# Latest technological advancements in stencil printing processes for Ultra-fine-pitch flip chip bumping down to 60µm pitch

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**ABSTRACT**

*Stencil printing remains the technology route of choice for flip chip bumping because of its economical advantages over traditionally costly evaporation and electroplating processes. This paper brings up all the technological challenges and up to date advancements in all processing steps of 6"wafer bumping of peripheral array structures at Ultra-fine-pitches (UFP) of 100µm pitch and especially 60µm pitch. Innovative electroformed stencils have been manufactured with a thickness down to 20µm. Both type 7 (2-11µm) and type 6 (5-15µm) pastes of eutectic composition Sn63/Pb37 have been successfully employed for wafer bumping at 100µm pitch. Bumping using 25 µm stencil thickness has yielded bump heights of 42.3±3.8µm and 43.6±3.5µm for type 7 and type 6 pastes, respectively. A newly developed type 8 paste (2-8µm) has been used for the first time to bump chips with peripheral contacts at 60µm pitch. A 20µm thick electroformed stencil was used with 35µmx80 µm oblong apertures. Printing at 60µm pitch has yielded very promising results and has proved the capability of electroformed technology to manufacture accurate and robust thin stencils. The bump height at 60µm pitch was measured to be 28 ±3 µm. The present study provides insights into the processing issues for further development of UFP technologies such as Ultra fine paste printing behaviour, its reflow and slump characteristics as well as discussion in stencil manufacturing and printing machine alignment issues for UFP bumping.*

***Keywords:*** *wafer bumping, flip chip, Ultra fine pitch, stencil printing, type 8 paste, type 6 paste, electroformed stencils.*

## 1. Introduction

The attractiveness of flip chip technologies lays on the superior electrical performance, higher thermal conductivity, smaller size and higher I/O counts which are mandatory requirements for advanced semiconductor applications. However, a substantive shift towards flip chip interconnection technologies will be witnessed only with accomplishment of cost reduction, reliability improvement and cost-efficient high density substrate technologies [1]. Low-cost flip chip bumping technology has become a reality with implementation of electroless nickel plating process for under bump metallization (UBM) in conjunction with stencil printing of solder pastes for the formation of solder bumps [2].

Stencil printing of solder paste for flip chip wafer bumping offers among others the advantages of cost-effectiveness and compatibility with pre-existing printing equipment in a surface mount assembly line [3-7]. The state-of-the-art in wafer bumping using the conventional stencil printing technology (laser-cut steel and Nickel-electroformed stencils) is at about 120µm pitch for peripheral arrays and 150µm for area arrays [3]. Significant technological improvements have been reported in literature regarding the capability of Ultra Fine Pitch (<120µm) (UFP) wafer bumping [9-11]. This progress is extremely significant especially in view of Moore's law prediction that the bits/chip grow by a factor of 4x every three years [8]. However, the advancements to UFP bumping can not be realised without parallel progression to very fine paste and stencil manufacturing. The emergence of ultra fine type 7 pastes (2-11µm) and lately of type 8 (2-8µm) pastes as well as recent developments in fabrication of very thin electroformed stencils with very small aperture dimensions have sparked significant work in the area of UFP wafer bumping.

This paper discusses in depth the latest advancements and the open issues in electroformed stencil technology. It presents the results of our recent studies on UFP stencil printing of type 6 and type 8 solder pastes for bumping of 6" wafers with pitches at 100µm and 60µm, respectively.

## 2. Technology Implementation

### *2.1 Wafer Designs & Chemical Metallisation*

The wafers used in this study had a diameter of 6". The wafer at 100µm pitch had a thickness of 680 µm whereas the wafer at 60µm pitch had a thickness of 320µm. The wafers at 100µm pitch consist of 540 chips with a size of 5mm x 5mm. Each chip has 176 I/O's with the pads arranged in a peripheral configuration. A total number of 95040 pads exist on the wafer. The pads have an octagonal shape with a diameter of 40 µm. The electroless Ni/Au plating technology of (TUB) was used to deposit 2 µm Ni /80 nm flash Au (over the chip passivation layer) high UBM pads on the Al metallization pads. The lateral overlappment of the Ni/Au UBM pads on the chip passivation layer is also 2 µm on both sides. The Electroless chemical metallization process finally yields 44 µm UBM pad size. Detailed description of TUB's Electroless Ni/Au technology approach (ENIG) can be found in literature [2]. Correspondingly, the wafer with peripheral arrays at 60µm pitch has 577 chips with a size of 5mmx5mm with 296 pads per chip. A total number of 170792 pads exist. The passivation opening on the Al pad was 20µm and the same ENIG process was applied to deposit 4 µm Ni/80nm Au over the chip passivation layer. The UBM size of the wafer after application of Ni/Au is 28µm. Figure 1 shows the Ni/Au UBMs at 60µm pitch which proves that the ENIG process is feasible to very small wafer pitches.

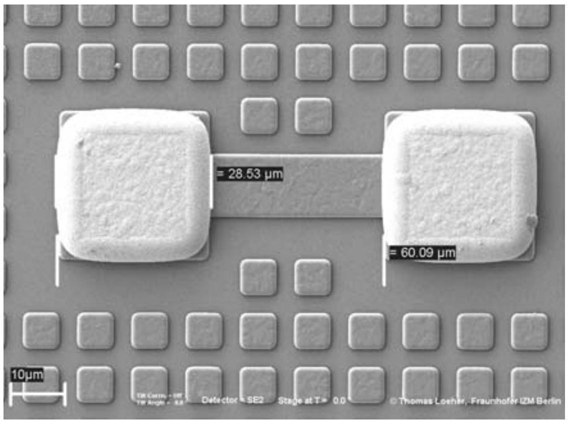



Figure 1: Electroless Ni/Au UBMs at 60µm pitch. UBM size is 28µm.

### *2.2 Stencil design rules & Selection of stencil manufacturing method*

The criteria for the selection of stencil manufacturing technology were aperture wall quality, dimensional consistency, positional accuracy and stencil production cost. Our previous studies on stencil printing of UFP structures at 80 µm and 60 µm pitch have shown the great potential of laser-cut steel stencils although aperture quality still remains dependent on the technical expertise of laser stencil manufacturers, and availability of fine-tuned laser guns in the market [9]. Recent refinements in the laser cutting process have been developed to improve even more the quality of stencil apertures including smaller laser spot sizes and water guided laser cutting techniques. One advantage of laser cut stencils compared to electroformed is that the material is pre-tensioned from the framing process prior to cutting, which in turn reduces the stencil deformation. Laser cutting is a sequential process; therefore as the number of I/O increase on the design so does the time to manufacture the stencil. This can be a significant disadvantage for wafer bumping stencils at fine and ultra fine (<120µm) pitches with a high number of apertures because as the number of holes increases the manufacturing time rises to an almost uneconomical point. Also the heat melt interaction during the cutting process can create rough inner sidewalls which in turn produce apertures with a larger surface area and therefore have a tendency to minimize paste release. In addition, the heat generated in the cutting process must be controlled as not to warp the stencil during manufacturing or damage the fine webs required for UFP printing. Electro polished stencils are normally laser cut stencils which have been smoothed using electrochemical or mechanical polishing methods. However all metal stencil types can be treated in this manner after manufacturing.

The cost factor becomes profoundly significant considering an approximate cost of 3 $/100 laser-cut apertures and the large number of apertures needed for UFP structures. In contrast, electroformed stencils with good aperture wall quality and reasonable manufacturing cost per wafer design; and not per aperture, appear as a rational alternative solution especially for UFP wafer structures. Hence, electroformed technology was selected for the stencil manufacturing in this study. It should be noted that UFP research has been conducted with laser-cut steel stencils at very fine and ultra fine pitches and results can be found in the literature [3,9]. It was also intended to prove the capabilities of the electroformed technology to make very thin foils with good robustness for continuous printing and with good aperture smoothness and dimension accuracy. For the wafer at 100µm pitch, oblong apertures of 50µmx125µm were designed and a foil thickness of 25µm was selected. The aperture design for wafer bumping always takes into consideration the existing rules for fulfilment of aspect (>1.5) and area (>0.66) ratios for efficient paste transfer on the pads but also considers to hold the minimum separation distance to avoid paste bridging. For bumping at UFP, it is very difficult to find the gold solution to satisfy the above mentioned design principles [4,9,11]. The design for 100µm pitch wafer yields an aspect ratio of 1.5 and an area ratio of 0.71, respectively. The aperture design for the wafer at 60µm pitch employed oblong apertures of 35µmx80µm and a foil thickness of 20µm was selected. The aspect and area ratios were 1.75 and 0.61, respectively.

### *2.3 Technological challenges & achievements in electroformed stencil manufacturing at UFP*

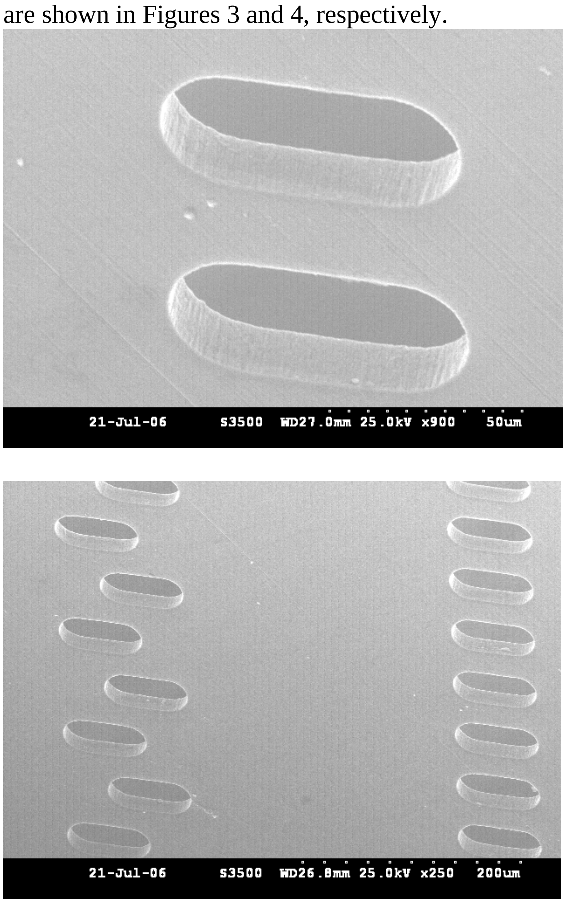
The conventional electroformed stencil manufacturing process involves taking a conductive mandrel such as stainless steel and applying a dry film layer of photoresist. This photoresist layer is then photo patterned and developed. The photoresist left on the mandrel after photolithography defines the apertures. The substrate is then placed into an electroplating solution and a current is applied to the mandrel. The metal normally deposited to generate the stencil is nickel or a nickel alloy. Since electroplating is an additive processes versus the other subtractive techniques mentioned above to manufacture solder paste stencils the deposited metal follows precisely the photoresist mold. After plating, the photoresist remaining in the apertures is removed and the finished stencil can be framed.

Conventional electroformed stencils suffer from a few disadvantages. Firstly, the photolithography step employs substrates, resist material and mask technology which does not permit high definition photolithography with smooth sidewalls. In addition, this coupled with high current DC electroforming means that the thickness uniformity and uneven gasket formation with the stencils can cause poor uniformity during printing. Lastly, as the pitch decreases so must the stencil thickness to allow effective paste transfer, however. very thin stencils can suffer from elastic deformation. Most stencil providers do not compensate for this deformation during the manufacturing process which is a critical factor to ensure good registration between the wafer and the stencil. The stencil is seen as a critical component in the printing process. Without the correct stencil it is impossible to achieve a high yield manufacturing process. The stencil must have the correct thickness uniformity and aperture tolerance for the selected application.

#### *2.3.1 MicroStencil product*

MicroStencil Ltd. has developed a novel MEMS based fabrication process for the generation of large area precision electroformed stencils primarily used in the flip chip and wafer level packaging industries. The use of different substrate materials, high resolution masks and photoresist chemicals allows the company to generate very high resolution aperture molds. This coupled with an advanced electroplating set-up enables the production of stencils with high aperture tolerances, smooth sidewalls, and good thickness tolerance across the active area to allow uniform and consistent prints through the stencil.

The two main challenges facing the production of ultra-fine pitch stencils are the ability to create a defect free photoresist mold and to compensate for the deformation from the framing forces on the stencil. Regarding the ability to produce high resolution photoresist molds, all stencils are manufactured in a class 100 cleanroom for all processing steps including electroforming. In addition, high resolution photoresist and photomasks are employed in the process giving a high definition photolithography process. Figures 2a and 2b show characteristic SEM micrographs of the smooth side of the 35µmx80µm electroformed apertures at 60µm pitch. Figures 2a and 2b delineate the smooth side of the stencil which will be in contact with the wafer during printing ("wafer side"). Roughness measurements taken by a Cyberoptics Vantage laser profilometer show a smooth side roughness of 0.11µm and 1.1µm for the 60µm pitch and 100µm pitch stencils, respectively. Correspondingly, the rough side of the stencils which is going to be the paste ("print side") is dependent on the nickel grain structure and has been found to have a roughness of 0.73µm and 0.83µm for the 60µm and 100µm pitch stencils, respectively. Laser-cut steel stencil of 30µm thickness at 100µm pitch has only a slight better smoothness of 0.51µm of the "print side" than the electroformed stencil. Cross-section views of the electroformed stencils at 60 µm and 100µm pitch are shown in Figures 3 and 4, respectively.




Figures 2a & 2b: Electroformed nickel apertures 35µmx 80µm at 60µm pitch. Stencil thickness: 20µm

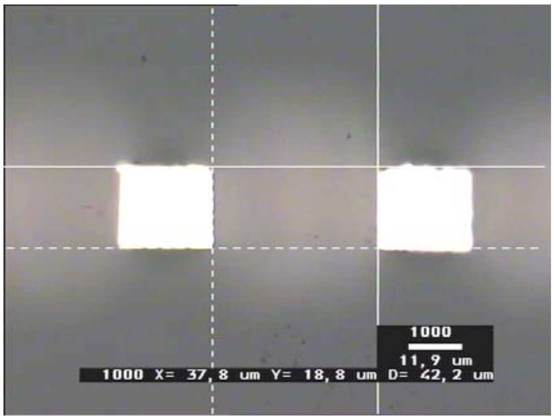



Figure 3: Transverse cross section view of electroformed stencil at 60µm pitch. Foil thickness:~20µm.

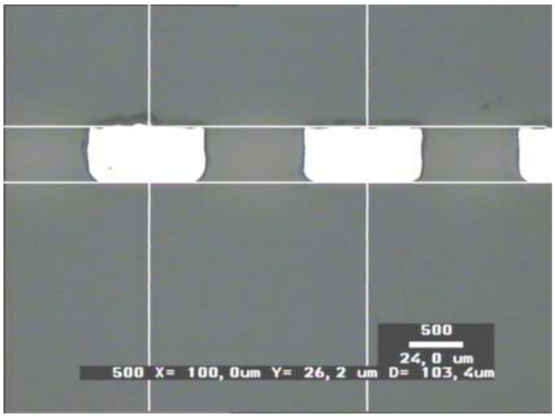



Figure 4: Transverse cross section view of electroformed stencil at 100µm pitch. Foil thickness:~25µm.

The top rough side in Figures 3 and 4 are the "print sides" for wafer printing. The aperture dimensions were measured by an OKM Planaris system and were compared with those derived from cross sectional analysis. The apertures in both 60µm and 100µm pitch stencils were found to have a deviation of only ±2 µm from the original Gerber data. Figures 3 and 4 also indicate the capability of electroformed technology to produce straight aperture walls without tilt and this is important especially at UFP where the separation distance between print deposits should be maintained as in the original design in order to avoid bridging. Figure 4, in case of the 100µm pitch stencil, shows also a small undercut on both sides which is about 4.4µm. This undercut does not appear at 60µm pitch stencil as shown in Figure 3. The existence of undercut may affect adversely the good sealing between stencil and wafer resulting in some paste crawling under the stencil. Nevertheless, it does not seem to be so critical in the 100µm pitch stencil and more importantly does not exist in the 60µm pitch stencil where paste smearing would be even more crucial than in 100µm pitch wafer printing.

### *2. 3. 2 Control of stencil deformation*

Previous studies by the University of Greenwich and Heriot Watt University, UK have shown that stencils thinner than 100 microns would elastically deform during the framing process [12]. Since the deformation is elastic it can be compensated for in the manufacturing process by adding a scaling correction factor. Normally thin stencils are mesh mounted onto a screen mesh which is tensioned in an aluminium frame. The framing procedure ensures the stencils are pulled flat for the printing process.

Modeling studies have been performed on thin stencil deformation [12]. After analyzing the modeling data, MicroStencil subsequently ran an investigation on 25, 50 and 75 µm thick electroformed foils with different aperture densities to measure deformation [13]. It was considered as important to confirm the modeling results since the simulations have used mechanical properties of annealed nickel whereas electroplated nickel can potentially give different characteristics depending on plating set-up. It is important to understand this material property so deformation can be compensated for in manufacturing. The results from this trial showed that the stencils deform differently in the x and the y axis and therefore would have to be compensated for separately in each axis. The reason behind this difference is due to the anisotropic formation of the nickel crystals during electroforming. By using the data from this set of experiments correction factors were incorporated into the manufacturing process of the 60 and 100 micron pitch stencils for this investigation. The stencils were measured prior to framing and after framing across the design area to measure the subsequent deformation. The results from this are displayed in the Table 1below.

### *2.3.3 Further improvements in Ultra-Fine-pitch electroformed stencil fabrication*

The manufacturing of the thin stencils in this study has pointed out the promising future for electroformed stencils for UFP printing. Further optimisation in the photolithography parameters will yield improvements in the profile of the aperture sidewalls. Excellent results have already been demonstrated using this process to produce stencils however future refinements in the process can improve the quality of stencils supplied.

The stencils used in the present study were plated using a standard Nickel plating composition which produces a fairly soft nickel material of around 220HV hardness. MicroStencil has recently refined its plating process to produce harder nickel with 480HV hardness or greater. This harder nickel material will be less likely to wear from the printing forces and will also deform less from both the framing and the printing process.

Other changes in the plating setup target to modify the surface roughness of the stencils. Initially, it was thought that a rough stencil top surface would aid paste roll and hence aperture fill however with the very fine particle solder pastes the solder spheres actually get entrapped in the large nickel grains and therefore may cause smearing across the stencil surface [11]. This can be slightly compensated for by using a higher print pressure however this high force can speed up stencil degradation. Therefore the plating set-up at MicroStencil has now been modified to produce stencils with a very smooth top surface.

### *2.4 Solder paste materials*

Previous studies have shown that type 6 (5-15µm) and even finer pastes are appropriate for UFP bumping (pitches<120µm). It has been shown that type 6 may marginally be used up to 100µm pitch wafer bumping based on the aperture design [3,11]. Previous studies have shown that a minimum of 5-7 particles in the apertures should be accommodated for good paste transfer efficiency [11]. Experimental studies have compared bumping results at 100µm pitch of type 7 (2-11µm) paste with the standard type 6 (5-15µm) paste [11]. The difference in printing and bump height distribution was not significant and therefore the differentiation of type 7 from type 6 is not necessary. Type 6 paste which has been already established in the market for wafer bumping can be used for wafer bumping applications ranging from 300µm to 100µm pitch. For UFP applications (<120µm) and always based on the aperture design decided for each specific application, a new type 8 powder was fabricated and was provided as paste. Type 8 has a powder size from 2-8µm which is essentially half of the type 6 powder size. Type 8 was used in the present study for bumping at 60µm pitch (35µmx80µm apertures) whereas type 6 was employed for bumping at 100µm pitch (50µmx125µm apertures). The standard type 6 paste is commercially available whereas the type 8 paste is a developmental product. However, the rheological

Table 1: Measurements for stencil deformation for a) 60µm pitch, 20µm thick foil and b) 100µm pitch, 25µm thick foil.

| | | Gerber data (µm) | after fabrication (µm) | after framing (µm) | deformation from framing (µm) |
|---|---|---|---|---|---|
| 60 micron pitch | North to South | 134510.5 | 134510 | 134520.7 | 10.2 |
| | West to East | 134563 | 134563 | 134545 | -18 |
| 100 micron pitch | North to South | 131244.1 | 131244 | 131.2542 | 10.1 |
| | West to East | 131244.1 | 131244 | 131.233 | -11.1 |

properties of both pastes are similar since it was decided by the manufacturer to use the same chemistry for the newly type 8 as for the standard type 6 paste. The viscosity of both pastes at a shear rate of 10/sec is 240 ± 50 Pa sec. Figure 5 shows print deposits at 60µm pitch on monitor wafer after short heating for flux evaporation. The powder size of type 8 paste has been confirmed to be 2-8µm at a percentage larger than 90%.

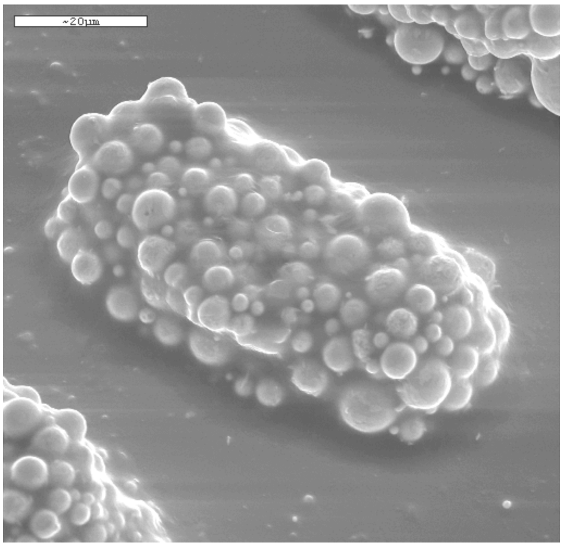



Figure 5: Developmental type 8 paste. Powder size Range: 2-8µm. Print deposits at 60µm pitch.

**3. Printing results & Discussion**

A type 8 Sn63Pb37 paste (2-8µm) was used for 6" wafer printing at 60µm pitch and the electroformed stencil was supplied by MicroStencil Ltd. A DEK 265 Horizon printer was employed for printing; it has a registration accuracy of ± 25µm. Rubber polyurethane squeegees angled at $60^o$ were fitted to the printer. Polyurethane squeegees work better with electroformed stencils than stainless steel. As it was mentioned before, due to intrinsic roughness and matte print surface of the nickel electroformed stencil, it is difficult to get a very clean print swipe unless very high squeegee pressure is used. Such a high pressure is unwanted because it usually creates flux bleeding and paste smearing at the bottom surface of the stencil. Rubber squeegees flex upon printing and can scoop/clear the paste much better from the nickel surface. Apart from this, stainless steel squeegees are quite hard and may destroy instantly the very thin stencil foils. Nevertheless, it is intended to use also stainless steel squeegees when stencils with harder nickel will be produced. Metal squeegees can potentially improve the resultant bump height uniformity over polyurethane squeegees.

Printing speeds in the range of 5-15 mm/sec were applied along with a printing pressure of 3-4 Kg for a 250mm long polyurethane squeegee. These parameters could ensure a clean print sweep with the minimum pressure used and proper filling of the apertures. The printing speed range is in agreement with other reported values in the literature [4]. Contact printing is used and in general is the most appropriate choice compared to snap-off printing for wafer printing at pitches smaller than 120µm. In fact, the 20µm thin foil at 60µm pitch can severely be flexed upon snap-off printing resulting in significant stencil deformation as discussed in section 2.3.2. In contrast, contact printing might protect the thin foil from repeated elastic deformations.

Printing at 60µm pitch is in fact very challenging for the alignment between wafer pads and the stencil apertures. Although 3 fiducials have been used for alignment always an offset should be always used to improve the registration with the existing equipment at TUB. Stencil deformation as discussed in section 2.3.2 is extremely important and should be monitored firstly after stencil framing. Slight deformation can result in unavoidable mismatch between the wafer and stencil. In addition to deformation due to the framing process, repeated printing may also contribute to stencil stretching. In the present study, measurements were taken to monitor deformation to ensure that the alignment of the framed stencil to the wafer was acceptable. After 20 prints and manual cleaning of the stencil-which may also deform it- good alignment was always achieved. Figure 6 shows print deposits of type 8 paste at 60µm pitch. The deposit thickness is 20µm in agreement with the foil thickness. The deposits have dimensions about 35μmx77μm on the top surface and about 41μmx84μm on the bottom surface. Based on the fact that the aperture walls are straight as shown in Figure 3, the larger deposit dimensions at the bottom may have resulted from either a slight slump of the paste under the given printing conditions or due to the small amount of undercut on the stencil at the wafer side. The top dimensions show good paste release for type 8 paste from the electroformed apertures. Some paste has remained in the stencil on the circumference of the oblong aperture. The separation distance of the deposits ranges from 15μm to 19μm. Our targeted separation distance of 25μm has not been achieved due to the paste slump properties.

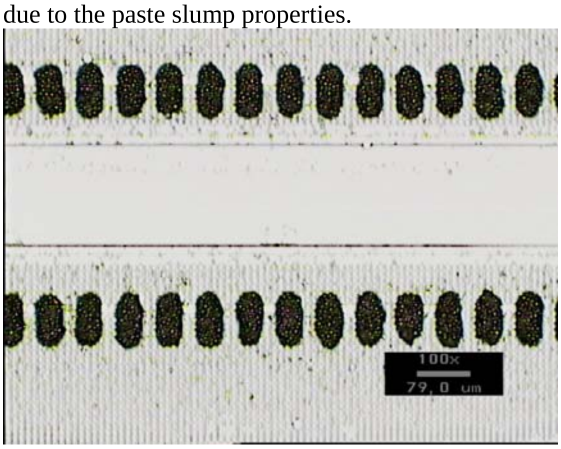



Figure 6. Wafer printing at 60μm pitch with type 8 (2-8 μm) paste.

The paste release of type 8 from the electroformed apertures is very good since the aspect (1.75) and area (0.61) ratios for the apertures are higher than 1.5 and 0.5 which are reported as the minimum requirements for paste release from electroformed stencils [11]. Nevertheless, the print deposit definition can be further improved by intervening into the intrinsic paste properties such as paste tackiness, paste rheological behaviour, and examining their interaction particularly with nickel surfaces. As the smoothness of the aperture walls and of the nickel stencil surface improve, this will in turn improve the paste roll, aperture filling, and optimise the paste release. The increase in the nickel hardness will also improve significantly the gasketing between the wafer and stencil and consequently the distance between deposits will become safer for the subsequent paste reflow. Printing at 100μm pitch with type 6 paste has yielded print deposits with worse definition compared with printing type 8 paste. The reason for this is due to much better packing density of type 8 paste 8 in the 50μmx125μm apertures compared with the type 6 paste particles. This subsequently affects the print definition and the paste cohesiveness. Although the aspect and area ratios for print at 100μm pitch were larger than 1.5 and 0.66, the paste release of type 6 suffers more than type 8 paste. This finding implies that the finer particle size of type 8 paste and the larger particle packing density (~10) in the aperture play a paramount role for paste release and print definition.

**4. Bumping results & Discussion**

Wafers at 60μm pitch and 100μm pitch were printed with type 8 and type 6 pastes respectively and subsequently were reflowed in inert atmosphere with less than 20 ppm oxygen. The reflow of type 8 paste creates many tiny solder balls. Furthermore, flux bleeding can carry particles between the deposits (see Figure 6)which can not fully coalesce to the main bump during reflow and appear as tiny balls on the bump foot. Solder balling is much more intense for bumping at 60μm pitch than for bumping at 100μm pitch with type 6. On the other hand, it is very crucial for bumping at 60μm to have a very good alignment of the apertures with the pads with the minimum possible offset allowed by the printer. Otherwise, adjacent deposits coalesce resulting in bridging or solder stealing and subsequently producing poor bump coplanarity. Bumping at 60μm pitch yields bumps with a height of 28μm±3μm. The bumps at 100μm pitch have a height of 42.3±3.8μm. Figure 7 shows a perspective of a chip with bumps at 60μm pitch.

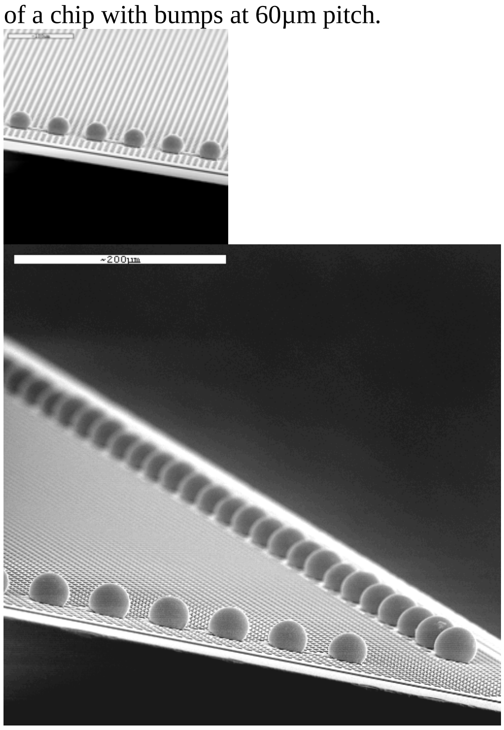


**Figure 7: Wafer bumping at 60μm pitch. Bump height: 28μm ± 3μm.**

Figure 8 provides a cross section view of the bumps at 60µm pitch. The bump height measurements agree well with the optical microscope measurements. Figure 9 shows the bump height distribution of bumped chips at 60µm. Shear test of the bumps with a shear speed of 50µm/sec at a shear height of 10µm has yielded shear strength values of 7.8 kg/mm$^2$. The shear failure mode was found to be fracture in the Sn63Pb37 solder. The failure mode is shown in Figure 10.

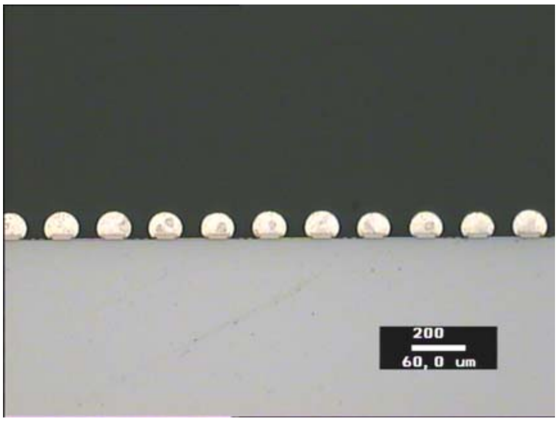



Figure 8. Cross section of bumped chip at 60µm pitch.

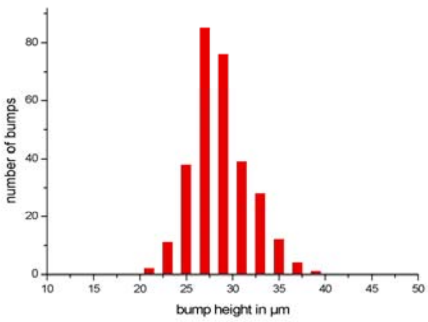



Figure 9. Bump height distribution at 60µm pitch Average height: 28µm ± 3µm.

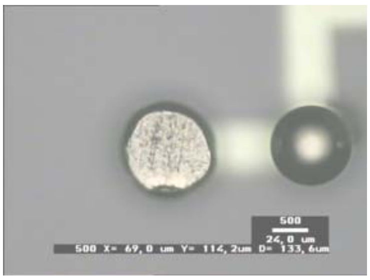


Figure 10: Shear mode for bumps at 60µm Pitch. Fracture occurs in the solder.

## 5. Conclusions & Future Work

Printing at 100µm and 60µm pitch with electroformed stencils has yielded very promising results for bumping at ultra fine pitches. The bump height at 60µm pitch was 28 ± 3µm. New type 8 paste (2-8µm) has been developed and used for bumping at 60µm. The fabrication of even smoother and harder nickel stencils will be the next development step in electroformed technology for UFP wafer bumping.

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