As originally published in the IPC APEX EXPO Proceedings.

A Revolutionary Printing Solution for Heterogeneous Surface Mount Assembly

Clive Ashmore, Mark Whitmore
DEK Printing Machines Ltd
11 Albany Road
Weymouth
Dorset, UK

Abstract

As consumers the expectation of increased functionality within new products is a given. However there comes a time where this tireless demand for product efficiency starts to stretch the design for manufacture (DFM) rules. Fabricating products with decreasing feature size and increasing complexity is not the issue nor is producing products that have larger components; the dilemma is when products require both.

This predicament is now upon the Surface Mount Assembly (SMA) community, the imminent role out of 0.3mm CSP looks to be pushing the feature size below 200 micron but still RF shields and connectors are required - or put another way heterogeneous assembly is looming upon us.

The main issue surrounding the stencil printing process when dealing with heterogeneous assembly is area ratio (the ratio between stencil aperture open area and aperture wall area). When complying to traditional design rules and maintaining area ratios greater than 0.66 then it becomes near impossible to design a print process for a wide mix of fine and large pitch components.

Whilst developments in solder pastes and stencil manufacturing techniques in recent years have allowed skilled operators to push the area ratio rule of thumb to 0.5-0.6 to accommodate 0.4CSP assembly, the next generation of component technology (0.3CSP's) is one step beyond this capability.

To address this, new techniques have been investigated with the aim of increasing solder paste transfer efficiency in the screen printing process. Of several techniques investigated one has stood out and has been the subject of intense laboratory trials. The results of this investigation have shown that existing area ratio rules can be seriously challenged and broken to permit 0.3mm pitch CSP assembly within a traditional SMT process. Details of these new developments together with substantive paste transfer efficiency data will be presented.

Introduction

Within this paper the revolutionary printing solution (Squeegee) that has been introduced in previous work [1] will be further explored. The aim of this paper is to test this system with several of the premium brand solder pastes used within the SMA global community.

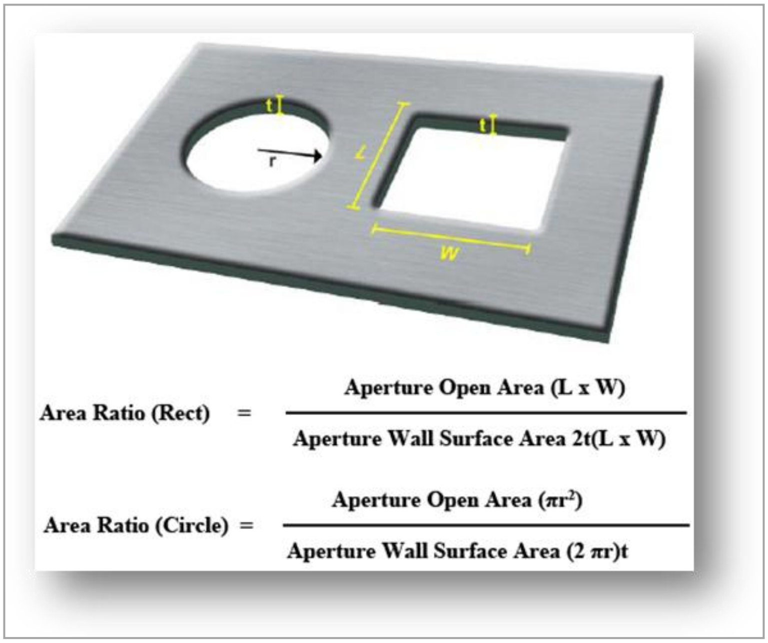
The results from this paper will allow the reader to observe if an activated squeegee has the capability to perform with different materials; thus allowing the Engineer to better understand the robustness and capabilities of this squeegee technology and help answer the question will it work for me?

The stencil design rules

So what stops manufacturing Engineers from producing heterogeneous products? To answer this question the IPC standard - 7525[2] needs to be investigated.

The IPC specification introduces the concept of **Area Ratio** and **Transfer Efficiency**; the following sections will consider these elements and their impact to heterogeneous assembly.

Area Ratio – As illustrated in Fig1, the area ratio calculation in its simplest form is a ratio between the Aperture opening area and Aperture wall surface; therefore the factors that make up an aperture, stencil thickness, aperture diameter, width and length all influence the resultant Area Ratio. If we take two examples we can observe the effects; a stencil of 100 microns and a circular aperture of 240micron would result in an area ratio of 0.6 by changing the diameter to 200 the Area ratio would now be calculated as a value of 0.5. Needless to say the act of calculating Area Ratio simply allows the Engineer to quickly register an apertures dimension and produce an integer. The significance of this value is explained in the next section.



$$\text{Area Ratio (Rect)} = \frac{\text{Aperture Open Area (L x W)}}{\text{Aperture Wall Surface Area 2t(L x W)}}$$

$$\text{Area Ratio (Circle)} = \frac{\text{Aperture Open Area } (\pi r^2)}{\text{Aperture Wall Surface Area } (2\,\pi r)t}$$

Fig 1 – Area Ratio

Transfer Efficiency – This section looks at how the aperture dimensions (Area Ratio) affects the apertures ability to transfer the material from inside the aperture onto the substrate.

In a perfect world no matter the size of an aperture and therefore its Area Ratio, all of the material deposited into the aperture would be released into a perfect "brick" of solder paste. In reality there are complex forces of adhesion and cohesion at work, thus resulting in varying degrees of transfer efficiency.

To understand how this happens we need to revisit the Area Ratio calculation, we know that the Area Ratio value is made up of an aperture open area divided by aperture wall surface area (Fig2).

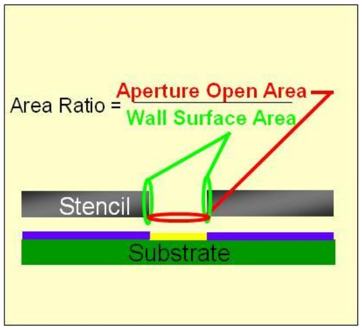


Fig 2 – Area Ratio a graphical representation

As can be seen in Fig 2, once an aperture has been filled with solder paste the material has two interfaces in which to bond; these being the Wall surface Area and the Pad Surface. It is these two interfaces that influence the resultant deposit.

Fig 3 illustrates the “release” effect of aperture size; the “Large Component” represents an example in which the Aperture Open Area is greater than the Wall Surface Area; in this case the adhesion is greater on the pad than the aperture walls therefore during the lateral movement of separation almost all of the material contained within the aperture will be transferred.

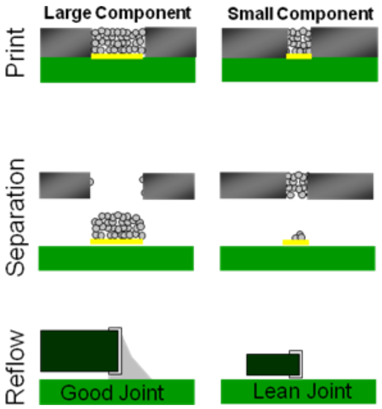


Figure 3 – Illustration of Transfer Efficiency

The “Small Component” shows the effect of having a greater Wall Surface Area than Aperture Open Area; in this case there is more material adhesion to the aperture wall than the pad, thus resulting in the majority of material staying within the aperture.

Therefore the efficiency of material released (transfer efficiency) from an aperture is interdependent on the Area Ratio, the relationship between Area Ratio and Transfer Efficiency is shown in Fig 4. It can be seen from Fig 4 that this correlation between Area Ratio and Transfer Efficiency is not constant; as the Area Ratio decreases so does the Transfer Efficiency, this correlation keeps a linear relationship until a “break point” after this point the relationship collapses. It is this point that is of interest to a process engineer as this breakpoint represents the minimum Area Ratio in which acceptable levels of Transfer Efficiency (70%-75%) can be achieved.

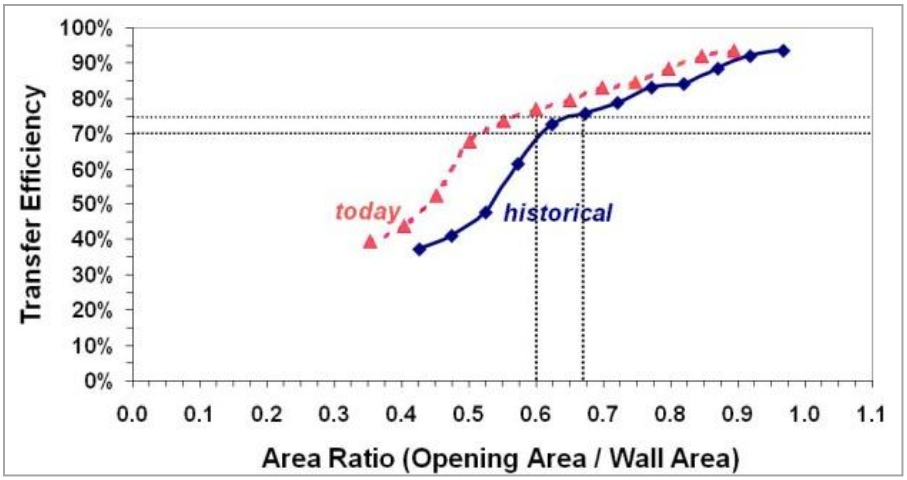


Figure 4 – Graph showing Area Ratio against Transfer Efficiency

Dilemma

As the miniaturization program rolls through the SMA community the aperture geometries will become smaller; this on its own it not a major issue, there are materials today that can cope with ultra fine pitch printing; Semicon processes use Type 7 solder paste alongside sub 50 micron thick metal masks . The dilemma quickly approaching the SMA community is the requirement of ultra fine pitch devices (0.3mm CSP) to be assembled alongside large form factor devices (RF shields, Tantalum capacitors).

So what stops this from just happening? If we cast our minds back to the Area Ratio and Transfer Efficiency discussion we can appreciate that reducing the aperture size to accommodate the 0.3mm CSP has the consequence of reducing the Area Ratio which in turn reduces the Transfer Efficiency, thus the smaller apertures will not produce a full print. A simple answer to this dilemma would be to reduce the metal mask thickness as this would reduce the Area Ratio for the smaller aperture but a thinner stencil would be incapable of delivering the required solder volume to the larger devices. A number of studies[3-5] have indicated that locally stepping the stencil thickness in the fine pitch areas (Stepped Stencil) is a potential solution but the challenges on implementing stepped stencils into mainstream makes this a “messy” process to apply. Other methods of increasing Transfer Efficiency have been focused on stencil material and fabrication methods[6-8]

Solution

The solution to this dilemma is to take a fresh look at the mechanics of the printing process; the filling of the aperture is vital to the print process, if you don’t fill the aperture then the print deposit is never going to be volumetrically correct. However the filling process also influences the aperture release characteristics; as we have outlined above in the Transfer Efficiency section, the bond force of the material to the pad (land) significantly affects the overall release process. As a result if the filling process fails to pack the material into the aperture such that the material does not make a chemical bond then poor release will result.

So how do we improve the materials ability to pack into small apertures? The answer to this question can be found in the material properties that are currently been used in SMA production. The solder paste materials have a pseudoplastic[9] characteristic, one that allows the material to change its viscosity depending upon the sheer rate. Therefore if the shear energy imparted into the material can be increased, the material will becomes less viscous and its ability to flow into small apertures is increased, thus the packing of the material in challenging Area Ratio apertures is improved. As a result the aperture is not only filled with the desired volume of material but the chemical bond onto the pad is also made such that during the release process the bond force will overcome the wall surface bond tension therefore allowing the material to be released more efficiently.

The traditional method of increasing the aperture fill for challenging Area Ratio has been to increase the squeegee (attack) angle, typically moving from 60 deg to a 45 deg angle but as highlighted in previous work[10-12] this increase in attack angle is not free from pitfalls; therefore a different method of improving aperture fill needs to be discovered one in which the improved filling of apertures can fit alongside the day to day process engineers requirements.

The remainder of this paper will look at our new squeegee technology Squeegee that aims to give an answer to the dilemma outlined above in Fig 3 and 4.

This Squeegee squeege uses proprietary technology to energize the print medium such that it locally modifies the rheology of the solder paste in order to increase fluidity; this action improves the packing density of particles into apertures, enhances the cohesive bond between solder paste particles and allows material to freely drop from the squeegee blades, leading to paste management benefits, Fig 5 shows the units attached to an automatic printer.

Fig 5 – Activated Squeegees

Materials and toolsets

The print platform used was a DEK Galaxy; the equipment was fully calibrated to ensure the performance matched the manufactures specifications. A set of 170mm, 60 degree, 15mm overhang Squeegee squeegees were utilize. To reduce external variation within the experiment the pressure mechanism of the squeegees were calibrated before each run.

The stencil technology employed was laser cut Stainless steel (grade 330) with a metal thickness of 100 microns, this technology and material were chosen for its everyday approach, the authors' desire was to ensure the stencil technology replicated the majority of process running within SMA facilities.

To ensure the affects of the Squeegeesqueegees were isolated from external noise, the substrates were fabricated from anodized aluminum 1.4mm gauge plate; these boards were numbered and run in sequence for each run. The substrates were supported with a custom vacuum plate and an over top snug (O.T.S) rail system used for transportation.

To ensure the print deposits were measured in a timely manner a Cyberoptics SE300 utilizing the micro-pad sensor was employed.

Table 1 outlines a summary of all the materials used throughout the experiment.

Table 1 – Materials

Stencil material	Stainless Steel (Grade 330)
Stencil thickness	100 microns
Stencil fabrication method	YAG
Solder pastes	A,B and C (refer to Table 2)
Solder particle range	IPC classified Type 4
Metal loading	89.9%
Tooling	Custom Vacuum
Squeegee length	170mm
Squeegee overhang	15mm

Solder Paste

The materials used throughout this investigation were chosen to encompass suppliers from the three major manufacturing economies. All materials were specified as type 4, Pb free, no clean and current production offerings; Table 2 shows the nomenclature used throughout the paper and associated region.

Table 2 – Solder Paste

Material identifier	Region
A	Asia
B	Americas
C	Europe

Stencil

The stencil design used for this experiment is shown in figure 6, it can be seen that the design includes many standard SMA devices but for the purpose of this investigation the 4 reducing Area Ratio arrays and 0.3mm CSP will be used to create analysis for the purpose of comparing the 3 materials with and without Squeegee the new squeegee technology. Figure7a shows the Area Ratio Arrays in more detail. It can be seen that the design has aperture openings ranging from 550 - 100 microns resulting with Area Ratios ranging from 1.375 - 0.25, it is felt that this design will give adequate resolution. Figure 7b illustrates the design for the 0.3mm CSP, the aperture diameter is 160 micron; giving an Area Ratio of 0.4.

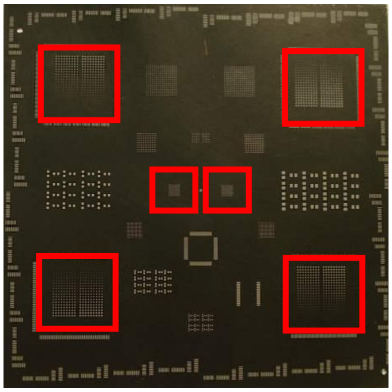


Figure 6 - Test print design showing area ratio arrays and 0.3mm CSP.

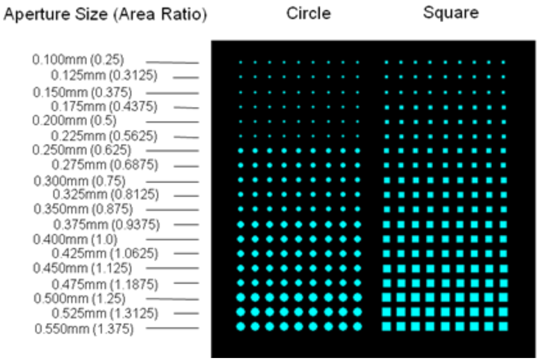


Figure 7a- Area ratio arrays with figures (calculated for 100 micron stencil thickness).

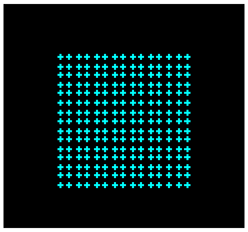


Figure 7b - 0.3mm CSP design calculated for 100 micron stencil thickness.

Experimental Procedure

In order to perform a comparison between 3 materials and the effect of Squeegee squeege, six experiments were conducted. Each run consisted of 14 uninterrupted prints; the print parameters used during the experiment are shown in Table 3. To ensure the results were not skewed by noise the first four prints were discarded thus allowing the process to stabilize, also to further reduce noise, stencil cleaning was not performed during the 14 print run; the subsequent 10 prints were measured and data collected.

Table 3 - Parameters

Parameter	Value
Print speed	50mm/s
Print Pressure	4 Kg
Separation Speed	3mm/s
Separation Distance	3mm
Temperature	22.3
Relative Humidity	48%

Results and discussion

Due to space constraints within this paper the results from this experiment will be shown in terms of transfer efficiency for the round apertures only; the transfer efficiency curves will be shown for each material with/without Squeegee the new technology, regions of the curves that show significant findings will be enlarged in order to aid the reader.

Each data point represents the mean of all the collected records over the 10 inspected substrates for each given aperture size. To aid in comparing the results, the graphs will be split into the 3 materials, with the Squeegee squeegee technology on/off results superimposed onto the same graph.

To complete the analysis the Transfer Efficiency process capability (Cp) was also calculated, 1.33 was used as the target based on nominal aperture volumes with a tolerance of +/- 40%.

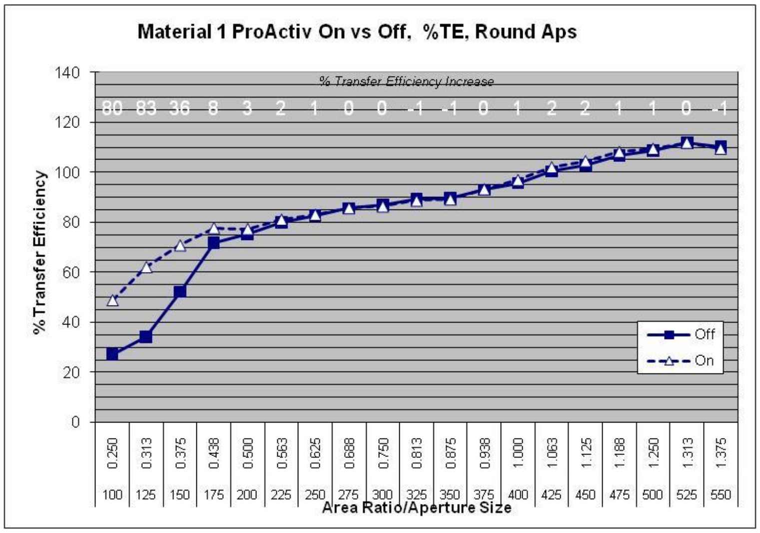


Figure 8 - Material 1 Transfer Efficiency (All)

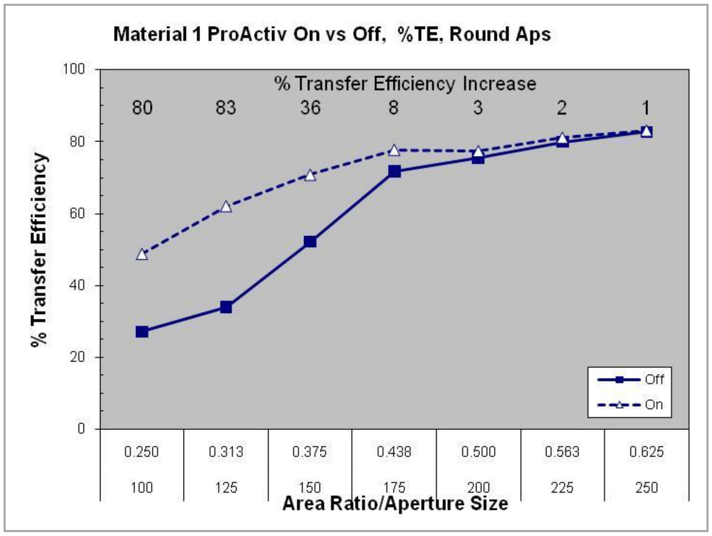


Figure 9 - Material 1 Transfer Efficiency (100-250 microns)

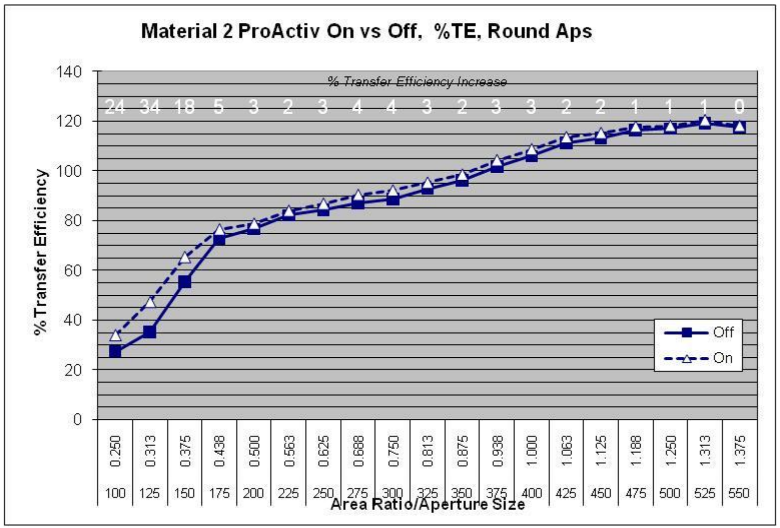


Figure 10 - Material 2 Transfer Efficiency (All)

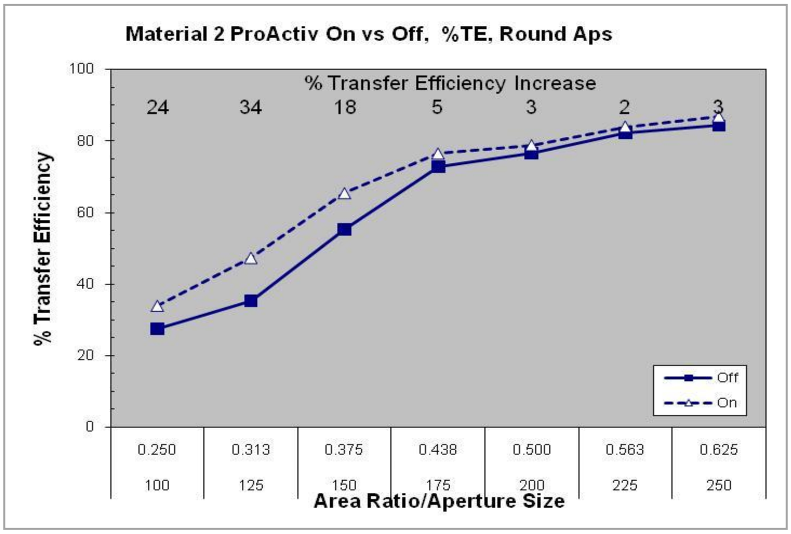


Figure 11 - Material 2 Transfer Efficiency (100-250 microns)

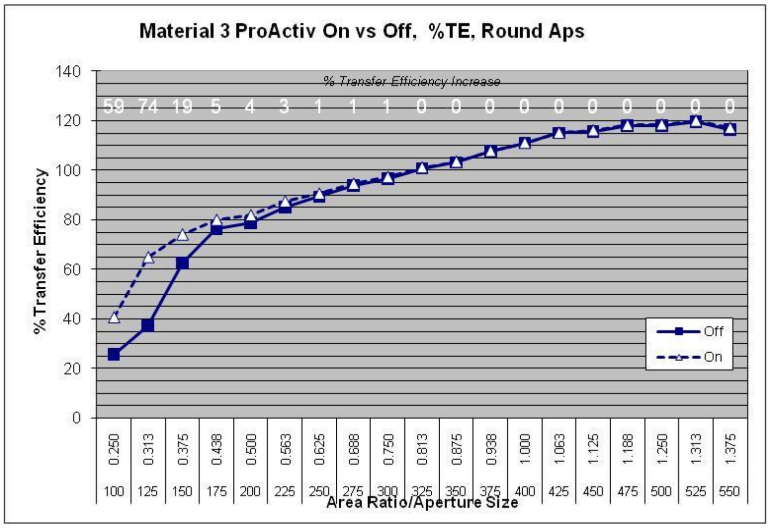


Figure 12 - Material 3 Transfer Efficiency (All)

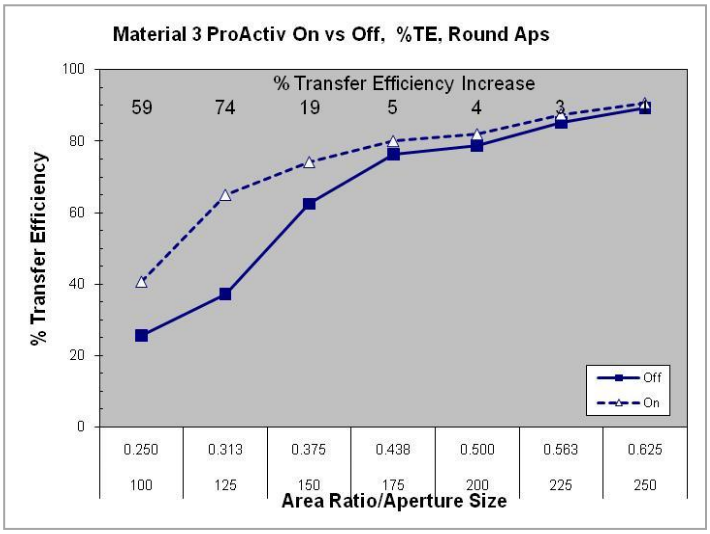
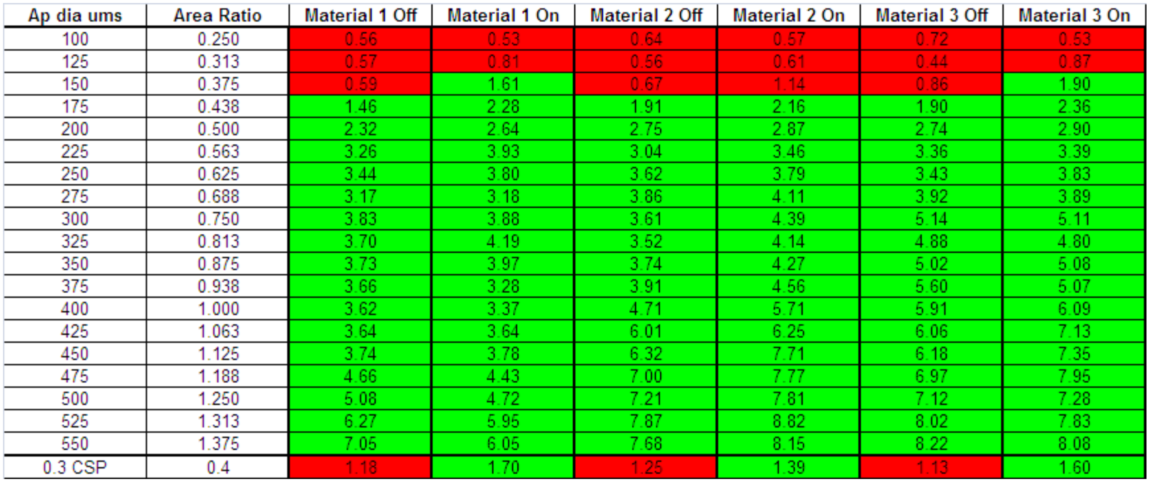


Figure 13 - Material 3 Transfer Efficiency (100-250 microns)



Ap dia ums	Area Ratio	Material 1 Off	Material 1 On	Material 2 Off	Material 2 On	Material 3 Off	Material 3 On
100	0.250	0.56	0.53	0.64	0.57	0.72	0.53
125	0.313	0.57	0.81	0.56	0.61	0.44	0.87
150	0.375	0.59	1.61	0.67	1.14	0.86	1.90
175	0.438	1.46	2.28	1.91	2.16	1.90	2.36
200	0.500	2.32	2.64	2.75	2.87	2.74	2.90
225	0.563	3.26	3.93	3.04	3.46	3.36	3.39
250	0.625	3.44	3.80	3.62	3.79	3.43	3.83
275	0.688	3.17	3.18	3.86	4.11	3.92	3.89
300	0.750	3.83	3.88	3.61	4.39	5.14	5.11
325	0.813	3.70	4.19	3.52	4.14	4.88	4.80
350	0.875	3.73	3.97	3.74	4.27	5.02	5.08
375	0.938	3.66	3.28	3.91	4.56	5.60	5.07
400	1.000	3.62	3.37	4.71	5.71	5.91	6.09
425	1.063	3.64	3.64	6.01	6.25	6.06	7.13
450	1.125	3.74	3.78	6.32	7.71	6.18	7.35
475	1.188	4.66	4.43	7.00	7.77	6.97	7.95
500	1.250	5.08	4.72	7.21	7.81	7.12	7.28
525	1.313	6.27	5.95	7.87	8.82	8.02	7.83
550	1.375	7.05	6.05	7.68	8.15	8.22	8.08
0.3 CSP	0.4	1.18	1.70	1.25	1.39	1.13	1.60

Figure 14 – Process Capabilities

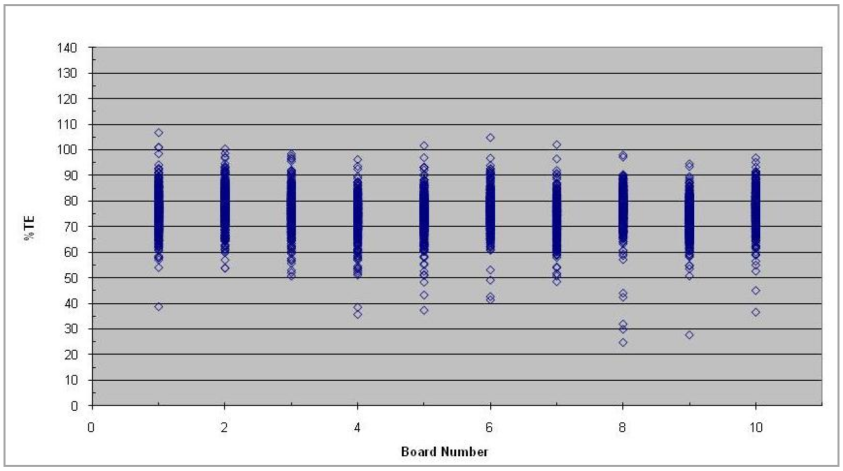


Figure 15 – 0.3mm CSP Material 1 Squeegee Squeegee off

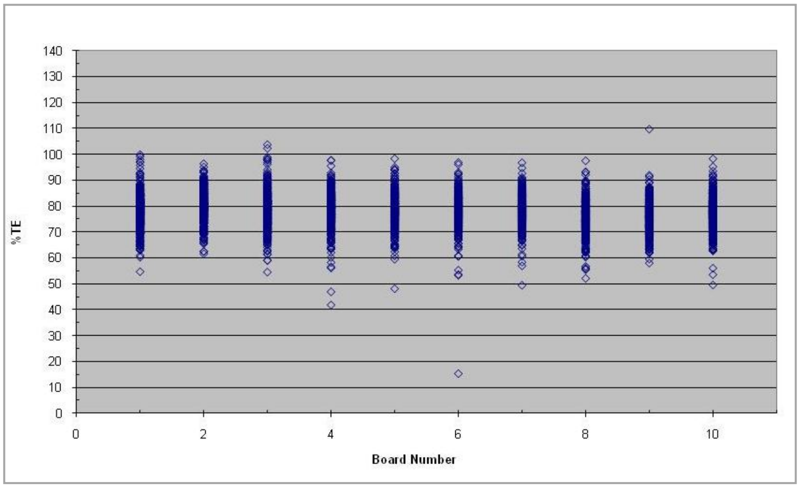


Figure 16 – 0.3mm CSP Material 1 SqueegeeSqueegee on

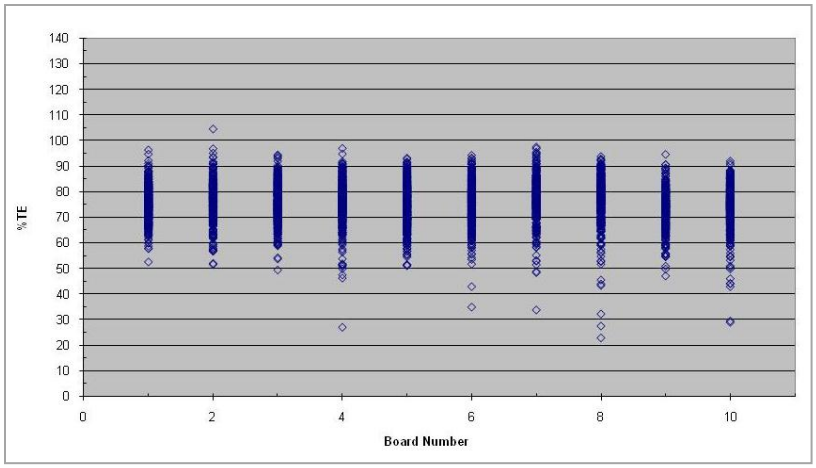


Figure 17 – 0.3mm CSP Material 2 SqueegeeSqueegee off

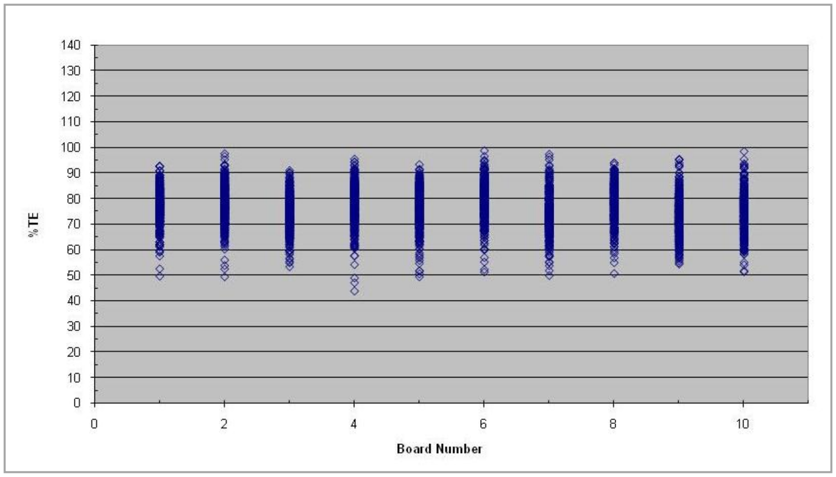


Figure 18 – 0.3mm CSP Material 2 SqueegeeSqueegee on

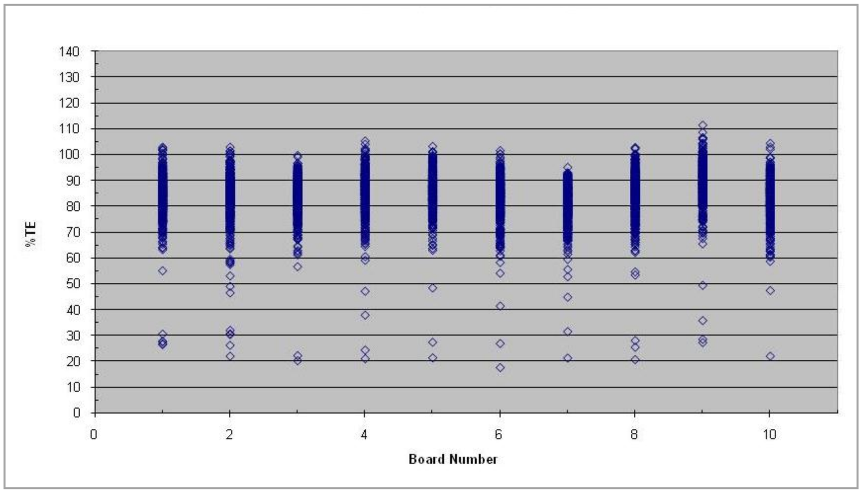


Figure 19 – 0.3mm CSP Material 2 SqueegeeSqueegee off

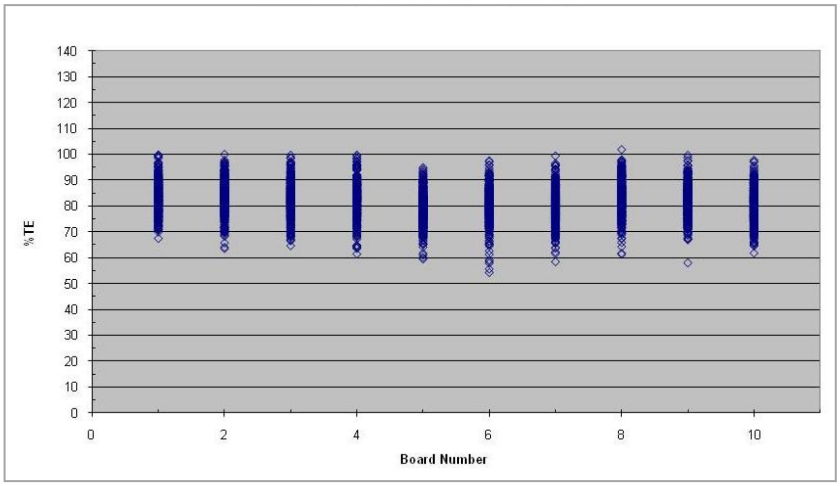


Figure 20 – 0.3mm CSP Material 2 SqueegeeSqueegee on

The results from the six runs are illustrated above; the findings for the three materials will be analyzed as follows – Transfer Efficiency, Process Capability and 0.3mm CSP device.

Transfer Efficiency Analysis and Discussion

Figures 8 to 13 show the effects of both the Squeegeesqueegee and Material, as an opening statement we can see that the effect of Squeegeesqueegee is transparent until the aperture design drops below an Area Ratio of 0.5. This effect is a useful characteristic as process engineers do not want process designs/rules to be unduly affected.

Once the Area Ratio drops below 0.5 we can see that with Squeegeesqueegee enabled, the transfer efficiency curve is “extended”, this indicates that the action of Squeegeesqueegee is increasing the transferred volume and is therefore having a positive effect on the printing of small Area Ratio apertures.

Figure 8 illustrates the extension for Material 1; in this the 100 micron diameter apertures experienced 80%, whereas the 200 micron only experienced 3% difference, this indicates that the Squeegeesqueegee effect is only present in smaller apertures. Analyzing the remaining materials (figure 10 - 13) through the transfer efficiency “lens” we can see that although the improvement in process ability is present, material 2 shows less of a reaction than material 1 and 3; this indicates that material characteristics are still important in the overall print process or another way of viewing this result is to say that Squeegeesqueegee will not standardize the results for any material.

Process Capabilities Analysis and Discussion

But of course viewing the data only as average data points is too “abstract”; to build up the analytical picture of the process with/without Squeegee we need to analyze the results with respect to nominal’s and tolerances. Figure 14 illustrates the process capability (Cp) results, from this data we can see several relationships emerge.

The first of these observations is the overall improvement to the Cp numbers when the squeegee is enabled, this improvement starts from apertures that are greater than 350 microns (Area Ratio 0.875), this finding indicates that the squeegee is not altering the average volume of paste deposited (due to the transfer efficiency curves mirroring each other) but the spread of data is becoming tighter and therefore more repeatable.

Furthermore Figure 14 clearly shows the effect that the squeegee has on the more challenging aperture design; it can be seen that for material 1 and 3 the ability to print 150 micron apertures is only achievable with the aid of the squeegee where as material 2 shows that its physical properties limits its capability to 175 micron aperture (Area Ratio 0.438).

Figure 14 also indentifies the Cp values for the 0.3mm CSP, this device breaks away from the previous data sets as this device represents a “real life” application where as the Area Ratio Array represents an analogue in which to test against. The 0.3mm CSP apertures are 160 micron with an associated Area Ratio of 0.4; this represents the Heterogeneous dilemma discussed at the beginning of this paper – Ultra small apertures printed with standard thickness stencils.

The results show an interesting and favorable result for the process engineer, as illustrated within Figure 14, all 3 material shows that the 0.3mm CSP device is only capable with the inclusion of the squeegee; this indicates that the additional activation within the solder paste is improving the ability to print ultra fine apertures. As a further observation, the results also shows that the analogue is accurate and linear by the fact that material 2 has been identified as less capable printing the 0.3mm CSP than materials 1 and 3, this was predicted by the analogue.

0.3mm CSP Analysis and Discussion

The final part of this analysis will isolate the 0.3mm CSP data. Figure 15 to 20 presents the data in a scatter plot format; this allows the structure of the data set to be viewed sequentially and outliers identified for each material. The importance of outliers within a printing process is significant as this illustrates the number of boards containing a manufacturing defect, otherwise known economically as lost profit.

The influence of the squeegee can be clearly seen when observed in the scatter plot view, without the squeegee the occurrence of boards with 1 or more outliers is between 5 and 10 (0 to 50% yield) depending on material type. The occurrence of outliers is eradicated with the inclusion of the squeegee; this is a significant finding within the report and should be seen as evidence that Area Ratios of 0.4 have been successfully printed alongside standard aperture geometries. Another way of viewing this observation is to state that Heterogeneous assembly has been successfully conducted within this experiment.

Conclusions and thoughts

At the beginning of this paper we discussed the ongoing battle between miniaturization and the constraints that are present within today's manufacturing processes. We know that there are ways around these constraints but they are a half way houses at best, in fact they can lead to increased costs, decreased throughput and lower yields ; but because the miniaturization program is not waiting nor slowing these deficient solutions are been seriously considered.

The activation of solder paste through an energized squeegee assembly has been tested with 3 materials within this paper and although the test and material choice is not totally inclusive, the work outlined in this paper has shown that the squeegee system has been able to locally modify the print medium such that it is now possible to print extremely challenging Area Ratios using standard stencils and solder paste.

This technology has the capability to deliver to the SMA community a remedy to the miniaturization headache.

References

1. Whitmore M, Ashmore C , " Pro Activ – A new printing technique for mixed technology (heterogeneous) assembly, SMTA October 2010
2. IPC – 7525 Stencil Design Guidelines
3. Coleman B, "Squeegee Blades Design for Step Stencil" SMTAI August 2008
4. Coleman B, "Step Stencil Design When 01005 and 0.3 mm Pitch uBGAs Coexist with RFShields", SMT, February 2009
5. Coleman B "Step Stencil Design for Handheld" IPC Apex, 2009
6. Burkhatter E et al, "Transfer Efficiency in Stencil Printing", SMT, May 2007
7. Coleman B et al, "AMTX Electroform vs Laser Cut Electro Nickel Foil", SMTAI, October2006
8. Ashmore C, "Mass Imaging Of Lead Free Materials - What Impact Does Stencil Technology Have?", IPC Chicago, 2005
9. http://en.wikipedia.org/wiki/Shear_thinning - Accessed 18/12/10
10. Ashmore C et al, "optimizing the Print Process For Mixed Technology" SMTAI, October 2009
11. Mohanty R, "What's in a Squeegee Blade?", Circuit Assembly, May 2009
12. Babha G et al, "A New Angle on Printing", Global SMT & Packaging, February 2009