Optimizing Solder Paste Printing For Wafer Bumping

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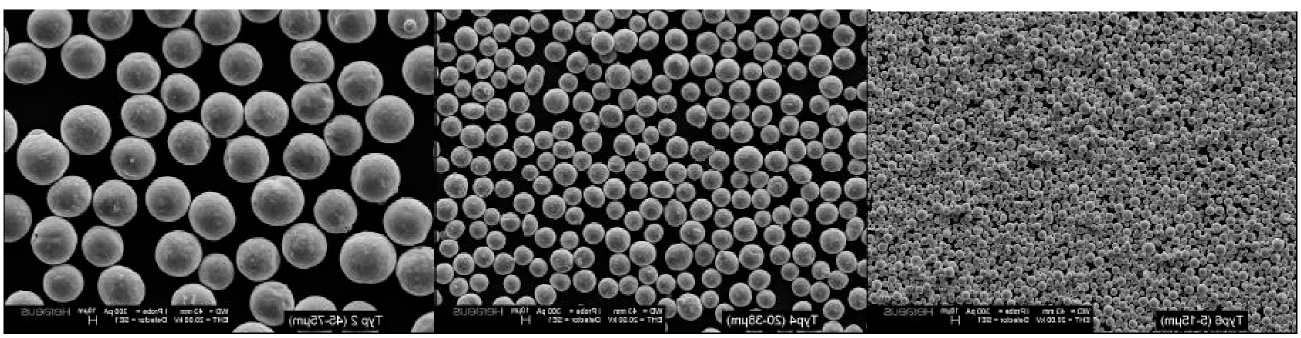
Abstract
Recently, wafer bumping using solder paste with very fine solder powder has come into focus as more cost effective than conventional sputtered or plated methods. This additive method revolves around a stencil printing process similar to conventional SMT with the exception of the extremely small pitch and desired deposit size. The results and findings of a print process array of experiments are presented that focus on optimal print deposit area consistency. Variables such as squeegee type (polymer vs. metal), separation speed and snapoff distance are compared and contrasted.

Introduction
Wafer bumping with printed solder paste can utilize standard SMT printing tools but with a few important and crucial process elements not typically common in standard SMT printing. Literature[1] on this subject stresses the need for polymer squeegees instead of the metal squeegee typical in today's SMT process. Research on this subject suggests the requirement for a print gap or "off contact" printing. The small aperture diameters and narrow spacing typical of die pad configurations dictate a much smaller particle size than standard SMT as in Figure 1.

Type 2: 25-45 microns | Type 4: 20-38 microns | Type 6: 5-15 microns



SMT (no fine pitch) | SMT(Fine pitch, CSP) | Wafer Bumping

Figure 1 - Powder Types and Applications

To verify these requirements for success in wafer bumping, a high density print test design was created. Several Electroformed Nickel (E-FAB) stencils were fabricated in different thicknesses and an array of print experiments was performed. Measurement was accomplished via real time X-ray on printed blank 200mm wafers.

Test Pattern Design
In order to study the print process effects specific to wafer bumping technology, 200mm wafers were chosen as the base substrate. Although the largest and most challenging wafer diameters are currently 300mm, the blank wafer price difference was roughly 7:1 and it was believed that the crucial basics that are discovered on the 200mm wafer are pertinent to the 300mm. The aperture and pitch were chosen to be 6.5 mils and 9 mils respectively based on inputs from our stencil supplier. To worst case the aperture density the apertures were arranged in 10 X 10 arrays with a 13 mil spacing between them to simulate a saw path. A 3mm no-aperture border was included to facilitate handling and prevent smearing of the print after printing. The file was created using a standard CAD package and resulted in a rather large file (292Mb), not uncommon for wafer bumping design files. There are a total of 453,000 apertures in the design as shown in Figure 2.

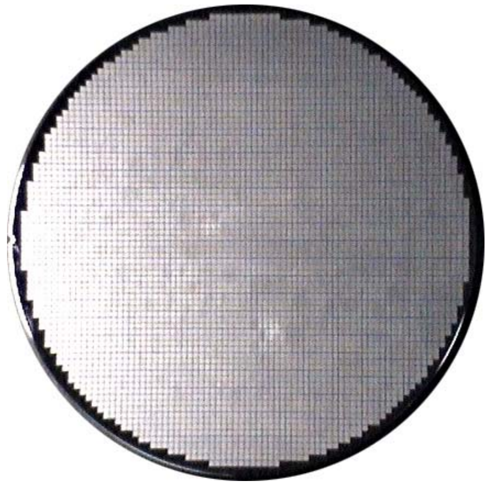


Figure 2 - Test Pattern Design

Tooling

Standard tooling that is basic to all SMT automated printers is inadequate for wafer bumping for two reasons. The first is obvious. The form factor for a wafer is round and standard SMT is rectilinear. Although the standard support hardware would be adequate to support the wafer during the print operation, the moving belt rail system would not be effective in transporting and locating a disc. The tooling must provide a flat support that interfaces a disc to a rectangle or square as in Figure 3.

The second need for dedicated tooling stems from the significant cohesive forces encountered during separation. For this study two stencils of typical thickness (2.0 and 2.7 mils) for this application were fabricated. If we consider the aperture wall lateral surface area ($2\pi rh$) they were $18.5in^2$ and $25in^2$ for 2.0 and 2.7 mil stencils respectively. The surface area (πr^2) being printed on the wafer is 15 in^2 included in only a 194mm (7.6") diameter circle. The tooling must provide integral vacuum hold down of significant magnitude to hold the wafer during the separation phase of the print process. Failure to do this properly will result in the wafer adhered to the bottom of the stencil as in Figure 4.

Figure 3 - Wafer Vacuum Nest

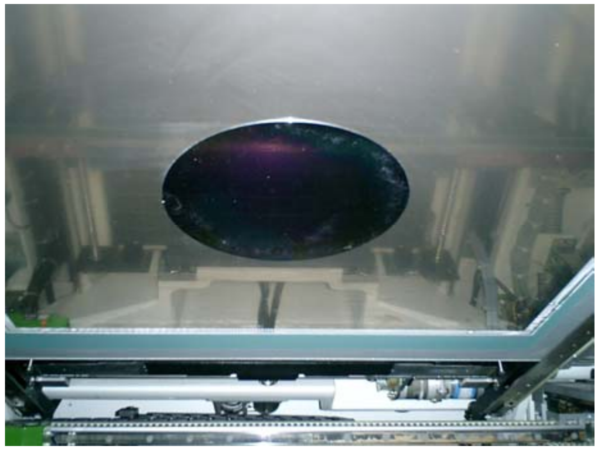


Figure 4 – Wafer Stuck on Stencil Bottom

Measurement

A non-contact automated method of 100% inspection of solder deposit volume over the wafer surface resulting in color or 3D mapping would be ideal for this study. This was not available at the time of this study so a quantified "audit" of each printed wafer was taken using real time X-ray and BGA analysis software. Since X-rays are only absorbed by the solder powder in the printed deposits and silicon has only marginal absorption properties, a two dimensional area measurement at a fixed power provides a good indication of deposit variability.

A strip of 100-deposit arrays down the middle of the wafer parallel to the squeegee direction involved 7600 measurements. A measurement of 1 array (center) and data field (lower right) are shown in Figure 5. When the data is analyzed in blocks of 100 and plotted it provides a virtual cross- section of deposit consistency by location.

In a parallel study[2,3] using the same water soluble solder paste (Heraeus DSC09-419) and 2 mil E-FAB stencil, the bump formation and shape were shown to be very consistent using the 6.5 mil aperture as shown in Figures 6, 7 and 8. This study utilized an FR4 test coupon with 4 mil diameter ½ oz copper pads on 12 mil centers. Reflow was done exclusively in 25ppm nitrogen. Coupons were then washed in DI water in a standard SMT hydrocleaner. Since the cleaner has both upper and lower belts, standoff clips were temporarily placed around the coupons to prevent damaging the bump surfaces during cleaning.

In addition to gathering deposit area data, the BGA analysis software also measures diameter and shape. The best indicator of trends in this study, however, was found to be deposit area.

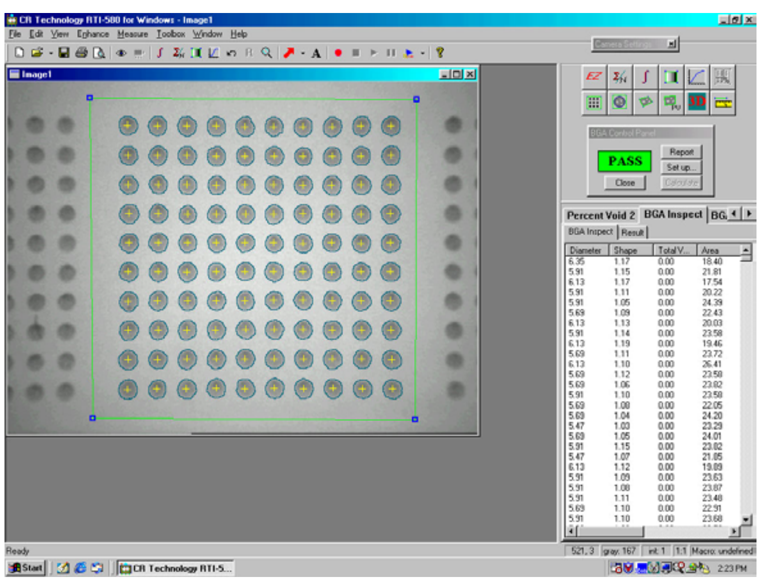


Figure 5 - Imaged Array and Data Field

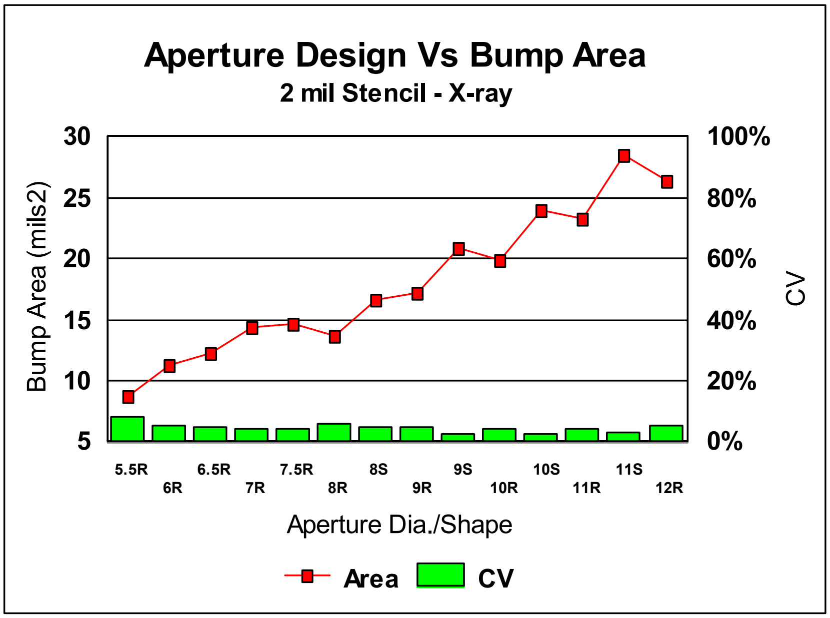


Figure 6 X-Ray Bump Area Data

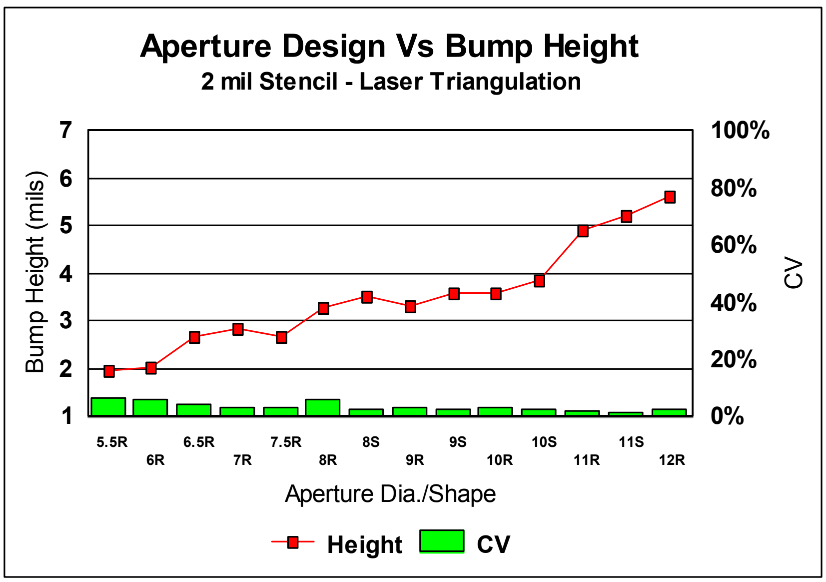


Figure 7 Laser Bump Height Data

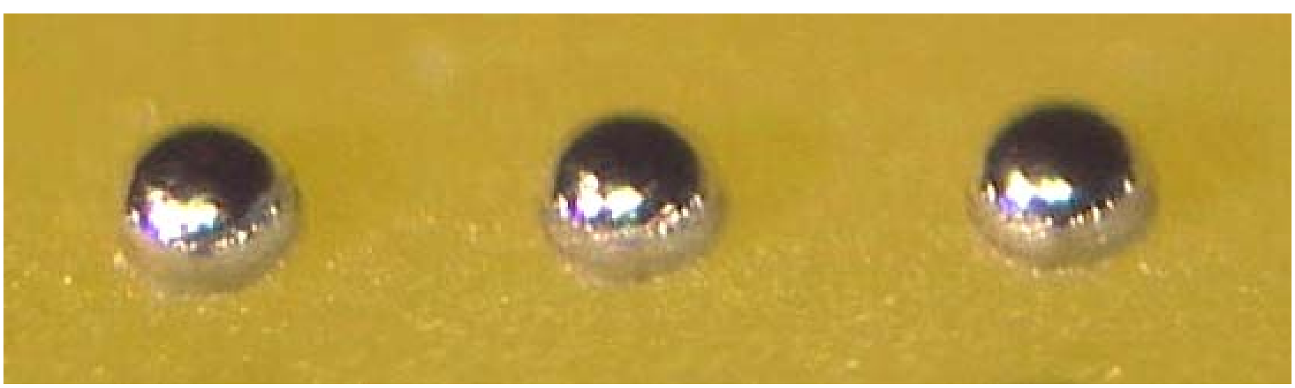


Figure 8 Reflowed and Cleaned Bumps Using a 2 mil Stencil and 6.5 mil Aperture

Experimental Matrix
Table 1 shows the 15 experiments that were run in this study. The printer used was a DEK 265GSX which has programmable squeegee pressure (fixed at 1kg/in squeegee), separation speed, print speed (fixed at 20mm/s) and print gap (distance between bottom of stencil and wafer). Red squeegees are hard (94-97) durometer and black squeegees are medium (75-80) durometer. For the experiments with a print gap, only fast separation was used in that the screen "peels" away from the wafer just slightly behind it as it travels across the wafer. The stencil was hand cleaned with a lint free wiper before each sample was printed. Care was taken to avoid contaminating the bottom of the wafer with solder because the X-ray will find solder on either surface of the wafer.

Table 1 – Experiment Matrix

Experiment	Stencil Thickness	Squeegee	Gap (mm)	Separation Speed
A	2	Red	0	0.1mm/s
B	2	Black	0	0.1mm/s
C	2	Red	0	20mm/s
D	2	Black	0	20mm/s
E	2	Red	3	20mm/s
F	2	Black	3	20mm/s
G	2.7	Red	0	0.1mm/s
H	2.7	Black	0	0.1mm/s
I	2.7	Red	0	20mm/s
J	2.7	Black	0	20mm/s
K	2.7	Red	3	20mm/s
L	2.7	Black	3	20mm/s
M	2.7	Metal	0	0.1mm/s
N	2.7	Metal	0	20mm/s
O	2.7	Metal	3	20mm/s

Print Gap and Separation Speed
The print gap or snapoff distance was found to be the most critical setup variable in this study. On-contact printing that is typical of a standard SMT printer setup results in an uncontrolled separation of the stencil to the wafer. When separation occurs swiftly an auditable pop occurs sounding much like a base drum beat. The vertical oscillations of the stencil foil not only produce the sound but spray any remaining material in the apertures onto the wafer surface as can be seen in Figures 9 and 10. Different splatter patterns were observed with the slowest (0.1mm.s) and the fastest (20mm/s) separation speeds.

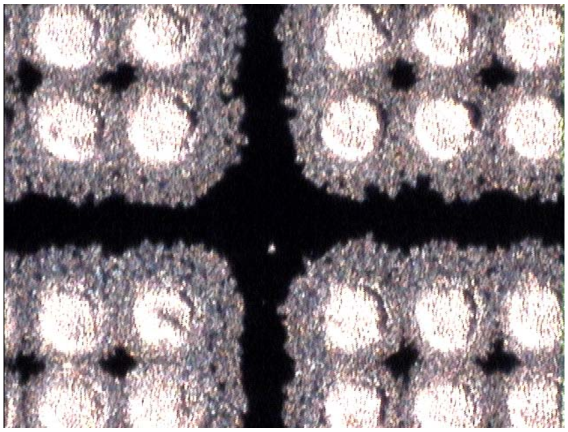


Figure 9 - Contact Print - Fast Separation

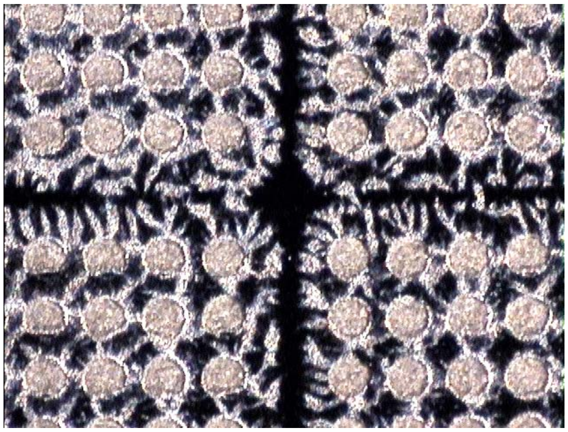
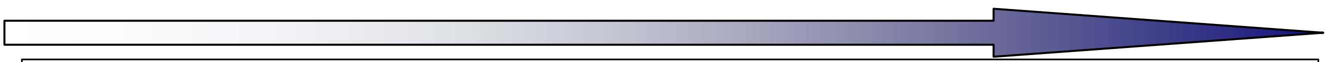


Figure 10 - Contact Print - Slow Separation

Figures 11, 12, 13 and 14 show the X-ray data for the hard polymer squeegee with both fast and slow separation for both thickness stencils (experiments A, C, G & I). Each plotted data point represents the minimum; maximum (red vertical line) and average deposit area in mils^2 (blue horizontal bar) for an array of 100 bump deposits. For this type of chart the print direction is left to right. As can be seen in the data, fast separation results in more area variability than slow separation. Figure 15 illustrates an array with bump deposit area variability. Figure 16 shows a close-up of an another contact print anomaly that appears to the naked eye to be the result of a drop of solvent and turns out to be simply an island of deposits with no splatter surrounding them.



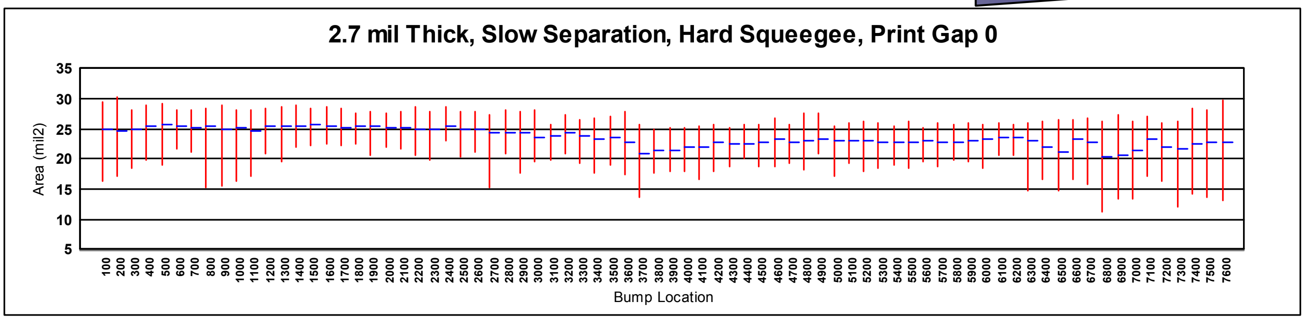


Figure 11 - Experiment “A” X-Ray Area Data

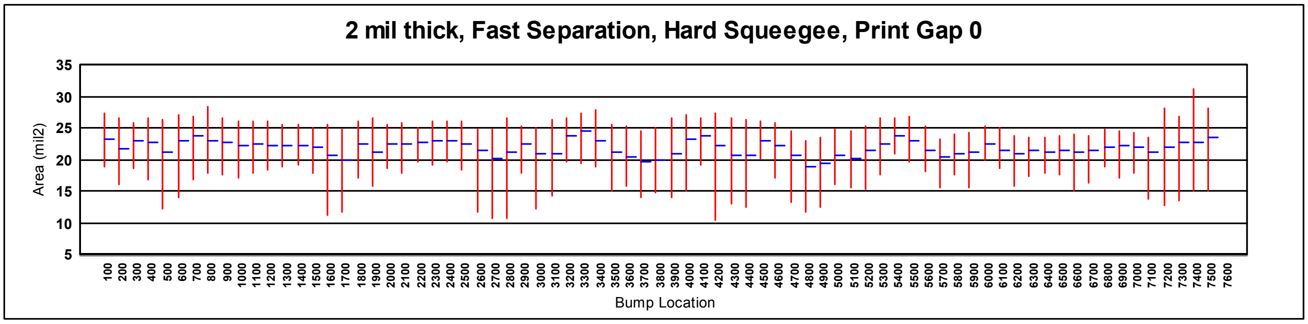


Figure 12 - Experiment "C" X-Ray Area Data

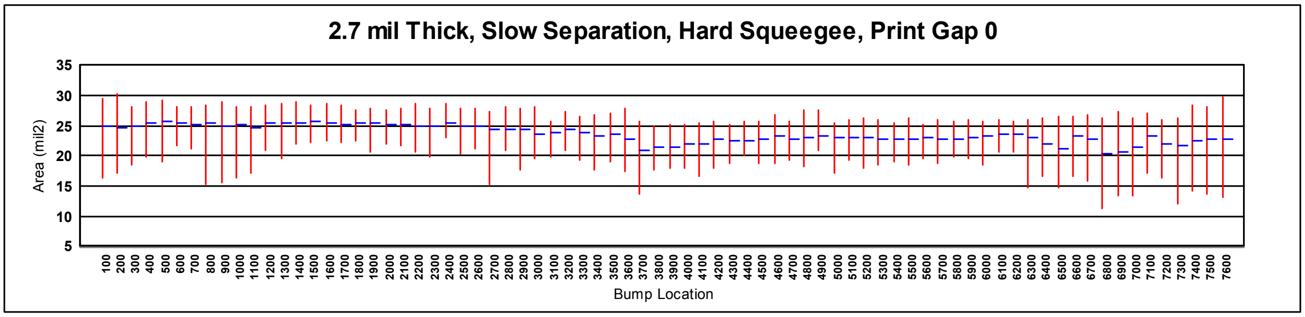


Figure 13 - Experiment "G" X-Ray Area Data

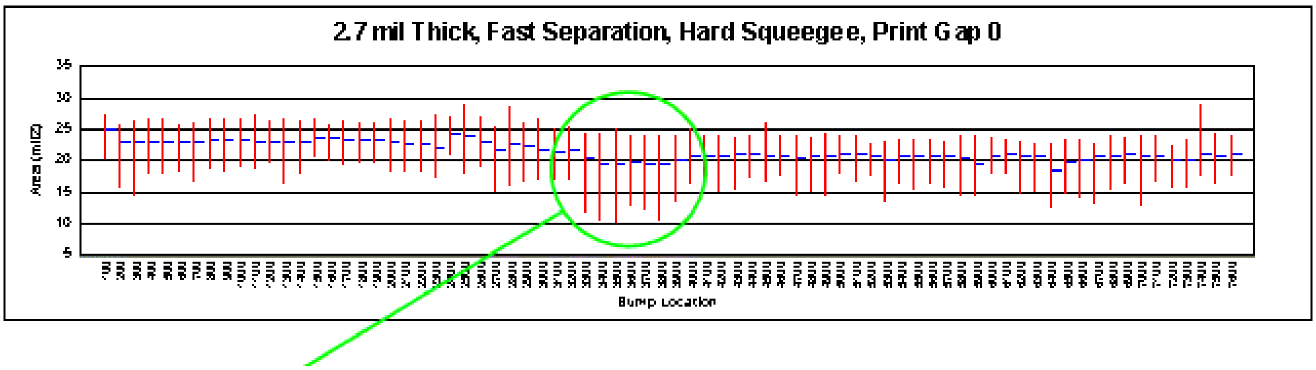


Figure 14 - Experiment "I" X-Ray Area Data

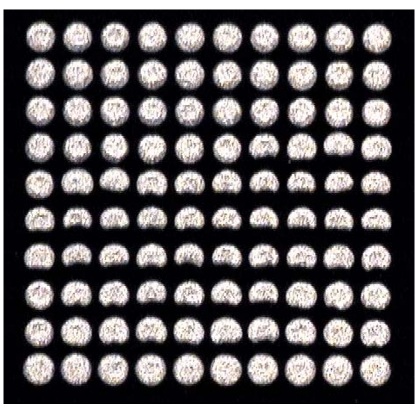


Figure 15 - Typical Array With Area Variations

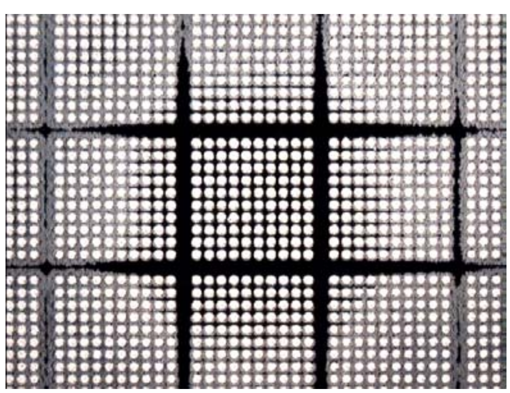


Figure 16 - Contact Print Anomaly

For the experiments with a print gap, the print gap was started at 0.5mm and gradually raised until it was observed that the stencil was separating slightly behind the trailing edge of the squeegee and there was no uncontrolled separation. This ended up to be 3 mm, which happens to be equal to the maximum distance that can be programmed in our printer for controlled separation distance. For this reason controlled separation speed was of no value and set to the maximum of 20mm/s speed.

The critical need for print gap with high density aperture designs such as this is very similar to printing ground planes on hybrid circuits using thick film pastes and fine mesh screens. The combination of the increased tackiness of the wafer bumping paste due to the high surface area of the type 6 powder and the large surface area being printed over a relatively small area (compared to typical SMT designs) creates a large total cohesive force that needs to be broken at the moment of stencil separation. For this design and paste the total cohesive force to be separated is 85LbF. If the release of this bulk force is attempted simultaneously the stencil will pop and splatter will occur. This is most probably why the slow separation is slightly better than the fast separation in that the final area after the stencil has separated the controlled 3mm distance left un-separated was observed to be smaller than if fast separation was attempted.

These printing defects are eliminated when the correct amount of print gap is included in the setup recipe. Figures 17 and 18 show the results of the two equivalent experiments (E and K) with 3mm of print gap. Although there was still some slight variability at the ends of the wafer, the results were considerably better than with no print gap. Figures 19, 20 and 21 show examples of good print results with off contact printing.

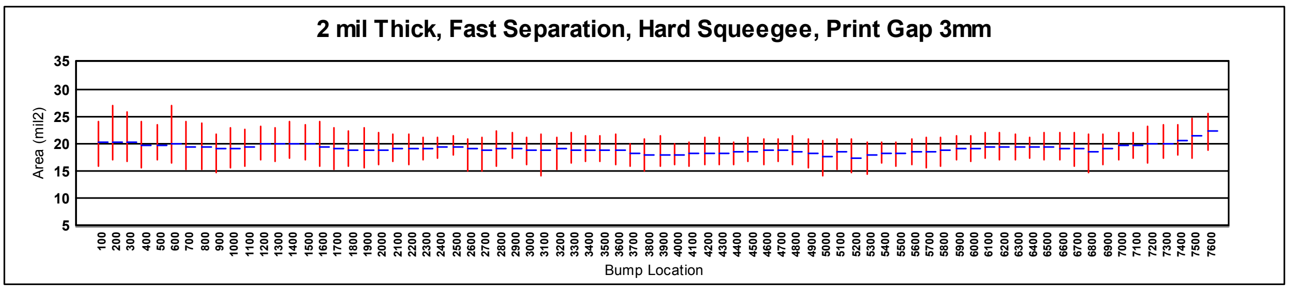


Figure 17 - Experiment "E" X-Ray Area Data

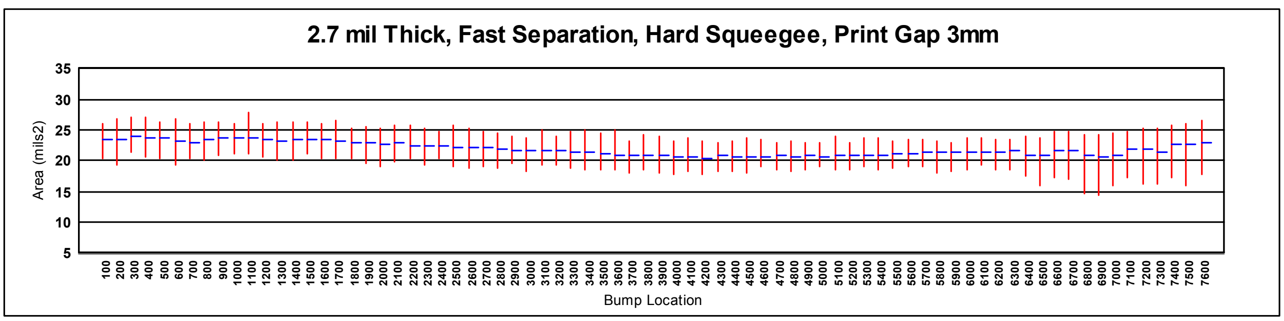


Figure 18 - Experiment "K" X-Ray Area Data

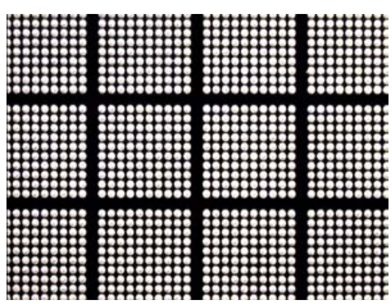


Figure 19 - Good Print

Figure 20 - Close-Up

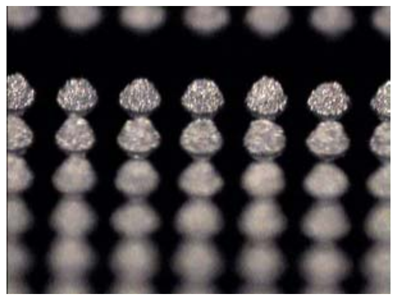


Figure 21 - Bump Side View

Squeegee Effects

All three squeegees were run at the same pressure of 1kg per inch of squeegee length. The difference in results obtained between the two polymer squeegees was somewhat subtle as can be seen in Figures 22 and 23. The thicker stencil had more edge variability which was most probably due to its higher rigidity because this data is only for the 3mm off contact data.

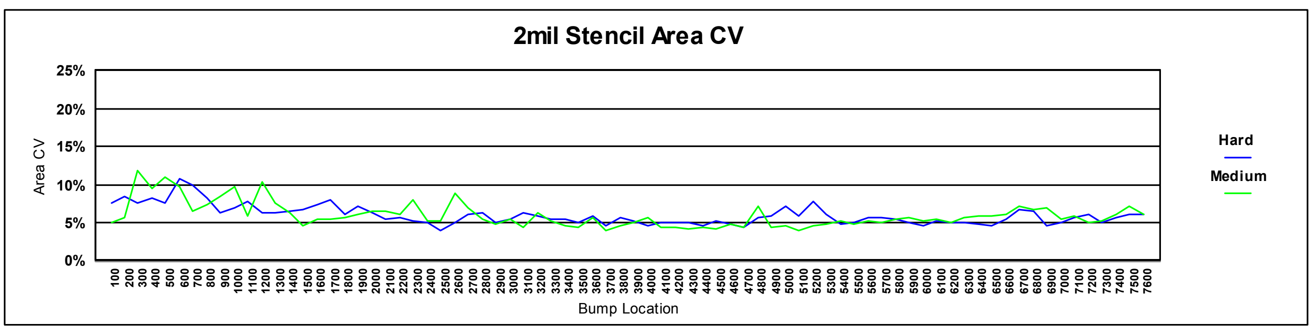


Figure 22 - Experiments E & F X-Ray Area CV Data

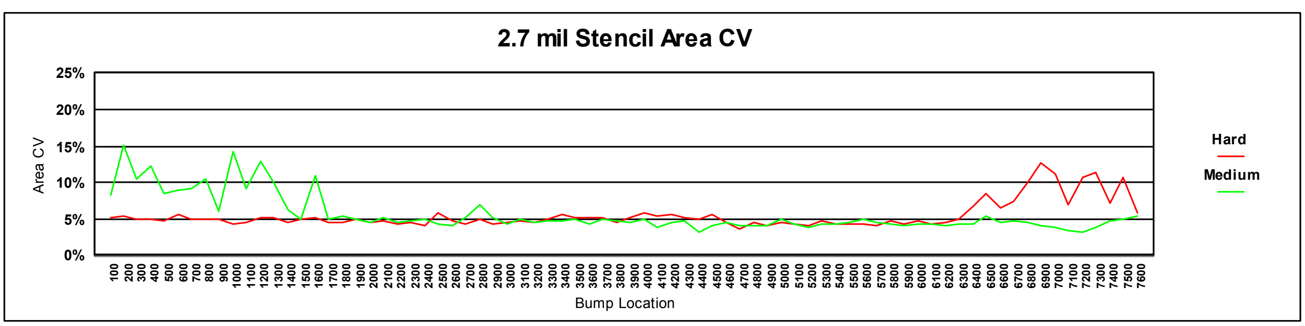


Figure 23 - Experiments K & L X-Ray Area CV Data

Metal squeegee effects were considerably more variable, even with off-contact printing, as can be seen in Figures 24, 25 and 26. Most of this variability came from incomplete wiping. Streaks of material were left on the top surface of the stencil as can be seen in Figure 27, where the polymer squeegee left a perfectly clean wipe pattern (Figure 28).

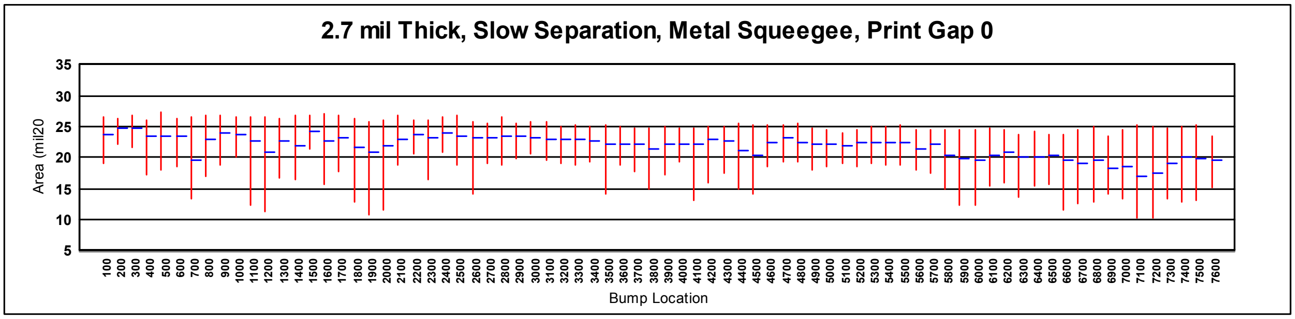


Figure 24 - Experiment "M" X-Ray Area Data

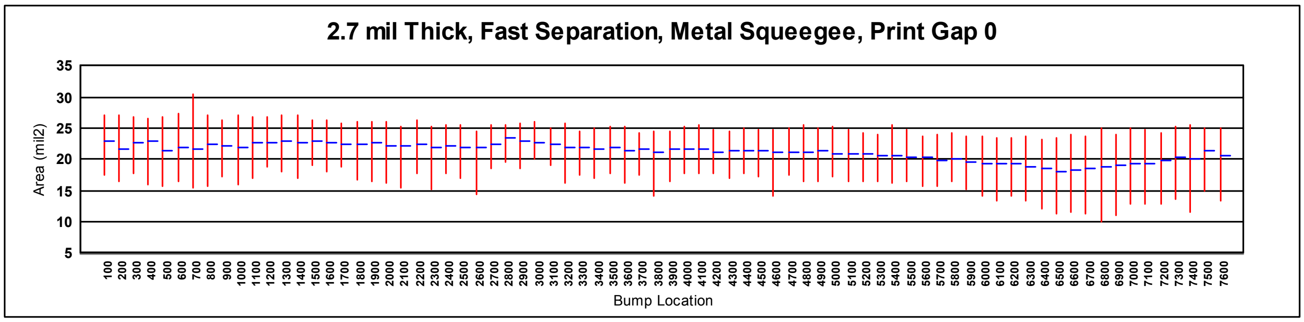


Figure 25 - Experiment "N" X- Ray Area Data

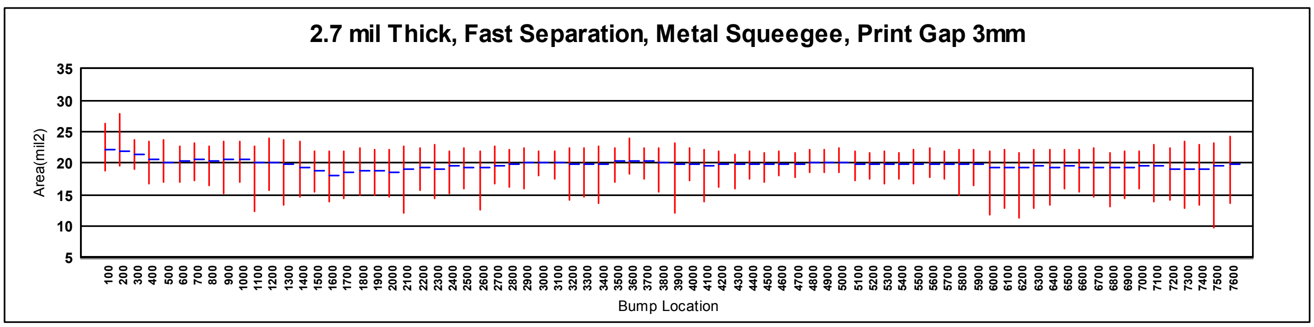


Figure 26 - Experiment "O" X- Ray Area Data

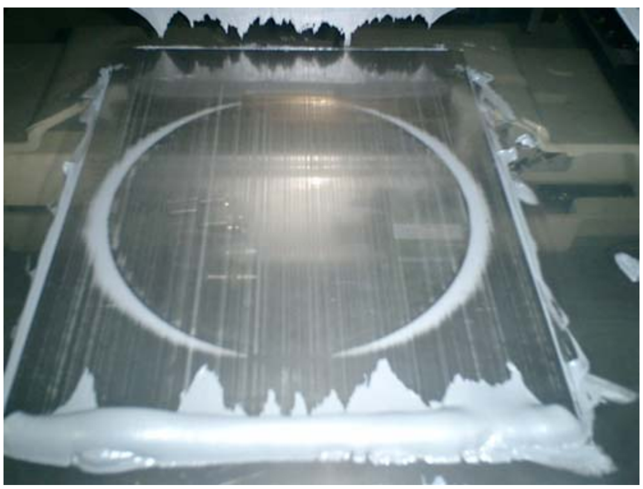


Figure 27 - Metal Squeegee Wipe Pattern

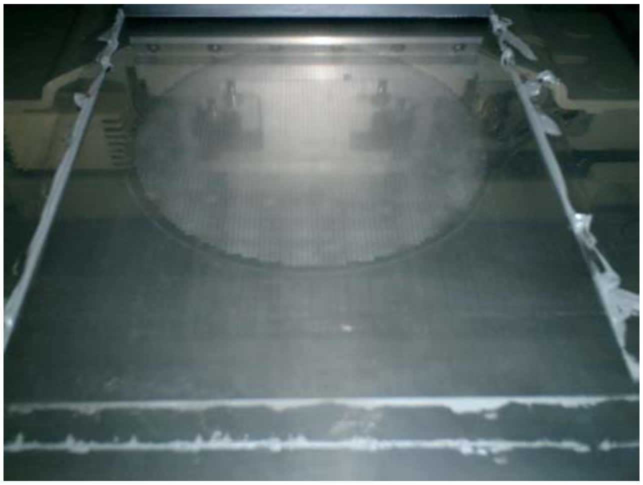


Figure 28 - Polymer Squeegee Wipe Pattern

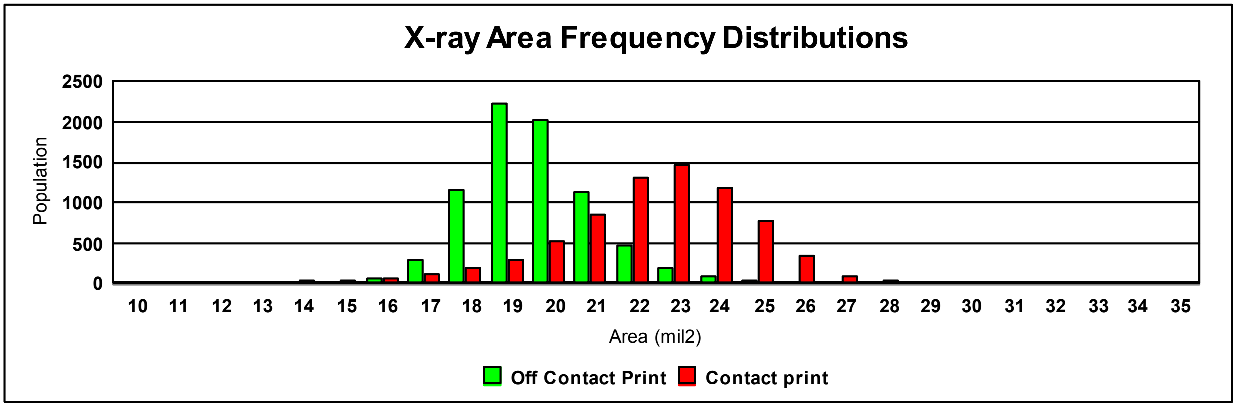


Figure 29 - Off-Contact Printing Benefits

Conclusion

From this study which involved measuring 228,000 bump deposits out of 6.8 million printed, several valuable wafer bumping print process elements have been identified and verified.

- Considerable print gap (off-contact) is critical to preventing screen "popping" and the resultant splattering of the wafer surface with flux and solder particles.
- Off-contact printing also yielded a much tighter print deposit area distribution as in Figure 29.
- The wafer must be supported by flat rectilinear tooling with vacuum hold-down.
- Very slow separation for a 3mm distance is inadequate to prevent this "popping".
- Metal squeegees simply do not wipe as well as polymer squeegees. The preferred squeegee is hard durometer polymer.
- X-ray BGA analysis techniques combined with visual analysis are viable quantitative measurement tools for wafer bump print assessment.

References

1. Johnson, Alden, Tutorial: How to Select the Best Stencil for SMT and Advanced IC Package Printing, *Chip Scale Review*, April 2003
2. Coleman, Bill, Stencil Design and Performance for Flip Chip / Wafer Bumping, APEX proceedings, February 2004
3. Synder, John, Solder Paste Characterization for Bumping Applications, APEX proceedings, February 2004

Acknowledgement

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Optimizing Solder Paste Printing For Wafer Bumping

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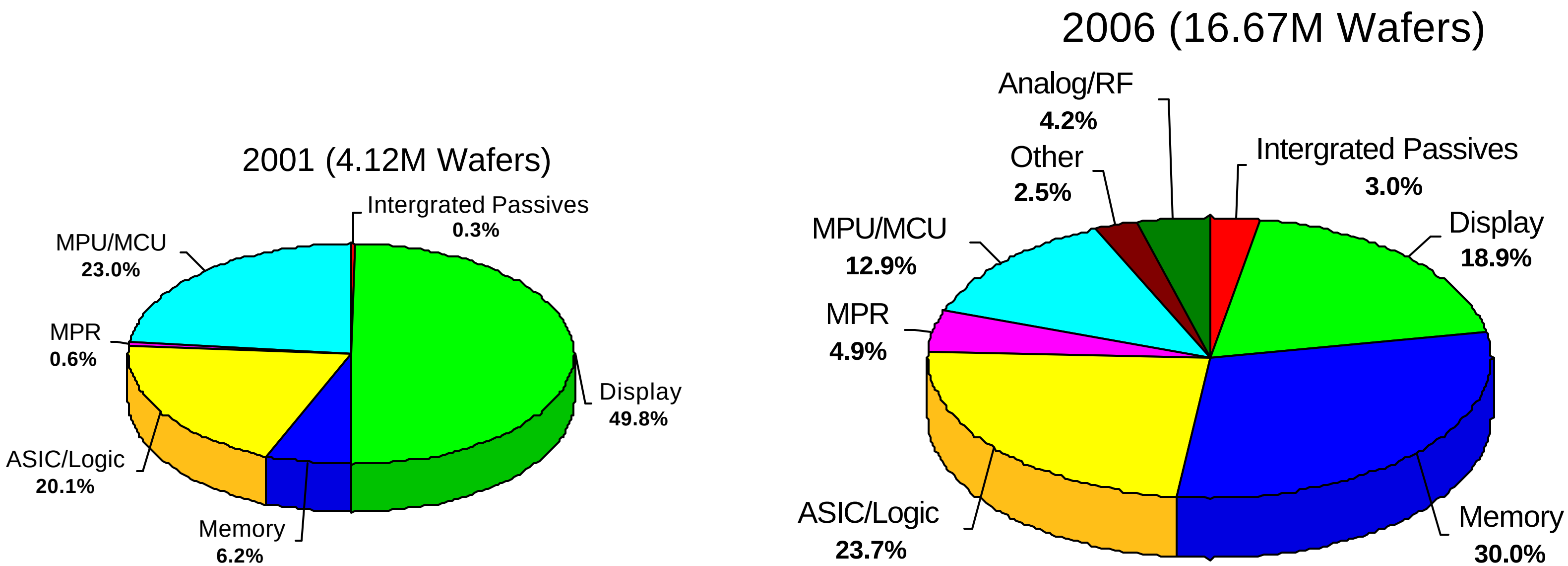
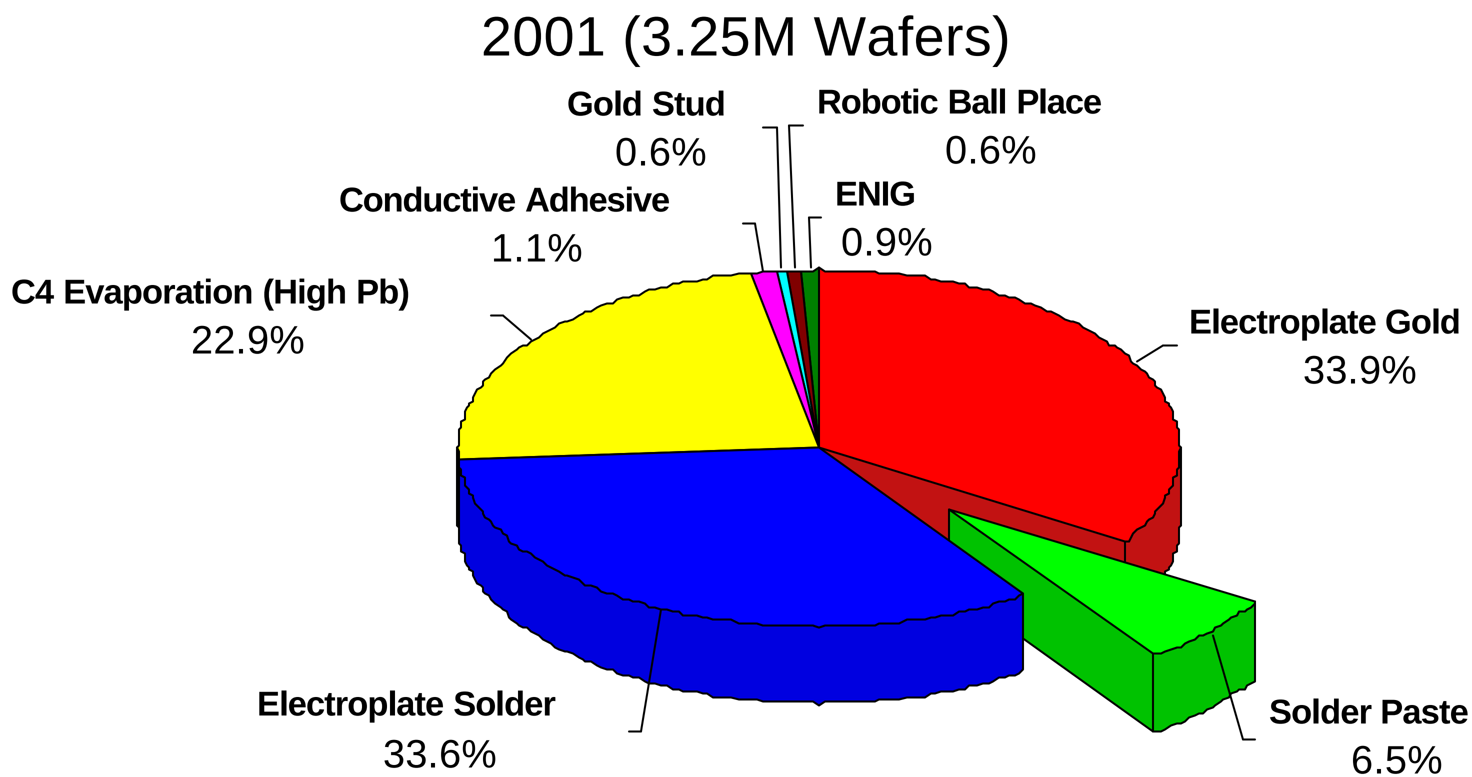
Bumped Wafer Projection by Device Type



Source: *Prismark*

Global Bumped Wafer Production by Technology

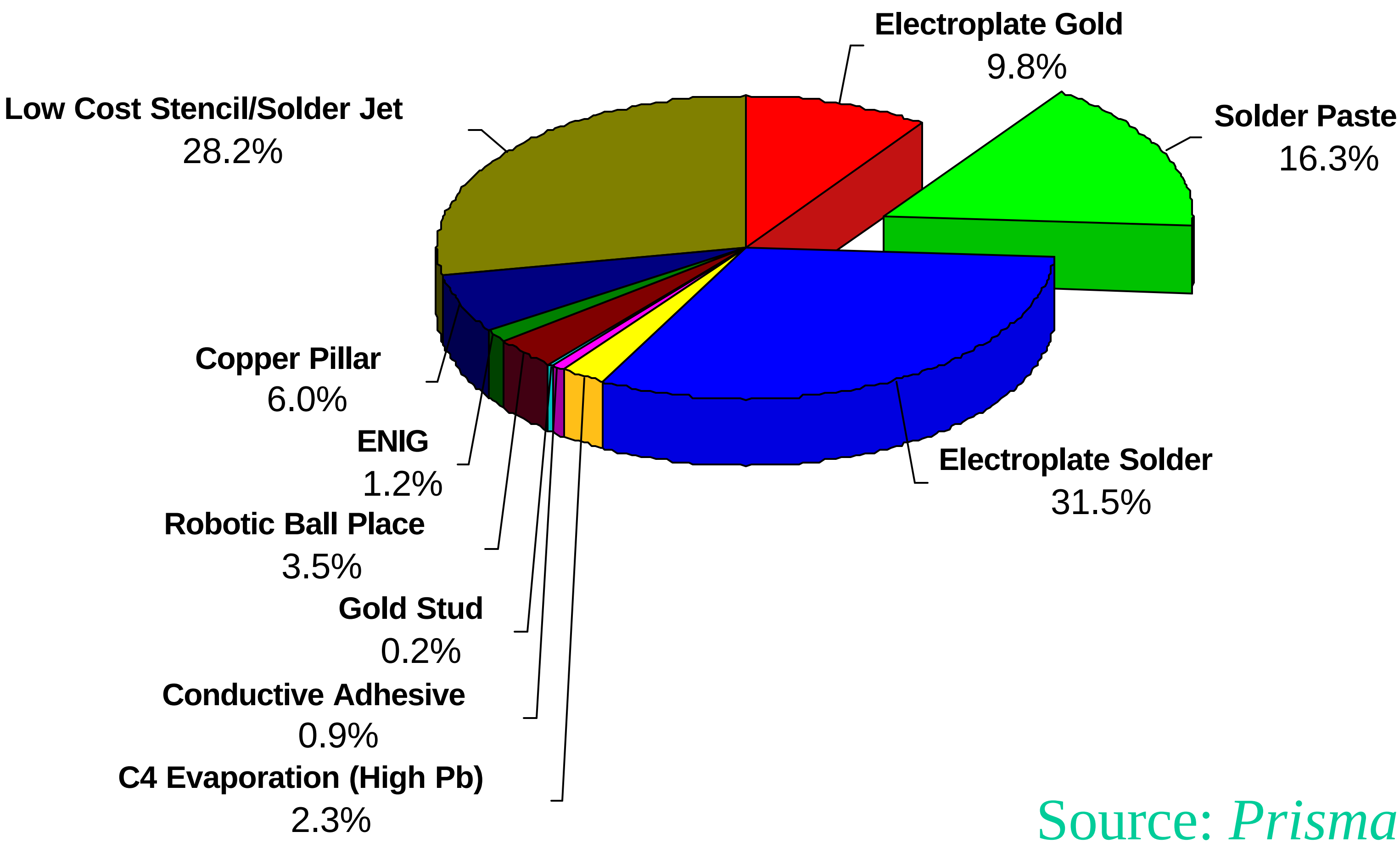


Source: *Prismark*

Note: Includes Flip Chip, TAB, Wafer CSP's and thin film passives, 200mm wafer equivalent values

Global Bumped Wafer Production by Technology

2006 Pedicted (23M Wafers)

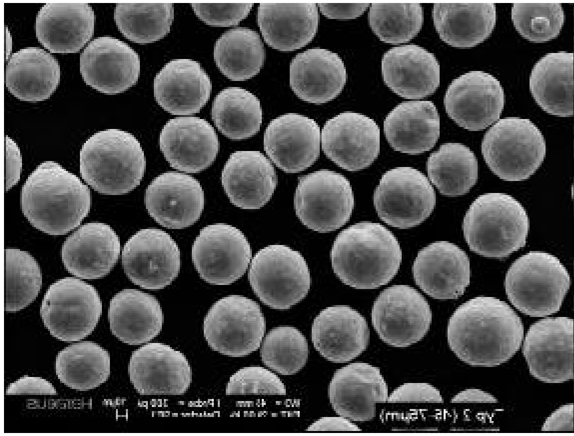


Source: *Prismark*

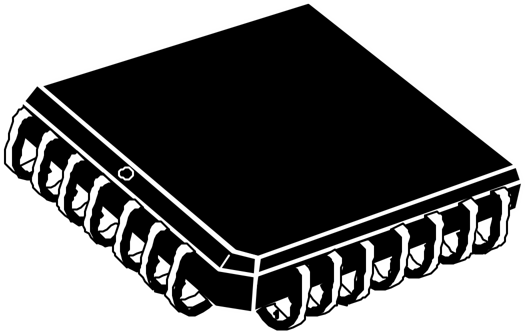
Note: Includes Flip Chip, TAB, Wafer CSP's and thin film passives, 200mm wafer equivalent values

Wafer Bumping Solder Powder

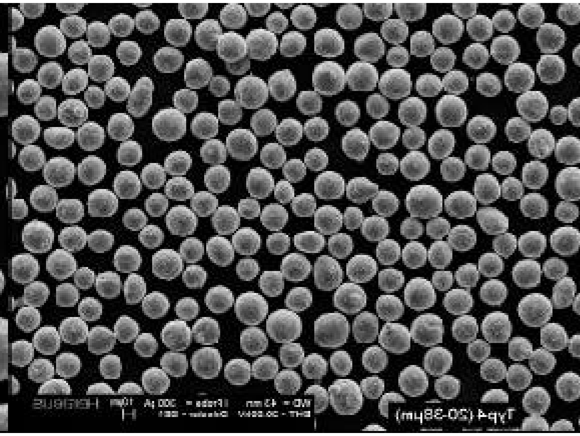
Type 2: 25-45 microns



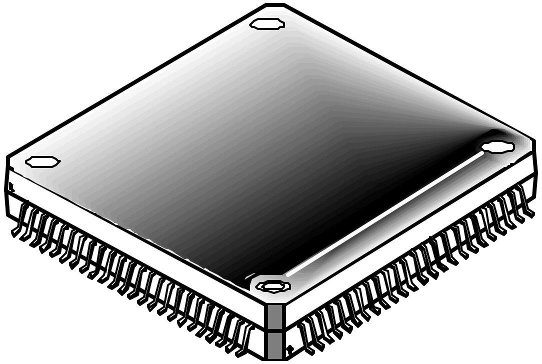
SMT (no fine pitch)



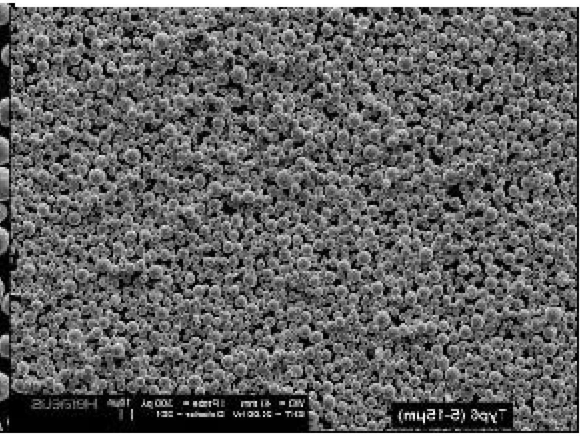
Type 4: 20-38 microns



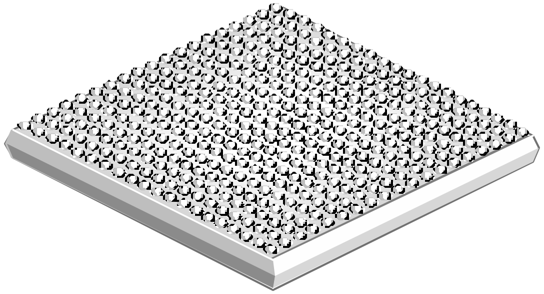
SMT(Fine pitch, CSP)



Type 6: 5-15 microns



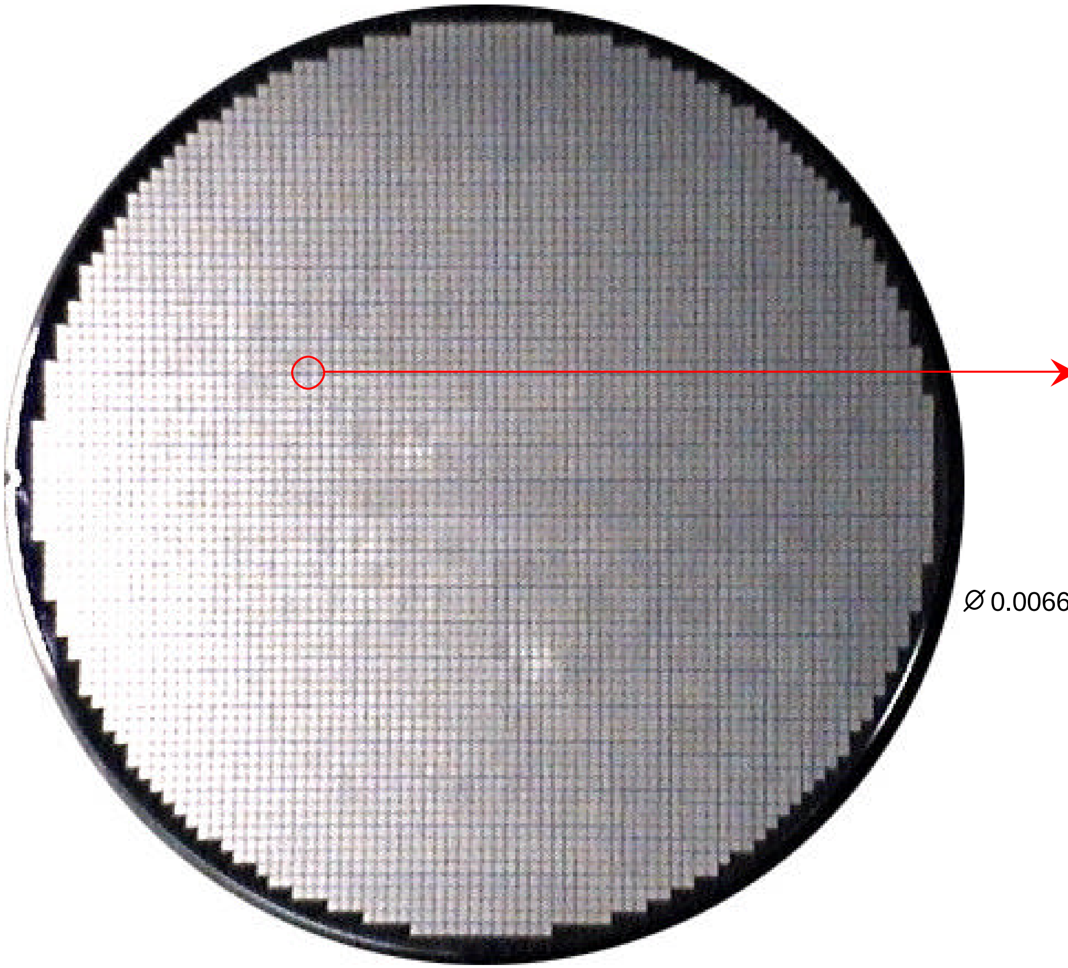
Wafer Bumping

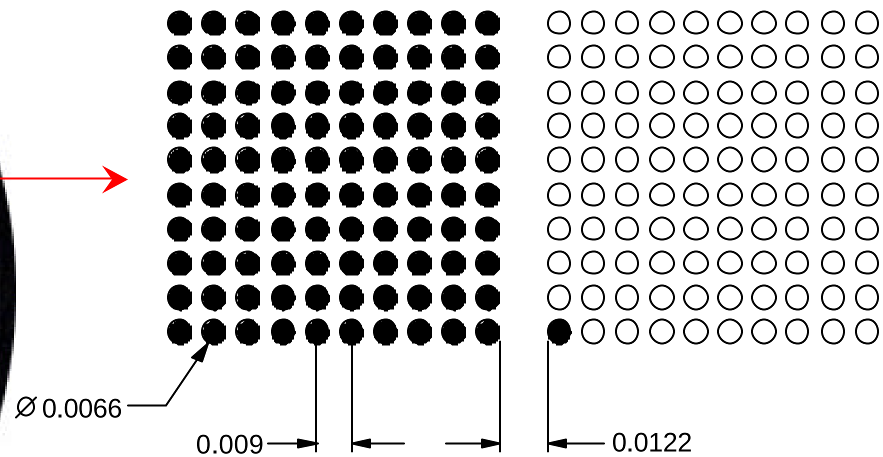


Heraeus

Wafer Bump Print- Test Pattern Design

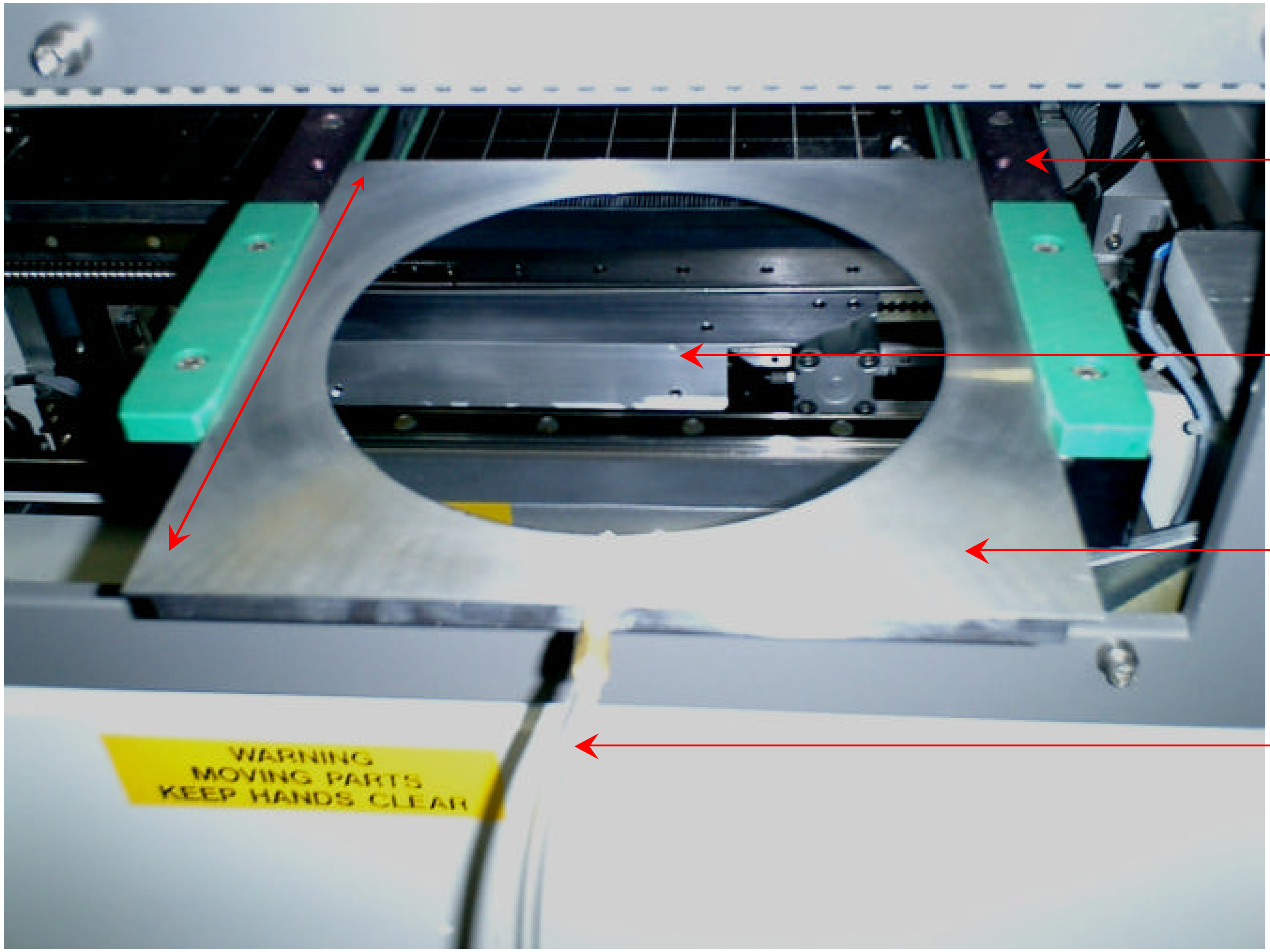
200mm Wafer





453,000 Apertures

Wafer Printing Tooling



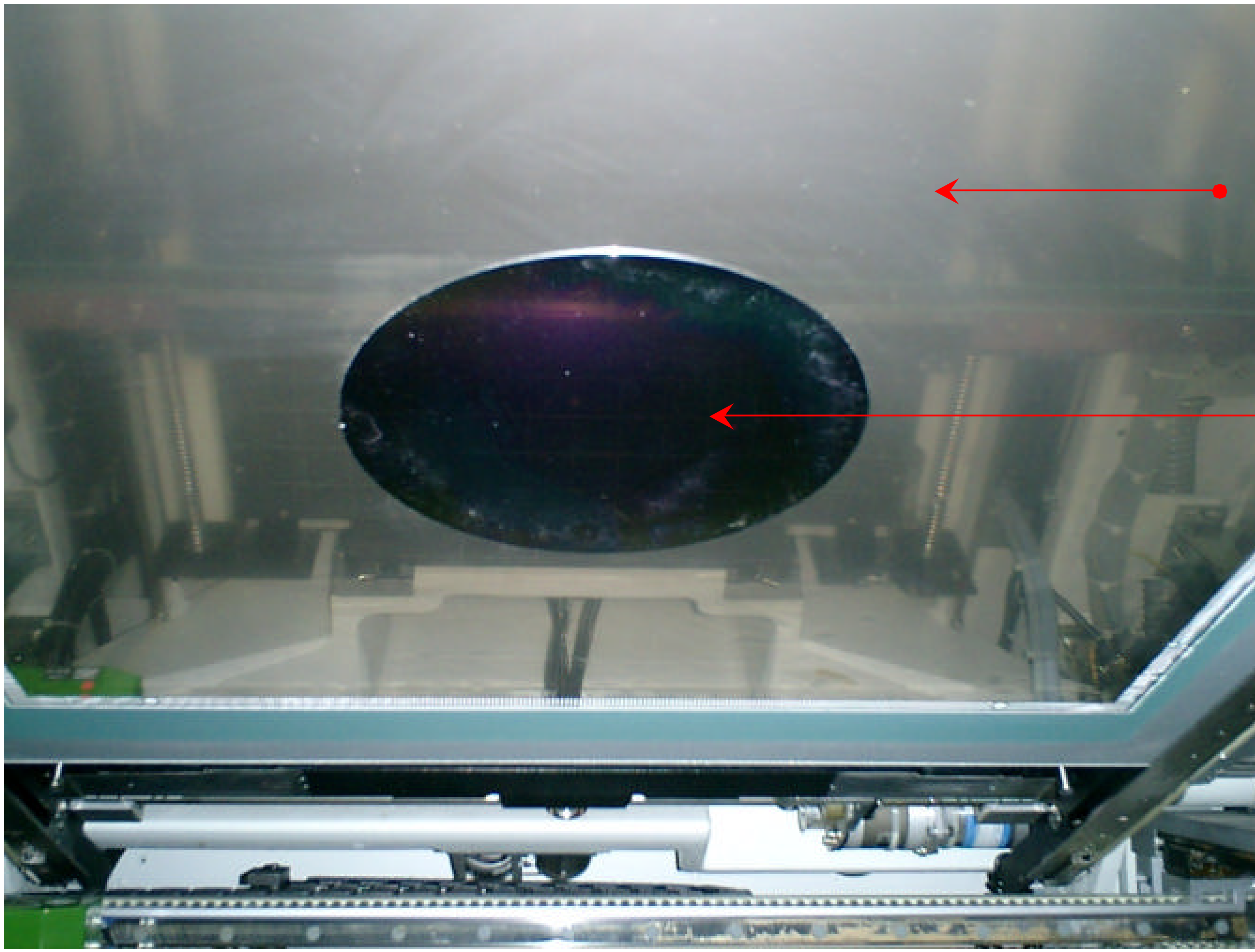
Printer Rails

Wafer

Nest

Vacuum

Wafer Stuck on Stencil - Low vacuum

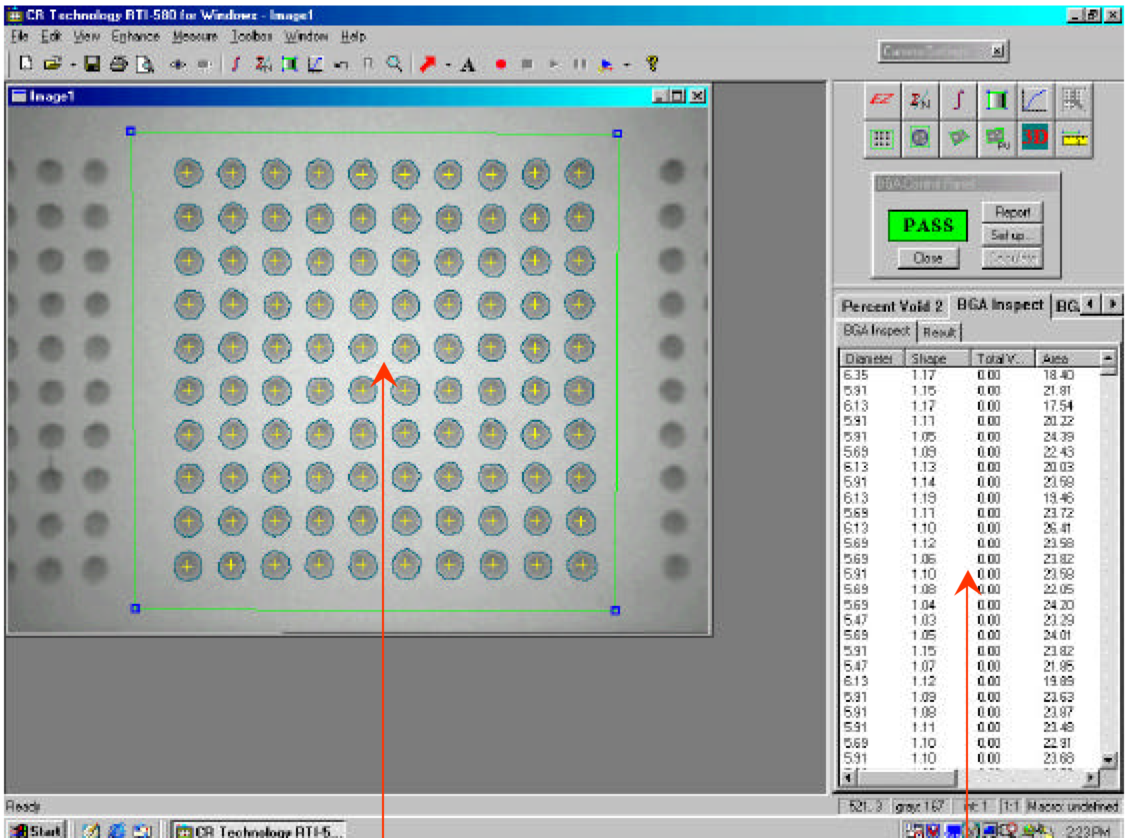


Stencil Underside

85 lbf

Wafer

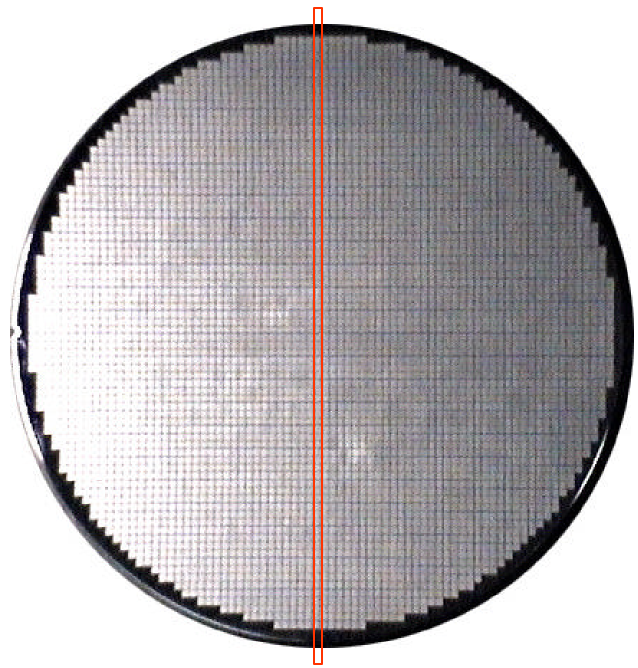
Real Time X-ray Measurement of Print Deposits



100 Deposit Array

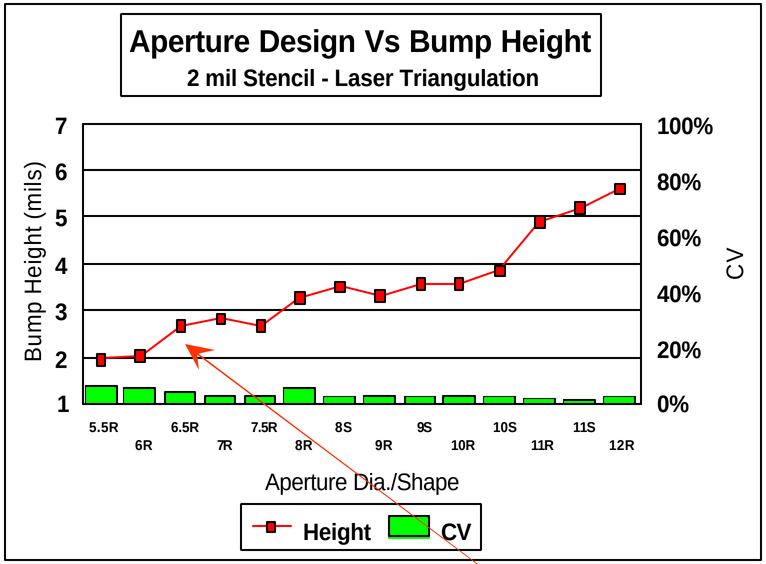
Data File

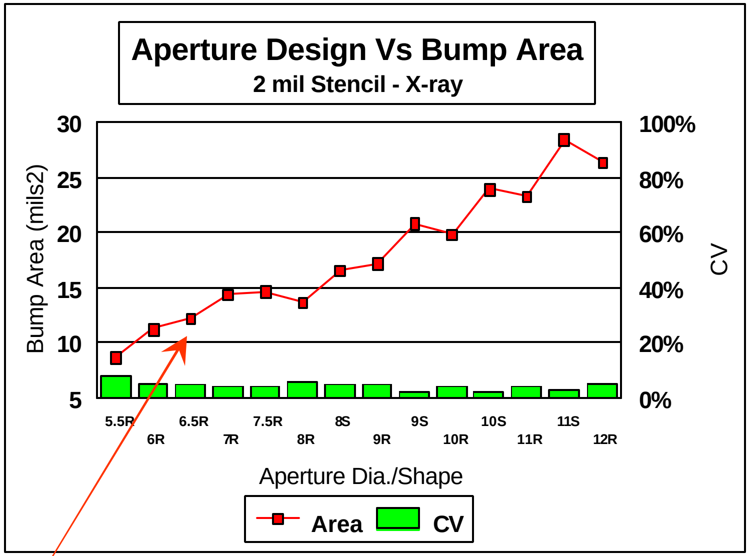
Print Direction

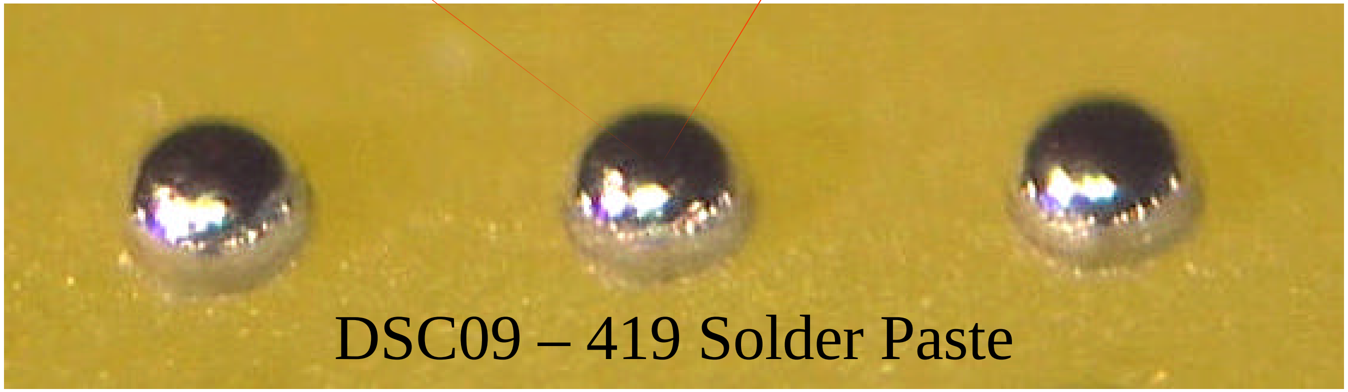


Measurement Window

2 mil E-FAB Stencil – 6.5 mil aperture Reflowed Bumps







Experiment Matrix

Experiment	Stencil Thickness	Squeegee	Gap (mm)	Separation Speed
A	2	Red	0	0.1mm/s
B	2	Black	0	0.1mm/s
C	2	Red	0	20mm/s
D	2	Black	0	20mm/s
E	2	Red	3	20mm/s
F	2	Black	3	20mm/s
G	2.7	Red	0	0.1mm/s
H	2.7	Black	0	0.1mm/s
I	2.7	Red	0	20mm/s
J	2.7	Black	0	20mm/s
K	2.7	Red	3	20mm/s
L	2.7	Black	3	20mm/s
M	2.7	Metal	0	0.1mm/s
N	2.7	Metal	0	20mm/s
O	2.7	Metal	3	20mm/s

Fixed Variables

Squeegee Pressure: 1kg/in

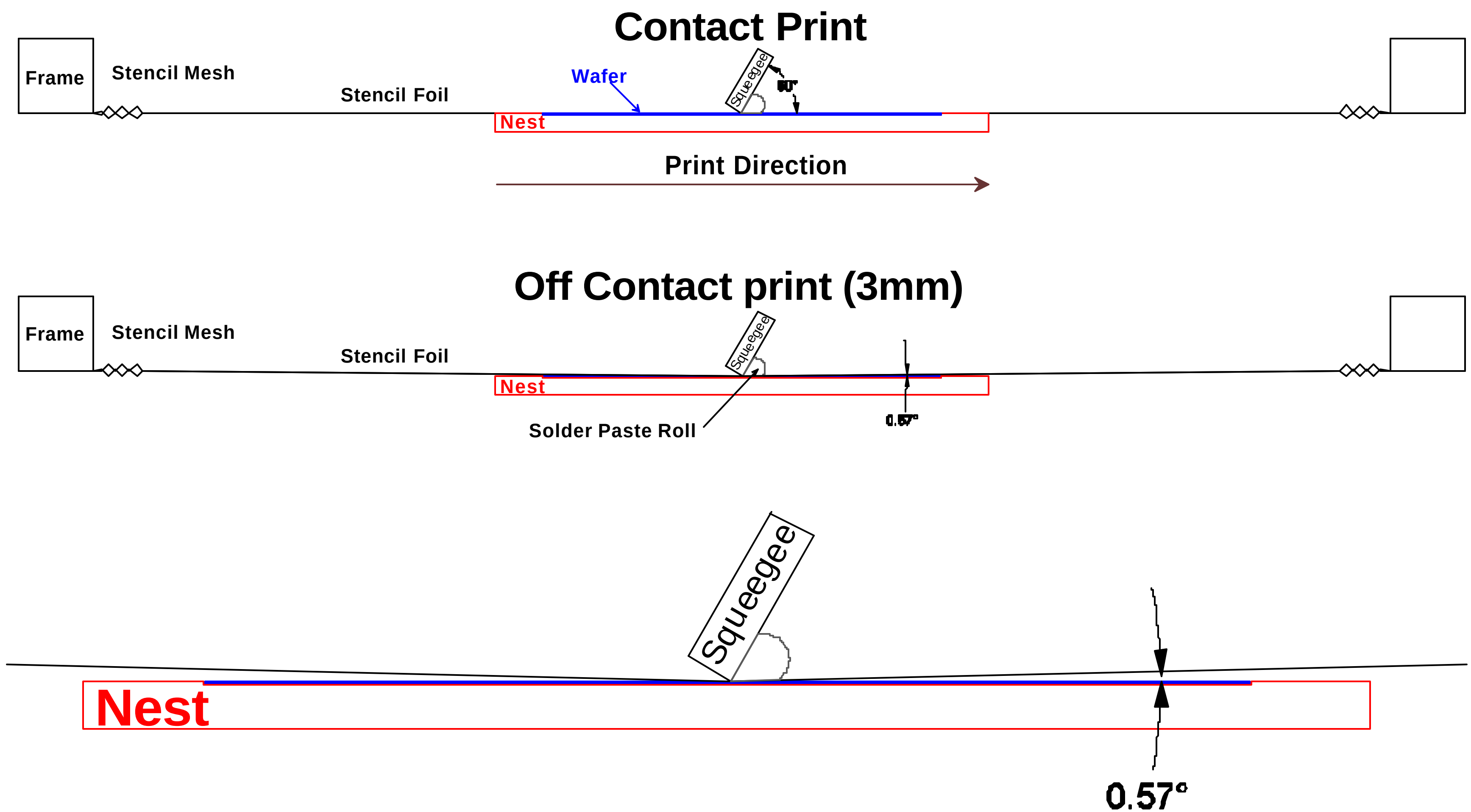
Print Speed: 20 mm/s

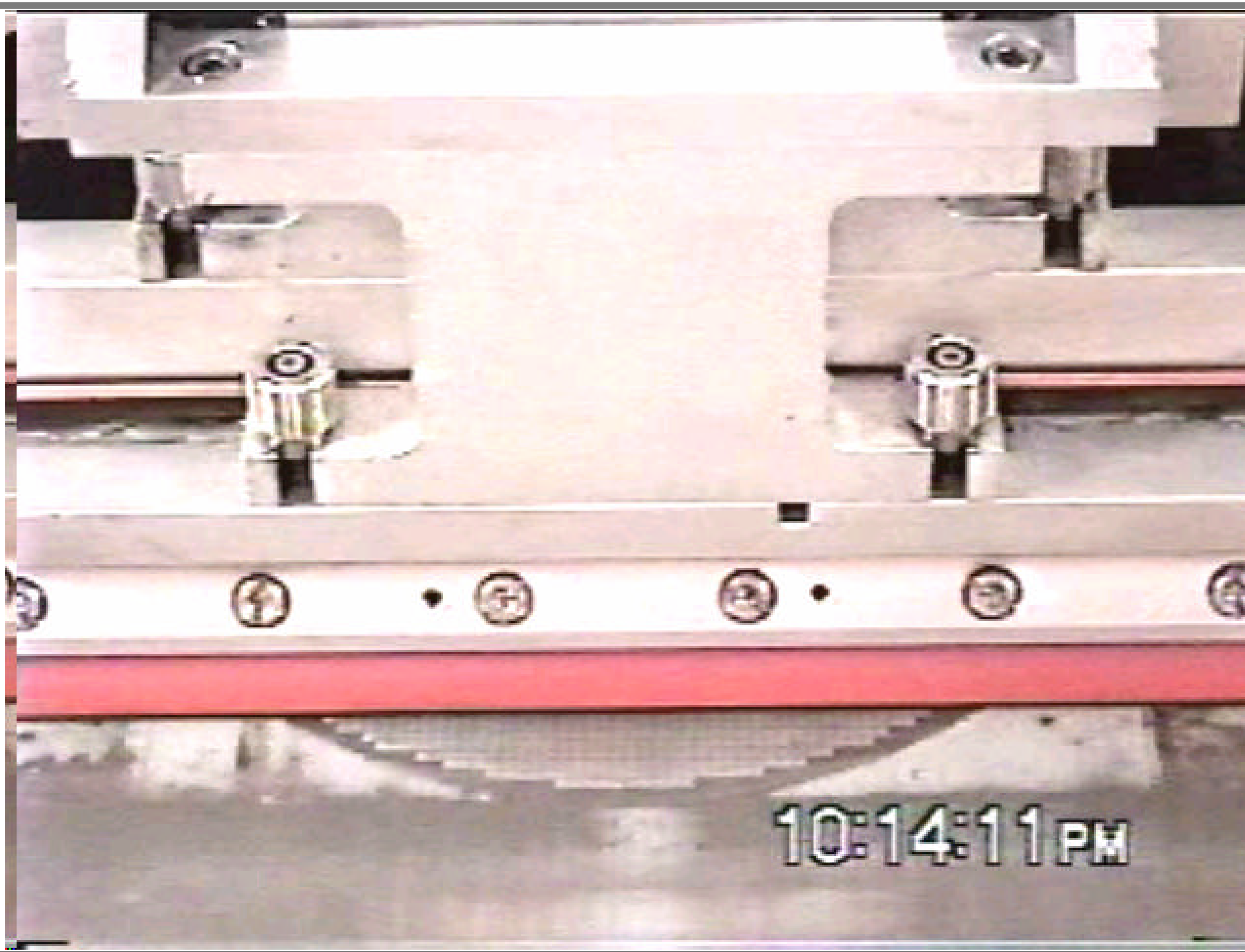
Separation Distance: 3mm

Black = 75-80 durometer

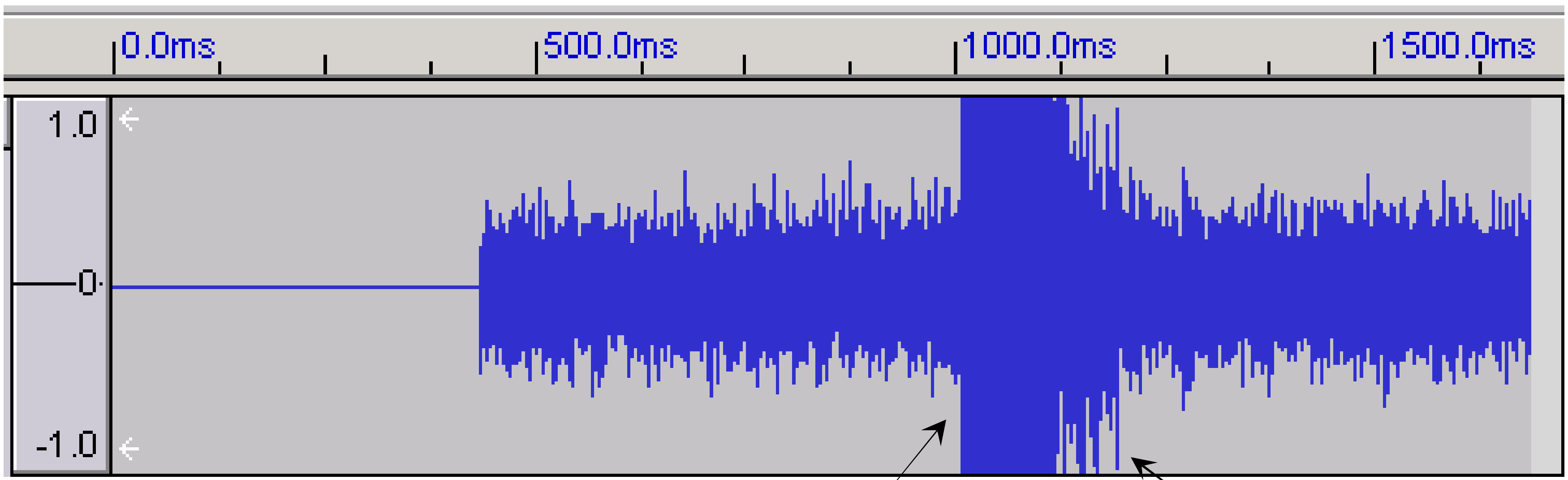
Red = 94-97 durometer

Print Gap


Contact Print
Frame
Stencil Mesh
Stencil Foil
Wafer
Squeegee
Nest
Print Direction
Off Contact print (3mm)
Frame
Stencil Mesh
Stencil Foil
Squeegee
Nest
Solder Paste Roll
Squeegee
Nest
0.57°


10:14:11 PM

Screen Popping Similar to Drum Beat

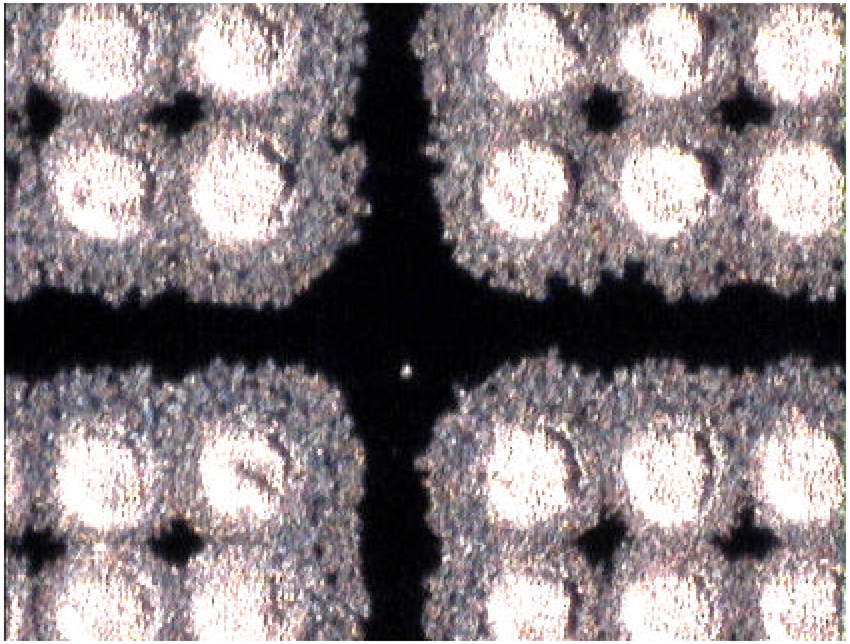


Initial Release

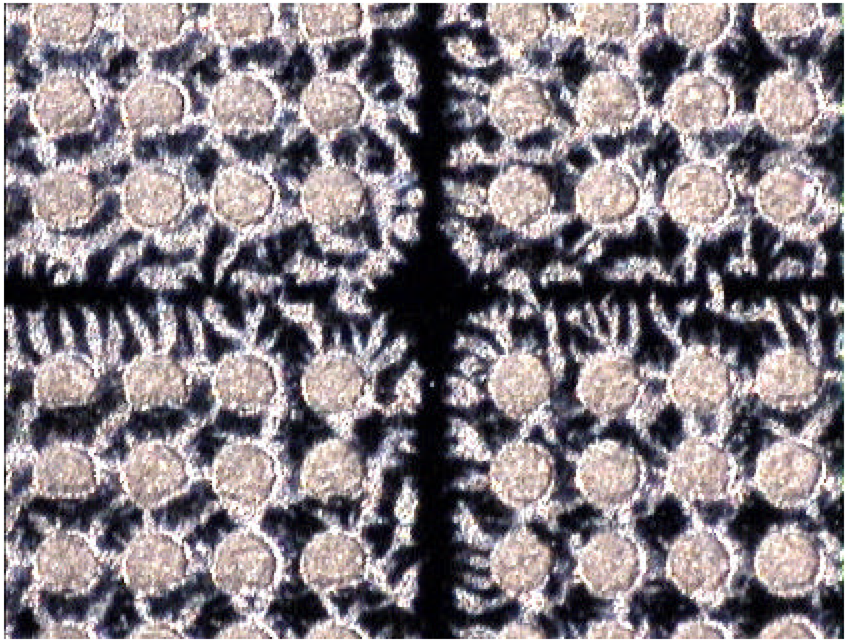
Foil "Ringing"

Whole event ≈ 200ms

Effects of Screen Popping

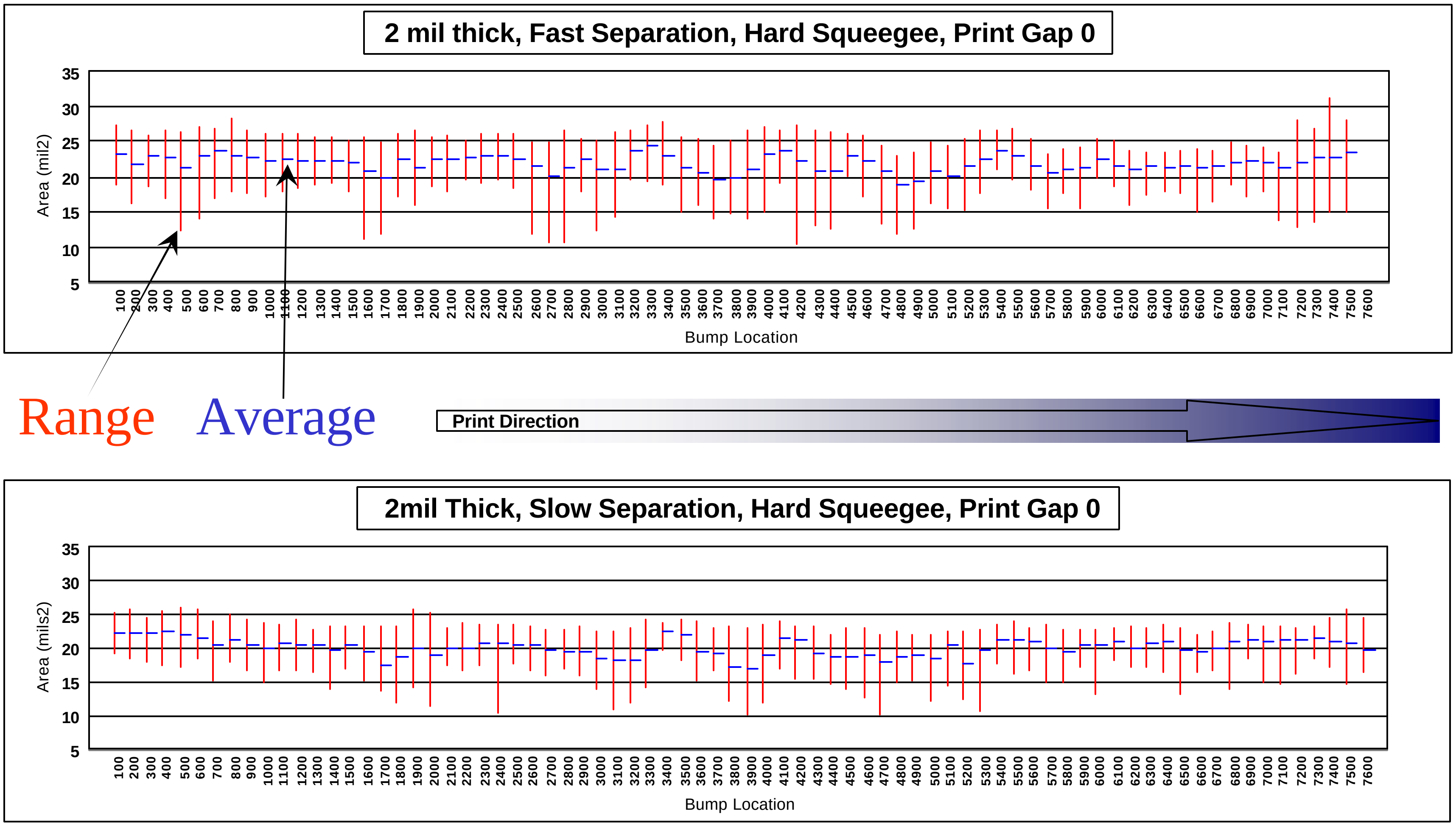


Fast Separation
(20mm/s)



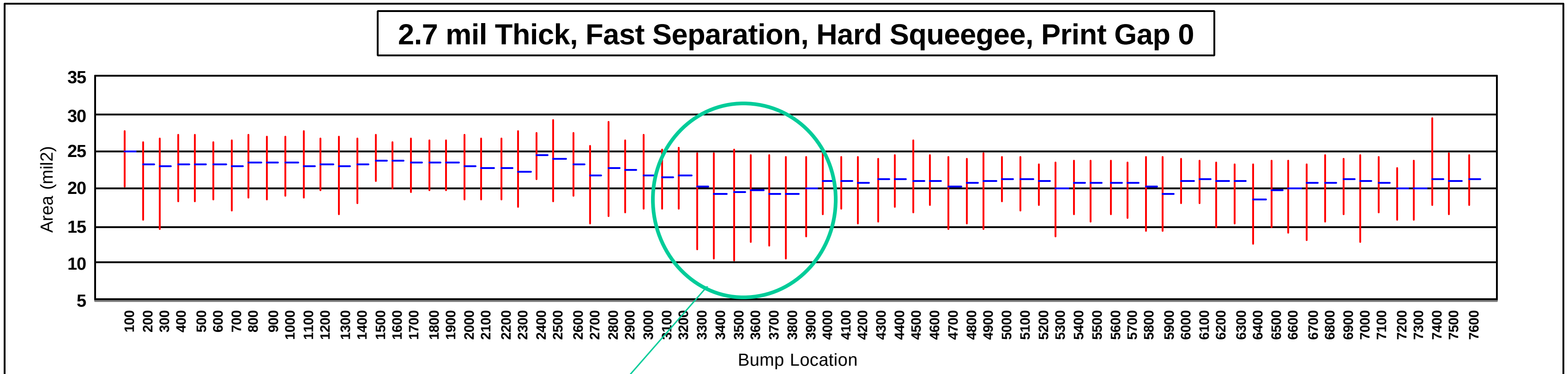
Slow Separation
(0.1mm/s)

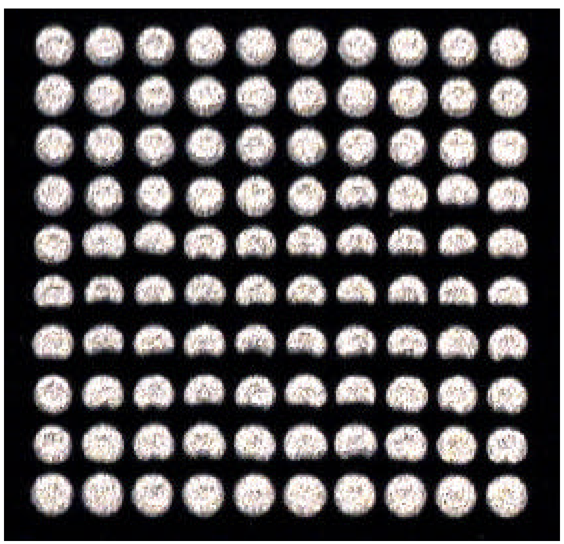
Separation Speed Effects – X-ray Area Data

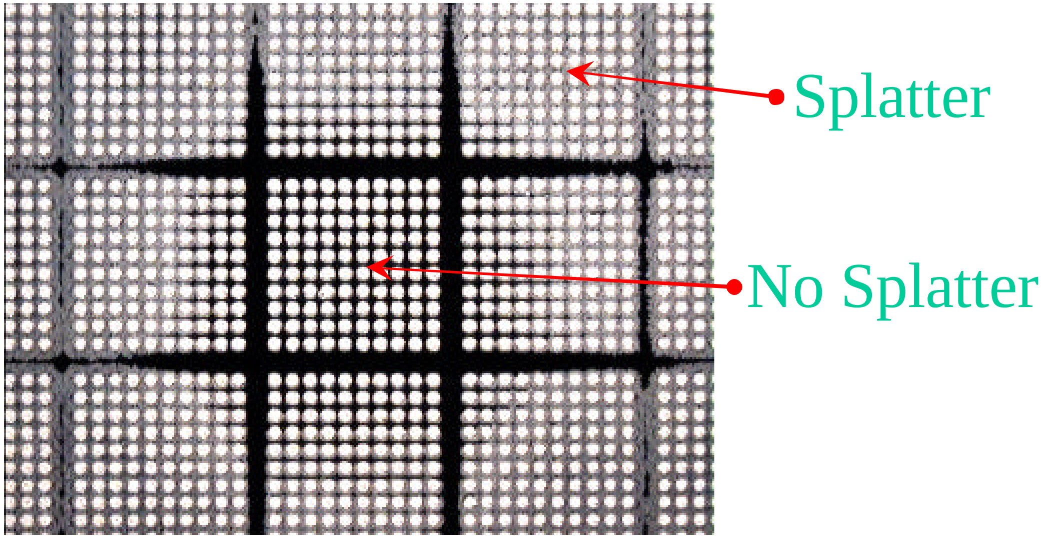


Heraeus

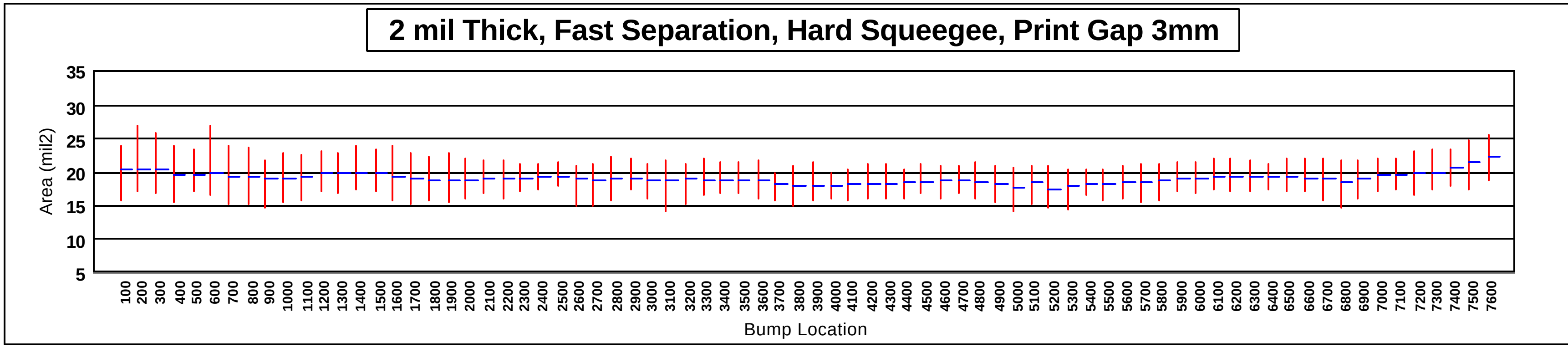
Contact Print Area Variability

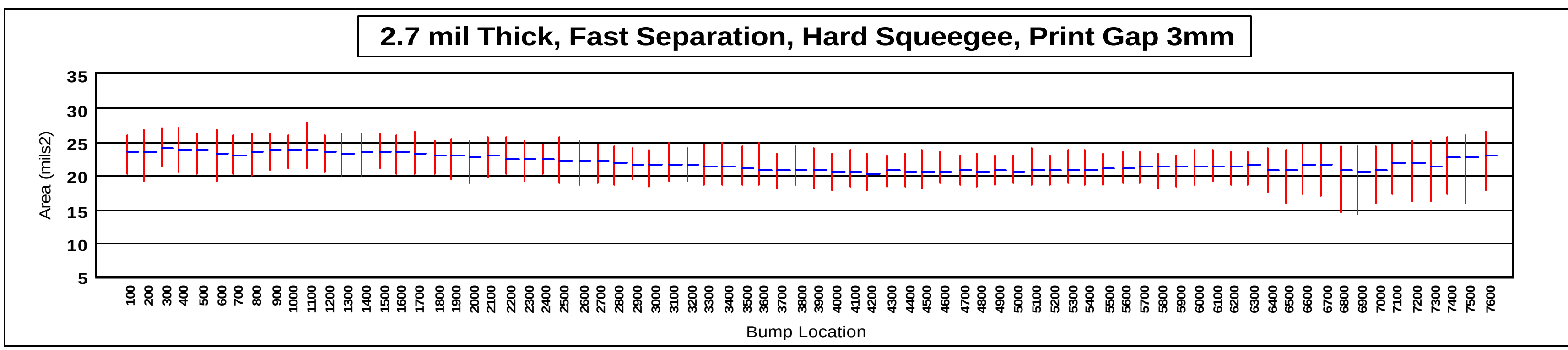




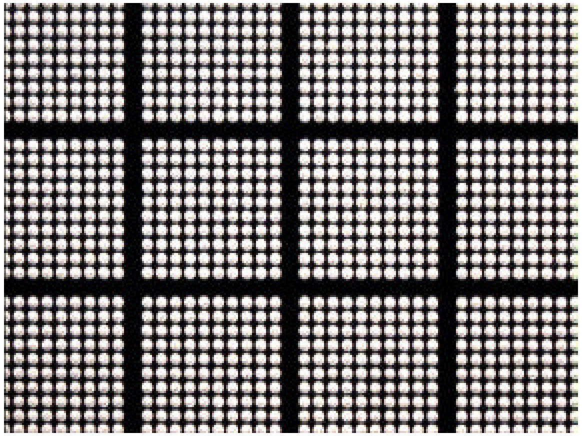


Off Contact Printing for More Consistent Deposits

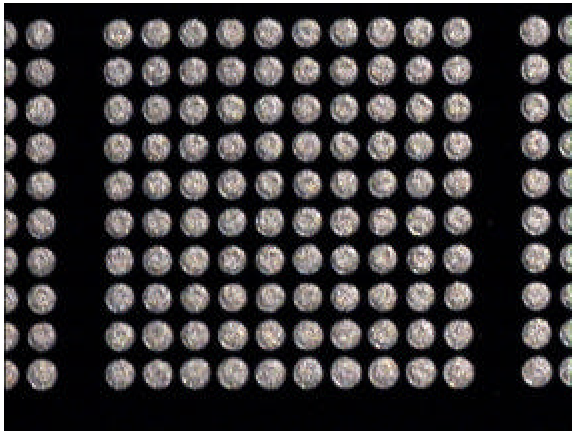




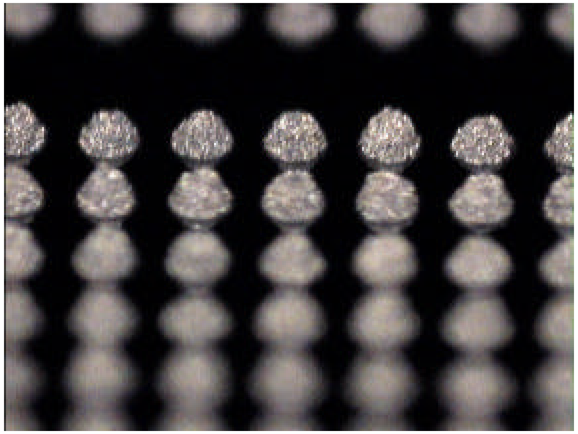
Off Contact Print Quality



Typical Print

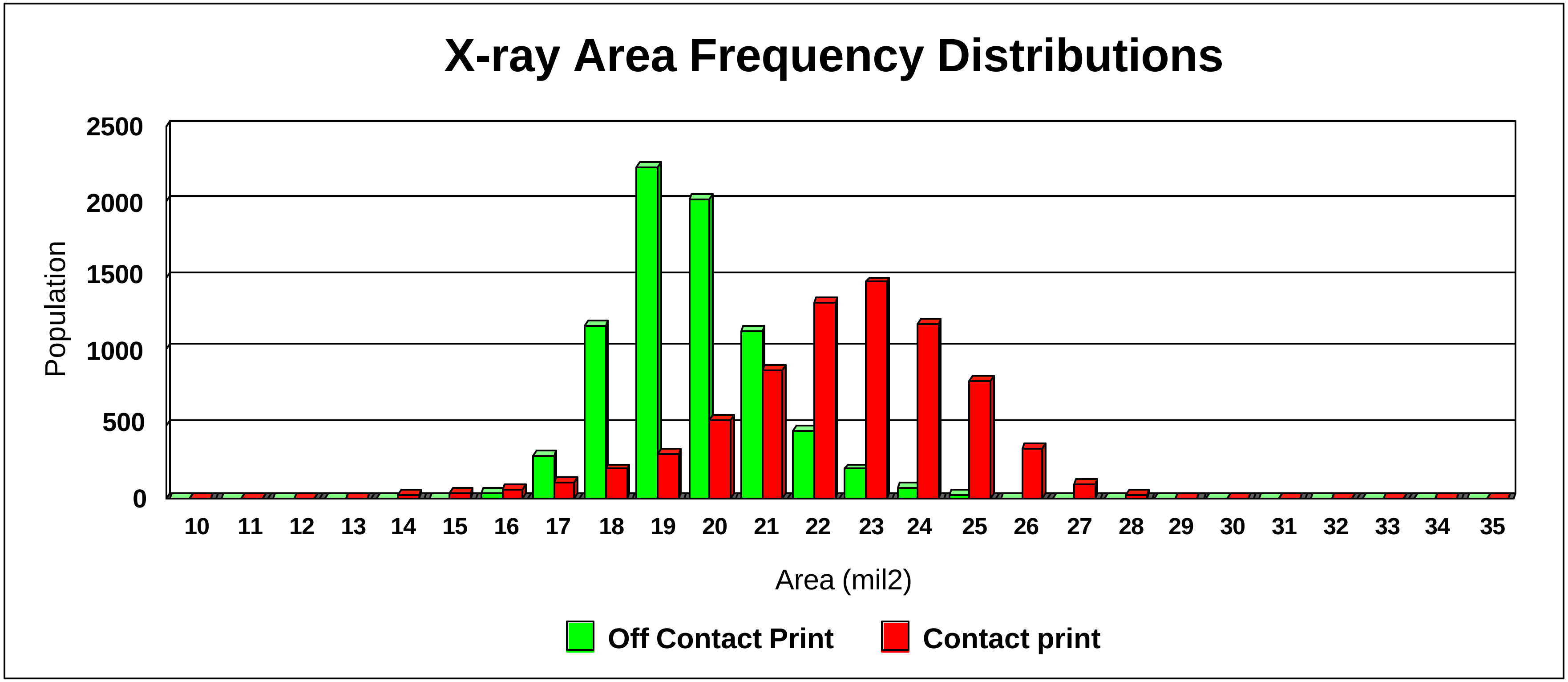


100 bump Array

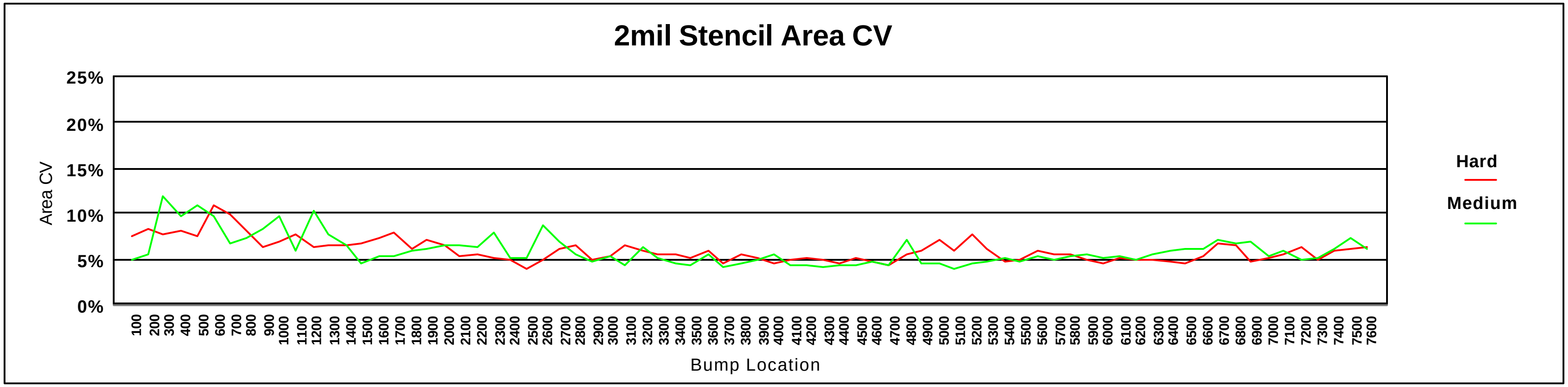


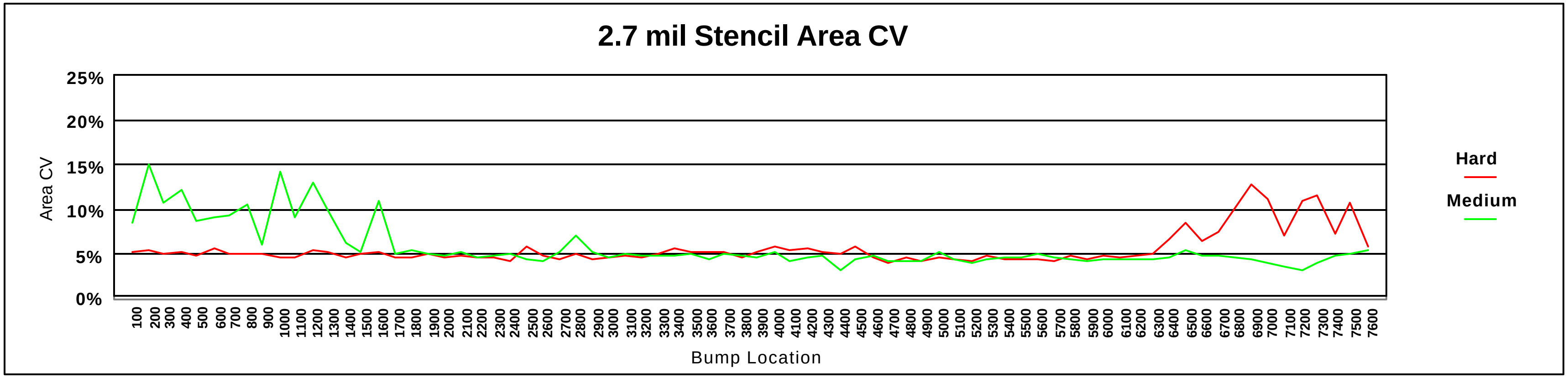
Deposit Profile

Frequency Distributions

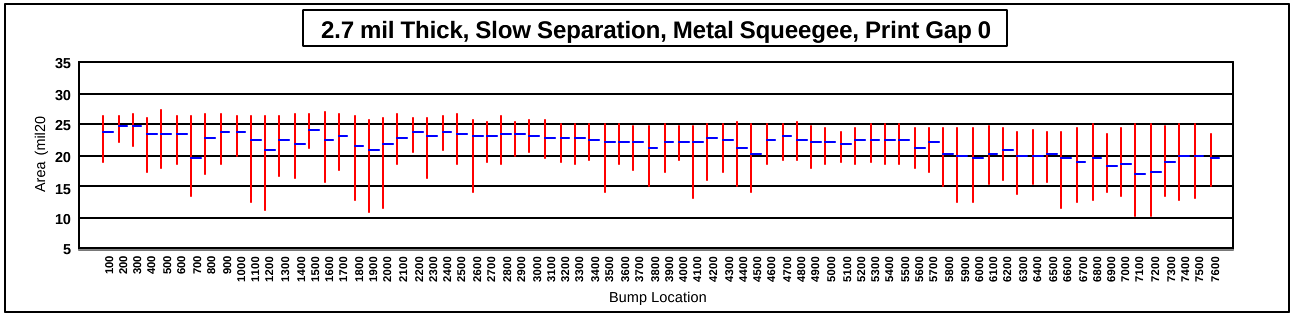


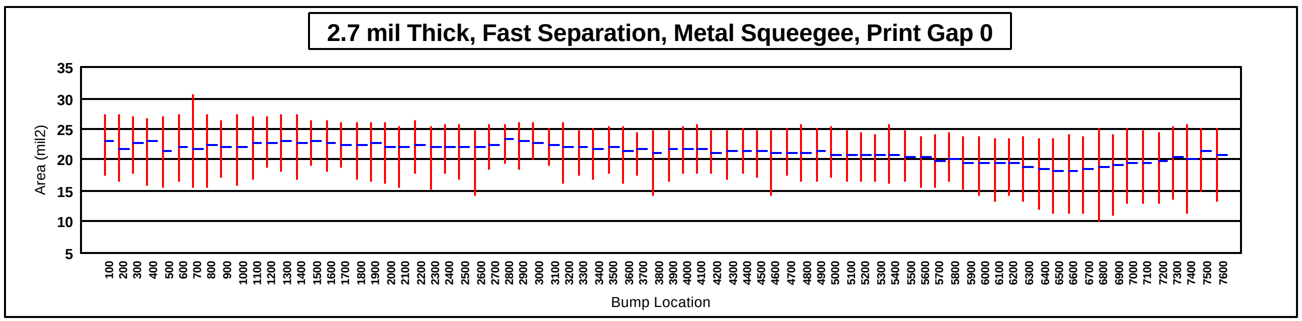
Squeegee Effects – Medium & Hard Polymer

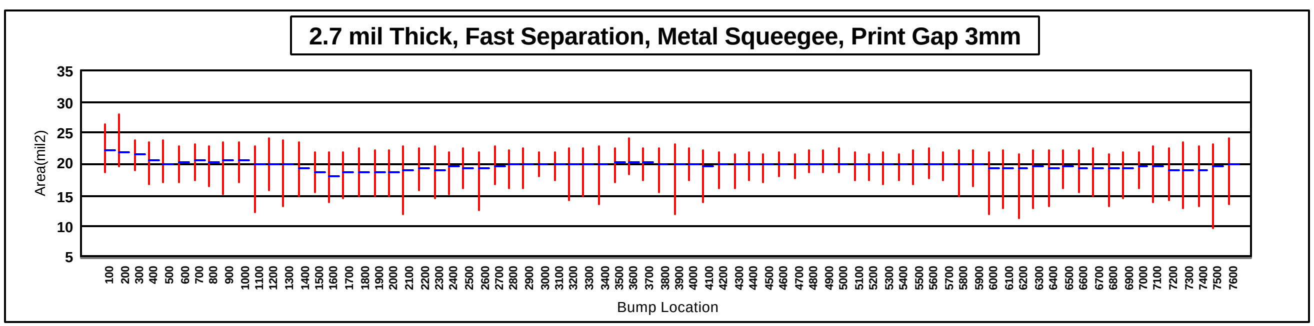




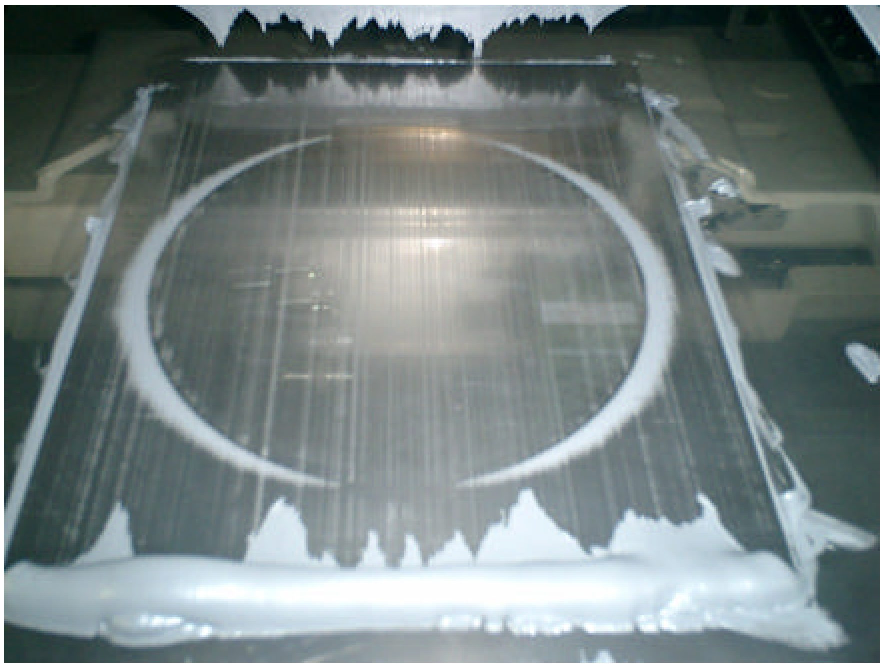
Squeegee Effects - Metal



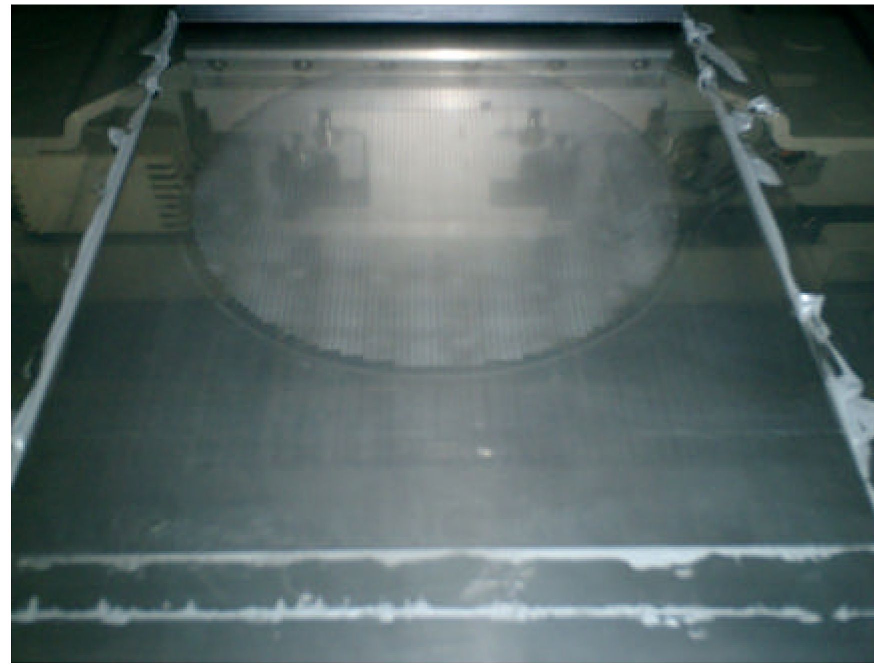




Squeegee Wipe Patterns



Metal Squeegee Streaks



Hard Polymer Wipe

Conclusions

From this study which involved measuring 228,000 bump deposits out of 6.8 million printed, several valuable wafer bumping print process elements have been identified and verified.

- Considerable print gap (off-contact) is critical to preventing screen "popping" and the resultant splattering of the wafer surface with flux and solder particles.
- Off-contact printing also yielded a much tighter print deposit area distribution as in Figure 29.
- The wafer must be supported by flat rectilinear tooling with vacuum hold-down.
- Very slow separation for a 3mm distance is inadequate to prevent this "popping".
- Metal squeegees simply do not wipe as well as polymer squeegees. The preferred squeegee is hard durometer polymer.
- X-ray BGA analysis techniques combined with visual analysis are viable quantitative measurement tools for wafer bump print assessment.