Performance and Printing of Pb-free Solder Paste for 100-micron Pitch Geometries

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Abstract
Recent advances in chip technologies have prompted a rapid increase in the density of solder joints in electronic components. Further reductions in pitch are likely, leading to joint structures exhibiting sub 0.100mm (100µm) dimensions. EC legislation from mid 2006 bans the use of Pb, for most applications, in solders which means that next generation solder pastes will have to be Pb-free.

One low cost assembly solution is stencil printing/wafer bumping of fine particle solder pastes. For ultra fine pitch applications this will present significant challenges and there is a requirement to understand the sub processes in stencil printing at ultra fine pitch. Paste roll; aperture filling/release; post print behavior and paste open time have been examined using fine particle Pb-free solder pastes, and solder paste rheology, particle size distribution, metal content, flux type and stencil aperture attributes have been investigated to provide ultra fine pitch solutions.

In this paper we report that solder paste printing has been achieved at sub 100µm pitch using Pb-free solder paste with IPC type-6 (15-5µm) and type-7 (12-2µm) particle size distributions. For the type-6 paste, full array printing was achieved with 50µm deposits at 110µm pitch, and for peripheral printing patterns, 60µm sized deposits at 90µm pitch. For type-7 paste sub 100µm pitch printing was achieved for full array patterns. 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 suggest that each is suitable for different specific application geometries.

Reflow trials indicated that solderability of the small volumes depended heavily on reflow profile ramp rates and reflow atmosphere. Process models for introducing inert nitrogen reflow atmospheres are presented.

Introduction
Fine pitch assembly at the sub-100 micron level is currently being driven by the need for higher I/O capabilities on smaller components. Area array packaging formats, i.e. Flip Chip, have emerged from as solutions to fulfil future this need. This is demonstrated by increased circuit density capability coupled with a reduction in real estate coverage on the supporting Printed Circuit Board (PCB). However, as the trend towards further miniaturisation and higher operating speeds continues, new and innovative interconnection technology solutions are required which, are capable of supporting future flip chip applications. Flip chip interconnection involves the assembly of unpackaged chips directly to the PCB; this solution yields solder joints at geometries similar to those of the semiconductor chips i.e. 100-micron and below. Further reductions in the scale of flip chip geometries are expected to ensure the technology keeps abreast of future product applications and IC designs,[1-6] with typical joints exhibiting diameters of 30µm.

Although much interest has focused on the miniaturisation of next-generation electronics packaging technology, future interconnections are also subject to a fundamental revision in the soldering process. The revision is being brought about by the environmental concerns regarding the potentially toxic Pb content of conventional 63%Sn 37%Pb soldering material, which has led the European Union (EU) to propose draft directives banning the use of Pb in electronic systems. In its latest form the ban falls under the 'Restriction of the use of hazardous substances in electrical and electronic equipment' (RoHS) directive; June 2006 being the given date.[7] This has resulted in a large amount of work within the electronics industry to find a suitable replacement for Sn63Pb37 and Sn62Pb36Ag2 alloys. An alternative alloy of interest is SnAg3.8Cu0.7, which is the subject of this investigation.

Achieving an ultra fine pitch capability for Pb-free solder paste requires a reduction in particle size. In order for the stencil apertures to be filled during the printing process, a rule of thumb is that the average aperture diameter / average particle size ratio is = 5[8], hence, existing solder pastes containing an IPC type-3 particle size distribution (PSD), 45-20µm, are not compatible with ultra fine pitch printing applications. Thus, Pb-free solder alloy powders are now being developed exhibiting PSDs of 15-5µm (IPC type-6) and 12-2µm (IPC type-7).

Moving from a type-3 to type-6 PSD increases the number of particles, per unit volume, by a factor of fifteen and has significant effect on paste rheology. Changing from tin-lead to a Pb-free solder also affects the rhelology due to the lower density of the Pb-free solders. (7.5g/cm^3 for SnAg3.8Cu0.7 compared to 8.4 g/cm^3 for Sn63Pb37), which will, in effect, increase the metal content volume. Additionally, the increased melting temperature of Pb-free places demands on the ability of the flux medium to protect the powder from oxidation during the preheat stage of the reflow profile. Therefore, altering flux mediums to cope with this will have a large impact on the rheology of the solder paste.

The stencil printing process is useful for producing high volume low cost joints, however, it does account for almost 60% of assembly defects.[9, 10] As a result of these findings, there is a requirement to understand the sub processes in the stencil printing so that the process of ultra fine printing can be optimised.[11, 12]

Experimental

Two types of Pb-free, SnAg3.8Cu0.7, solder paste were used for the printing evaluation of ultra fine pitch deposits, these having a type-6 and a type-7 PSD powder suspended in a no clean flux medium. The rheological properties of each solder paste had been adjusted so that sufficient paste roll, squeegee drop off and stencil cleaning on print stroke were achieved. Each paste was also characterised and compared with Brookfield and Malcom viscosity measurements.

The solder paste was printed onto a range of substrates, these being Ni/Au plated FR-4 Cu laminate, a test PCB that incorporated sub 100 micron sized surface pads (30-70micron) arranged in full area array and peripheral array patterns and finally a 4" silicon test wafer. The printing was done using an industry standard DEK 265 printer fitted with twin polyurethane (rubber) squeegee angled at 60°. Adjustments were made to the printer parameters, namely printing stroke speed, squeegee pressure, print gap for off-contact printing and separation speed for on-contact printing. The printed deposits were inspected for shape definition and consistency, volume, and paste material breakdown using a high magnification stereomicroscope and a Scanning Electron Microscope (SEM).

Although the emphasis of this study was to evaluate the differences between type-6 and type-7 Pb-free solder paste materials, the stencil technology utilised is integral to a successful paste printing process. Such challenges at the stencil level have been previously identified and as a result Microstencil Ltd based at Heriot-Watt University, Edinburgh, have been using micro engineering techniques alongside novel electrodepositing processes to develop next-generation stencil technology capable of providing ultra fine pitch geometries. Figure 1 illustrates the improved aperture quality and consistency using the micro engineering technology process at Microstencil. This patented process has a number of advantages over existing conventional stencil technology, namely: (1) uniform metal deposition across the surface of the stencil releasing the same volume of paste through each aperture; (2) apertures formed with micron tolerance and hence, no variation in aperture shape and diameter; (3) apertures exhibiting perfectly formed vertical and smooth sidewalls; (4) a novel electrodeposition process generating the desired material properties, providing extended stencil lifetime.

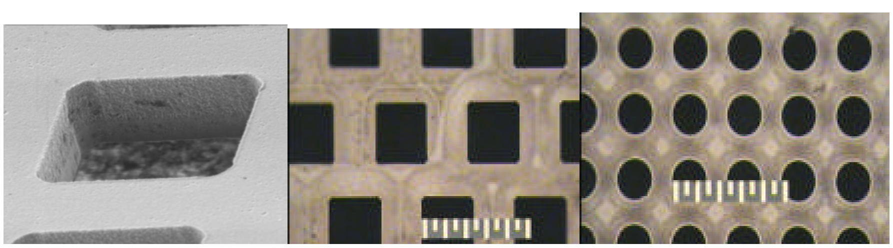

Figure 1 - SEM and Optical Images of 50µm Square Apertures at 90µm Pitch from the Electroformed Nickel Stencil and the Ultra Fine 30µm Circular Apertures at 50µm Pitch; Note the Inclusion of the 100µm Fiducial Markers on the Optical Images

The arrangement of apertures on the stencil covered an area of approximately 100 mm^2, which is appropriate for wafer bumping applications (based on a 4" Si wafer). The design incorporated both square and circular apertures, ranging in width/diameter from 30 to 90 microns. Apertures of each dimension were arranged in peripheral and full area array patterns ranging in pitch from 150 to 50 microns. This design provided a wide variety of web spacings, so that the printing limits of the fine particle solder paste could be observed. Each area also included larger fiducial apertures (100 microns in size) so that any breakdown in paste printing within an area could be attributed to the apertures if print deposits were still achievable from the larger fiducial apertures.

The definition of the stencil apertures can be clearly seen in Figure 1; the choice of the different shapes was to investigate aperture filling, release processes and print limits. Square and circular shaped apertures intrinsically yield different volumes for the same aperture diameters. Additionally, web areas will be slightly larger between circular apertures, thus aiding the printing and stencil fabrication processes for ultra fine web applications. Solder paste release mechanisms will also differ for different shapes due to stress gradients at the aperture edges etc. Packing densities may also differ between type-6 and type-7 PSD solder pastes for the two aperture shapes.

Results and Discussion

Acceptable printing results were defined when the following criteria were fulfilled: (1) consistent sized paste deposits observed over the whole printing pattern; (2) no bridging; (3) no skipping or (4) smudging. Subsequently, the printing limits are defined at the point where the rules for acceptable printing start failing. The printing can fail by having too high printing pressure, too fine a web in the stencil aperture patterns or an excessively fluid solder paste, which can cause bridging and deposit smearing. Inconsistent sized deposits and skipping can be attributed to insufficient aperture filling or release problems such as clogging.

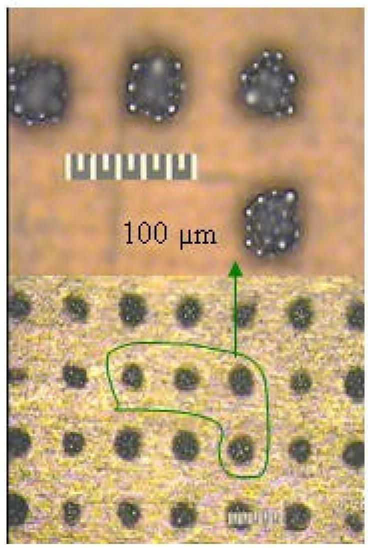

Figure 2 - Optimal Printed Deposits from type-6 Pb-free Solder Paste: Peripheral Pattern (top) at 90µm Pitch, 55µm Diameter Deposits from 50µm Square Apertures. Full Array (btm) at 110µm pitch, 55µm Diameter Deposits from 50µm Square Apertures

Using the above criteria for the type-6 paste, the ultimate fine pitch printing limits were found to be 55µm sized deposits at 90µm pitch for peripheral printing and 55µm sized deposits at 110µm pitch for full area array patterns (shown in Figure 2) at printing speeds of 10-30mms^{-1} and squeegee pressure of 5-6 kg along a 100mm wide squeegee; off contact printing, with a print gap of 0.2mm, was also preferred for this ultra fine pitch geometry.

At finer pitches there was a breakdown in the printing of the type-6 paste, demonstrated by a smearing of the print patterns. This smearing occurred at larger values of pitch for the full area array patterns, compared to the peripheral patterns. In fact the smearing did not occur for peripheral patterns until below 90µm pitch. This breakdown can be attributed to paste bleeding between apertures on the underside of the stencil, at full array when the pitch is less than 110µm for web values less than 50µm. Figure 3 displays full array printing at the ultimate pitch value of 110µm and Figure 4 the paste bleeding on the underside of the stencil at a finer pitch. Initially it was thought that the paste bleeding was due to having a too high printing pressure. However, lowering the pressure appeared to have no effect, furthermore, adjusting the other remaining parameters, namely printing speed and print gap also had no effect. It appears that this is the printing limit for this paste type in terms of full area array pitch value.

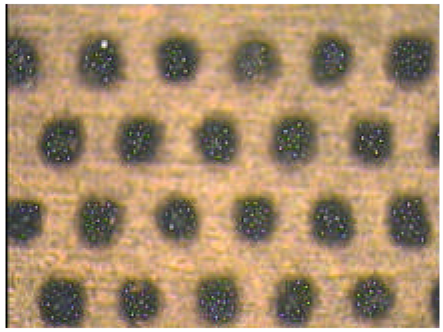

Figure 3 - Optical Image Illustrating Type-6 Paste Print at 110µm Pitch Pattern

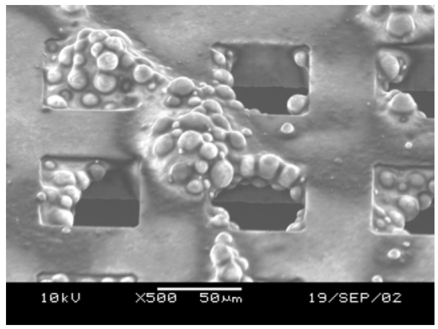

Figure 4 - SEM Micrograph Highlighting Type-6 Paste Bleed at sub 100µm Pitch Pattern

Paste bleeding can be explained by the fluid nature of the paste allowing bleeding into small capillaries between adjacent apertures during the stencil printing. One may argue that the reason for smearing at such fine pitch and web can be attributed to paste slump. However, paste slump was not problematic at these fine pitches for the peripheral patterns. In this case marginal slump was observed, as printing through the 50µm stencil apertures at 90µm pitch produced 55µm-sized deposits. However, this implied that a 35µm web was not sufficient to cause the smearing/bridging seen in the case for full array patterns at larger values of web spacing. Observing the underside of the stencil seen in Figure 4 further strengthens the argument for paste bleeding in the full array case. It is clear to see that solder paste remains in the web areas between adjacent apertures after the stencil has been removed; this indicates that the solder paste bled into capillaries between apertures during the printing stroke, thus causing smearing.

In full array patterns the density of open apertures over the printing area increases dramatically compared with the peripheral patterns. For finer pitches and more importantly web spacings, this may cause the stencil to warp slightly thus producing small capillaries between the underside of the stencil and the surface which is being printed on. If the paste is too fluid, then flow into the capillaries will occur. Improving the tackiness and reducing the fluidity of the paste can improve the printing performance at ultra fine pitches.

Using the type-7 solder paste, the printing limits and ultimate performance differed from those of the type-6 paste. In this case the limits of the printing at both peripheral and full array were much finer as were the aperture sizes, which the type-7 solder paste could fill. Consistent full area array printing was achieved for 50µm apertures at pitches below 90µm down to an ultimate value of 30µm apertures at 60µm pitch. In all cases there were no reported signs of smearing caused by paste bleeding. This observation can be accounted for by the packing differences in the type-7 paste and implies that the type-7 paste is less fluid than the type-6 paste and unable to flow into tiny capillaries between adjacent stencil apertures at fine web sizes.

The packing density of the fine particles in a deposit from a type-7 solder paste appears to be greater than a similar sized deposit composed from the type-6 PSD solder paste (see Figures 5, 6). The increase in packing density suggests that the solder paste will be less fluid and less likely to flow. Additionally the combination of a higher packing density and smaller PSD of the particles from the type-7 accounts for the fact that smaller stencil apertures can be filled when using this distribution compared to using the type-6 PSD.

As can be seen in table 1, the smallest aperture that could be printed through using the type-6 PSD solder paste was 50µm, whilst the type-7 solder paste could be printed through an aperture as small as 30µm. Current methodology predicts that printing into small apertures can only be achieved if the average particle size is around 5 times smaller than the aperture size. In the case of type-6 PSD the average particle size of 10µm can fill an aperture 5 times its size, thus agreeing with this philosophy. However, in the type-7 PSD case the average particle size of 7µm can fill apertures as small as 4 times the average size; this may be attributed to the enhanced packing ability of the smaller particles. Further work is being done in order to characterise these two paste types in more detail, with regards to how the rheological properties differ between the two pastes and what influence these properties have on the printing process.

Slump was not observed in the deposits from the type-7 solder paste; in fact, the deposit sizes were smaller than the apertures through which they were printed.

Table 1 - Stencil Design Guidelines for Ultra Fine Pitch Printing

Aperture diameter/µm	**80**	**50**	**30**
Aspect ratio	1.6	1.0	0.6
Area ratio (square aperture)	6.4	4.0	2.4
Area ratio (circular aperture)	5.0	3.1	1.8
Type-6 printing	Yes	Yes	No/ aperture filling inhibited
Type-7 printing	Yes/not 100% paste release	Yes/not 100% paste release	Yes

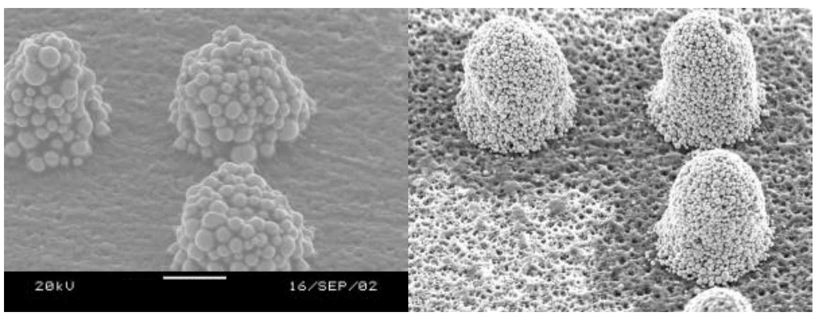

Figure 5: SEM Images of 70µm Solder Deposits from Type-6 (top) and Type-7 (btm) PSD Solder Pastes; Clearly Displaying a Higher Packing Density of the Pb-free Solder Alloy Particles in the Type-7 Case

Figure 5 displays printed deposits from the two paste types using the same aperture pattern. Comparing the two printing patterns reveals that the type-6 deposits appear larger than those from the type-7 paste. The fact that the deposits from the type-7 paste are smaller than the apertures indicates an aperture release deficiency. This is supported by Figure 7, which shows a 60µm stencil aperture after printing. When using the type-6 PSD solder paste, the aperture exhibits full paste release, conversely in the case for the type-7 PSD, a significant amount of solder paste remains adhered to the stencil aperture walls implying that full paste release has failed to occur. This may be due, in part, to the paste having a higher value of tack or solid-like properties, or a reduction in wall slip between the solder alloy particles and stencil wall.

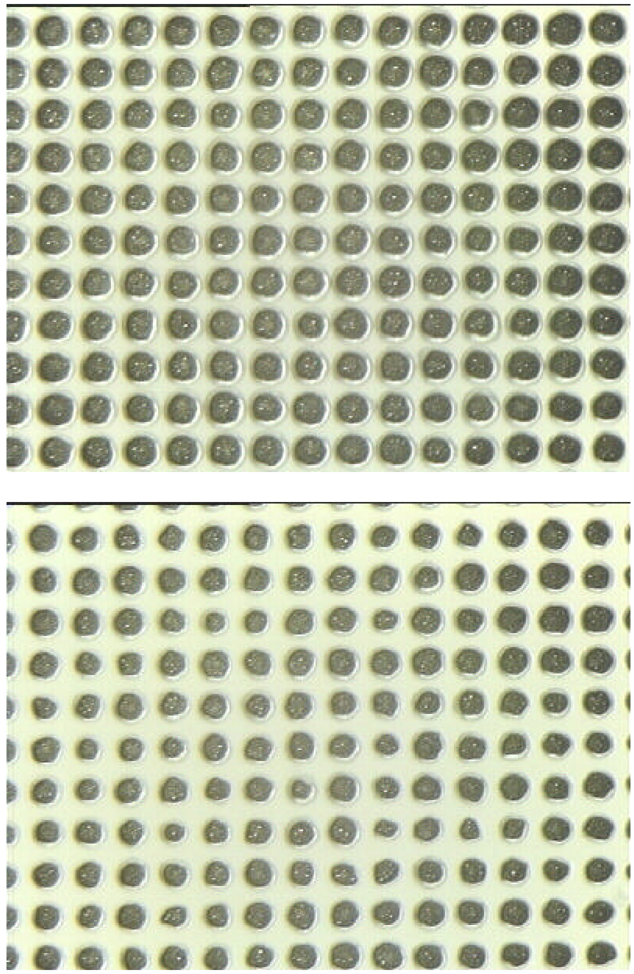

Figure 6 - Comparison of Type-6 (top) and Type-7 (btm) Printed Deposits at 90µm Pitch, 60µm Square Apertures. Solder Paste Deposits from the Type-6 Paste are Larger than those from the Type-7 Paste (65µm compared to 45µm) indicating Better Paste Release for the Type-6 paste at these Geometries

Paste release from the apertures depends on the aperture aspect ratio, area ratio, print gap and ultimately paste rheology. When the stencil is drawn away from the substrate, paste release will occur when the pull force exerted by the tackiness (or surface tension) exceeds the drag force exerted by friction between the aperture walls and the solder paste. Increasing the aspect and area ratios above 1.6 and 0.66 respectively effectively increases the surface area in which drag force is created. Therefore the aspect and area ratios are, in essence, a measure of the drag force expected, as larger values of these ratios will yield lower drag forces and hence aid release. Conversely, a paste with a higher value of tack will exert a greater pull force, as surface tension will dominate, and the paste is able to release from apertures of a higher aspect ratio. It may be argued that the increased value of tack will result in the paste adhering to the aperture walls, however, if the tack value is not too high the larger area of the pad surface compared to the aperture wall area will supply a higher pull force compared to drag.

Wall slip, which essentially aids in the reduction of the drag force, is produced by the lubricating effect of the flux medium in the solder paste. Wall slip simulations have shown that lowering the PSD effectively reduces the thickness of a liquid layer between the aperture sidewall and particles, thus increasing the drag force and inhibiting full paste release. Although the rules for aspect and area ratio governing aperture release are satisfied, it appears that the type-7 paste has a too high value of tack force for 100% aperture release. However, caution must be applied when adjusting the tack of this paste type to improve release as making the paste more fluid may cause the paste to bleed for full area array ultra fine pitch applications.

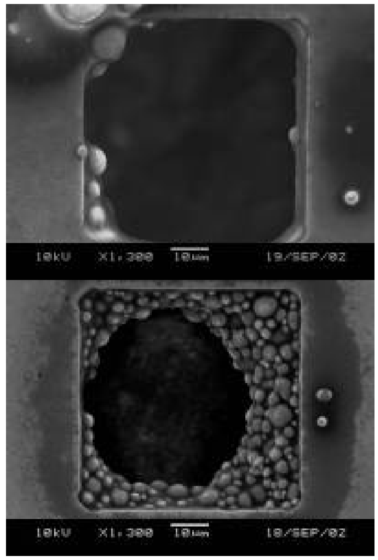

Figure 7 - Comparison of Aperture Release from Type-6 (top) and Type-7 (btm) Solder Paste from 60µm Square Apertures. The type -7 Paste Displays Deficiencies in Aperture Release

The comparison of the two paste types reveals that both pastes are suitable for fine pitch stencil printing for flip chip assembly applications. However, the higher value of tack, supplied by the type-7 PSD paste, is able to print to much finer pitch limits for full area array patterns, unlike the less viscous type-6 paste. The smaller PSD in the type-7 paste also permits the filling of much smaller stencil apertures. On the other hand, the type-6 PSD solder paste can yield larger deposit volumes. This being due to the fact that this paste type has a more efficient aperture release due to a more fluid consistency at the aperture walls. Consequently, and importantly, the required solder paste volume can be controlled, in part, by selecting between the two paste types.

Upon completion of the printing trials identifying the ultimate pitch and web, the two paste types were also used to explore the possibility of wafer bumping a 100 mm^2 silicon wafer comprising 576 flip chip sized dies. The surface pads on the die, ranging from 60µm to 80µm, were arranged in full array and peripheral patterns at 150µm and ultimately 125µm pitch. It is worth noting that each full array pattern comprised of 256 pads and each peripheral pattern contained 64 pads, therefore, each 100 mm^2 silicon wafer contained over 90,000 pads for the solder paste to be printed onto.

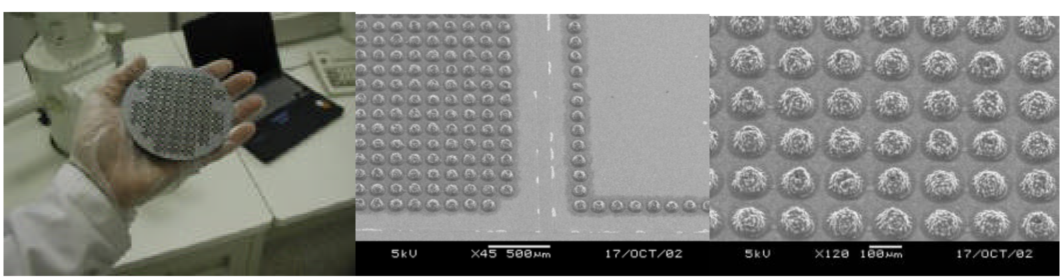

Figure 8 - Pb-free Wafer Bumping Capability on a 4-inch Silicon Test Wafer Incorporating Flip Chip Sized Die with Pads arranged in Full Area Array and Peripheral Array at 150 and 125µm pitCh

With regards to the printing limits already discussed in this section, printing at the more coarse geometries (150µm and ultimately 125µm) with type-6 and type-7 PSD Pb-free solder pastes for wafer bumping was easily achieved (see Figure 8). Furthermore, the behaviour of the two pastes types as seen in the study for the test PCB remained similar. For example, the type-6 PSD paste delivered more volume than the type-7 PSD paste for the same shaped apertures. Furthermore, the square shaped apertures also yielded greater deposit volumes. The results seen in Figure 10 are encouraging for an implementation of a Pb-free wafer bumping process, furthermore, the finer pitch results from the test PCB printing do indicate that this process can further reduce aperture size enabling sub 100µm Pb-free interconnects.

Reflow Results

The investigations concerning the effect of oxygen ppm on the coalescence of the fine Pb-free particles were performed on a Soltec Quantis 10-zone conveyer type reflow oven, the oxygen ppm was monitored using an integral probe.

Reflow profiles were designed to include fast and slow ramp rates, which reflected typical values found in industrial applications. The nitrogen atmosphere purity was controlled to 90ppm O_2 (highest purity), 500ppm and 2000ppm (lowest purity).

Good solderability/coalescence of the fine particle Pb-free solder paste was observed when printed deposits formed a central globule of solder after reflow; see Figure 9. Unfavourable solderability was observed when the fine particles failed to coalesce; in this case a halo of solder particles surrounded the central globule, or there was a non-complete coalescence of the particles.

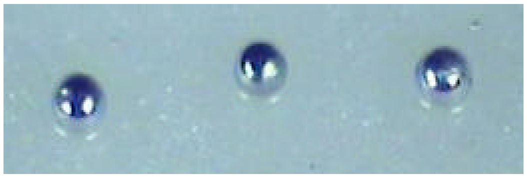

Figure 9 - 100µm Solderballs Observed after Successful Reflow

For the fast ramp rates both the type-6 and type-7 pastes, yielded good coalescence for oxygen levels up to 2000ppm; no observable differences were seen in the reflowed globule between 90ppm and 2000ppm.

However, at 2000ppm, for some of the longer slower ramp reflow profiles, the fine particle solder paste did not reflow successfully, shown in Figure 11

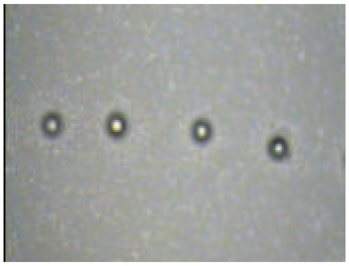

Figure 10 - Successfully Reflowed Solder Paste Deposits at 500ppm, all Profiles

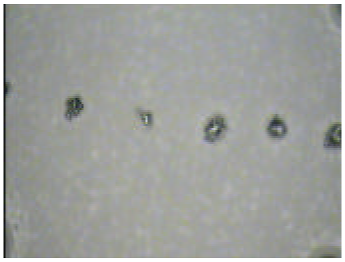

Figure 11 - Solder Paste Deposits after Reflow (Slow Ramp Rate) at 2000ppm

This investigation indicates that oxygen concentrations below 500ppm are required for longer or slower ramp reflow profiles (shown in red in Figure 12).

The range and required O_2 concentrations for successful reflow of the fine particle solder pastes are detailed in Figure 12.

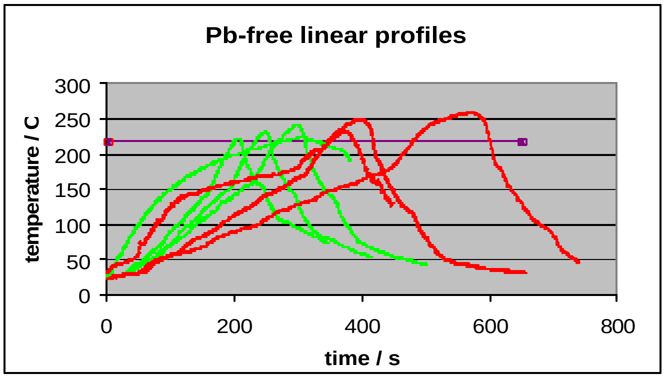

Figure 12 - Reflow Profiles used in the Solderball Test, Profiles in Red Require < 500ppm O_2

The Pb-free reflow profiles were also used to evaluate soldering to immersion Ag and ENIG (Au/Ni) finishes at flip chip geometries. With the nitrogen atmosphere being required as a prerequisite, reflow was completed in a SEHO belt driven convection oven with an oxygen concentration between 200-400ppm.

Acceptable reflow soldering was observed for all reflow profiles, indicating that the type-6 and type-7 pastes are acceptable for reflow, in nitrogen (<500ppm) at flip chip geometries for both Ag and ENIG coated pads. Figure 13 displays reflowed deposits of a type-7 Pb-free paste.

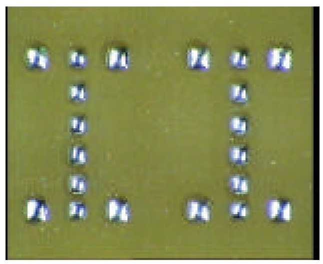

Figure 13 - Reflowed Deposits from Type-7 Solder Paste Printed on 70µm Diameter Pads at 110 mm Pitch

Conclusion

In light of demands for finer pitch interconnection existing SMT infrastructure and associated materials have been extended to provide next generation solutions. Fine particle Pb-free solder paste materials have been formulated and their rheology optimised in terms of shear thinning and visco-elastic properties to enable successful stencil printing at ultra fine pitch geometries. This refinement to Pb-free solder paste together with the introduction of micro engineered stencil technology has enabled a comprehensive investigation into the sub processes involved during the printing process.

Characterising the performance of the type-6 and type-7 PSD paste materials, in terms of both their printing and reflow attributes, has identified differences between the PSD types which are key to understanding and establishing design guidelines for ultra fine pitch interconnection. Questions have been raised previously regarding the performance of paste materials exhibiting such fine particles. Due to the inferior quality of conventional stencil technology in producing, typically, 50µm aperture structures, early research into paste performance was hampered by the effect of stencil capability on the paste evaluation. However, with the introduction of micro engineered stencil technology capable of producing aperture structures exhibiting 60µm pitch, both the type-6 and type-7 paste materials have been comprehensively assessed throughout the printing process.

Investigating the printing process at these small scale geometries is imperative to further understanding how these newly formulated pastes will perform. Differences in the behaviour of the materials were highlighted regarding aperture fill and subsequent release of paste from the stencil. The difference in packing density of the particles was found to be quite significant even though the powder PSD only varied from 15–5µm (type-6) to 12-2µm (type-7). This difference resulted in the type-7 paste successfully printing at 30µm aperture size, whereas the type-6 was only successful at 50µm aperture. Differences in paste tackiness resulted in the less tacky type-6 material demonstrating bleed when printing fine pitch full array patterns. Conversely, type-7 paste showed no signs of bleed on the same footprints. However, the high value of type-7 tackiness resulted in problems during release of the paste from the smaller apertures, whereas the type-6 exhibited excellent release characteristics.

This study has highlighted the printing issues encountered for fine pitch interconnection and how the formulation of the appropriate paste type can be engineered to provide a material and deposition process capable of demonstrating the geometries required. Further research will include a further study of paste formulation at these PSDs and how the paste rheology impacts at this new level of stencil printing.

Process solutions for the reflow of fine particle Pb-free solder paste, show that, at flip chip geometries, inerted reflow is essential. For linear reflow profiles having slow ramp rates (greater than 300s) the oxygen concentration must be < 500ppm. For oxygen concentration between 200-400ppm the solder paste deposits reflowed well on Ag and ENIG coated pads over a large reflow process window; peak temperature up to 260°C, time to liquid > 600s and time above liquid up to 130s.

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