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ABSTRACT

The drive to use ever finer pitch printing of solder pastes has raised a number of questions regarding the quality of the printed paste. This study was undertaken to investigate the effects of a number of factors (solder composition, metal particle size, and resist thickness) on the quality of fine pitch stencil printing, and the results are encouraging for the users of fine pitch printing and lead-free solders. First, if the total metal content is adjusted to compensate for the changes in density, the traditional high quality printing can be maintained when using lead-free solder pastes. Second, the size of the metal particles in the pastes does have a significant effect on the quality of the printed paste, which improves as the particle size is reduced. However, there is a balance to be achieved with the increased incidence of solder balling when using pastes having the finer particles. Third, the robustness of the printing process restricts any adverse effects of the thickness of the solder resist, resulting in only minor deterioration in print quality when using resists thicker than 30 mm.

1. Introduction

The maintenance of high yields and low defect levels during periods of rapid changes in technology and materials is a major challenge for the industry. The drive to fine pitch stencil printing, and the introduction of lead-free solders, are just two factors that have to be understood and accommodated by pcb assemblers, whilst retaining high yields etc. Low defect assembly is critically dependent on the paste printing stage, which in turn is directly related to the printer and paste used. The paste itself is a multi-component system that is sensitive to the properties and interactions of the various constituents, and consists of metal particles suspended in a flux vehicle system. The metal particle size and size distribution, which can be varied depending on the application, will certainly affect paste printing performance, and therefore have to be understood. Competitive pressures to reduce equipment size and to maximise circuit performance have created new challenges in fine pitch solder paste printing. New pastes are required which use small sized metal particles, and a better knowledge of their printing characteristics and print quality are essential. This work was undertaken not only to investigate the effect of these critical factors (i.e. the paste make-up) but also to include studies of the effects of some new lead-free solders, and of the thickness of the solder resist.

A plethora of new lead-free solders has been suggested to meet the challenge posed by the impending ban on the use of lead in solders. They involve new solder compositions using metals such as silver, bismuth and copper, together with new flux formulations. These new materials raise issues of yield, performance, and product reliability. Traditionally acceptable solder joint failures rates are around 100 ppm(2), but these levels are under threat from increases in component density and reductions in component lead pitch. Previous studies have shown that ~ 60% of the defects identified after reflow soldering originated during the paste printing stages, thus emphasising the key nature of this step on assembly yield. Hence this work has also included an investigation of the printing performance of three commercially available lead-free solders compared to that of a lead-containing solder paste.

Another important aspect related to printing performance is the substrate structure and surface finish. In previous work the effect of distorted substrates on fine pitch printing had been reported(3). In this investigation, the previous work has been extended to cover the effect of varying the solder resist thickness.

2. Experimental

2.1. Evaluation of printing deposit

A test printed circuit board and stencil were designed to evaluate fine pitch printing performance (down to 300µm), see Figure 1. The stencil was stainless steel, 100µm thick, laser cut with apertures arranged on orthogonal axis. The design comprised an aperture array repeated in many locations, with three different pitches and two orientations. An aperture group array comprised three sets each of 0.4, 0.35 and 0.3mm pitch aperture arrays, and the 0.4mm pitch was repeated but turned through 90°. The aperture group arrays are repeated to give a 3 X 3 pattern, which then provides the board aperture arrangement. The stencil did not have the dots around each aperture array; these dots were used as a reference for paste deposit measurements.

In this work a laser scanning profiler (UBM with a triangulation sensor) has been used to measure the profiles of the print deposits. Two criteria were selected to characterise the printing deposit, print volume and wall angle (3). Print volume in this work is given as a percentage of the stencil aperture volume. For acceptable printing quality the paste volume should be greater than 60%, and less than 90%. If the printing volume is less than 60%, there is insufficient paste, and possible skipping on the paste deposit. If the paste volume is greater than 90%, excess paste may be deposited non-uniformly, eg. *"dog ears"* on QFP type pads.

It is critical to deposit the correct amounts of paste cleanly onto the substrate, to form a reliable solder joint. The wall angle is one measure of the shape of the printed deposit. The larger the wall angle of the solder deposit, the sharper the edge of the solder deposit. The wall angle should be larger than 20° for good printing. A wall angle, smaller than 20°, will probably result in bridging. More details about this measurement technique, and the characterisation of printed solder paste can be found in Ref(3).

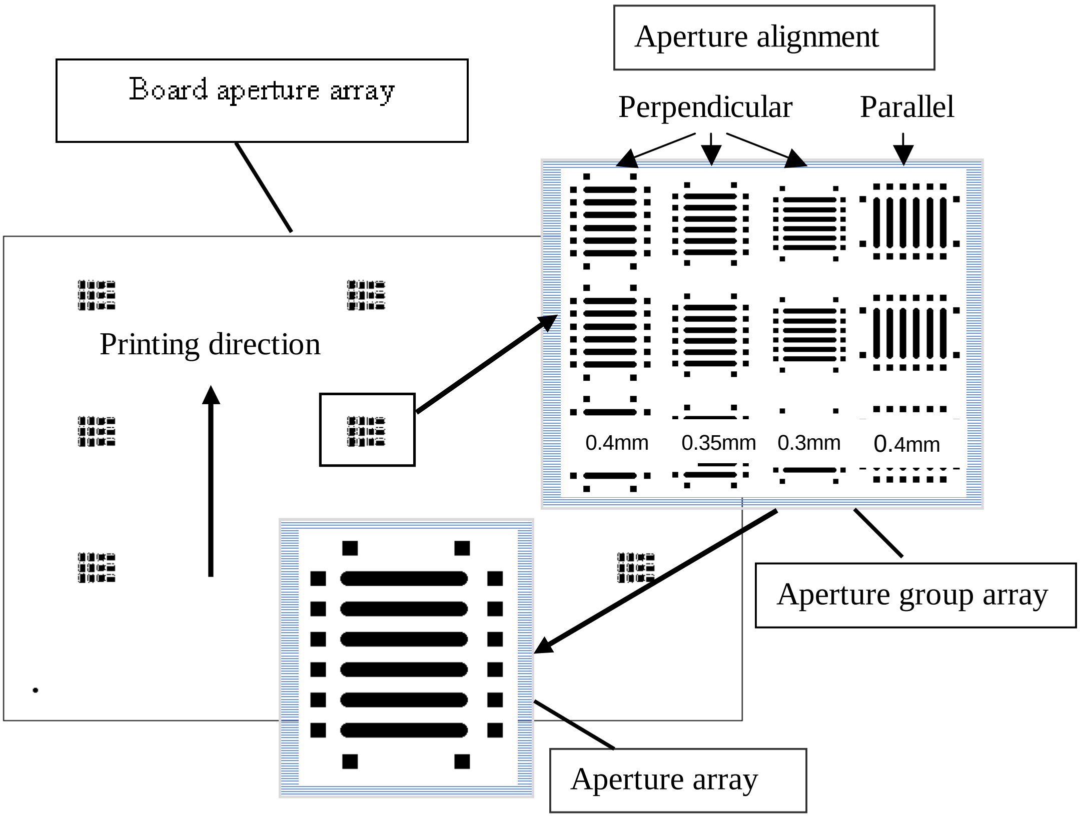


Figure 1: Test board and stencil design

2.2. *The fine pitch printing and reflow performance for different metal particle sizes*

Two SnPbAg solder pastes, A and B, with three different metal particle sizes were printed using 300mm pitch 60° metal squeegee at 24°C/40% RH. Pastes A and B are both described as no-clean pastes, Paste A is formulated as a high printing speed paste, and paste B can accommodate a wide range o printer cycle times. The paste particle sizes and printing parameter settings are listed in Table 1. The paste was printed continuously for 50 prints without any stencil cleaning. The 6th and 50th prints were measured using the laser scanning profiler. The prints measured were the perpendicularly aligned, 0.4, 0.35 and 0.3 mm pitch in the middle row of the *aperture group array* on the middle position of the *board aperture arrangement*. The 8th print was reflow soldered using the same reflow profile for both paste types. The boards after reflow were visually inspected using an optical microscope with up to 45 times magnification, to check for solder ball formation.

Table 1: The paste particle sizes and printing parameter settings

Paste	Particle size range (µm)	Average Particle size (µm)	Type	Printing load (kg)	Printing speed (mm/s)	Separation speed (mm/s)
Paste A	10-25	17.5	5	3.6	90	1.0
	20-45	32.5	3			
	53-75	64	2			
Paste B	10-25	17.5	5			
	20-45	32.5	3			
	53-75	64	2			

2.3. *The fine pitch printing performance of different lead-free solder alloy pastes*

For these printing tests three commercial lead-free solder pastes, C, D and E, were used in conjunction with Paste A and with printing conditions of 300mm pitch, 60° metal squeegees at 24°C/40% RH. The pastes and printing parameter settings are listed in Table 2. Pastes C and E are both SnAgCu pastes, but from different manufactures. Ten prints were printed for each paste, the 6th, 8th and 10th prints were measured using the laser scanning profiler. The prints measured were the perpendicularly aligned, 0.4, 0.35 and 0.3 mm pitch in the middle row of the *aperture group array* on the middle position of the *board aperture arrangement*.

The lead-free paste C, and paste A, were also continually printed using squeegees over 6 hours at 28°C/75%RH, to evaluate their stencil life in this harsh environment. Six prints were taken after 0, 2, 4 and 6 hours. In between printing, each paste was conditioned by moving the paste backwards and forwards on a blank area of the stencil. The printing speed and separation speed were the same as above, but the printing load was reduced to 2.2kg. The apertures measured for the sixth print were the same as above.

Table 2: The pastes and printing parameter settings

Paste	Type	Printing load (kg)	Printing speed (mm/s)	Separation speed (mm/s)
Paste A	SnPbAg	3.6	90	1.0
Paste C	SnAgCu	3.6		
Paste D	SnAg	4.2		
Paste E	SnAgCu	4.2		

2.4. The effect of solder resist on fine pitch printing

A new print circuit board design was made to assess the printing performance as a function of different resist thicknesses. The stencil was a stainless steel 100µm thick laser cut with an array of QFP apertures, and a selection of tracks leading away from the pads. The design comprised 400, 350 and 300µm pitch with different tracks and via combinations, as shown in Figure 2. The four rows of apertures are labelled A to D, and further details of these are shown in Figures 2a to 2c for the 0.4mm apertures. The arrangement between row A and B is different, but for clarity only a detail of row A is given. The Figures show the pads and the resist window in grey, and the critical (minimum) distance between pad and resist for 0.4mm pitch was set to 50µm for all aperture arrangements. Figure 2b illustrates the basic arrangement from row C; the small dots at the end of each row are only on the PCB and are used as references for height measurements with the laser scanner. Figure 2a presents the tracks (0.150 mm thick). In Figure 2c again the tracks are 0.15mm thick, the vias have 0.5mm pads and 0.4 mm drill holes, and the via separation was set at the following values: 25, 75, 125, 175, 225, 275, 425, 475, 625, 675µm.

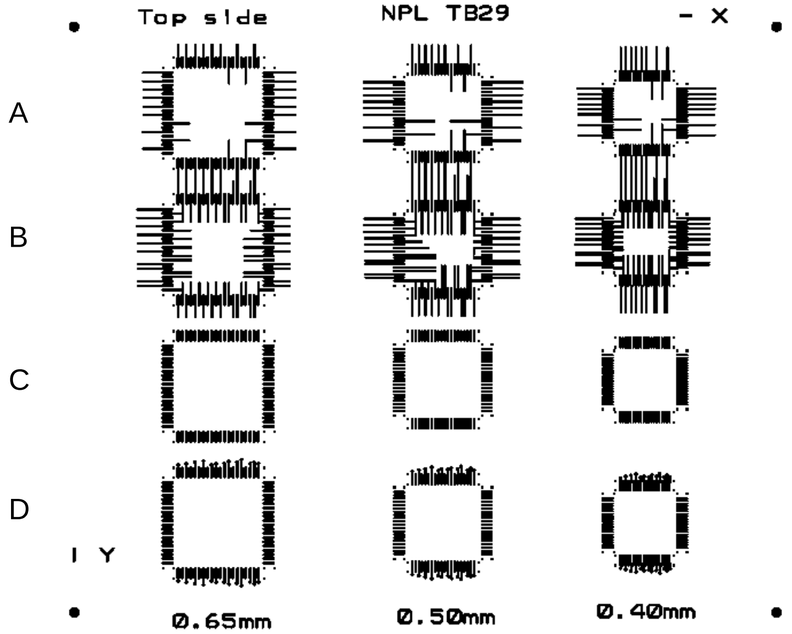


Figure 2: The test board and stencil design for substrate with solder resist

The PCBs were coated with a range of matt and gloss finish resists in the thickness range of 10 to 50µm. Paste A was printed using a 300mm pitch, 60° metal squeegees at 26°/40% RH.

The printing speed was 50 mm/s, and printing load was 4 kg. Printing was conducted with two print alignments, good print alignment between stencil and substrate to reflect the ideal situation, and some misalignment to simulate the practical situation for some large electronic boards used in industry. The analysis work was undertaken on the 0.4mm pitch patterns, and here the offset was 20µm in the y axis. The prints on the substrates with different thickness of solder resist were visually inspected using an optical microscope with up to 45 times magnification.

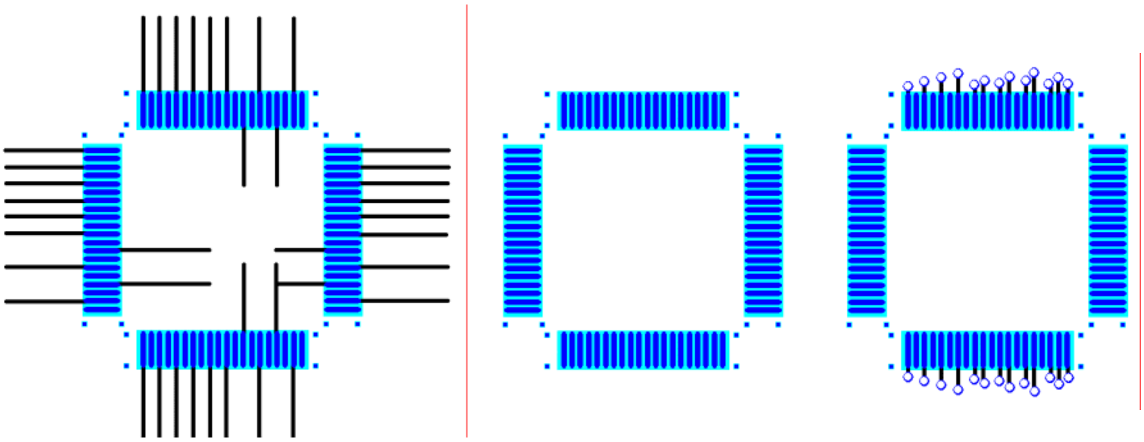


Figure 2a Figure 2b Figure 2c

Figures 2a,b,c: Detail of pad, track and via layout

3. Results and discussion

3.1. The effect of metal particle size on fine pitch printing performance

3.1.1. The fine pitch printing performance of pastes having different metal particle sizes

Two pastes, A and B, each having three metal particle sizes were printed. These two pastes have the same solder alloys and metal contents, but different flux systems. There was no significant difference in printing performance between the two pastes, as shown in Figures 3 and 4. Both pastes gave consistent printing between the 6th and 50th print for all three particle sizes.

The average printing volume and wall angle for the 6th and 50th print for the three metal particle size pastes are shown in Figure 5. The fractional print volume and wall angle decrease as the paste metal particle size increases. The type 5 paste (see Table 1, i.e. having the smallest particle size) produces the highest print volume and wall angle. The type 2 (see Table 1, i.e. having the largest particle size) pastes show the lowest fractional print volume and wall angle. The effects of print volume and wall angle are particularly evident on the fine pitch (300 µm) aperture. The effect can be attributed to the ratio of particle size to stencil thickness previously studied by Morris and Wojcik(4)and Hwang(5). Morris and Wojcik found that to obtain high quality prints, the ratio of particle size to stencil thickness should be less than ½. Hwang suggests the use of metal particle not larger than $^1/_3$ of the stencil thickness. In our work, the ration of particle size to stencil thickness varied as shown in Table 3.

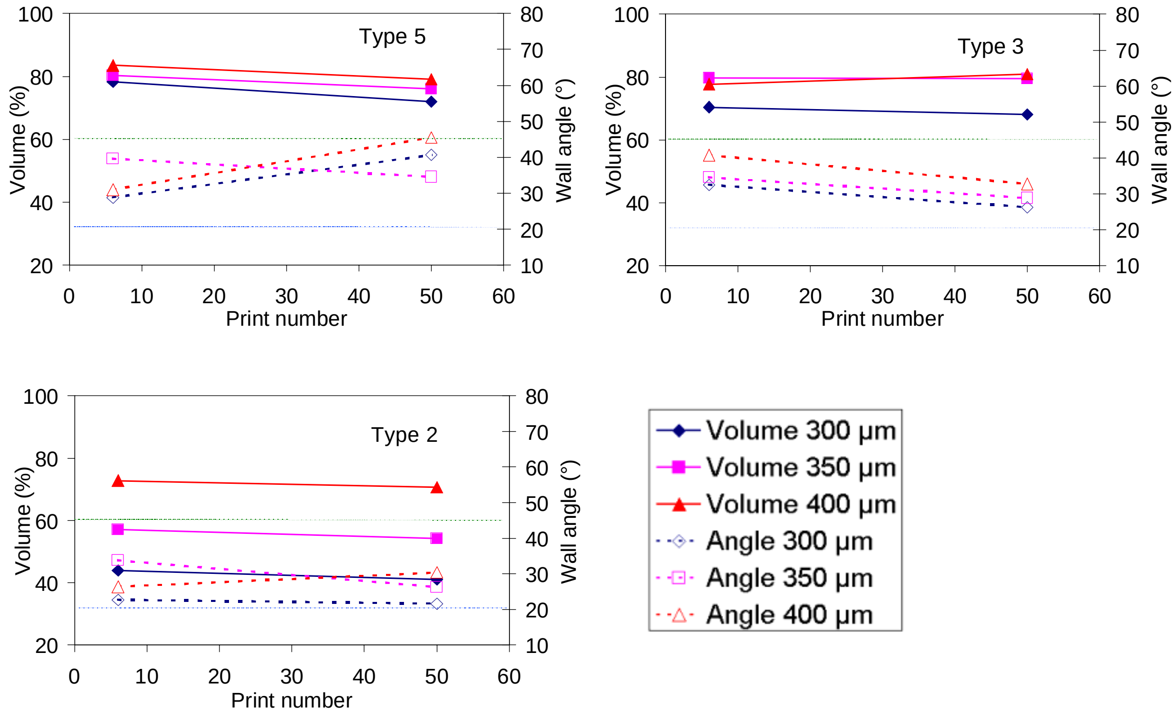


Figure 3 The variation of print volume and wall angle of 6th and 50th prints for paste A, for three particle size pastes

The results here confirm the observations on how the ratio of particle size to stencil thickness impacts on the print quality. With a ratio of larger than ½ with the type 2, paste the aperture pitch must be 0.4mm or above to achieve 60% volume deposit. Therefore type 2 pastes should not be used for fine pitch printing, with an aperture size of less than 400µm. Type 5 pastes are desirable to achieve a high fractional printing volume, 70%, for very fine pitch aperture (300 µm), and brick like deposits with wall angles of 40°.

Table 3: Interactions between particle size and stencil thickness

Solder paste type	Average particle size (µm)	Stencil thickness (µm)	Average particle size to stencil thickness ratio
2	64	100	0.64
3	33		0.33
5	18		0.18

It is interesting to note the influence of aperture size on print volume, and the data from Figure 5 are plotted as a function of aperture size in Figure 6. Type 2 paste is, not surprisingly, the most sensitive to aperture size as discussed above.

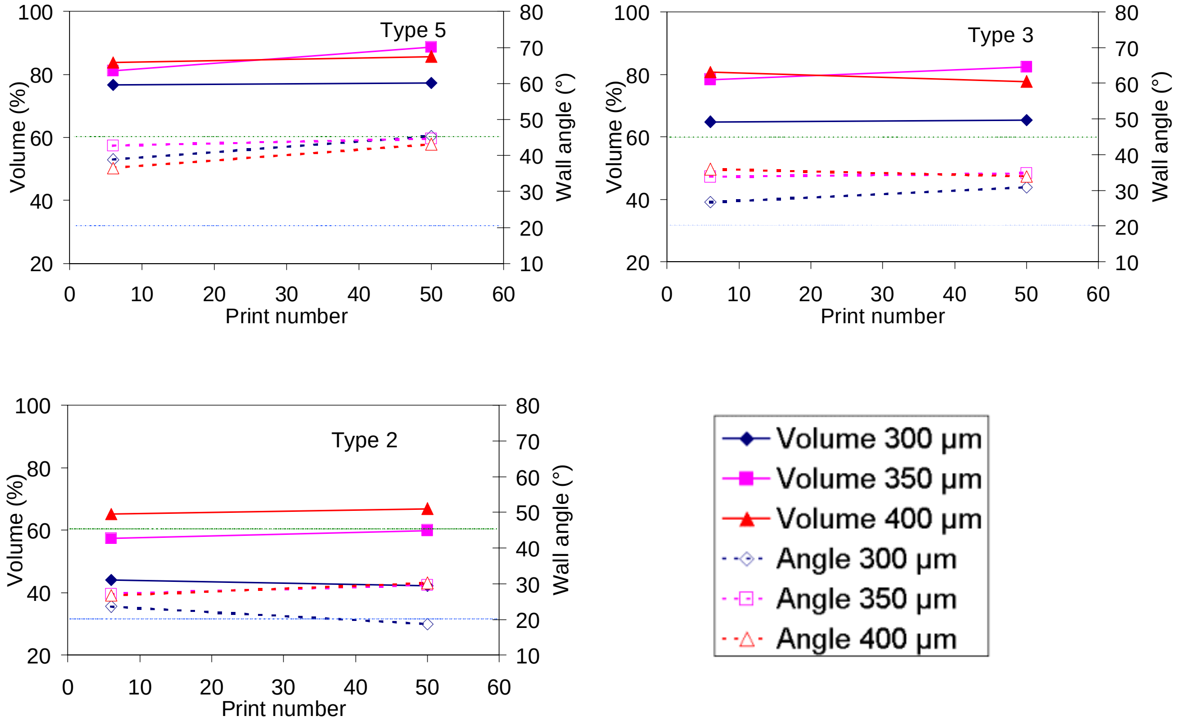


Figure 4: The variations of print volume and wall angle of 6th and 50th prints for paste B, for three particle sizes

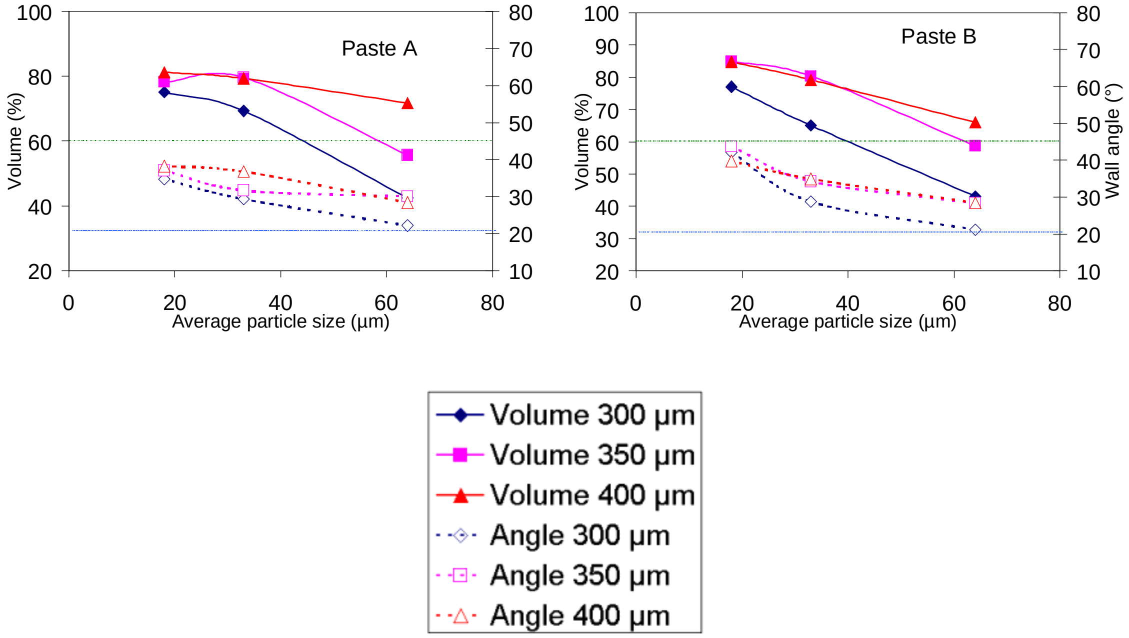


Figure 5: The variations of the average print volume and wall angle with particle size for paste A and B with three metal particle sizes

The printed volume of any paste depends on a summation of a number of forces. We will assume here that the aperture filling process is optimal and the aperture is 100% filled due to the correct selection of printing parameters. The printed volume is therefore dependent on the release process of the paste from the aperture as the board is dropped from the stencil. The forces acting on the paste are; gravity, the adhesive force between the paste and the board, the adhesive force between the paste and the aperture wall, and the cohesive force of the paste itself. From a manufacturing standpoint the important variable is the aperture size, and hence the relative magnitude of the adhesive force between the paste and the aperture wall. As the aperture area decreases the ratio of the aperture area to aperture perimeter decreases. Research(6) has shown that this area ratio is the principal factor affecting solder paste release. In the present work the area ratios are 0.68, 0.78 and 0.81 respectively for the three aperture sizes 300, 350 and 400 µm. The larger the ratio, the superior the printing.

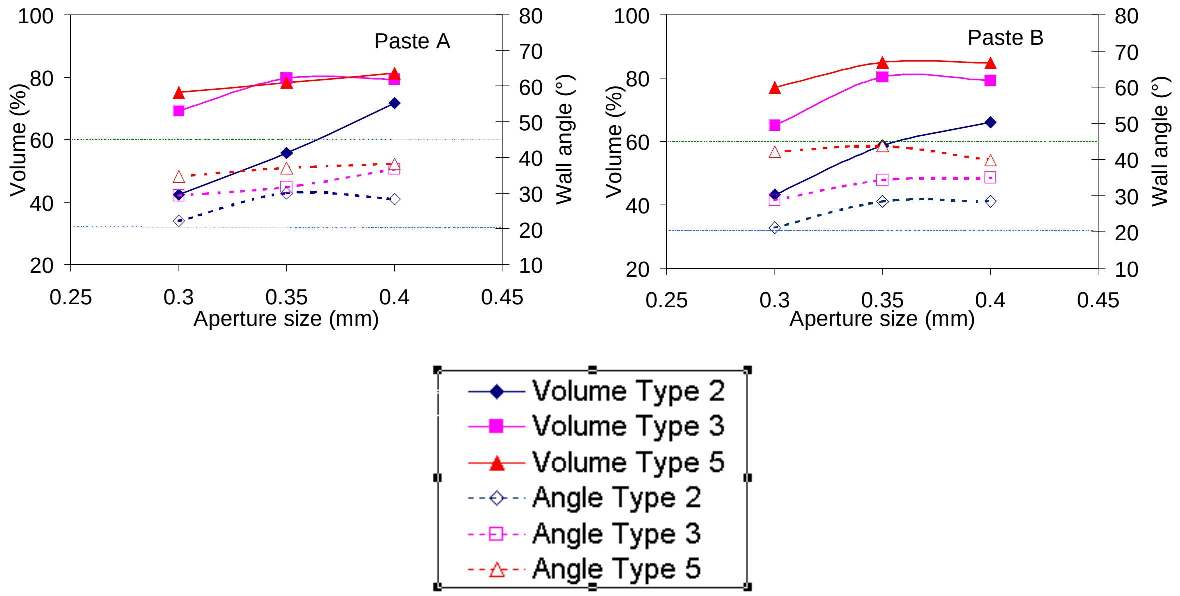
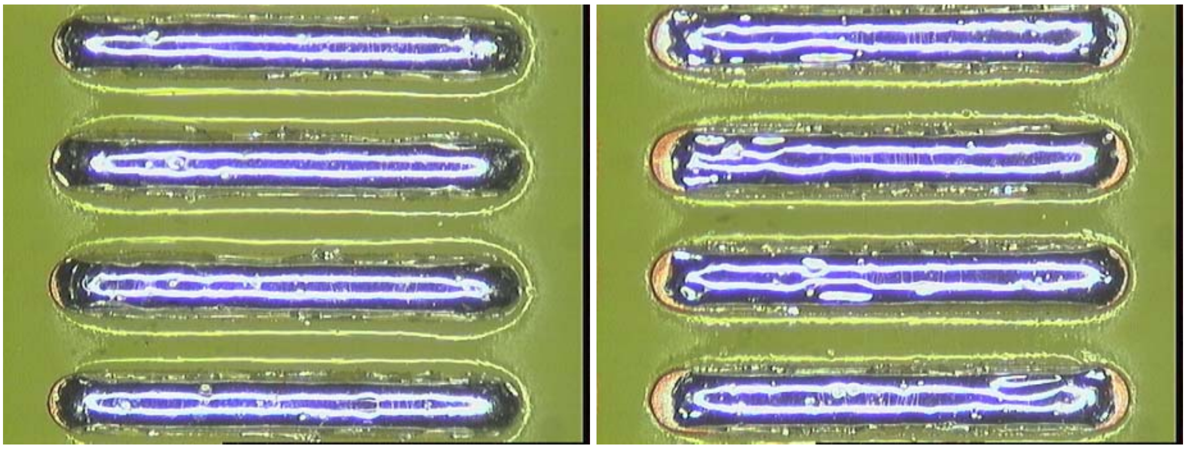


Figure 6: The variations of average print volume and wall angle with aperture size for paste A and B, for three metal particle size pastes

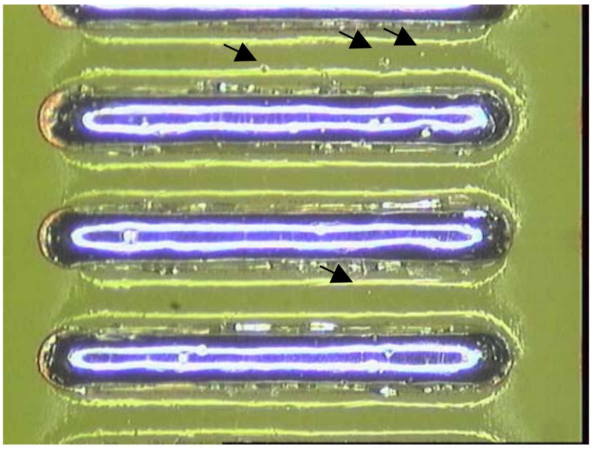
Changing the flux vehicle and the age of the paste, or its open time, will influence the adhesion forces. The solder particle size is also a factor as discussed above. A further factor influencing paste release is the effect of the aperture walls on the particle-particle interaction. As the particle size approaches a critical ratio of the aperture opening, probably around 0.4, the particles do not drop out easily but become wedged against the aperture walls. These two factors of stencil thickness and aperture size contribute together resulting in larger particles adhering in smaller apertures. Hence, the type 2 paste is more prone to poor printing in the 0.3mm pitch apertures.

3.1.2. The soldering property of different metal particle size pastes

To investigate the potential for solder balling, two solder pastes A and B having three particle sizes, were reflowed using the same reflow profile. The reflowed solder is illustrated in Figures 7 and 8 for pastes A and B respectively. Some solder balls (arrowed) were found using the type 5 pastes (i.e. the smallest particle size), but not with the type 2 and 3 pastes, as shown in Figure 7 and 8. With fine metal particles, the increase in relative surface area to volume increases the amount of oxide in the paste. Increased oxide potentially interferes with solder coalescence during reflow resulting in the ejection of solder balls. With low activity fluxes, where flux exhaustion may be an issue, the probability of oxides remaining as the alloy solidifies will be increased, and hence these alloys will have a greater tendency to solder ball. ***Hence that while fine particle sized pastes have the best print characteristics, they have an increased potential for solder balling.***

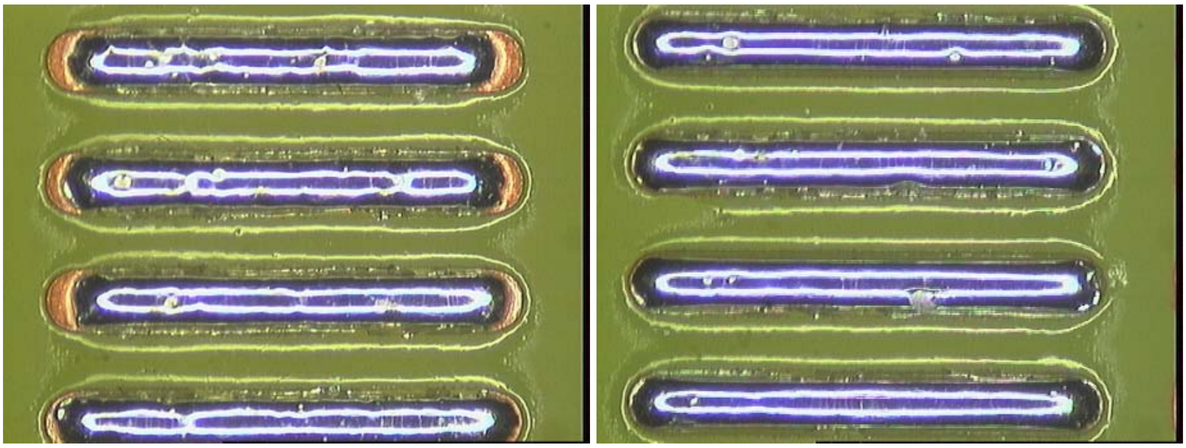


(Type 2) (Type 3)

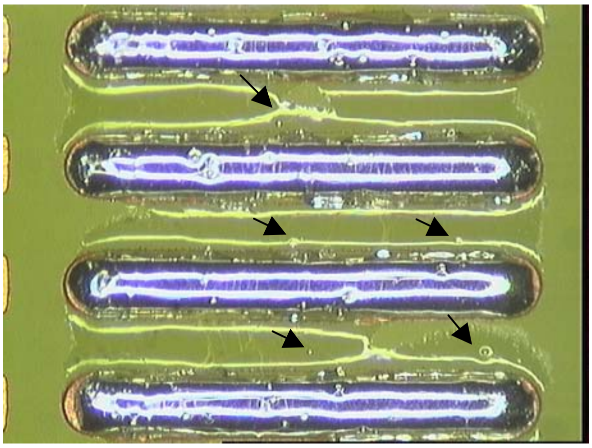


(Type 5)

Figure 7: Typical prints for paste A with three metal particle sizes after reflow



(Type 2) (Type 3)



(Type 5)

Figure 8: Typical prints for paste B with three metal particle sizes after reflow

3.2. The effect of solder alloy on fine pitch printing performance

The print volume and wall angle of 6th, 8th and 10th prints for different solder alloy pastes are plotted in Figure 9. The three commercial lead-free solder pastes have very similar printing performances to that of SnPbAg paste, and all have high print volumes and wall angles, with good consistency from print to print. Varying the solder alloy has two main impacts on the paste performance, these coming from the chemical properties and the density of the solder. The metal content is typically varied over the 88 to 91% range(7). Density effects have been studied previously and characterised(8). The chemical effects between most lead-free alloys are not significant and do not present any particular issues in formulating fluxes. Hence, to a large degree the flux vehicle controls the print properties. Consequently the paste manufacturers are clearly capable of making any necessary modifications to the flux vehicle to maintain print quality of the new solder alloys.

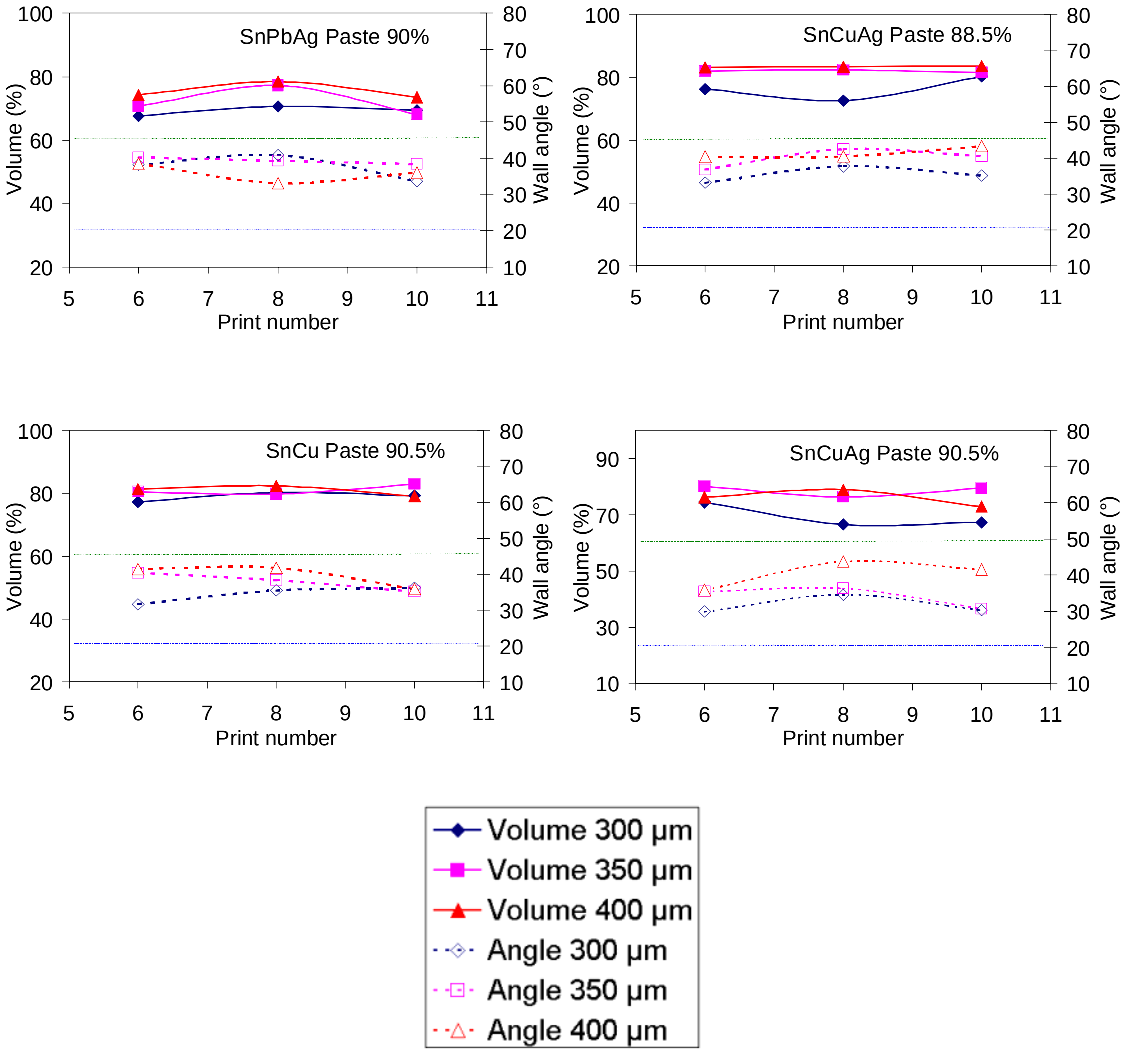


Figure 9: Print volume and wall angle on the prints with different solder alloy pastes

The paste stencil life is another critical performance metric that is used to characterise solder paste. The fine pitch printing performances of two solder pastes, lead-free (paste C) and lead-containing (paste A), over six hours are summarised in Figure 10. For both pastes there is at least a six hour stencil life at this high temperature and humidity combination. Therefore, there is no loss in performance in going to a lead-free solder paste, and here we successfully demonstrate fine pitch stencil printing of lead-free paste under harsh conditions.

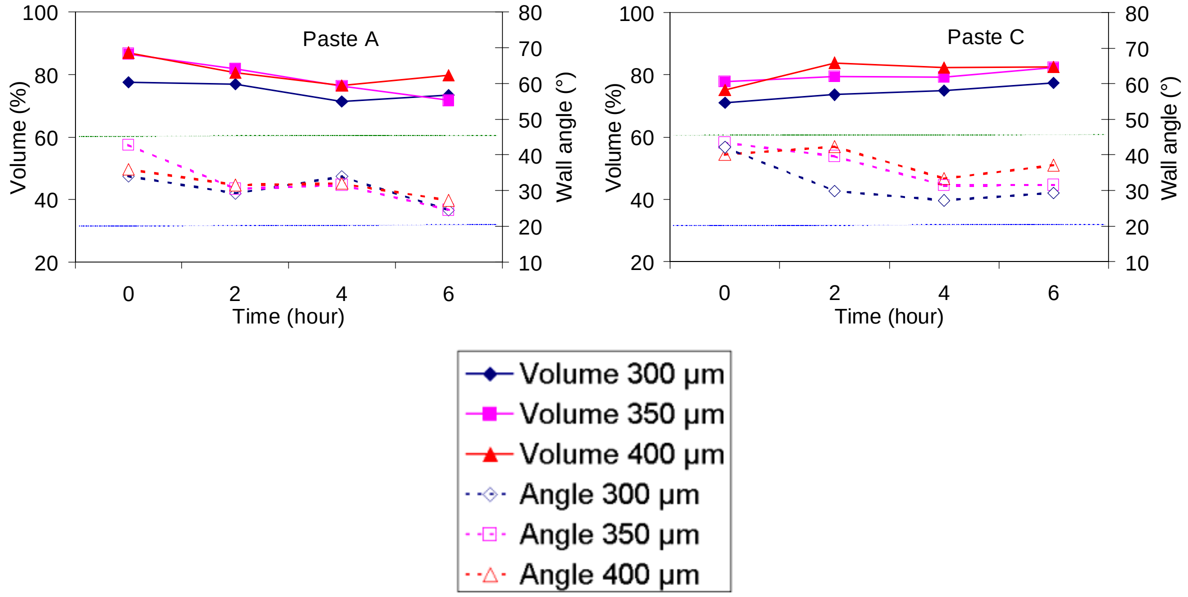


Figure 10: Print volume and wall angle with time for pastes A and C when printing in a 28°C/75% environment

3.3. *The effect of substrate with solder resist on fine pitch printing performance*

Solder resist is widely used on electronic assemblies and consequently the effect of thickness and surface finish on the printing performance was also investigated. Although the thickness of solder resist is generally about that of the copper track on the PCB, 40 and 50µm solder resists were used here to characterise the influence of increased thickness.

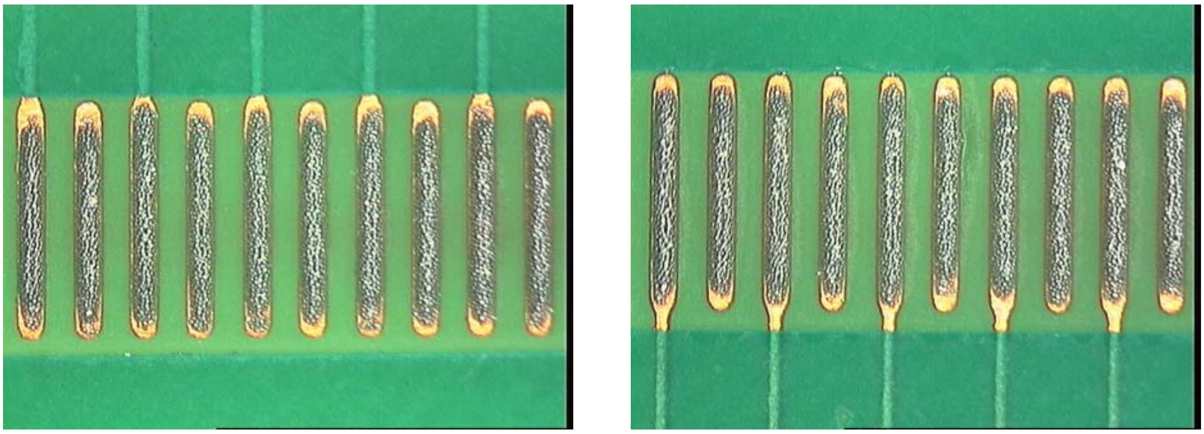
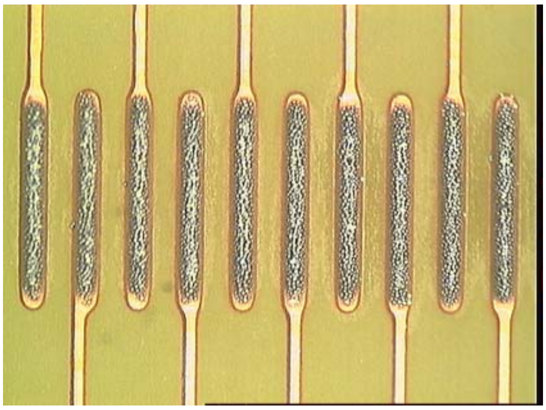


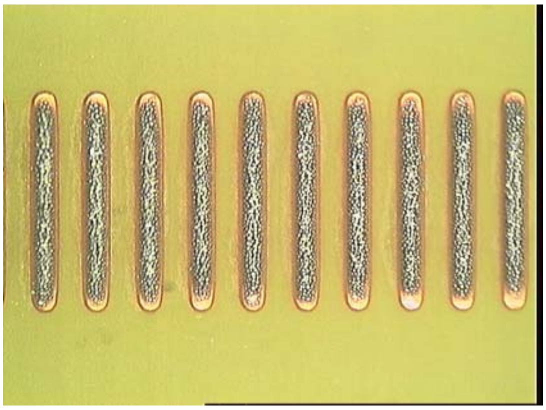
Figure 11: Typical prints with 0.4 mm pitch on 50µm solder resist
(print direction from bottom to top of image)

It was found that even with good alignment between stencil and substrate, and with the 50 µm resist board, very good printing performance was achieved, as illustrated in Figure 11. This Figure shows on the left the top side of the pattern from row A in Figure 2, and on the right side the bottom of the pattern from row A. There is no difference between these two images.

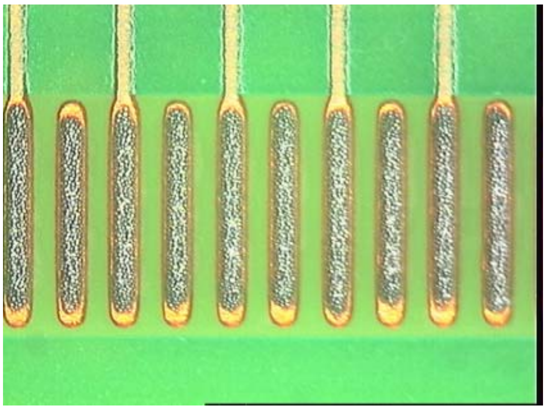
However, in production good alignment is difficult to achieve across a large board, and hence misalignment was simulated by shifting the stencil 20µm in the print direction. With this misalignment, the printing performance is a function of resist thickness shown in Figure 12. The images are again, on the left, from the top side of the pattern from row A in Figure 2, and on the right side from the top side of the pattern from row C in Figure 2. There was a little paste off the top of the copper pads when the resist was thicker than 30µm, and the printing performance deteriorated further with thicker resists. This may be due to a small gap between stencil and copper track when solder resist is thicker than the copper pads, as shown in Figure 13. The paste can bleed through the gap as the squeegee passes over. The bigger the gap with the thicker resist, the larger the amount of solder paste that can bleed onto the copper pads.



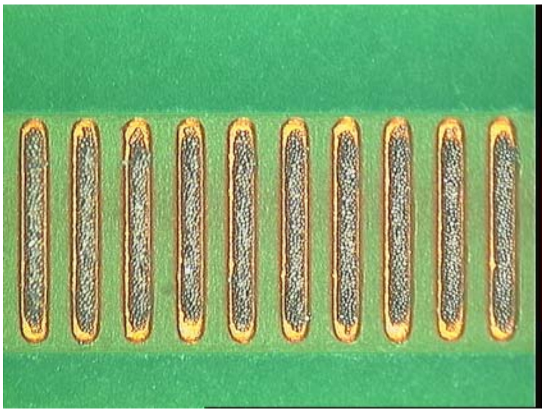
No resist



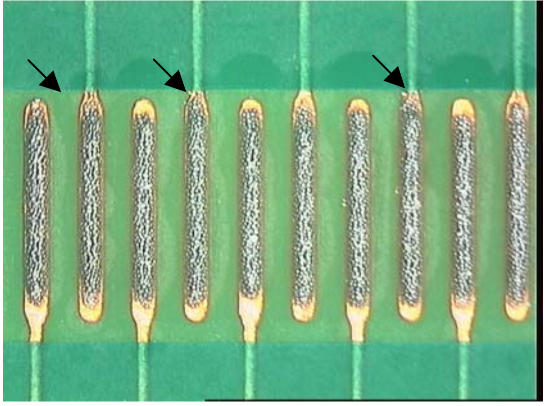
No resist



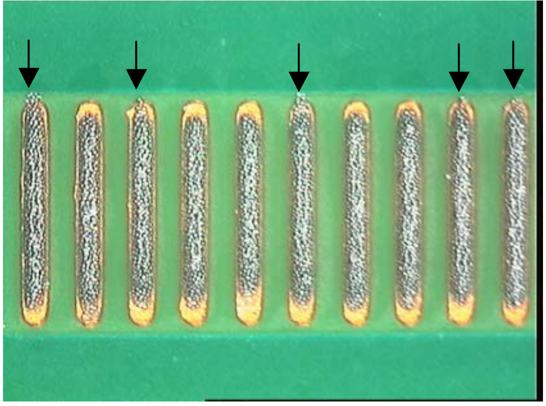
20µm resist



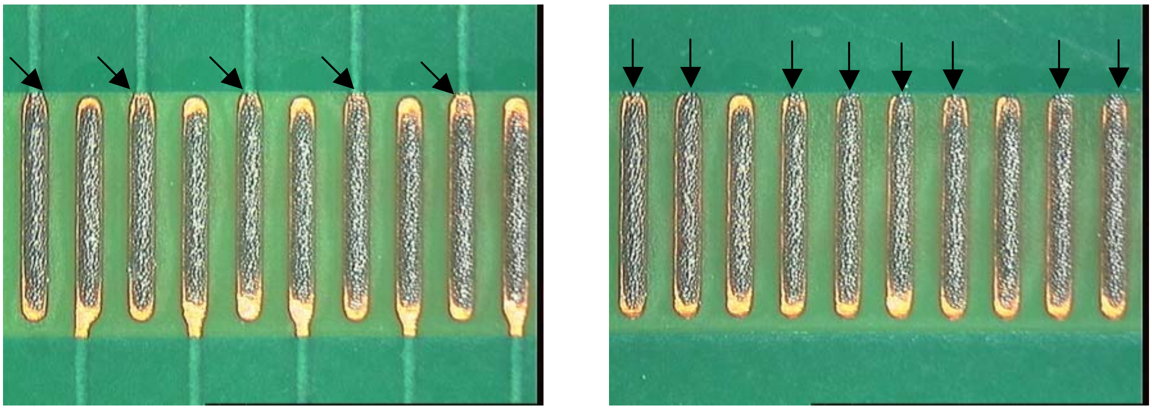
20µm resist



35µm resist



35µm resist



50µm 50µm

Figure 12: Typical prints with 0.4 mm pitch on the different thickness of solder resist Board (print direction from bottom to top of image)

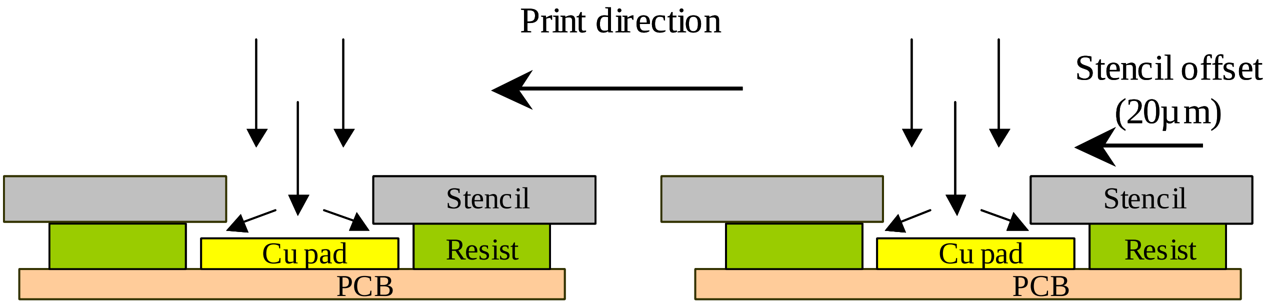
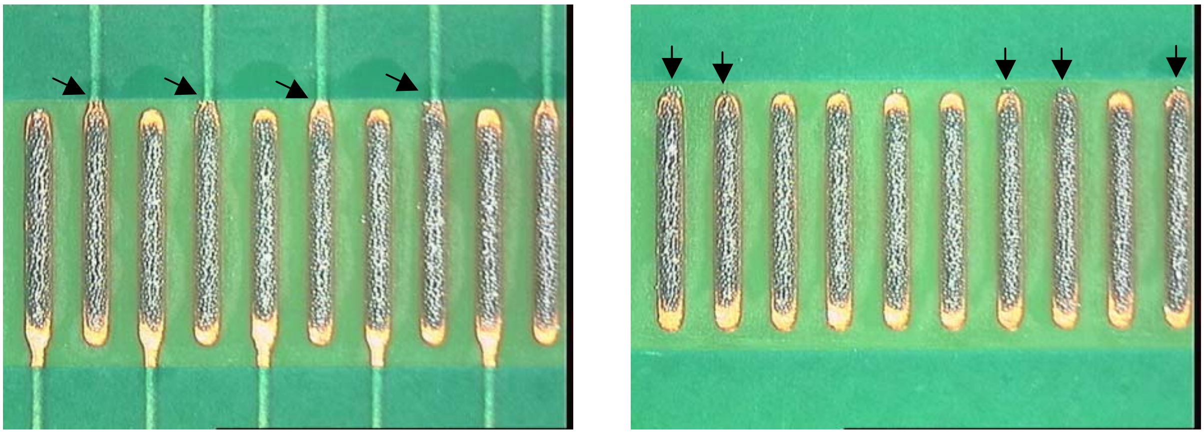


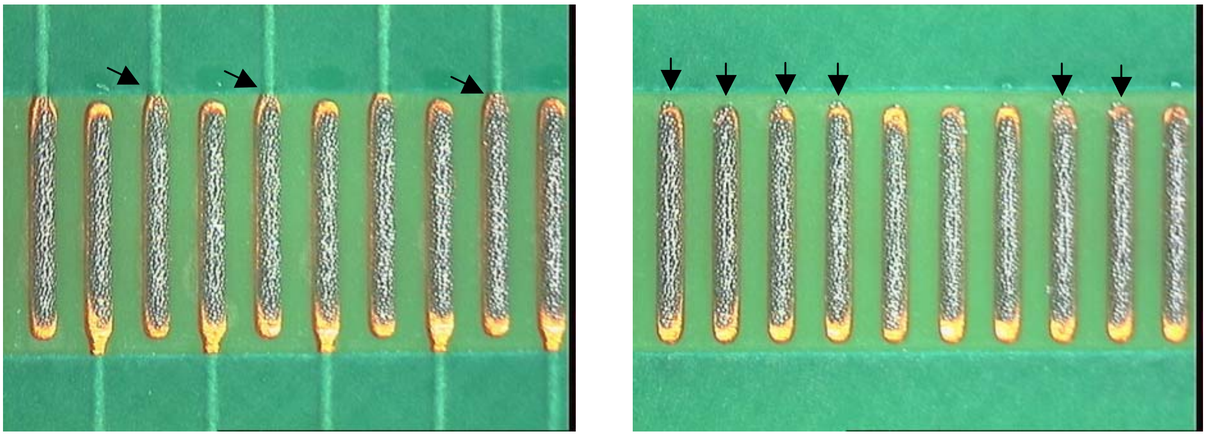
Figure 13: Diagram of printing on the board with solder resist at 400µm pitch

The results at looking at different surface finish, gloss and matt are shown in Figure 14. There was no significant difference for the prints with the different finishes, and from these results it is clear that the solder resist finish should not affect the printing performance.



Gloss 40µm

Gloss 40µm



Matt 40µm

Matt 40µm

Figure 14: Typical prints with 0.4 pitch on the boards with different finishes resist (print direction from bottom to top of image)

4. Conclusions

This work was carried out to investigate the effects of a number of factors (in particular solder composition, metal particle size, resist thickness) on the quality of fine pitch stencil paste printing. The salient findings were:

- The use of fine metal particles is the most effective way to improve the quality of fine pitch printing.
  - Type 2 pastes (i.e. those with the particle sizes > 50 µm) should not be used for fine pitch stencil printing, since it is difficult to achieve the desired 60% deposit particularly when using a fine (300 µm) stencil.
  - Type 5 pastes (i.e. those with particles in the 10-25 µm range) produce the best printing characteristics and achieve the desired high (70%) print volumes, even for fine pitch (300 µm) apertures
  - However, fine metal particles can result in a higher incidence of solder balling during reflow soldering.

- Fine pitch printing performance is not sensitive to the solder composition, and no specific issues are anticipated in fine pitch printing using lead-free solders. Adjusting the total metal content in the paste to compensate for density changes, results in acceptable quality for the fine pitch printing of the lead-free solder pastes. Printing with enclosed print heads was instrumental in achieving long stencil life under harsh environments.

- The effect of solder resist thickness on printing performance is not critical.

  - With good print alignment, the thickness of solder resist (even for 50 µm thickness) appears to have little effect on the quality of the print.

  - However, with some small misalignment, the quality of the print is degraded when using resists of thickness > 30 µm, and as the thickness is increased there is further deterioration. If good print alignment cannot be guaranteed, it is recommended to restrict the thickness of the resist to < 30 µm.

5. Acknowledgements

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