Stencil printing technology for fine pitch deposition of Pb-free flip chip interconnects

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Abstract

Advances in chip scale packaging technologies have prompted a rapid increase in the density of solder joints in microelectronics products. Further reductions in the pitch size are likely, leading to joint structures exhibiting sub-100µm dimensions. Stencil printing for flip chip packaging using fine particle solder pastes is a low cost assembly solution for fine pitch solder joint interconnects. However, for ultra fine pitch applications this technology has appeared to reach practical limits and a requirement to understand the sub processes in stencil printing at ultra fine pitch is needed. Paste roll, aperture filling/release, post print behaviour and paste open time need to be examined as experimental inputs the following parameters: fine particle Pb-free solder pastes and solder paste rheology, particle size distribution, metal content, flux type and stencil aperture attributes. The complexity in using stencil technology at such fine pitch geometry has indicated that the quality, consistency and yield are determined by a combination of variables that are involved in the stencil manufacture, paste formulation, and the process of deposition of the paste from the stencil.

An enhanced electroformed stencil manufactured using microengineering techniques is demonstrated in this paper. The tolerance of the apertures and the smoothness of the sidewalls are produced to provide consistent printing. As the interconnection pitch decreases the stencil thickness must also be decreased to allow a good paste release during printing. As the thickness of stencil goes below 100 microns elastic deformation from the framing process occurs. The stencil registration over a large area is analysed for three different stencil thickness and different aperture opening densities to determine this stretch. The stencil are also analysed in terms of lifetime to ensure they are robust enough to withstand up to 1000 prints.

In this paper we report that solder paste printing has been achieved at sub-150µm pitch using Pb-free solder paste with IPC type-6 (15-5µm) and type-7 (12-2µm) particle size distributions. The results satisfy the criterion that paste deposits can be produced at ultra fine pitch. Furthermore, subtle differences in the performance of type-6 and type-7 solder PSD paste suggest that they should be employed separately to specific application geometries. Sufficient volumes of paste are required during reflowing of the fine particle solder paste to produce sufficient stand-off between the flip chip device and PCB pad. Print consistency and uniformity of the bumps generated are also governed by the volume of solder paste for each deposit.

1. Introduction

Consumer's demand for lighter, cheaper, smaller and smarter electronic products are pushing the electronic industry to utilise the smallest packaging footprint possible. In that respect, flip-chip packaging is seen as the ideal packaging platform to satisfy the drive of portable electronics for more, faster and denser electrical I/O's. In spite of its superior packaging results, flip-chip packaging has not seen wide spread adoption until recently as the primary interconnection technology due to the high costs coupled with constant advances in alternative packaging technologies. One of the main barriers to utilising flip-chip packaging is the ability to apply the mechanical and conductive interconnects between the chip and the board. Stencil printing is seen as the lowest cost technique to deposit the interconnects however as the interconnection pitch pushes below 150 µm the conventional printing process suffers from poor yield.

For many of the flip-chip packaging techniques some of the processing of the device can be carried out at the wafer level rather than at the singulated die level. This therefore offers the advantage of carrying some of the packaging process in a serial manner. For wafer bumping, stencil printing has been shown to be the most cost effective technique when compared with evaporation and electroplating techniques [1]. The cost advantage of printing, coupled with the ability to deposit solder alloys and Isotropic Conductive Adhesives (ICAs), makes it a very attractive option for high volume, low cost flip-chip assembly.

Improvements in the Stencil manufacturing technology

There exist three methods to manufacture metal-based stencils: chemical etching, laser cutting and electroforming. As the drive towards denser interconnect electronic chips drives down aperture pitch below 100µm, metal stencil manufacturing techniques based on current wet etching, laser cutting or conventional electroforming become unsuitable. Small aperture stencils cannot be produced reliably using chemical etching, primarily due to the undercutting process of the etching step. Laser cut stencils ablate each aperture sequentially; as the number of apertures increases so does the time and cost of producing each stencil, making the process uneconomical. Moreover the difficulty of controlling the metal-laser interaction cannot guarantee systematic smooth aperture sidewalls for good paste release. Although conventional electroforming techniques can generate stencils with such aperture size, good reproducibility of the aperture shapes at such low pitch cannot be guaranteed. This variation in aperture shapes and the difficulty to control the roughness of the inner aperture walls render the reproducible deposition of a controllable volume and defined shape of deposits extremely difficult.

The stencil, shown in figure 1, was developed by MicroStencil Limited. The manufacturing process produces perfectly vertical and smooth sidewalls with apertures closely following the resist sidewalls during the electroforming process. The electroforming process generates the desired mechanical properties of the metal across the whole stencil. Apertures ranging from 1000µm to 7.5µm were successfully demonstrated in a reproducible manner, figure 1. Foils ranging in thickness from 20µm-200µm have been demonstrated to-date. In addition web spacing (spacing between the apertures) as small as 5µms have been demonstrated as shown in Figure 2. The ability to shrink the spacing between apertures enables the fabrication of larger apertures for the same pitch compared to conventional stencil manufacturing processes. This large aperture diameter can improve process yields by enabling the deposition of larger volumes of paste.

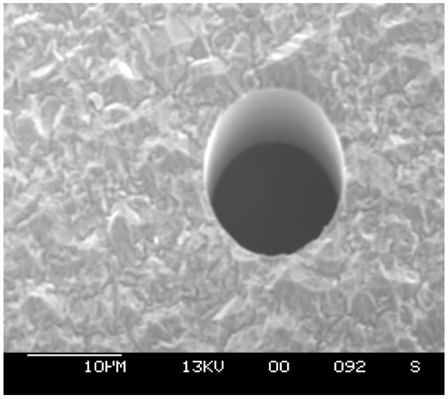


Figure 1, Microengineered stencil, 7.5µm diameter apertures

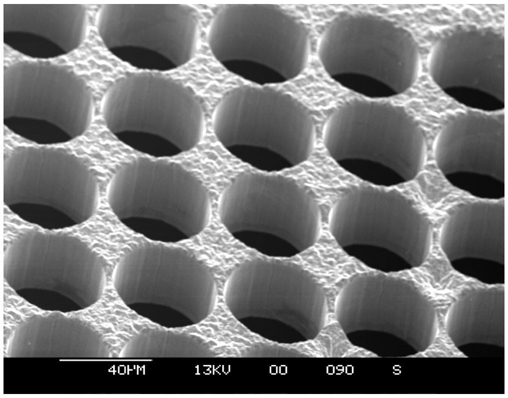


Figure 2, 50µm pitch, 45µm diameter aperture

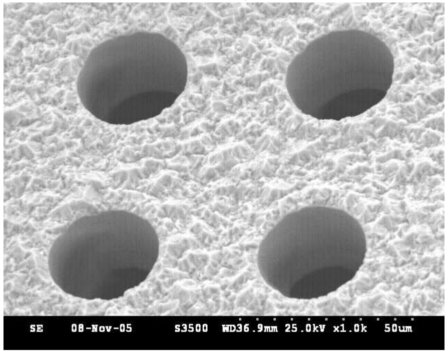


Figure 3, 60 µm pitch, 30 µm diameter apertures

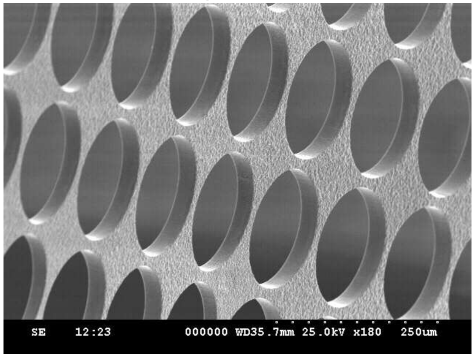
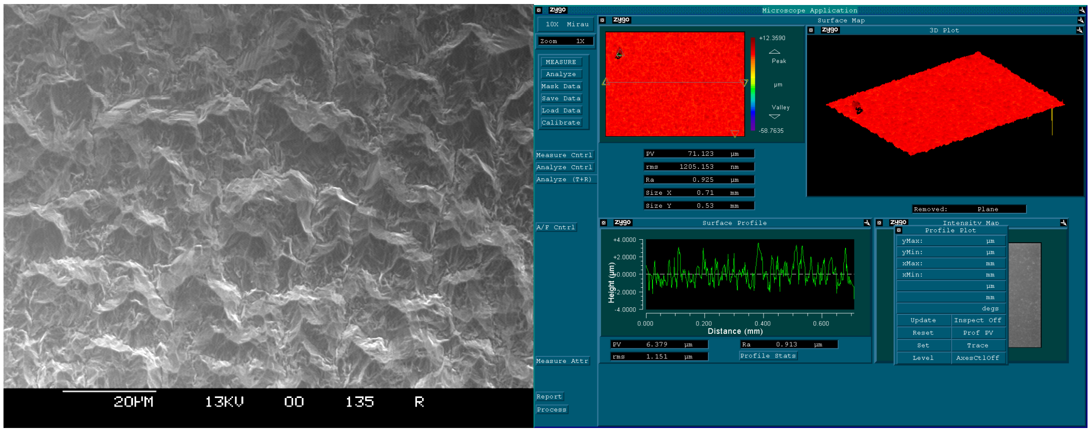


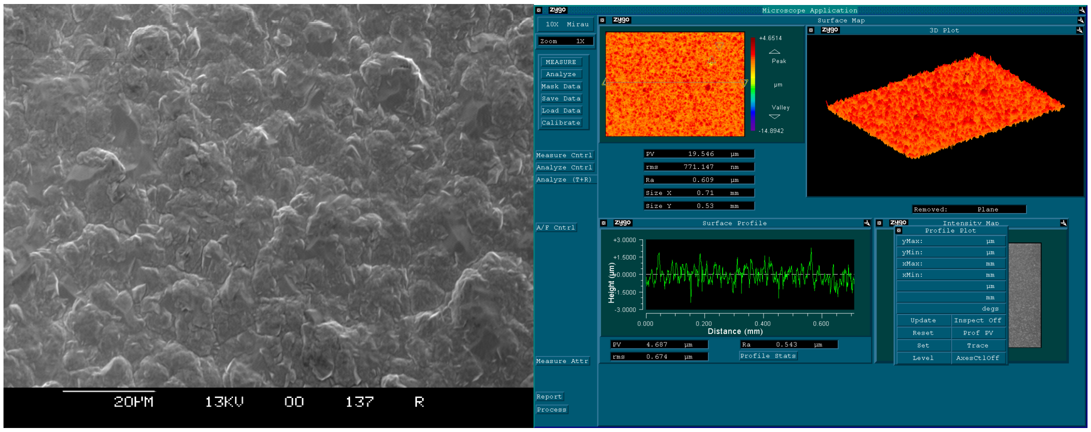
Figure 4, 200µm pitch, 175 µm diameter apertures

In order to achieve consistent and reliable prints during stencil printing, the paste must be able to roll evenly across the surface. Two factors which dictate the kinematics of this rolling motion are the driving force plus speed of the squeegee and the resistance offered by the stencil surface. The plating process employed during the manufacture of these stencils allows some control over the roughness of the top surface. For a standard type 3 paste a good paste roll is achieved by having a rough upper stencil surface however as the PSD of the paste decreases then with a very rough upper stencil paste smearing may occur therefore a smoother stencil surface is beneficial. Figures 5 & 6 demonstrate the difference in surface roughness by changing the electroplating parameters.



PV 71.123 µm
rms 1205.153 nm
Ra 0.925 µm
Size X 0.71 mm
Size Y 0.53 mm
Removed: Plane
PV 6.379 µm
rms 1.151 µm
Ra 0.913 µm

Figure 5, rough stencil top surface a) SEM image 1000X magnification, b) white light interferometer scan showing surface roughness measurements. roughness average of 0.913µm & root mean square of 1.151µm



PV 19.546 µm
rms 771.147 nm
Ra 0.609 µm
Size X 0.71 mm
Size Y 0.53 mm
Removed: Plane
PV 4.687 µm
rms 0.674 µm
Ra 0.543 µm

Figure 6, smoother stencil top surface a) SEM image 1000X magnification, b) white light interferometer showing surface roughness measurements. Roughness average of 0.543µm & root mean square of 0.678µm

Stencil aperture tolerance and stencil deformation

A tight aperture tolerance and a good stencil registration across the substrate for ultra-fine pitch printing are paramount to ensure good registration and print uniformity. In addition a smoother aperture sidewall will reduce the surface area which in theory should improve paste release during printing. The manufacturing process has demonstrated apertures which closely resemble the layout data. The top-side and bottom side aperture measurements show an accuracy of less than 3 microns versus the layout. Each aperture must be the same size to allow the same amount of paste to be transferred during printing.

As the aperture diameter decreases the stencil thickness must also be decreased for good paste release. An industry rule of thumb states that the stencil should be 2/3 the smallest aperture diameter [2]. For sub-150 micron printing this normally requires the stencil thickness to be 75 microns or less. Previous modelling work showed that thin electroformed Ni stencils will deform from the framing process elastically [3]. An investigation into stencil deformation versus stencil thickness and aperture density was carried out to enable a correction factor to be calculated for different stencil designs. Adjustments to the mechanical properties of the Nickel stencil form the plating process will change these deformation values and therefore a tight control over the electroplating process is critical.

For this investigation a 300mm circular stencil design split into quadrants with different aperture opening densities was used. Three different stencil thicknesses 25µm, 50µm and 75µm were fabricated. The total foil size from manufacture is 500mm x 500mm and the stencils were framed into 735mm x 735mm square aluminium frames. A polyester mesh tensioned to 45-50N was used for hold the stencils to the frame. The mesh around the stencils from framing was released in the centre of the stencil to ensure the foils were evenly bi-axially stretched from the framing process.

The aperture diameter used on this design was 100µms. The different quadrants had aperture opening densities of 0%, 25%, 50% and 64% which correlates to pitches ranging from 277 microns to 210µms. The stencils were measured using a coordinate measuring system after fabrication, framing and up to 1000 prints using the print parameters highlighted in the table below.

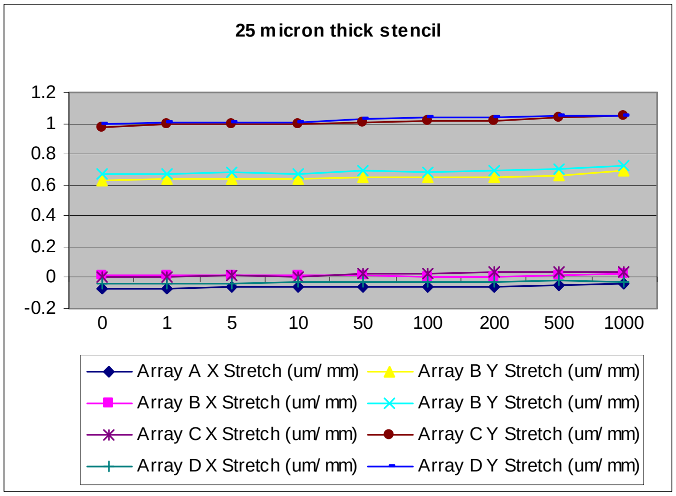
Printer type	DEK 265 horizon 03 printer
Print speed	25mm/s
Print pressure	6kg
Print gap	0mm
Squeegee type	mid-durometer polyurethane, 60degree blade angle.
Squeegee length	300mm

Table 1, print setup for deformation trials

The stencils after manufacture were within 5 microns across the whole 300mm design area compared with the layout data. The impact from framing is summarised in table 2. Graph 1 shows the deformation on the 25 micron thick stencil from framing and up to 1000 print strokes. It is seen that along the X axis the deformation from framing is greater than along the Y axis. The Y axis is the plane in which the squeegee travels along. This difference in deformation from framing is attributed to the difference in the mechanical properties of Nickel from electroplating. It is apparent that this deformation from framing is linear and elastic and can be compensated in the manufacturing process to ensure accurate registration. Further evaluation will be made in terms of framing tension forces to minimise or eliminate this deformation from the framing step completely and also the repeatability of this deformation. The stencils showed almost no drift after 1000 prints and showed no visible degradation from the printing forces however other stencil designs have shown more noticeable stretch from the printing process. More trials are currently underway using a print gap and a metallic squeegee.

		0% density	25% density	50% density	64% density
25 micron thick stencil	X	-0.07 µm/mm	0.01 µm/mm	0.01 µm/mm	-0.04 µm/mm
	Y	0.63 µm/mm	0.67 µm/mm	0.98 µm/mm	1 µm/mm
50 micron thick stencil	X	-0.17 µm/mm	-0.14 µm/mm	-0.16 µm/mm	-0.15 µm/mm
	Y	0.05 µm/mm	0.07 µm/mm	0.26 µm/mm	0.26 µm/mm
75 micron thick stencil	X	-0.22 µm/mm	-0.24 µm/mm	-0.22 µm/mm	-0.19 µm/mm
	Y	0.22 µm/mm	0.25 µm/mm	0.48µm/mm	0.49 µm/mm

Table 2, impact of deformation from the framing process



Graph 1, deformation in µms per mm from the framing and printing process in the x and y axis

Printing at ultra fine pitch using Pb-free solder paste

The WEEE and RoHS Directives which outline targets for electronic equipment re-use and recycling have called for the elimination of Pb in electronics. Traditional Sn-Pb solders must now be replaced with Pb free alloys. An alternative alloy of interest is the Sn 3.8%Ag 0.7%Cu material, which is used in this investigation. Printing at the 100µm pitch level requires a reduction in the particle size distribution (PSD) of the alloy from 20-45µm (type-3) to less than 15µm (type-6 and type-7). An industry rule of thumb states that in order for the stencil apertures to be filled during the printing process the average particle size ratio must be less than 5 times the aperture diameter [4]. Subsequently, Pb-free solder alloy powders are now being developed exhibiting type-6 (PSD 5–15µm) and type-7 (PSD 2-12µm). In order to satisfy this criteria the changes in PSD do inherently affect the solder paste properties; for example, moving from a type-3 to a type-6 PSD increases the number of particles (per unit volume) by a factor of fifteen and the fine particles in the solder pastes will inherently alter the paste rheology. In addition, the Pb-free alloy has an increased melting temperature of around

34° compared to the 63%Sn 37%Pb alloy. Therefore, the flux medium will be altered so that it can protect the alloy against oxidation at elevated temperatures; again the change in flux chemistry will have a large impact on the rheology of the solder paste.

A test pattern with different aperture diameters and pitches was designed for full array printing. Experimentation has already demonstrated that circular apertures offer a better paste release compared to square apertures due to the lack of sharp corners which can trap the small particles of paste [5]. The pitches on this stencil design are taken to meet future needs and far surpass most requirements for current dense array interconnects. A DEK 265 Horizon printer was fitted with twin mid-durometer polyurethane (rubber) squeegees angled at 45°. The main pitches evaluated in this investigation were 90µm, 100µm, 120µm, & 140µm. The stencil thickness was 40µm in order to fall in line with the conventional printing rule that the aperture diameter must be at least 1.5 larger than the thickness of the stencil [2]. The substrates were bare 4" Si wafers.

Adjustments were made to the printer parameters, namely printing stroke speed, squeegee pressure, print gap for off-contact printing for type-6 and type-7 PSD solder Pb-free paste. The range of print parameters investigated is given in Table 2. After each print was made the stencil was cleaned.

Print	Print Speed	Print Pressure	Snap-off	Print	Print Speed	Print Pressure	Snap-off
1	10	4	0	4	40	4	0
2	10	4	0.25	5	40	4	0.25
3	10	8	0	6	40	8	0
4	10	8	0.25	7	40	8	0.25

Table 3, range of print parameters investigated

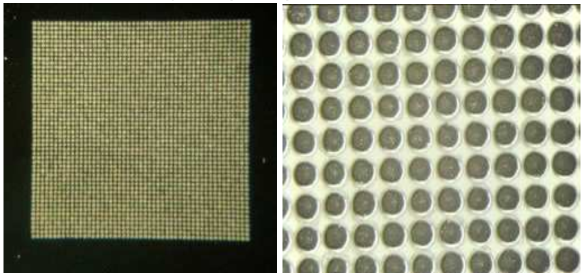


Figure 7, type 6 paste printing at 140 microns pitch a) & 7b), Print speed 40mm/s, Print pressure 8kg, Snap-off 0.25mm

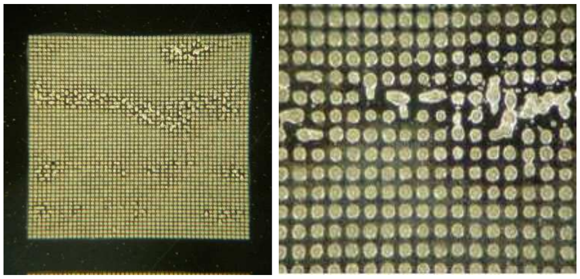


Figure 8, type 6 paste printing at 140 micron pitch a) & 8b), No Print Gap, Print speed 40mm/s, Print pressure 8kg, Snap-off 0mm

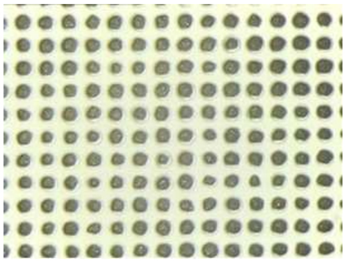


Figure 9, Low pressure, Print speed 40mm/s, Print pressure 4kg, Snap-off 0.25mm

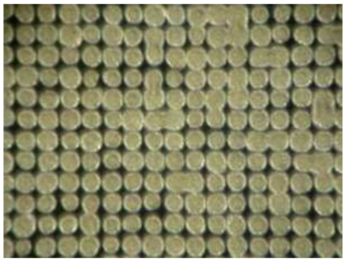


Figure 10, Print speed 10mm/s, Print pressure 8kg, Snap-off 0.25mm

This test array used in this investigation has a high density of apertures which would resemble a wafer bumping pattern. Due to the large percentage of aperture opening during the printing process the surface tension effects between the stencil and the wafer are very large when the stencil is in full contact with the substrate. During release the discharge of the stencil causes a reverberation which makes the foil act like an acoustic speaker; this, in turn, creates highly irregular solder deposits. Some regions print well while other regions show either low volume of solder deposits or bridging, as shown in Figures 5a & 5b.

When a low print pressure was exhibited the paste roll was not optimum and the resultant deposits were small and irregular as shown in Figure 6. However when a slow print stroke was used then bridging of the paste occurred as shown in Figure 7. This shows that a fast print stroke (40mm/s) coupled with a high print pressure and snap-off produced the most consistent prints as presented in Figure 4. It was however observed that as the aperture diameter decreased a reduction in the print speed aided in achieving consistent prints. This specific investigation demonstrates that good print results can be achieved from a first pass print but does not show the optimal printing parameters for this type 6. Further work is now underway to look at the cleaning frequency of this process using the microengineered stencils. As aperture sizes decrease the rate at which the paste clogs the apertures occurs faster, which in turn causes more frequent cleaning of the stencil.

More prints were carried out on bare FR-4 board to test the limits of the different paste types. The type-6 solder PSD paste was found to print through apertures as small as 50 microns while the type-7 paste printed down through 30 micron holes. Paste release was found to be better with the type 6 compare with the type 7 paste however the packing density of the solder alloy particles is better with the type 7 as shown in figure 11.

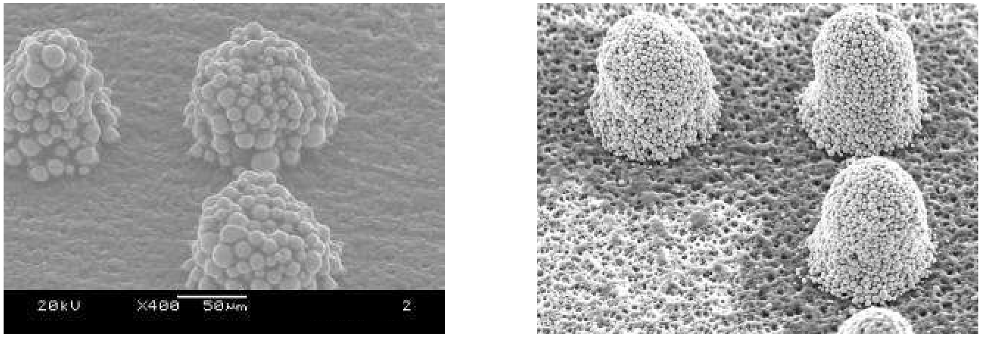


Figure 11, solder deposits from 70μm diameter apertures, a) type-6 solder PSD paste, b) type-7 solder PSD paste

Conclusions

This paper has demonstrated that solder paste printing at sub-150 micron pitch is possible. . Advancements in stencil fabrication methods have produced ‘state-of-the-art’ stencils exhibiting highly defined shaped apertures with a micron tolerances and smooth sidewalls down to ultra fine pitch, thus allowing for improved solder paste release at very small dimensions. Stencil deformation from the framing process was noticed and measured. This deformation must be compensated for to allow good registration to the bond pads during printing. Fine particle Pb-free solder pastes were used in this investigation.

Print deposits as small as 30μm were achieved at 60μm pitch with type-7 solder PSD paste and 50μm with type-6 solder PSD paste. Consistent full array prints were demonstrated with type-6 solder PSD paste at 140μm pitch. Experimental prints show that by varying the print parameters can significantly change the print results. Further work is now underway to look at print consistency from wafer printing and also cleaning frequency required for the micro-engineered stencils at ultra fine pitch.

References

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