

**Influence of Stencil and
Aperture Design on Fine
Pitch Printing for Various
Solder Paste Types**

**M Wickham, L Zou, M Dusek
and C P Hunt**

September 2003

Influence of Stencil and Aperture Design on Fine Pitch Printing for Various Solder Paste Types

M Wickham, L Zou, M Dusek and C P Hunt
Materials Centre
National Physical Laboratory
Teddington, Middlesex TW11 0LW, UK

ABSTRACT

This work has explored the limits of printing at fine pitch for three solder pastes having different particle sizes. It has employed stencils manufactured via three different routes (laser cut; laser cut and electropolished; electroformed) and apertures of different geometries (circular; square; rectangular) and different dimensions. Paste release from the stencil walls becomes key with small apertures, and in this work the ratio of the aperture area to side wall area (the ARR) has been found to provide a good guide in predicting print performance. It can be widely applied.

The results highlight that from the point of view of print quality, the combination of thin stencils and type 6 solder paste will yield the best performance, but this needs to be taken in the context of other factors in the assembly process. Stencil characteristics that provide the best performance are electroformed with circular apertures. Practicable limits are suggested for combinations of paste type, aperture width and stencil thickness.

© Crown copyright 2003
Reproduced by permission of the Controller of HMSO

ISSN 1473 2734

National Physical Laboratory
Teddington, Middlesex, UK, TW11 0LW

Extracts from this report may be reproduced provided
that the source is acknowledged

Approved on behalf of Managing Director,
NPL, by Dr C Lea, Head, NPL Materials Centre

CONTENTS

1	INTRODUCTION.....	1
2	EXPERIMENTAL PROCEDURE	2
3	RESULTS	5
4	DISCUSSION	9
5	CONCLUSIONS	14
6	ACKNOWLEDGEMENTS.....	14

1 INTRODUCTION

As electronics interconnection technology develops increasingly complex devices and the number of corresponding I/Os increase, the pitch of the components has continued to be reduced to the point where 0.4mm pitch QFPs are not uncommon. Some respite from this relentless march was achieved with the introduction of BGAs but even now, pitches here have commonly been reduced to below 1mm pitch with CSPs down to 0.2mm pitch and below. As the pitch is reduced, the ratio of the aperture area to sidewall area causes a reduction in print performance and this is shown in Figure 1, and detailed in Table 1. As this ratio reduces, changes have to be made in stencil design, technology and paste formulation to ensure that adequate quantities of solder paste are delivered by the process to the assembly.

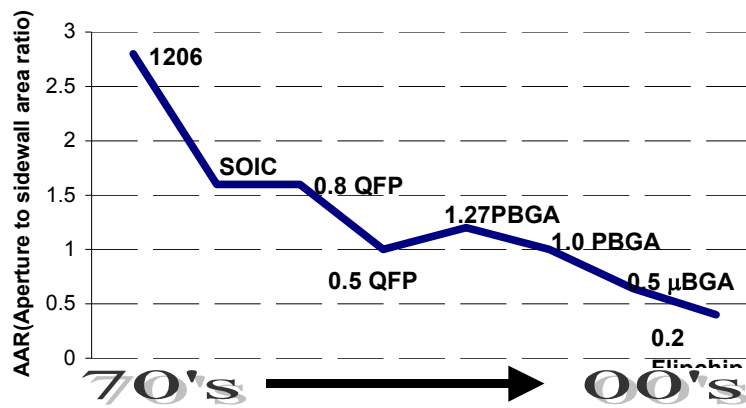


Figure 1 : Timeline for AAR (Aperture to side wall area ratio)

Table 1: Aperture area to sidewall area ratio (AAR) comparison for common SM components

Component type	Stencil thickness (mm)	Aperture size (mm)	Aperture area (mm ²)	Sidewall area (mm ²)	AAR
1206	0.15	1.8 x 1.6	2.88	1.02	2.8
1.27 SOIC	0.15	0.6 x 2.2	1.32	0.84	1.6
0.8 QFP	0.125	1.8 x 0.5	0.9	0.575	1.6
0.5 QFP	0.125	1.6 x 0.3	0.48	0.475	1
0.4 QFP	0.125	1.6 x 0.25	0.4	0.46	0.86
1.27 PBGA	0.125	0.6 dia	0.28	0.24	1.2
1.0 PBGA	0.125	0.5 dia	0.2	0.2	1
0.5 μBGA	0.100	0.25 dia	0.05	0.08	0.64
0.2 Flipchip	0.075	0.12 dia	0.011	0.028	0.4

This report covers an investigation undertaken by the Electronics Interconnection Group at the National Physical Laboratory into a comparison of paste types and stencil types for printing of solder pastes at pitches of 0.3mm and below.

2 EXPERIMENTAL PROCEDURE

The work was undertaken using a number of stencils manufactured to the design shown in Figure 2. the latter consisted of a range of apertures with different nominal widths. These were (from top to bottom) 150 μ m, 125 μ m, 100 μ m, 75 μ m and 50 μ m. The apertures were also varied with circular, square and rectangular shapes. The apertures used varied as follows (from left to right); 0201 (A), round (B), square (C, same area as B), round (D), square (E, same perimeter as D), rectangular (F, QFP type, apertures 1.6mm in length).

A	B	C	D	E	F	
						150
						125
						100
						75
						50

Figure 2 : Stencil design, with aperture designation and aperture hole size

A number of matching substrates (FR4) were also manufactured. These are illustrated in Figure 3. Because of problems in achieving the required pitches at low cost, the substrates were designed with a single large pad (3x2mm) for each set of apertures rather than an individual pad for each aperture.

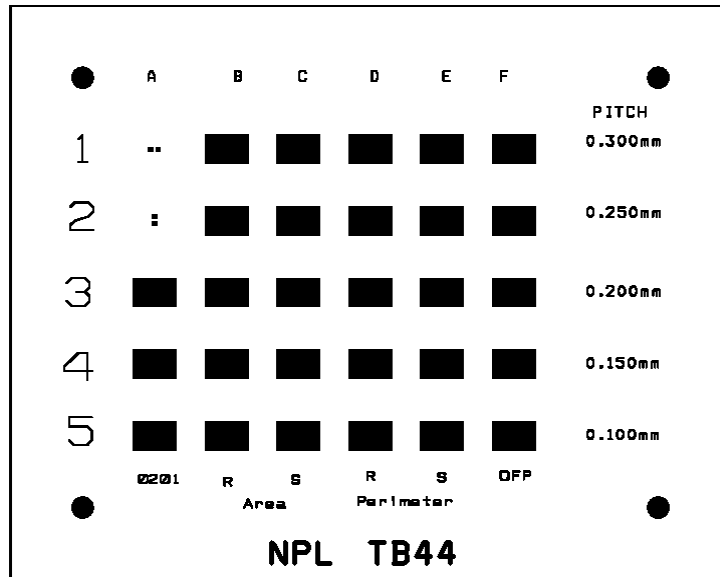


Figure 3 : Substrate design

The stencil was also designed to incorporate five images with differing aperture sizes that varied by set amounts of 5 and 10 μ m from the nominal, as shown in Figure 4. This was done to accommodate manufacturing tolerances between stencil suppliers, so that after the stencils were delivered, only the set of apertures closest to the required size were utilised. The centre image was the nominal size, left and right were sized -5 and 5μ m respectively, top and bottom -10 and 10μ m respectively. By changing the justification on the printer and rotating the stencil, any one of the five aperture arrangements could be used.

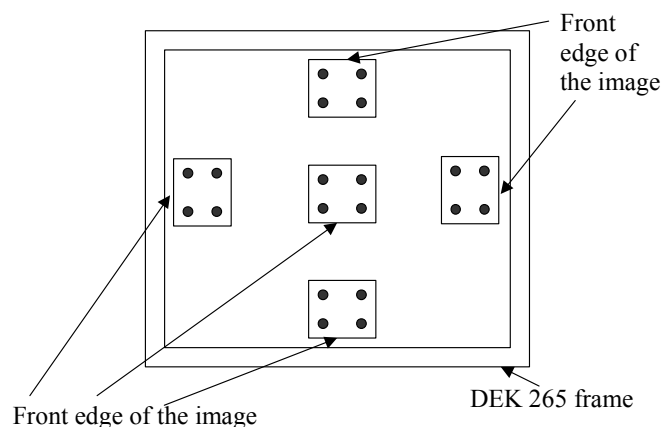


Figure 4: Stencil layout, showing alternate aperture array alignment

Three types of stencil were manufactured, in the following nominal thicknesses:

- Electroformed nickel – 75, 100 and 125 μ m
- Laser cut stainless steel - 75 μ m
- Laser cut stainless steel with an electro-polish - 75 μ m

Five types of solder pastes were tested during the project. These included one type 3, two type 4 and two type 5 pastes from several different suppliers. Several of the pastes were also available for enclosed print head printing.

The following print conditions were utilised with a DEK 265GS :

- Permaflex flexible metal squeegee blades with a print speed of 50mm/sec and a squeegee pressure of 3.0 kg.
- A Proflo enclosed print head was also used, again at 50mm/sec, with a system pressure of 8.0 kg and a paste pressure of 2 bar.

After printing, the substrates were inspected utilising either a laser scanning system or a binocular zoom microscope. Difficulties were encountered with a laser-based triangulation system, since the spot size of the laser was only marginal smaller than the solder particle size of the paste. For the finer solder particles the more curved surface presents difficulties for this type of detector, the comparable laser spot and particle size results in a wide range of scattered light from the surface. The detector is then unable to determine the surface height due to it receiving light simultaneously apparently from a wide range of heights. This measurement artefact of losing the surface leads to erroneous results. A further difficulty is encountered when the spot size of the probe laser beam is similar to that of the smaller particles, and hence detecting particles is a problem. These two factors conspire to provide weak reflected signals, and hence the technique fails. Finer spot systems with alternative focusing systems may provide more robust measurements. Because of these difficulties the quality of the prints were evaluated using manual inspection.

A single operator recorded microscope based measurements (x6 to x24 magnification). Based on wetted print area, the smallest print aperture of acceptable quality was determined and recorded. In a production environment if an aperture were printed with poor, or very poor, results, they would be considered unsuitable for further processing and would be scrapped. Examples of print quality are shown in Figure 5. In subsequent reporting of results here, printing performance was assigned a numerical value from 4 down to 1, 4 being good. Zero was also used when no paste was printed at all.

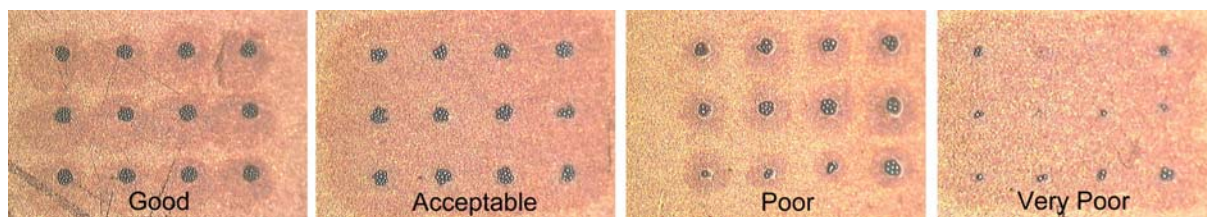


Figure 5: Examples of print quality, Good = 4, Acceptable = 3, Poor = 2, Very Poor = 1.

3 RESULTS

In discussing the following results it is useful to refer to AAR for the aperture arrays with varying stencil thickness; these numbers are calculated on the nominal values.

Table 2: Aperture area to sidewall area ratio (AAR) for experimental apertures

Stencil Thickness (μm)	Aperture Type	Aperture Opening (μm)				
		50	75	100	125	150
75	A	0.83	0.83	0.83	0.83	0.83
	B	0.19	0.28	0.38	0.47	0.56
	C	0.17	0.25	0.33	0.42	0.50
	D	0.21	0.32	0.42	0.53	0.64
	E	0.17	0.25	0.33	0.42	0.50
	F	0.32	0.48	0.63	0.77	0.91
100	A	0.63	0.63	0.63	0.63	0.63
	B	0.14	0.21	0.28	0.35	0.42
	C	0.13	0.19	0.25	0.31	0.38
	D	0.16	0.24	0.32	0.40	0.48
	E	0.13	0.19	0.25	0.31	0.38
	F	0.24	0.36	0.47	0.58	0.69
125	A	0.50	0.50	0.50	0.50	0.50
	B	0.11	0.17	0.23	0.28	0.34
	C	0.10	0.15	0.20	0.25	0.30
	D	0.13	0.19	0.25	0.32	0.38
	E	0.10	0.15	0.20	0.25	0.30
	F	0.19	0.29	0.38	0.46	0.55

The following Tables present a summary of the results from visual inspection of printing various pastes through the above stencils. The printing results are all with metal squeegee blades as detailed above, with the exception of those samples marked “/Proflow”, which were printed using an enclosed print head.

Key : F = rectangular aperture
 B = round aperture with same area as square aperture below
 C = square aperture with same area as round aperture above
 EF75 = electroformed nickel 75 μm stencil
 EF100 = electroformed nickel 100 μm stencil
 EF125 = electroformed nickel 125 μm stencil
 LC75 = laser cut 75μm stencil
 LCEP75 = laser cut electro-polished 75μm stencil

- Values in italics represent the smallest printed aperture of accepted quality
- Values followed by a * signify poor printing at this aperture size
- Values followed by a # signify very poor printing at this aperture size

Table 3: Tables of minimum printable aperture opening

Paste A / Type 5	Apertures		
Stencil	F	B	C
EF75	<i>75</i>	<i>75*</i>	<i>75#</i>
LC75	<i>100</i>	<i>100*</i>	<i>100*</i>
LCEP75	<i>75</i>	<i>100</i>	<i>100</i>
EF125	<i>100</i>	<i>125/100#</i>	<i>125/100#</i>
EF100	<i>75#</i>	<i>100*</i>	<i>100*</i>
EF75/Proflow	<i>75*</i>	<i>100*</i>	<i>100*</i>

Paste B / Type 3	Apertures		
Stencil	F	B	C
EF75	<i>100#/125*</i>	<i>125#</i>	<i>125#</i>
LC75	<i>100*</i>	<i>125#</i>	<i>125#</i>
LCEP75	<i>100#</i>	<i>125#</i>	<i>125#</i>

Paste C / Type 4	Apertures		
Stencil	F	B	C
EF75	<i>100</i>	<i>100*</i>	<i>100#</i>
LC75	<i>100</i>	<i>100#</i>	<i>100#</i>
LCEP75	<i>100</i>	<i>100#</i>	<i>125</i>
EF75/proflow	<i>100</i>	<i>125*</i>	<i>125*</i>

Paste D / Type 5	Apertures		
Stencil	F	B	C
EF75	<i>100</i>	<i>100</i>	<i>100*</i>
EF75/proflow	<i>100</i>	<i>100*</i>	<i>100*</i>

Paste F / Type 4	Apertures		
Stencil	F	B	C
EF75	<i>100</i>	<i>125*</i>	<i>125*</i>

These results are further shown graphically in Figure 6 for 75µm thick electroformed nickel stencils. The lower limit for aperture opening for a typical type 3 paste for this stencil type is

around 150 μm in diameter, although print quality at even this aperture size is poor. Using a typical type 4 paste can improve this to around 125 μm in diameter, but below this point, type 4 paste print quality can deteriorate rapidly. Moving to the finer type 5 paste will improve the ability to print apertures at 100 μm diameter, but below this point, print quality rapidly deteriorates.

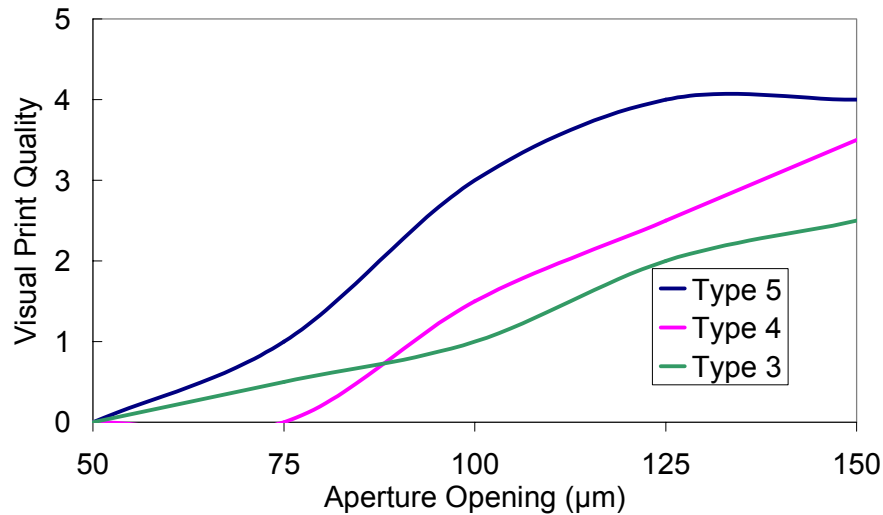


Figure 6: Comparison of past print quality for pastes of different particle sizes. Using a 75 μm thick stencil with circular apertures.

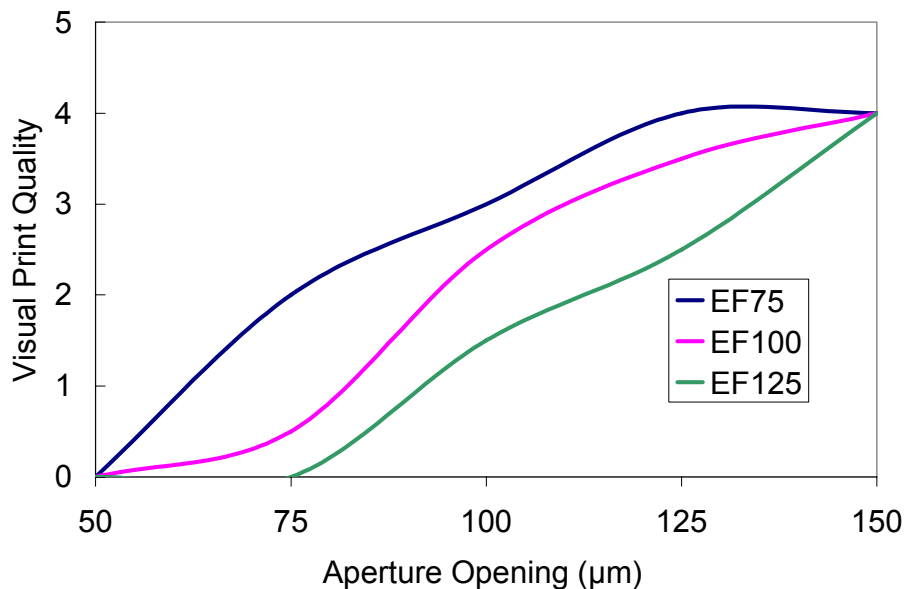


Figure 7: Comparison of print results with different thickness of electroformed stencils, using type 5 paste and B circular apertures.

Figure 7 shows a comparison of the print performances using stencils of different thicknesses. Using type 5 pastes all stencils showed acceptable results at 125 μm aperture openings but below this aperture size, the thinnest stencil significantly out performed the thicker stencils. At 75 μm aperture openings, the thicker stencils fail to print at all. The thinner stencil prints better because it has less wall area. In order for paste to release from the stencil, the adhesion of the paste must be greater to the board than to the wall of the stencil.

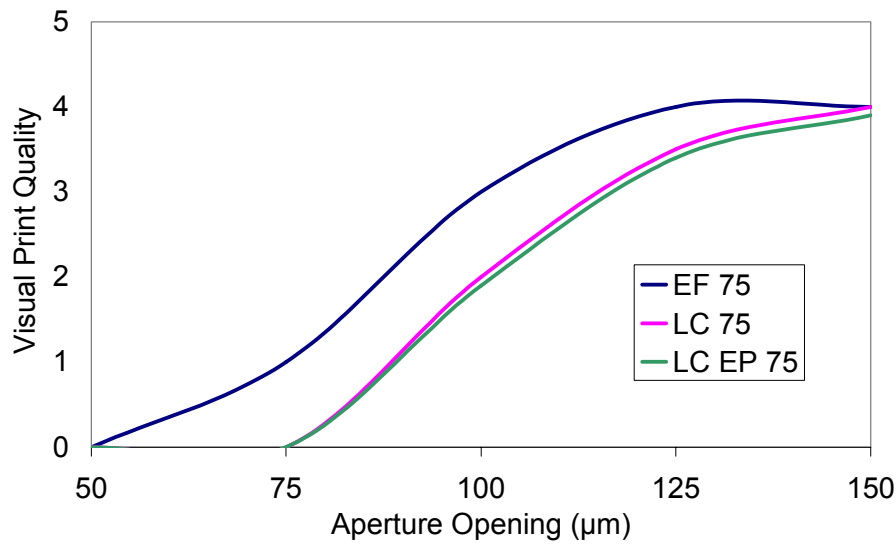


Figure 8: Comparison of different stencil finishes, using type 5 paste with 75 μm thick stencils and circular apertures

Figure 8 highlights the results for three different stencil types of the same thickness using type 5 paste (EF = electroformed nickel, LC = laser cut, LCEP = laser cut electro-polished). There are marginal differences between the three stencil types with electroformed nickel stencils slightly out performing the other two types.

4 DISCUSSION

The results in Table 3 appear to indicate that printing using rectangular apertures is more readily achievable than printing with square apertures. However, this is deceptive because of the relative shape and size of the apertures. With a rectangular aperture, only the extreme ends of the aperture are subjected to paste retention from three sides. The remainder of the aperture is only subjected to paste retention from two sides and therefore the stencil in these areas retains less paste. This is shown diagrammatically in Figure 9. With a square aperture, paste retention by the stencil affects the whole aperture. In practice, the printing at the ends of a rectangular aperture is of the same quality as the printing of a square aperture of similar size.

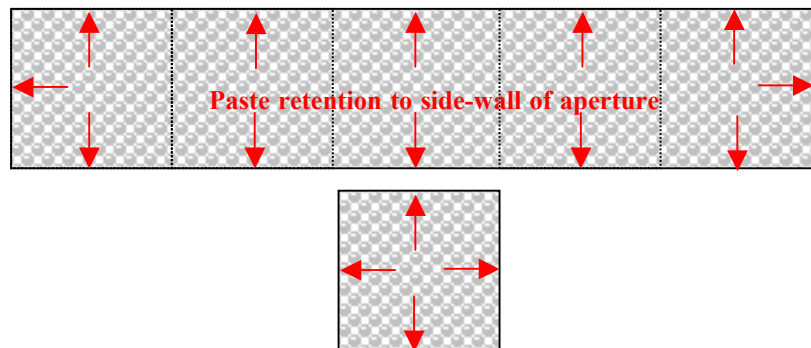


Figure 9 : Comparison of paste retention in rectangular and square apertures

Comparing the print quality using circular and square apertures in the results above, it can be seen that circular apertures marginally out perform square apertures of the same open area. The rectangular apertures print considerably better in the central region, where paste retention is only from two sides. The AAR values for these apertures are 0.48, 0.28 and 0.25 respectively for rectangular, circular and square apertures (F, B and C). Examples of these prints are shown in Figure 10.

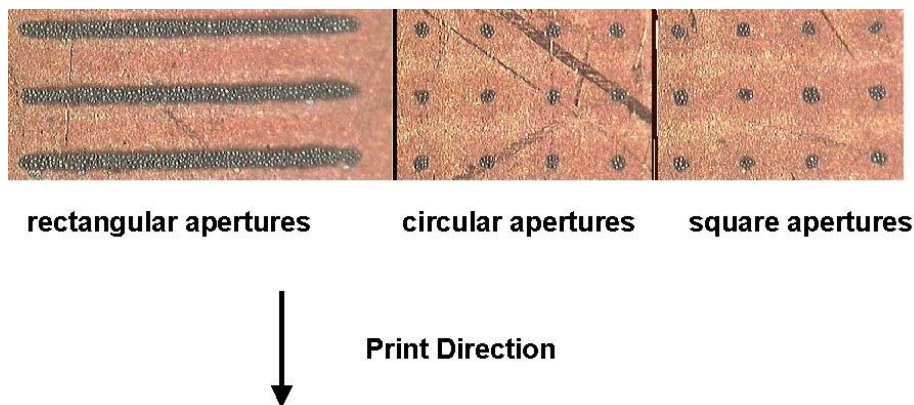


Figure 10: Comparison of printed type 5 paste through 75 µm wide apertures with a 75 µm thick electroformed stencil

One of the reasons why circular apertures may be better is that individual particles can only touch the wall of the aperture in a single place. With square apertures the corner particles can touch two walls simultaneously and these particles maybe more likely to be retained in the aperture after paste release. This is shown diagrammatically in Figure 11.

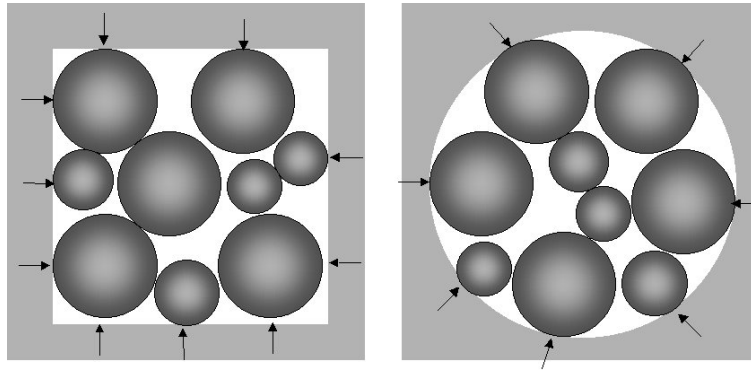


Figure 11: Comparison of particle edge touching in square and circular apertures (with touching particles marked)

Analysis of the results with respect to particle size clearly demonstrates that printing is improved using smaller particle sizes. Details of the IPC standard for solder particle distributions are given for reference in Table 4. Careful examination of Figure 12 clearly shows the better packing densities and printing performance achieved using the smaller particles.

Table 4 : IPC solder particle paste sizes

IPC Particle Type	Range in Particle Size (μm)	Mesh Size (threads per inch)
3	25 – 45	325 > < 500
4	20 – 38	400 > < 635
5	15 – 25	635 >

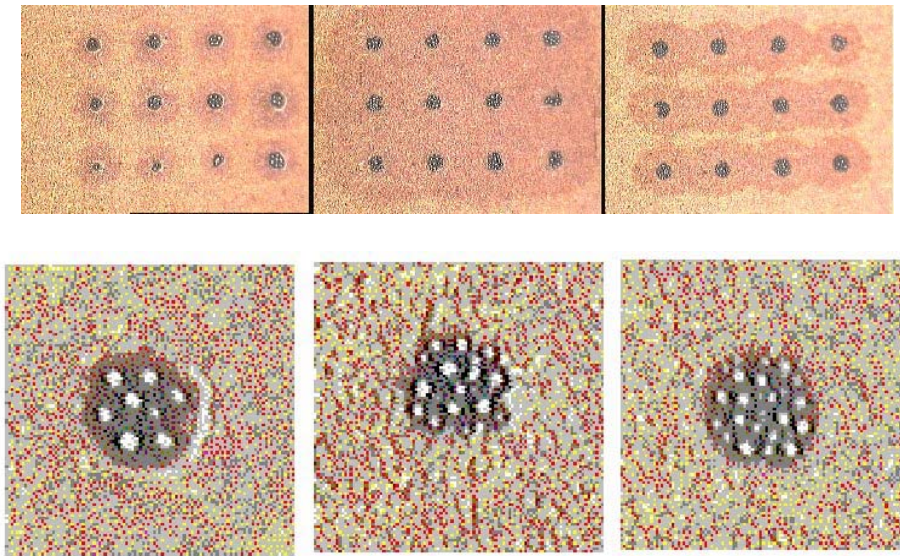


Figure 12: Examples of printing with different particle sizes, using 100µm circular apertures with a LCEP75 stencil

The above specific observations can be generalised by reviewing the results in terms of the AAR. In Figure 13 the results are presented for the three electroformed stencils with the Type 5 paste and the three aperture designs, B, C and F are shown.

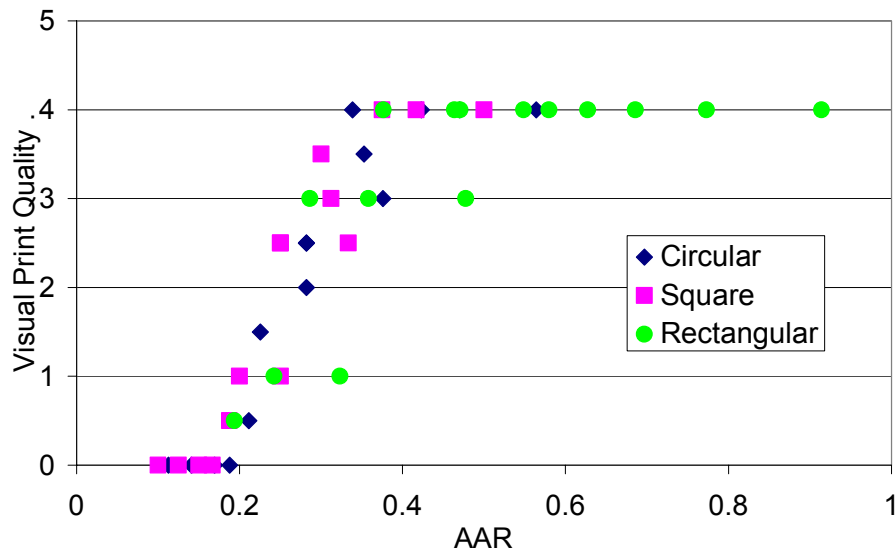


Figure 13: The AAR for electroformed (75, 100 and 125µm) stencils with Type 5 paste and three aperture designs (B, C and F)

Figure 13 results suggest there is little difference in print performance between different aperture designs in terms of AAR. This is a surprising result, since the AAR value apparently applies equally for all three aperture shapes. The significant difference in geometry between the rectangular and circular apertures of minimum opening is accommodated by the ratio, the difference being that the rectangular aperture width is at least $25\mu\text{m}$ smaller than the diameter of the circular aperture. Similar data for the type 4 paste, not plotted here, show similar behaviour between the apertures. In specific instances the behaviour described in Figure 11 may well be influential, but these results show this is only a marginal effect overall.

The AAR results averaged over the three aperture styles for the two paste types, 4 and 5, are plotted in Figure 14.

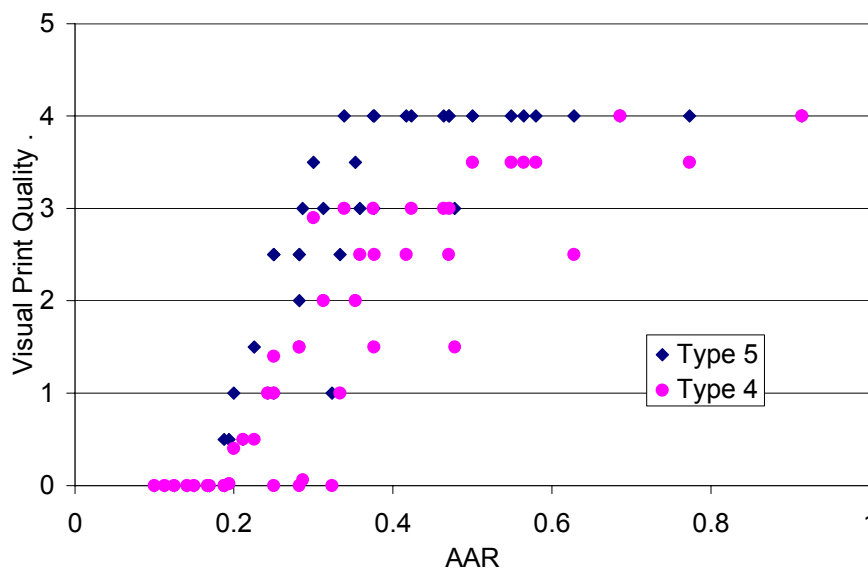


Figure 14: The AAR for electroformed (75, 100 and $125\mu\text{m}$ thick stencils and three aperture designs (B, C and F)) stencils with type 4 and 5 pastes

These results show that the AAR does differentiate between the performance of different paste types. The AAR should be above 0.5 and 0.8 for good printing for the type 5 and 4 respectively.

A final comparison between the stencil finish is shown in Figure 15, using the type 5 paste, and again with all three aperture designs (B, C and F). The results show minor differences between the lasercut and the lasercut and electro-polished stencils, with perhaps the lasercut performing slightly worse. The electroformed stencil outperformed the other two by about 0.1 AAR. Such a performance enhancement may be critical for ultra fine pitch printing with flip-chip style components.

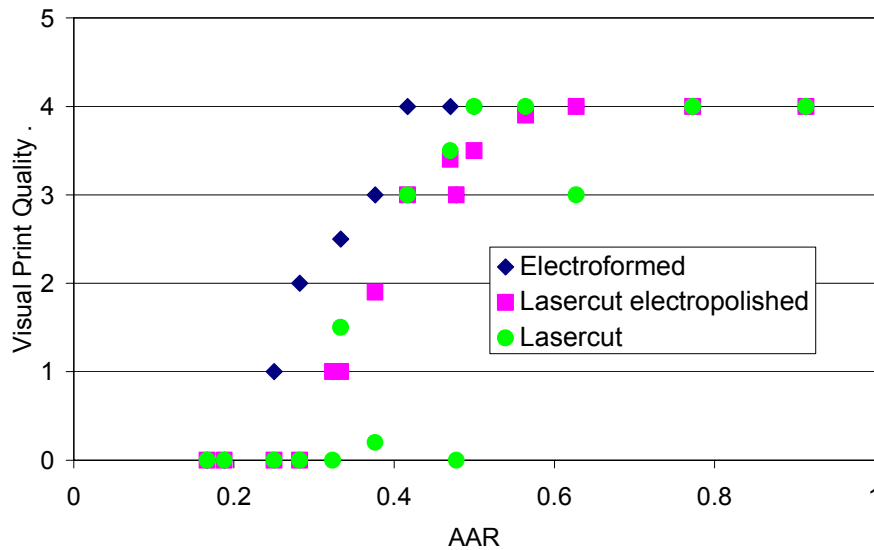


Figure 15: The AAR for 75 μ m electroformed, lasercut electro-polished and lasercut stencils. (Three aperture designs (B, C and F) and type 5 paste)

It should be noted that print quality is not the only parameter that should be considered when deciding on the paste particle size. Whilst smaller particles may improve print quality, their reflow performance is also important. Smaller particles have a greater surface area per unit volume than their larger equivalents and are therefore prone to having a higher oxide content. This may lead to higher levels of solder balling and may restrict the usable lifetimes of these pastes. With the average particle size and therefore particle mass being smaller, reflow profiling is also more critical. If any solvents remain in the paste after preheating, these can evolve rapidly into gas during the reflow portion of the soldering profile. This may also lead to solder balling as solder particles can be ejected from the joint during this gaseous evolution. Smaller particles, being lighter, are more likely to be ejected than larger particles, thus again leading to an increased propensity to solder balling in finer particle pastes. Indeed, some paste manufacturers do not have any plans to produce commercially type 5 pastes for surface mount assembly, as they consider them insufficiently robust for these applications.

5 CONCLUSIONS

To improve the quality of ultra fine printing ($\leq 150\mu\text{m}$ pitch), the following aspects need to be carefully considered :

- Thinner stencils achieve better paste release
 - $75\mu\text{m}$ is a practicable minimum stencil thickness
 - Thinner stencils can be sourced but will be more prone to damage during use
 - Thinner stencils may not provide sufficient paste volume for larger pitch components
- Minimum aperture openings are dictated by stencil thickness and manufacturing technology, aperture openings of diameters or widths smaller than stencil thickness are not recommended for any stencil technology
- For apertures at and below $100\mu\text{m}$ width, electroformed stencils perform slightly better than electro-polished laser cut or laser cut stencils
- Circular apertures can achieve slightly better paste release than square apertures of the same open area
- Pastes with finer particle sizes achieve better packing densities for small aperture openings but may be prone to greater solder balling

Practicable limits for ultra fine pitch printing should be considered as the following (finer printing may be possible with individual combinations of paste, stencil, aperture design) :

Type 5 pastes	100 μm wide apertures in 75 μm stencils 125 μm wide apertures in 100 μm stencils 125 μm wide apertures in 125 μm stencils
Type 4	125 μm wide apertures in 75 μm stencils
Type 3	150 μm wide apertures in 75 μm stencils

A concept of AAR (aperture area to sidewall area ratio) is introduced. For types 5 and 4 solder pastes and for electroformed stencils it has been shown necessary to have a value of 0.5 and 0.8 respectively, irrespective of aperture shape: circular, square or rectangular. It is suggested that this ratio can be widely applied with AAR values tabulated for a combination of stencil and solder paste types.

6 ACKNOWLEDGEMENTS

The authors are grateful for the support of the DTI as part of their Measurement for the Processability of Materials (MPI) programme, and of DEK Printing Machines, Kester, ESL, Indium and Loctite-Multicore Solders for their support regarding machines and materials.