump Height and Print Area Ratios.

Key Words: Stencil, Electroformed Stencil, Area Ratio, Bump Height, Flip Chip, Wafer Bumping

Introduction

The ability of the paste to release from the inner aperture walls depends primarily on three major factors: (1) The Print Area Ratio[1] for the stencil design, (2) The aperture side wall geometry, (3) The aperture wall smoothness. Item (1) is aperture design related while items (2) and (3) are stencil technology related. The Print Area Ratio is the area beneath the aperture opening divided by the area of the inside aperture wall: For a rectangle the Print Area Ratio = [(LxW)/ (2(L+W) T)]; for a circle or a square it is (D or S)/ 4T where L = aperture length, W = aperture width, T = stencil thickness, D = aperture diameter, and S = side of a square. The generally accepted design guideline for acceptable paste release is for the Print Area Ratio to be greater than .66. When the stencil separates from the substrate, paste release encounters a competing process: will it transfer to the pad on the substrate or will it stick to the side aperture walls? When the area of the surface receiving the paste is greater than 2/3 of the area of the inside aperture wall, the paste has a good probability of achieving 80% or better paste release. However, stencil technology has a direct influence on paste release and thus what is the acceptable Print Area Ratio. Stencil performance studies[2] have shown that Electroformed stencil, with mirror type aperture wall finish, release solder paste better than Laser-Cut or Chem-Etch stencils. Therefore AMTX electroformed stencils were used for this study.

In previous stencil studies[3], solder paste volume, solder paste volume dispersion, and the physical properties of the stencil were used to measure stencil performance. However in this study the solder paste bricks are melted during a reflow process forming solder bumps on the pads on the board. The Bump Height, Bump Diameter, Bump Area as well as the CV of each are the data basis for the present study.

Stencil and Board Design

The board design is shown in Figure 1. All of the pads on the board are 3.94 mils (100 micron) in diameter. The stencil design is shown in Table 1. The stencil apertures are larger than the board pads thus overprinting the pads. The Area Ratio and Theoretical Solder paste volume are shown for each stencil design. The Area Ratio (a measure of the ability of the paste to transfer from the stencil aperture to the board pad) is shown for the three-stencil thickness as a function of aperture size in Figure 2. The theoretical ball height is shown in Figure 3 for the different thickness stencils as a function of aperture size. This height is calculated from the truncated sphere formula $V_{bump} = \pi(H^3/6 + D^2H/8)$; where H = ball height and D = pad diameter. The theoretical amount of solder paste printed on the pad is the area of the aperture times the thickness of the stencil or $\pi A^2T/4$ where A is the diameter of the aperture and T is the stencil thickness. Normally solder paste shrinks about 50% when it is reflowed to form solid solder. Since V_{bump} is the volume of solid solder for the truncated sphere twice the amount of solder paste is needed to achieve this volume. Figure 3 shows the Theoretical Bump height based on the theoretical volume of solder paste printed for the three stencil thickness 1.5 mils, 2.0 mils and 2.5 mils for all the aperture designs. Note that the pad diameter on the board is the same for all sites at 100 microns. Figure 4 shows solder-bricks overprinting the 100-micron pads using a 2.0 mil thick AMTX E-FAB having an 11 mil circle aperture. Note the bottom row shows the pad without solder-paste printed on the pad as a reference. Figure 5 shows the solder bumps after reflow. The actual measured height of the solder bump (truncated sphere) is 4.6 mils (117 microns) compared to the theoretical height of 5.5 mils (140 microns). A close up of this solder bump is shown in Figure 6. Although contact printing was successful for printing solder paste for bumping the small substrate it may not be the best for printing on large fully populates wafers. An accompanying paper[4] describes printing of solder paste on a 200 mm fully populated wafer using 2.0 mil and 2.7 mil thick AMTX E-FAB. This paper demonstrates that off-contact printing gave significantly better print results.

Figure 1 - Test Board Layout

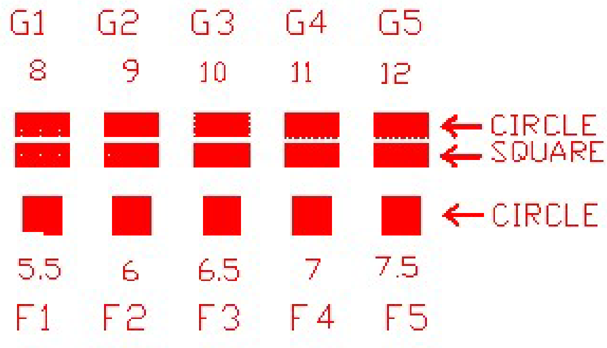

Table 1 - Stencil Design Configurations

Stencil Design Configurations										
Aperture Shape	**Aperture Size**	**Stencil Thickness**	**Area Ratio**	**Theoretical Volume**	**Stencil Thickness**	**Area Ratio**	**Theoretical Volume**	**Stencil Thickness**	**Area Ratio**	**Theoretical Volume**
Circle	5.5	2.5	0.55	59.4	2	0.69	47.5	1.5	0.92	35.64
Circle	6	2.5	0.60	70.7	2	0.75	56.5	1.5	1.00	42.41
Circle	6.5	2.5	0.65	83.0	2	0.81	66.4	1.5	1.08	49.77
Circle	7	2.5	0.70	96.2	2	0.88	77.0	1.5	1.17	57.73
Circle	7.5	2.5	0.75	110.4	2	0.94	88.4	1.5	1.25	66.27
Circle	8	2.5	0.80	125.7	2	1.00	100.5	1.5	1.33	75.40
Square	8	2.5	0.80	160.0	2	1.00	128.0	1.5	1.33	96.00
Circle	9	2.5	0.90	159.0	2	1.13	127.2	1.5	1.50	95.43
Square	9	2.5	0.90	202.5	2	1.13	162.0	1.5	1.50	121.50
Circle	10	2.5	1.00	196.4	2	1.25	157.1	1.5	1.67	117.81
Square	10	2.5	1.00	250.0	2	1.25	200.0	1.5	1.67	150.00
Circle	11	2.5	1.10	237.6	2	1.38	190.1	1.5	1.83	142.55
Square	11	2.5	1.10	302.5	2	1.38	242.0	1.5	1.83	181.50
Circle	12	2.5	1.20	282.7	2	1.50	226.2	1.5	2.00	169.65
Square	12	2.5	1.20	360.0	2	1.50	288.0	1.5	2.00	216.00

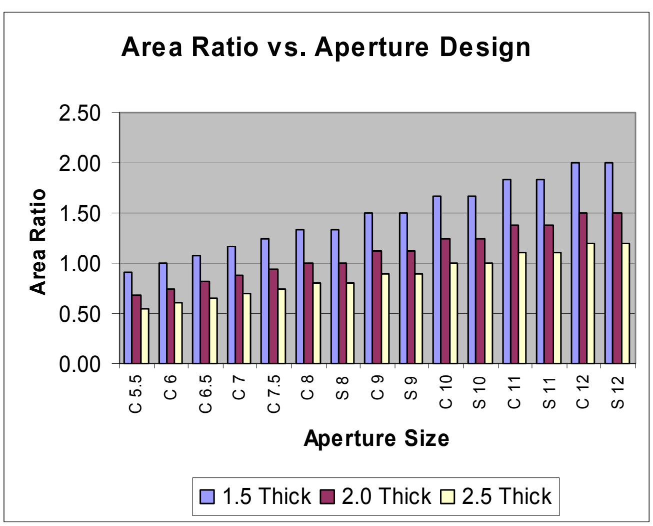

Figure 2 - Area ratio vs. Aperture Design

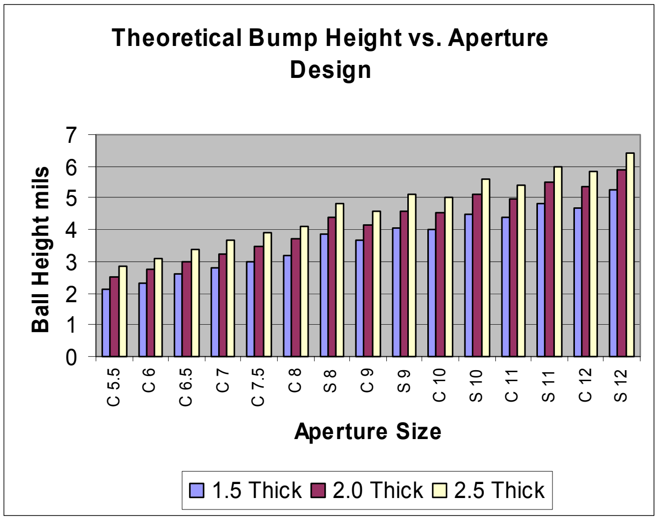

Figure 3 - Theoretical Bump Height vs. Aperture Design

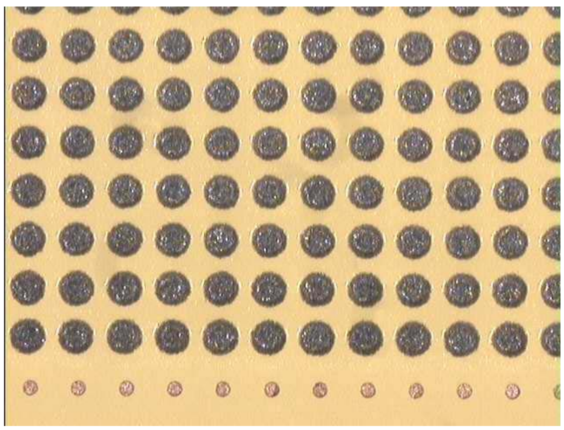

Figure 4 - Picture of Paste Bricks for an 11-mil Circular Aperture Using a 2-mil Thick Stencil

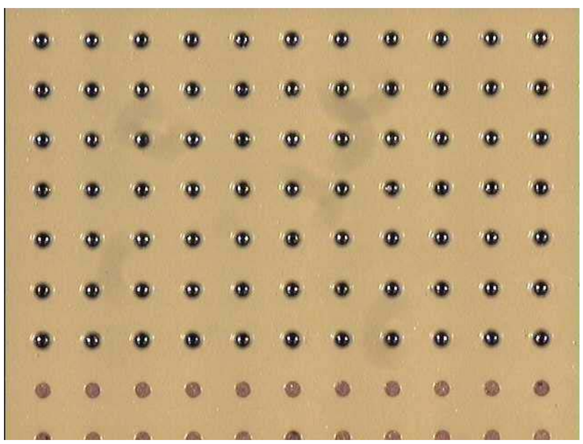

Figure 5 - Picture of Reflow Bump for Paste Brick of Figure 4

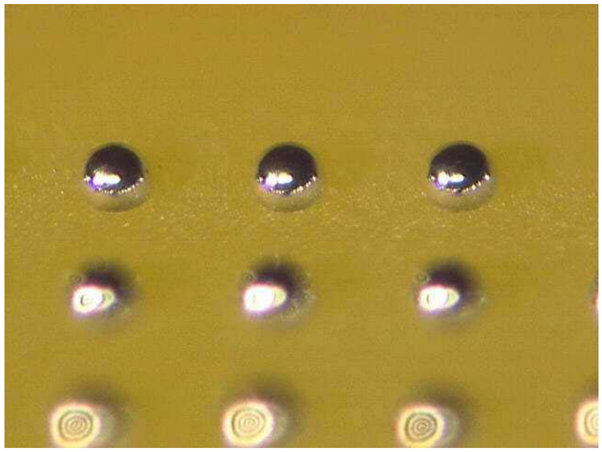

Figure 6 - Picture of a Close up of Bump in Figure 5

Measurements

Fr4 boards having 100-micron pads with 6,000 pad sites were used as the substrates. The printer was a DeK 265GSX which has a programmable squeegee pressure (fixed at 1kg/in squeegee length), separation speed (fixed at 2mm/sec), and print speed (fixed at 25mm/sec. A rubber squeegee of 80 durometer at 45^0 was used. There were two set up prints for each sequence followed by one forward and one reverse print. The data matrix consisted of 3 different thickness of stencils (1.5 mils, 2.0 mils, and 2.5 mils), three different solder paste (paste A and paste B are Type 6 water-soluble; paste C is a no-clean Type 6 paste) and two direction (forward and reverse) yielding a total of 18 printed boards. This yields a total of 108,000 data point sites.

The bump ball height was measured for all sites using CyberOptics laser scanning system with a PRS30 sensor having a 12 mil working range. An automated program was prepared for 100% inspection. For each 20 X 20 grid, the operator finds top of upper left ball by toggling X&Y searching for the shortest exposure time then automatic program is initiated. This program first measures the laminate height in all four corners of the grid to establish a baseline (average of all 4 readings), then moves to the first ball and takes 5 measurements 6 microns distance from each other and sorts for the two highest readings, averages them and subtracts the base height to yield the ball height. If the ball height is less than 1 mil then zero is entered. Once 20 balls are measured the data (1 row) is written to a text data file. This process is repeated until the entire 400 ball grid is complete, it then moves to the start point of the next grid and waits for the operator to align the beam. The data file is then imported into a spreadsheet.

The area or the bump and the diameter of the bump were measured for all 18 boards using an X-ray inspection system. Blank pads or pads very low in solder, artifacts, and small solder balls were filtered out by adjusting the Shape threshold and the Gray Level. The zoom was set to yield a 10 x 10 grid array of bump sites at full screen. All grids on each board were measured in-groups of 10 x 10; 4 groups per array site. The data was saved and the file imported into a spreadsheet.

Results

There are many ways to analyze the data, which has been collected. One way is to look at the ball height versus aperture size for the different paste types and different stencil thickness. This is shown in Figures 7, 8 and 9 for Paste A for the stencil thickness of 1.5mils, 2.0 mils and 2.5 mils. Figures 10, 11, and 12 show similar results for Paste C. The CV (Coefficient or Variance = Std Dev / Mean value) is also shown it these figures. Note that there is higher CV for the lower apertures especially for the thicker stencils. Also note that there is very high CV for the 12 mil square aperture. This relates back to a design violation for the stencil aperture. The web between apertures must remain at least greater than 1-1 compared to the thickness of the stencil. The web for the 12 mil aperture is 1.77 mils since the pitch is 13.77 mils. This web is too small and bridging occurs between apertures for the 2.0 and 2.5 mil thick stencils as seen in the CV numbers for Figures 8,9,11,12. A picture of the bridging between apertures for the 2.5 mil thick stencil is shown in Figure 13. Figure 14 shows the webs between apertures for the 1.5-mil thick stencil, which are well formed and OK. It can also be noted that there is no bridging of the circular apertures 12 mil in diameter on 13.77-mil pitch as seen in Figure 14. Since the spacing between apertures in only a point for the circle compared to the entire length of the square for the square the Nickel flow has an easier time to plate up between apertures for the circle.

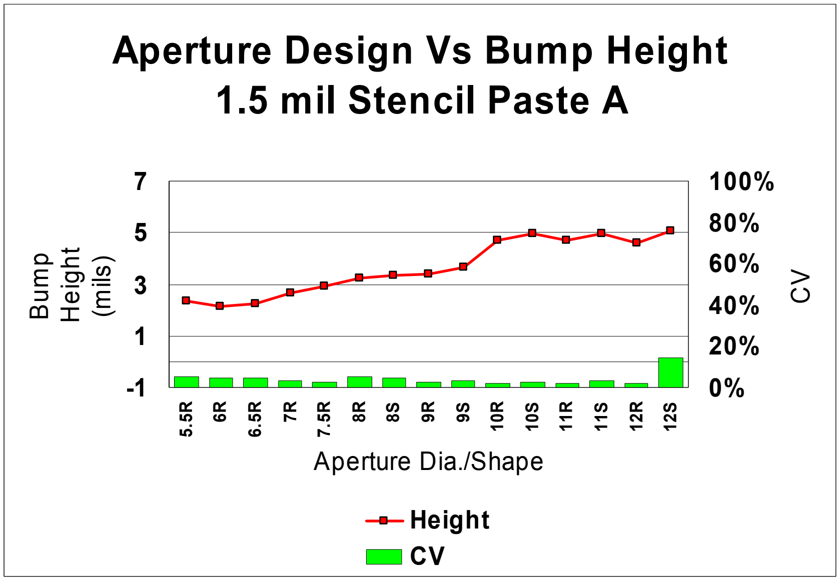

Figure 7 - Bump Height and CV vs. Aperture Design for 1.5-mil Stencil using Paste A

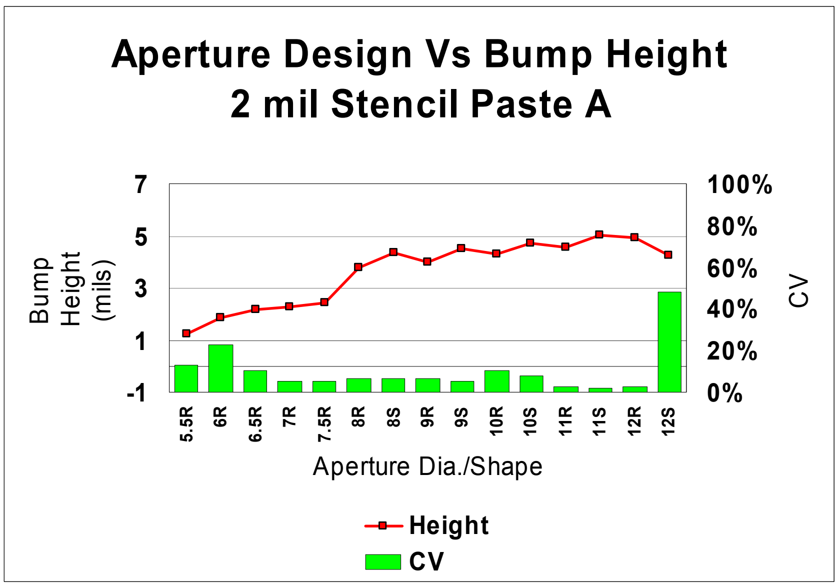

Figure 8 - Bump Height and CV vs. Aperture Design for 2.0-mil Stencil using Paste A

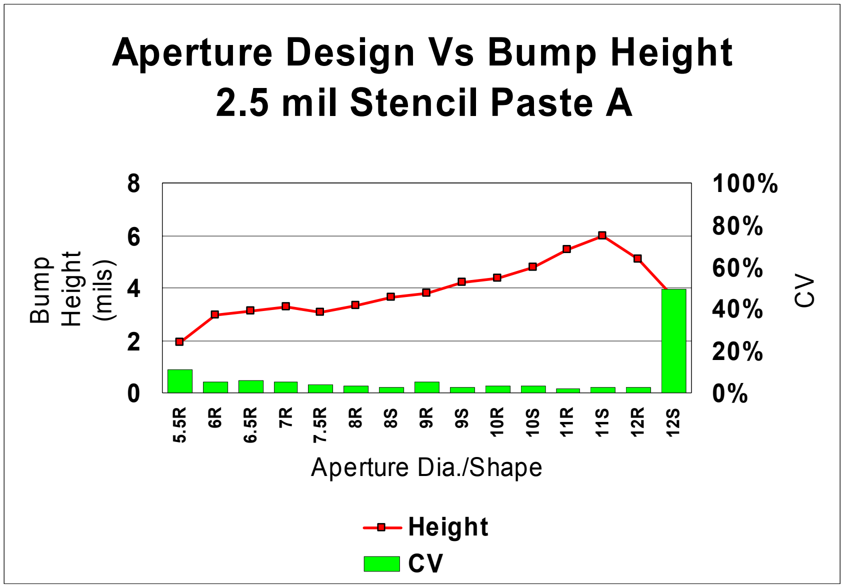

Figure 9 - Bump Height and CV vs. Aperture Design for 2.5-mil Stencil using Paste A

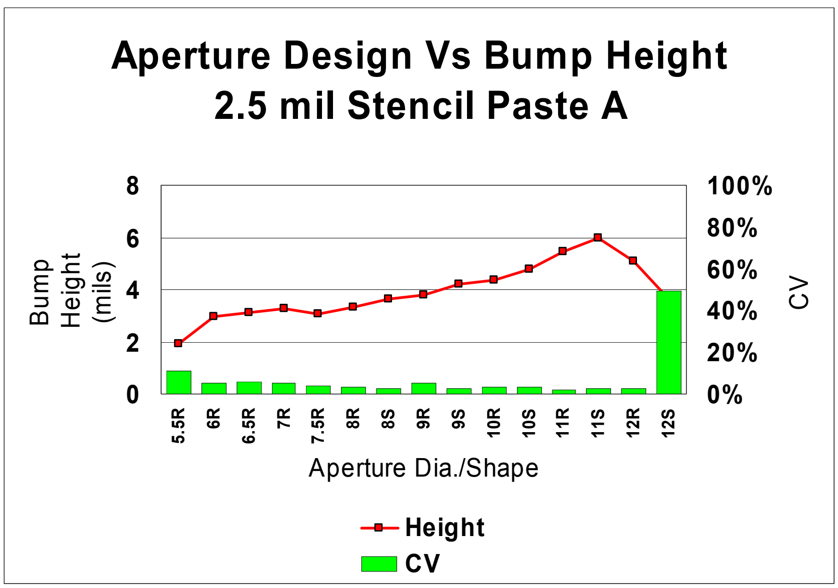

Figure 10 - Bump Height and CV vs. Aperture Design for 1.5-mil Stencil using Paste C

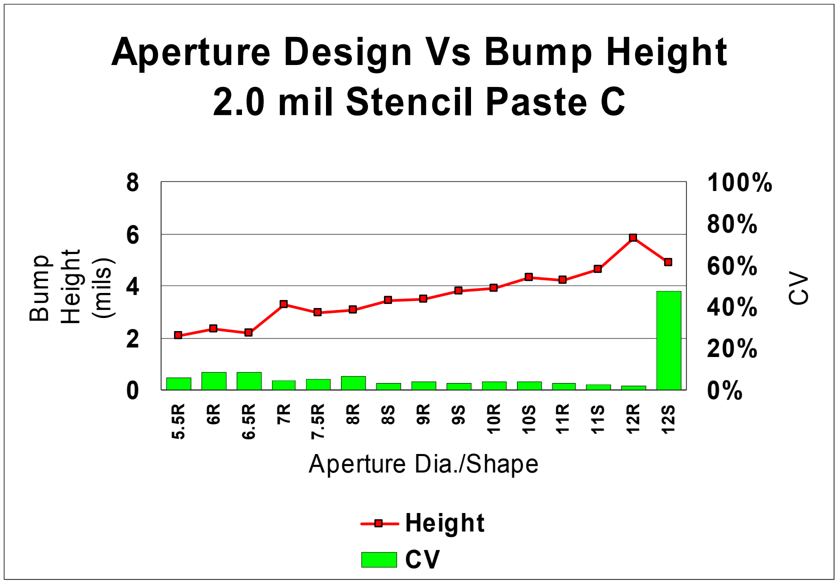

Figure 11 - Bump Height and CV vs. Aperture Design for 2.0-mil Stencil using Paste C

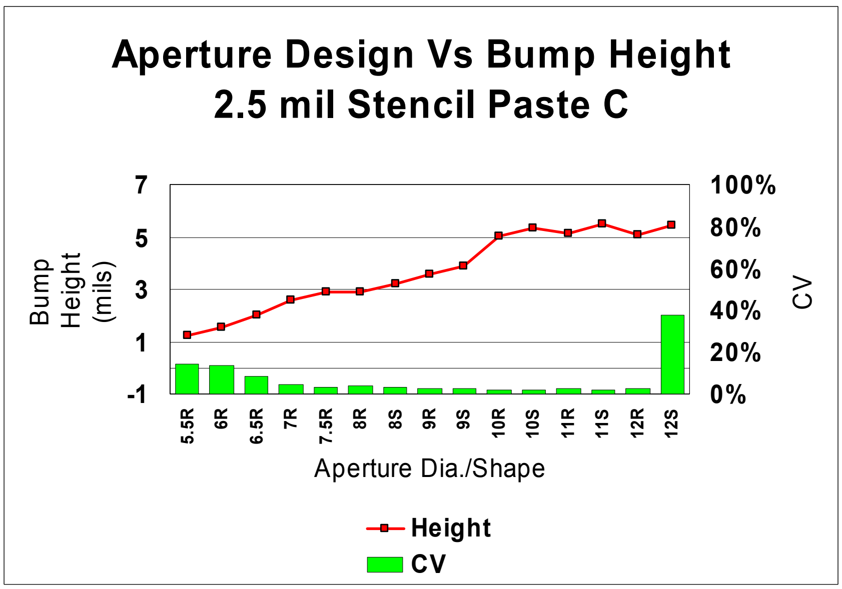

Figure 12 - Bump Height and CV vs. Aperture Design for 2.5-mil Stencil using Paste C

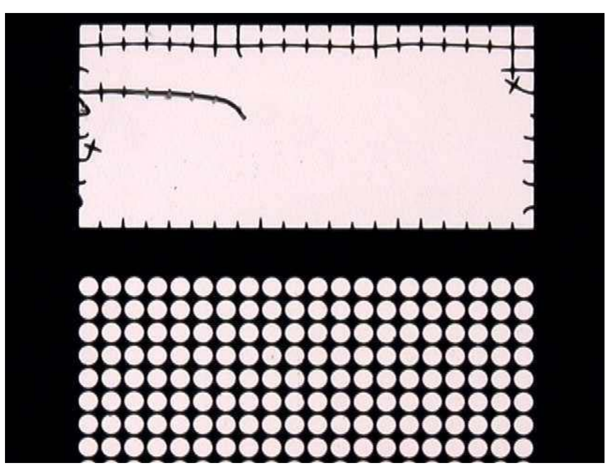

Figure 13 - Picture of AMTX E-FAB 2.5 mil Stencil with Web Design Violation (1.8-mil web)

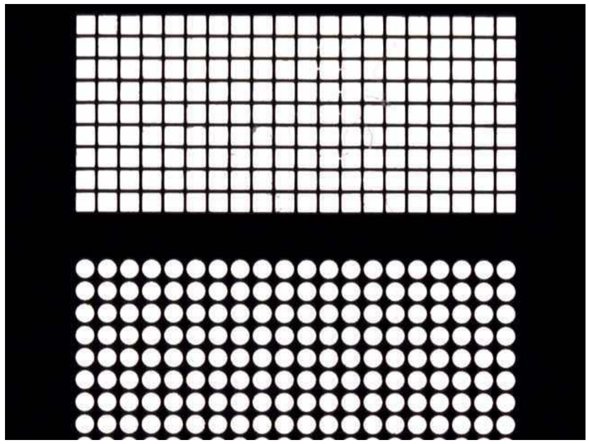

Figure 14 - Picture of AMTX E-FAB 1.5 mil Stencil with marginally OK Webs

A second way to view the data is to look at the bump height for all three stencils as a function of aperture size for each paste type. This data is shown in Figures 15,16, and 17. Note that the thinner (1.5 mil) stencil gives equivalent or slightly higher ball height than the thicker stencils (2.0 mil and 2.5 mil) for the small apertures. However when the aperture size is up around 9 to 10 mils the 2.5 mil thick stencil gives higher ball heights as might be expected based on the higher theoretical solder volume delivered by this stencil. The CV vs. aperture size for paste A, B, C is shown in Figures 18,19,20. In general the 1.5-mil thick stencil has lower CV's than the thicker stencils. Figures 21,22,23 show the Actual Ball height minus the Theoretical Ball height for the three different paste types. The thinner 1.5 mil stencil has a lower delta from the expected ball height than the thicker (2.0 and 2.5 mil) stencils.

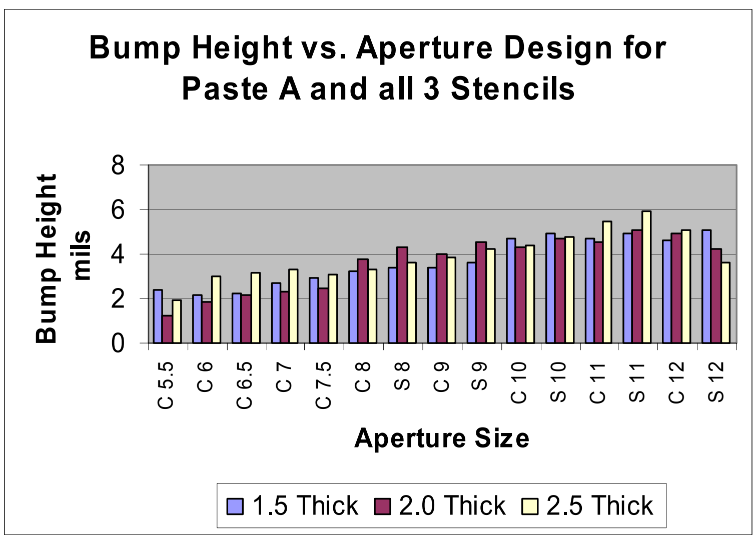

Figure 15 - Bump Height vs. Aperture Design (All 3 stencils) for Paste A

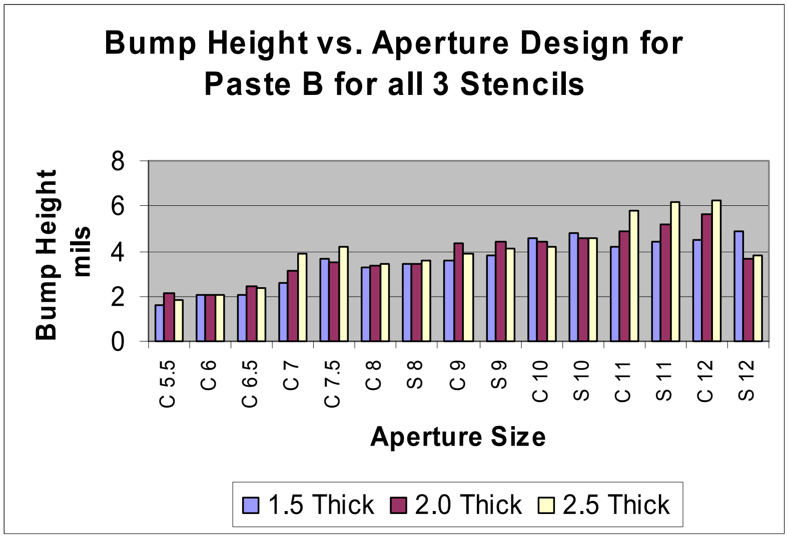

Figure 16 - Bump Height vs. Aperture Design (All 3 stencils) for Paste B

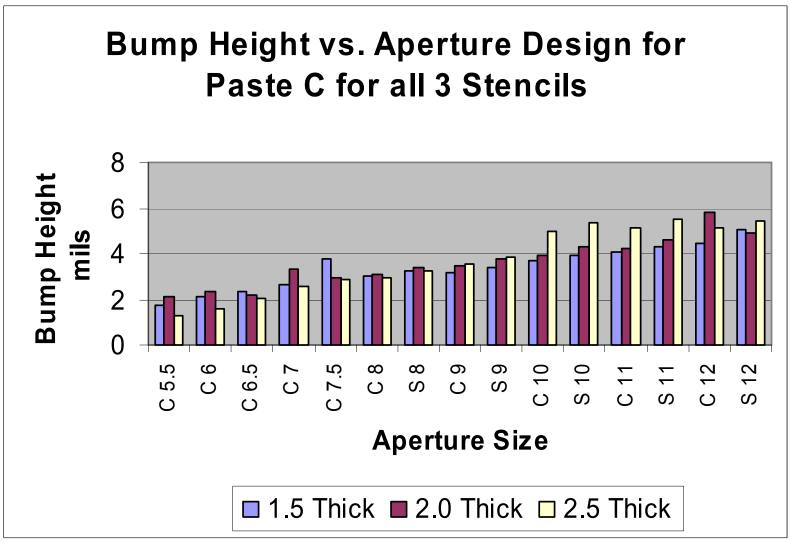

Figure 17 - Bump Height vs. Aperture Design (All 3 stencils) for Paste C

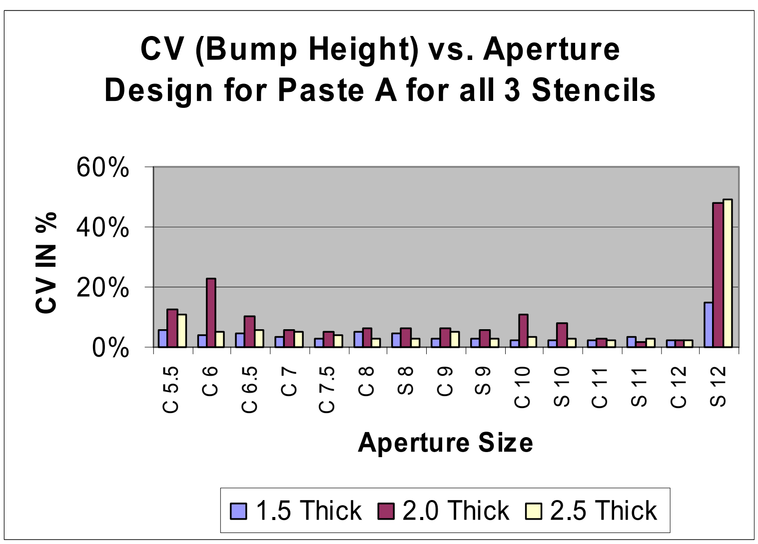

Figure 18 - CV vs. Aperture Design (All 3 stencils) for Paste A

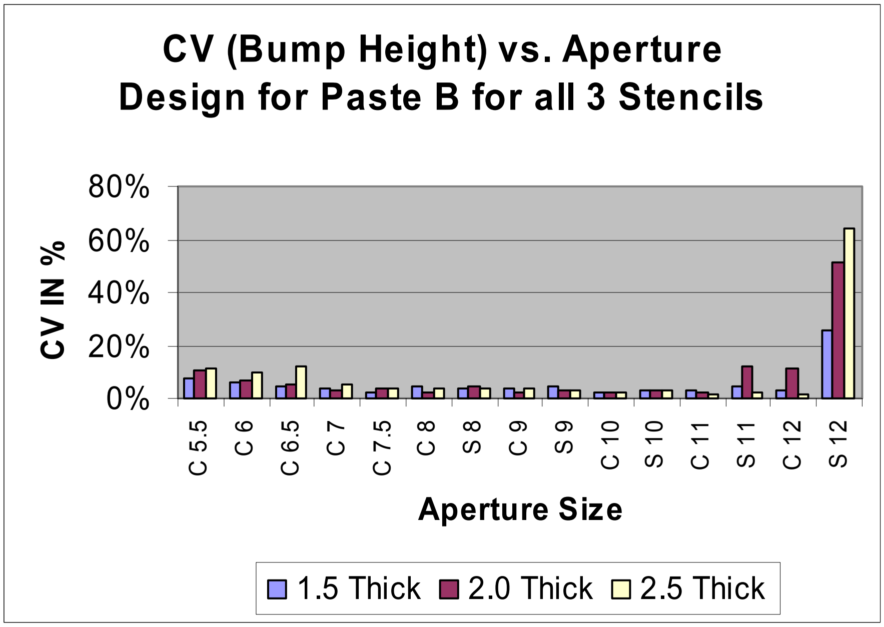

Figure 19 - CV vs. Aperture Design (All 3 stencils) for Paste B

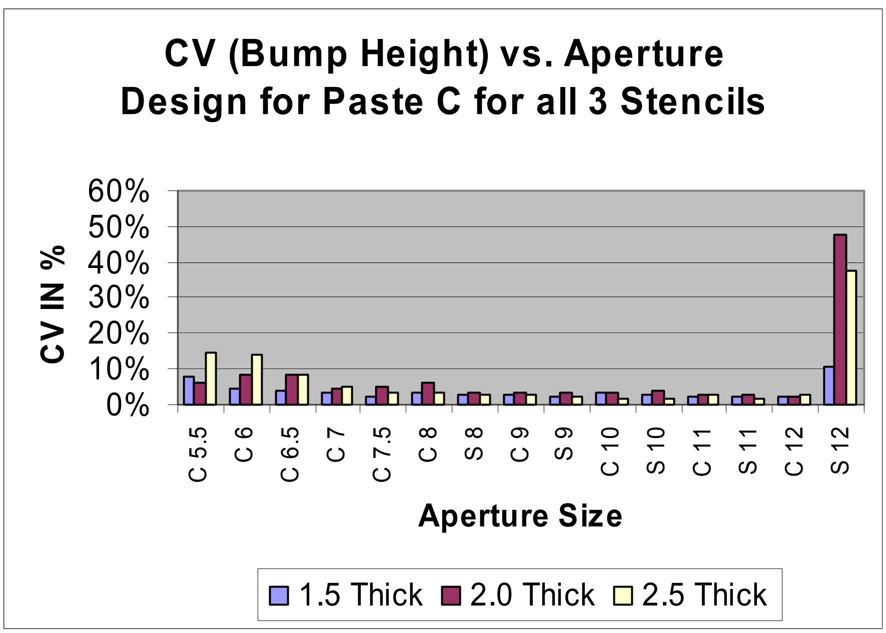

Figure 20 - CV vs. Aperture Design (All 3 stencils) for Paste C

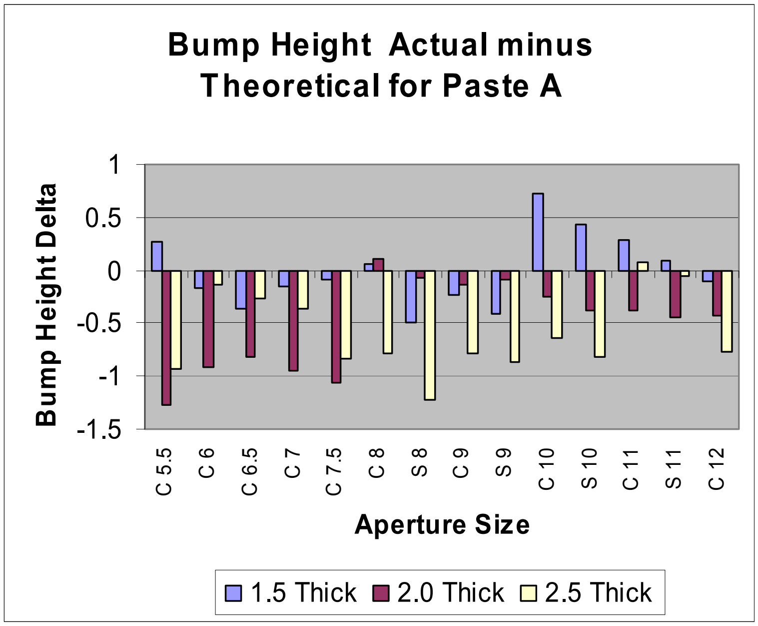

Figure 21 - Bump Height – Actual vs. Theoretical for Paste A

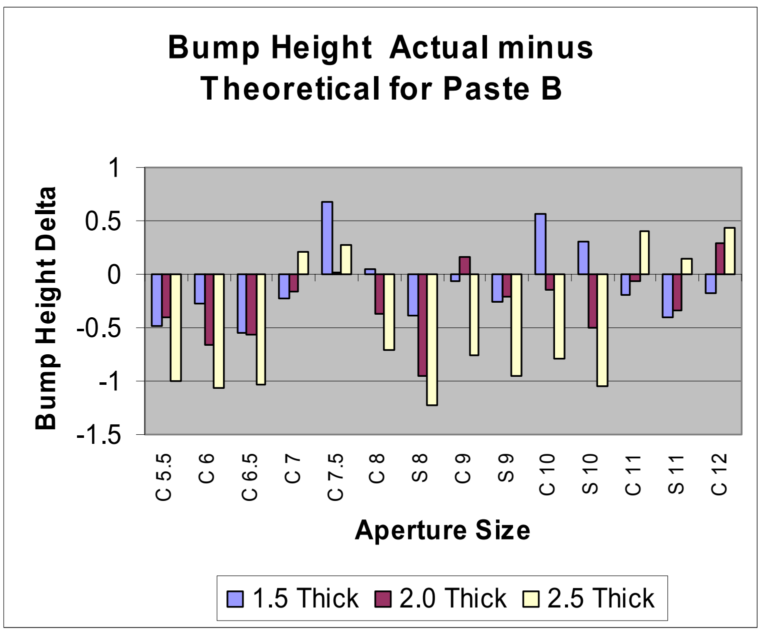

Figure 22 - Bump Height – Actual vs. Theoretical for Paste B

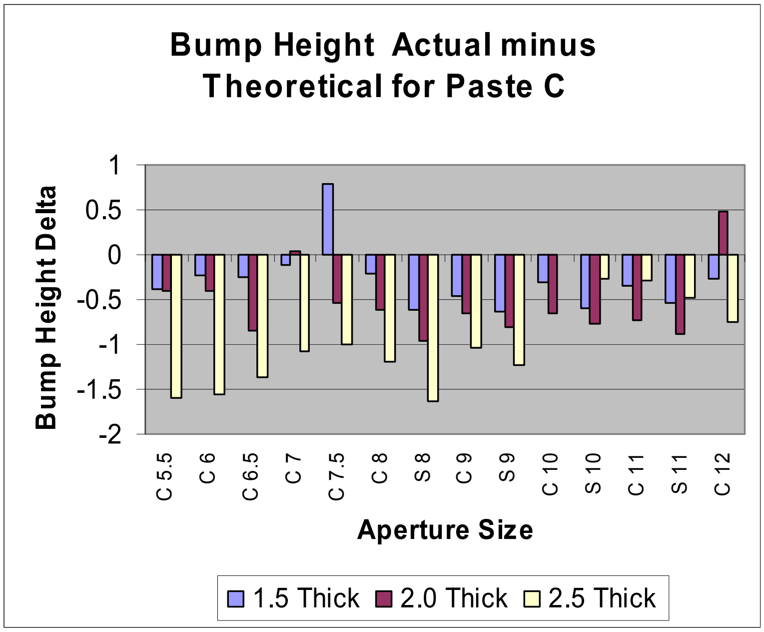

Figure 23 - Bump Height – Actual vs. Theoretical for Paste C

X-ray analysis was used to measure the area of the bump and the diameter of the bump, however the best indicator of the trends was found to be the bump area. The bump area vs. aperture size for paste B is shown in Figure 24. As seen there is not much difference in the bump area between the three different thickness of stencils for the smaller aperture sizes. However above 7.5 mil aperture size the thicker stencils provided a larger area. The exception is the 12 mil square but that result is expected because of the web failure for this aperture. Figure 25 shows the CV for paste B versus the aperture sizes. The 12-mil square is eliminated from this data but it is interesting to note the high CV of the 12-mil circle and the 11-mil square for the 2-mil stencil. The spacing between apertures is marginal for these aperture designs most probably resulting in some bridging between paste bricks, which shows up in the high CV's values. The CV are well behaved from the 11 mil circle aperture all the way down to the 6.5 mil circle aperture where the CV becomes high for the 2.5 mil stencil. At the 5.5 mil circle aperture the CV's rise to the 20% region. Figure 26 shows missing bumps using the X-ray area data for paste B versus the aperture sizes. As seen there are missing bumps for 5.5 mil circular apertures for all three thickness of stencils (1.5, 2.0, and 2.5 mil). There is one missing bump for the 2 mil thick stencil for the 6 mil circular aperture. After that there are no missing bumps until the aperture size reaches an 11 mil square for the 2 mil thick stencil. The 12-mil square has many missing bumps for all three stencils.

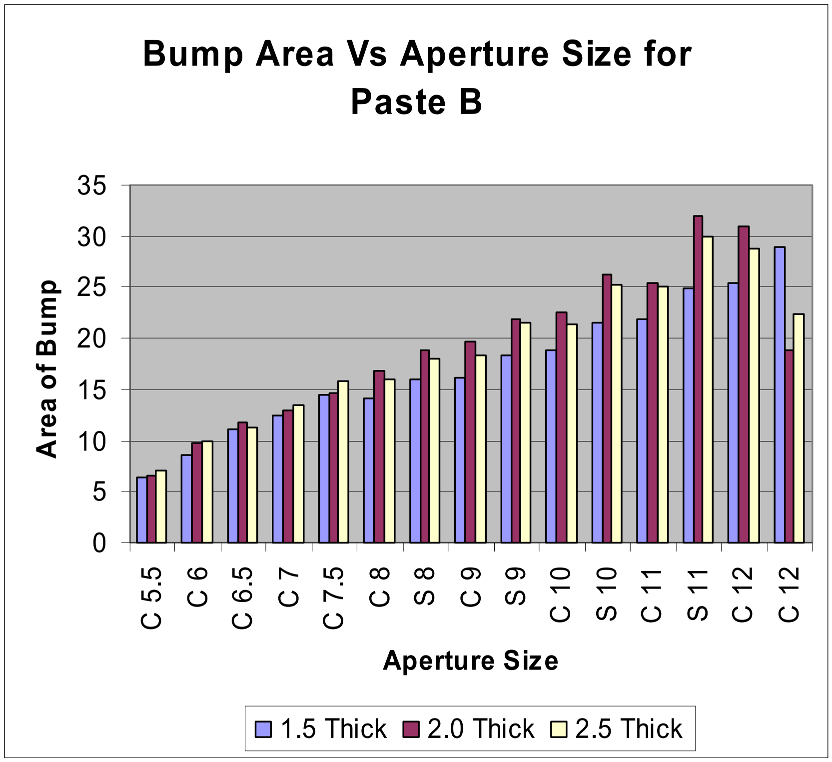

Figure 24 - Bump Area vs. Aperture design for Paste B

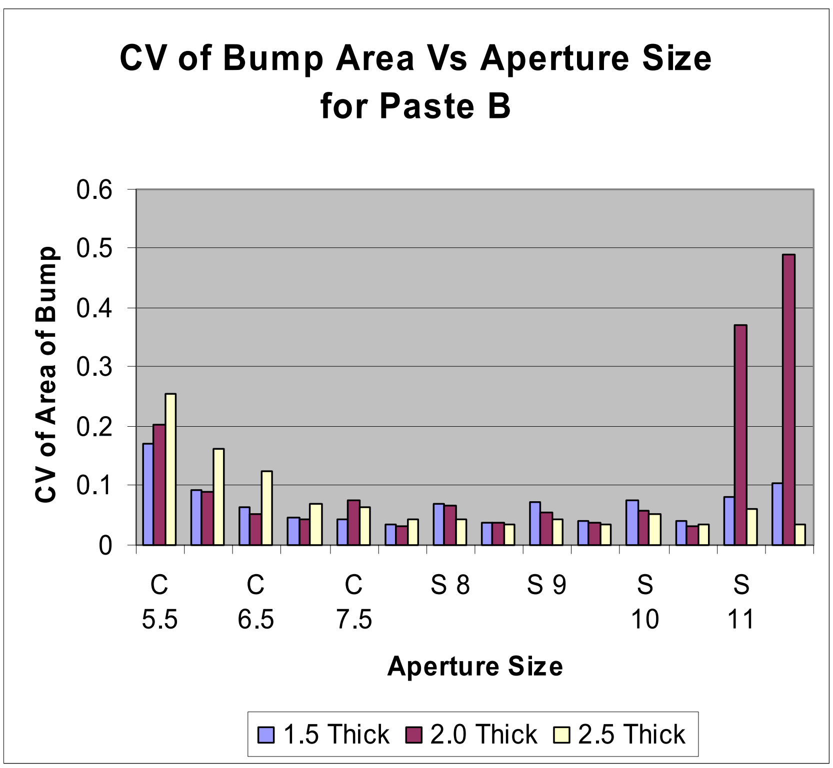

Figure 25 - CV of Bump Area vs. Aperture Design for Paste B

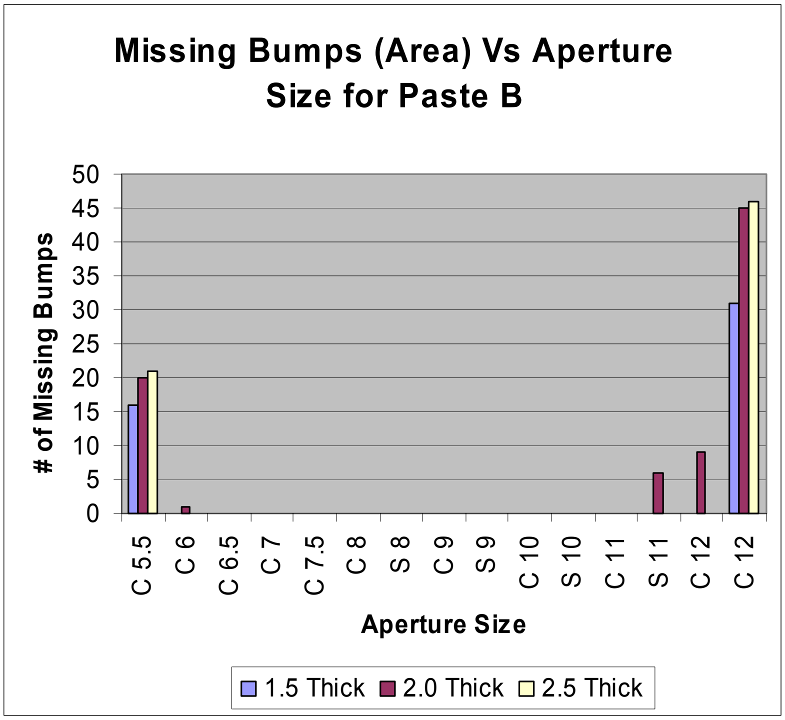

Figure 26 - Missing Bumps (Area) vs. Aperture Design for Paste B

Conclusion

- It is useful to consider the Area Ratio vs. Aperture Design (Figure 2) as well as the Theoretical Bump Height vs. Aperture Design (Figure 3) when deciding which stencil design should be utilized for bumping applications. When at all possible it is best to pick the largest aperture size (overprinting) and the thinnest stencil to give the required bump height.
- There are design limitations with the AMTX E-FAB Stencil, which need to be considered. The web between square or rectangle apertures must be kept at least 1.2 times the thickness of the stencil to avoid voiding of the web. With circular apertures the web may go as low as .75 of the stencil thickness without voiding.
- There are differences in bump height depending on which paste is used. Paste C has overall smaller bump heights compared to paste A and paste B (Figures 15,16,17). The 1.5-mil stencil gives almost equivalent ball height for paste C for aperture sizes up to the 9-mil square compared to the 2-mil and 2.5 mil thick stencils. Paste A gives the highest bump height for 6,6.5, and 7-mil circular apertures compared to Paste B and C.
- As expected the smaller aperture sizes gave higher CV values (Figures 18,19,20) since the Area Ratios are lower. The 2-mil stencil for some reason has high CV values for Paste A.
- When comparing the Actual bump height to the Theoretical bump height (Figures 21,22,23) the 1.5 mil stencil has less deviation than the 2.5 mil thick stencil for the smaller aperture sizes.
- All stencils showed some missing bumps for the 5.5 mil circular aperture (Figure 26). Only the 2-mil stencil showed (1) missing bump for the 6 mil circular aperture. There were no missing bumps for 6.5-mil circular apertures up to the 11-mil square aperture. At this point the 2-mil stencil had missing bumps for the 11-mil square and the 12-mil circle. The 12-mil square had missing bumps for all three stencils. Even though the webs are not completely broken for the 1.5 mil stencil there are hints that the web is necked down which can contribute to bridging between paste bricks. In this case one pad may hog all the paste leaving the other with a missing bump.

Acknowledgements

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