THE EFFECT OF AREA SHAPE AND AREA RATIO ON SOLDER PASTE PRINTING PERFORMANCE

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ABSTRACT
One of the most important design criteria for solder paste printing stencils is area ratio (AR), which is defined by the IPC-7525 as the area of aperture opening to the area of the aperture walls. Accordingly, the use of values for AR of at least 0.66 and above provides good printing performance. It is becoming more frequent in mixed assembly designs, where stencil thickness cannot be reduced to accommodate new fine feature components, that resulting AR levels become critically low and difficult to print. As this motivates our investigation on the printing performance of low AR stencil aperture designs, our research further explores the influence of aperture shape effects that AR itself does not account for. Aperture shapes that vary quite significantly from one another may exhibit unique printability characteristics despite also having equivalent AR values.

In this study, the printing process for miniaturized structures is evaluated using specially designed area ratio test stencils. The design of these stencils includes values for the AR from 0.65 down to 0.45 with rectangular apertures as well as circular apertures for reference. Additionally, the orientation of the rectangular apertures in relation to the printing direction is regarded. To include the effect of area shape, a sufficient number of apertures are gradually adjusted in length and width while still resulting in the same AR. The stencils used are laser-cut stainless steel foils in thicknesses of 80 µm, 100 µm, and 120 µm. Solder paste materials in Type 4 and Type 5 lead-free SAC305 alloy are also evaluated. The investigations contribute to explain the challenges of solder paste printing for highly miniaturized components.

Key words: stencil printing, fine pitch, area ratio, transfer efficiency, solder paste inspection, SPI

INTRODUCTION

The ongoing miniaturization trend in the SMT production induces new challenges and highly integrated systems. In the area of passive components the miniaturization leads to the introduction of the EIA size 01005 or smaller. Typical 01005 components are chip resistors and chip capacitors with the dimension of 0.4 mm x 0.2 mm. Despite numerous publications in this field already addressing the printing of such devices, a defined wholly optimized process remains unsolved and inspires further novel research ideas on this topic.

This paper focusses on the stencil printing process, because the highest amount of failure is assumed to be based on this process step [1–4]. Furthermore, the paper extends the preliminary work (e.g. [5–7]) by fundamental considerations. Thereby different values for the area ratio will be part of the investigation, which are purposely set to very low limits.

The influence of the aperture shape and orientation on the solder printing performance will be discussed. It is based on different forms of rectangles. Starting with a square the dimensions are incrementally changed, so that the square converts further into a rectangle. Furthermore each rectangle is additionally rotated by 90° to be able to evaluate the influence of the apertures direction towards the squeegee.

In addition to the previously described stencil aperture attributes, this research also explores different stencil thicknesses, solder pastes and a variation of the squeegee speed. The evaluation of all data will be based on the two criteria of transfer efficiency and standard deviation. For both experiments the same stencil layouts and same solder paste are being used. The paper concludes with an outlook and suggestions on the modification of the current calculation by limitations of aperture dimensions.

EXPERIMENTAL SETUP

The experimental setup includes three main variables, namely the layout by the PCB, the solder paste and the stencils used. A description of the experiment process is further explained.

PCB Layout

For the stencil printing experiments a black anodized aluminum plate is used as substrate material with dimensions of 160 x 160 x 1.5 mm. This material is highly rigid and planar, representing a near perfect printing surface to minimize its influence on the print process outcome. Furthermore the black aluminum material enables higher contrasts at the SPI, leading to more precise measurements. Figure 1 shows the general design of the printed solder paste deposits on the PCB.

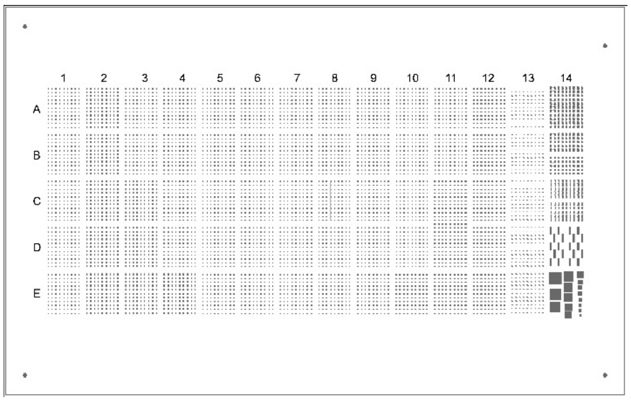

Figure 1. PCB and solder paste deposit layout

Solder Paste

The stencil printing test also aimed to compare four different no-clean SAC305 solder paste formulations varying by type and by manufacturer. Solder paste of Type 4 and Type 5 were used. By the IPC J-STD-005 at least 80 % of the alloy powder in a Type 4 paste measures 20-38 µm while a Type 5 paste contains the same ratio of alloy in 15-25 µm diameter particles. Due to the small dimensions of the tested apertures a difference in the printing performance attributed to particle size (i.e. Type) is assumed a reasonable possibility. Two paste vendor sources were also included in this study, named A and B, which were supplied in both Type 4 and Type 5 products. As the distribution of the solder paste particles is comparable, A and B mainly differ in the composition of their flux systems which affects rheology and printing capability.

Stencils

In total three stencils were used for the experiments. Firstly the stencils differ by their thickness and secondly by the size of their apertures (compare Table 1-Table 3). The general structure is identical. The layout (Figure 1) can be divided into rows and columns. Each row represents an area ratio, starting in Row A with AR of 0.45 and ending with AR of 0.65 in Row E. Each column in these tables represents different aperture shapes. Column 1 always has the shape of a circle, Column 7 is a square and Column 13 is the form of a diamond. Column 14 contains special types of structures that will not be discussed in this paper. Columns 2 to 6 and 8 to 12 are paired with the same dimensions and they only differ in their orientation towards the squeegee. Columns 2 to 6 face with the small side the squeegee (i.e. north-south orientation), whereby columns 8 to 12 face the squeegee with the long side of the rectangle (east-west orientation). Figure 2 illustrates the aperture design pattern across a row to show differences between the respective column groups of apertures.

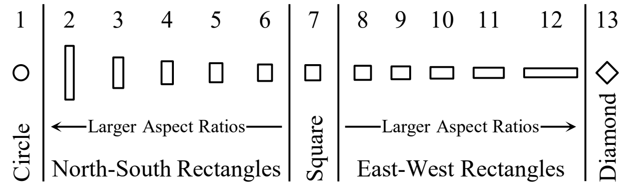

Figure 2. Column groups and aperture labels

The stencils used were made of stainless steel foil with laser cut apertures and produced for attachment in a Vector Guard (VG260) master frame system. A stencil nano-coating was not applied to any of these stencils.

Table 1. Aperture dimensions, 80 µm thickness stencil

Area Ratio	Column	2 12	3 11	4 10	5 9	6 8	7
0.45	X [µm]	94	104	114	124	134	144
	Y [µm]	308	234	195	172	156	144
0.5	X [µm]	110	120	130	140	150	160
	Y [µm]	293	240	208	187	171	160
0.55	X [µm]	126	136	146	156	166	176
	Y [µm]	292	249	222	202	187	176
0.6	X [µm]	142	152	162	172	182	192
	Y [µm]	296	261	236	217	203	192
0.65	X [µm]	158	168	178	188	198	208
	Y [µm]	304	273	250	233	219	208

Table 2. Aperture dimensions, 100 µm thickness stencil

Area Ratio	Column	2 12	3 11	4 10	5 9	6 8	7
0.45	X [µm]	130	140	150	160	170	180
	Y [µm]	293	252	225	206	191	180
0.5	X [µm]	150	160	170	180	190	200
	Y [µm]	300	267	243	225	211	200
0.55	X [µm]	170	180	190	200	210	220
	Y [µm]	312	283	261	244	231	220
0.6	X [µm]	190	200	210	220	230	240
	Y [µm]	326	300	280	264	251	240
0.65	X [µm]	210	220	230	240	250	260
	Y [µm]	341	318	299	284	271	260

Table 3. Aperture dimensions, 120 µm thickness stencil

Area Ratio	Column	2 12	3 11	4 10	5 9	6 8	7
0.45	X [µm]	116	136	156	176	196	216
	Y [µm]	1566	525	351	280	241	216
0.5	X [µm]	140	160	180	200	220	240
	Y [µm]	840	480	360	300	264	240
0.55	X [µm]	164	184	204	224	244	264
	Y [µm]	677	467	374	321	288	264
0.6	X [µm]	188	208	228	248	268	288
	Y [µm]	615	468	391	343	311	288
0.65	X [µm]	212	232	252	272	292	312
	Y [µm]	591	476	410	366	335	312

Print Test Procedure

Before the main experiments, a pretest was conducted to select the parameters for the squeegee speed, squeegee pressure and the separation speed using solder paste A. Parameters were determined by the *DOE Optimization* function within the Minitab software program and established per paste type. For each experiment 125 grams of solder paste material was used in combination with 200 mm long 60° SS squeegees. Table 4 identifies the equipment and print test parameters used in this study.

Table 4. Experimental tools and setting

Printing Machine Details	
Model	ASM DEK Horizon 03iX
Board Clamp	Foiled Overtop Type
Tooling	Grid-Lok Gold
Under Stencil Wipe	Wet/Vacuum/Dry ea. 5th Print
Squeegee	200 mm, SS, 60°, 15 mm O/H
Type 4 Paste Print Process	
Fast Print Speed	V = 80 mm/s, P = 5 kg, S = 6 mm/s
Slow Print Speed	V = 30 mm/s, P = 5 kg, S = 6 mm/s
Type 5 Paste Print Process	
Fast Print Speed	V = 55 mm/s, P = 6 kg, S = 2 mm/s
Slow Print Speed	V = 30 mm/s, P = 6 kg, S = 2 mm/s
SPI Machine Details	
Model	KohYoung 3020T
Camera	10 µm Resolution
Bare Board Teach	Not required due to the used substrate
Threshold	20 µm

The test routine (Figure 3) consisted of starting with four knead printing cycles, followed by an automatic under stencil wipe and then proceeding to the formal printing test schedule whereby SPI data collection commenced. Ten boards were printed at fast squeegee speed followed by ten more boards printed at slow speed. This test print sequence was repeated twice each using both paste brands and types for all three stencil thicknesses. The under stencil cleaner was programmed to perform a wet/vac/dry cycle after every fifth consecutive print. The complete DOE comprised 480 solder paste inspected boards.

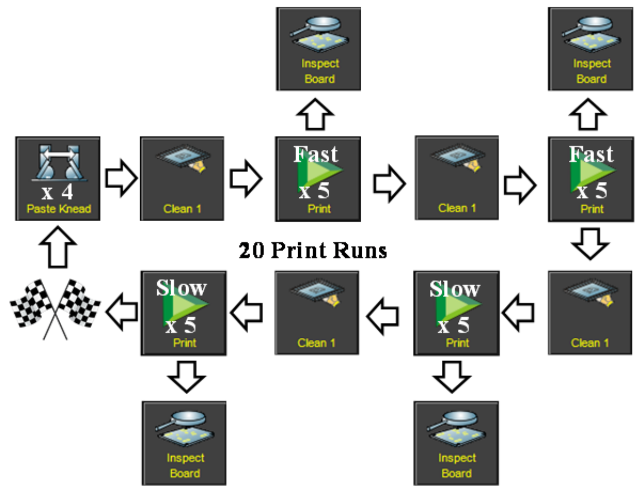

Figure 3. Print test sequence with 480 total prints

EFFECTS OF THE APERTURE SHAPE

The main object in this experiment is the investigation whether the aperture form or shape has an influence on the printing results. In the first part the general result will be taken into consideration with the analysis of all measured data of the transfer efficiency. In further steps the result will be filtered by the criteria of the solder paste type and the stencil thickness. The form comparison is based on adjacent apertures 2 vs. 3 vs. 4 etc. vs. 12. The shape can be analyzed using columns 1 vs. 7 vs. 13. Based on square apertures in columns 7, the orientation is observed comparing 2 vs. 12, 3 vs. 11, etc. up to 6 vs. 8 with the slightest varying aperture form.

Printing Results

With about 8 % higher transfer efficiencies, square apertures perform better than the circular structures. Further analyses of the basic forms indicate no significant difference between square and diamond. In the following, the variations of the rectangular apertures will be discussed.

Figure 4 shows the overall view on the transfer efficiency depending on the area ratio and the form. It includes the results of all printed boards. The form is visualized by the column number (Figure 2). In general the figure proves the plausibility and the correctness of the data, because the transfer efficiency rises with increasing area ratios. Furthermore the measured values show a clear tendency that the aperture form and orientation have an influence. If the aperture form is taken into investigation the high aspect ratio east-west oriented rectangles exhibit highest transfer efficiency (column 12). Beginning from the square (column 7) both orientations of rectangles perform better than the square, which seems to be nearly the minimum of every graph. In addition the aspect ratio (the difference between the wide and small side of a rectangle), which is rising towards the ends of the graph, shows possible correlation with the transfer efficiency.

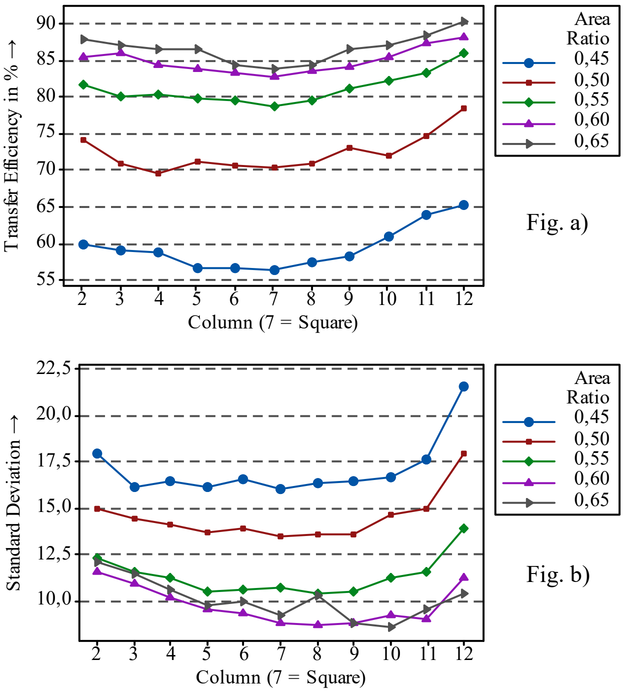

Figure 4. Influence of aperture shape and orientation based on transfer efficiency (a) and variation (b)

Besides the aperture aspect ratio, the aperture orientation shows evidence to influence the process. The apertures representing columns 2-6 have north-south orientation (i.e., the small side of the rectangle faces the squeegee) while the columns 8-12 are east-west oriented (i.e., the wide side faces the squeegee). Especially the area ratios 0.45 and 0.5 show the clear tendency that the aperture orientation has an influence. The transfer efficiency of the 0.45 area ratios raises about 3.5 % for north-south orientation and about 8.8 % for east-west oriented apertures compared to squares. This trend weakens with increasing area ratios but remains recognizable throughout all graphs. If the standard deviation is investigated the insights show that the east-west orientation also leads to a slightly higher standard deviation at low area ratios. For this parameter the squares show better results. The standard deviation for the area ratios 0.55 to 0.65 shows no significant differences and no trends can be observed.

Solder Paste Type

Due to the bigger assumed influence using a solder paste with coarser particles the first analysis will be focused on solder paste Type 4. The general appearance of the trends in Figure 4 (combined test results) seems to be consistent with Figure 5 (Type 4 paste results). The graphs show that the rectangle shape and the orientation have an influence. The effect in general seems not so obvious compared to Figure 4 but can still be recognized. The solder paste Type 4 shows that the transfer efficiency of the 0.45 area ratios raises about 1.6 % for north-south orientation and about 8.7 % for east-west orientated apertures compared to squares.

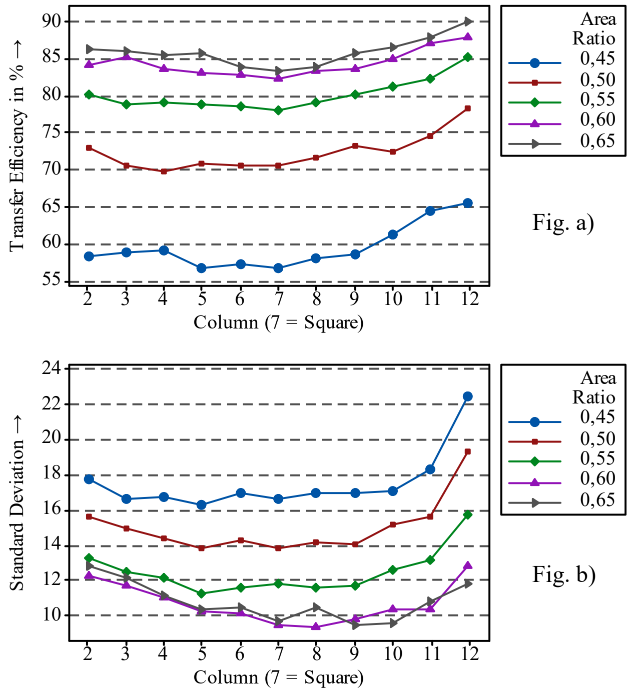

Figure 5. Influence of the aperture shape and the orientation for Solder Paste Type 4

The investigation of the standard deviation shows that the values for the two orientations are comparable for the variations 5-9. The biggest aspect ratios for the north-south orientation lead to a slightly increasing standard deviation for columns 2-4. The east-west orientation in column 10-12 implies the highest standard deviation for all area ratios.

Based on further examinations slightly better printing results are provided using solder paste of Type 5, as illustrated in Figure 6. Especially at area ratios of 0.55 and above a higher transfer efficiency is observed. The effect at area ratios of 0.5 and 0.45 is still measureable, but less marked.

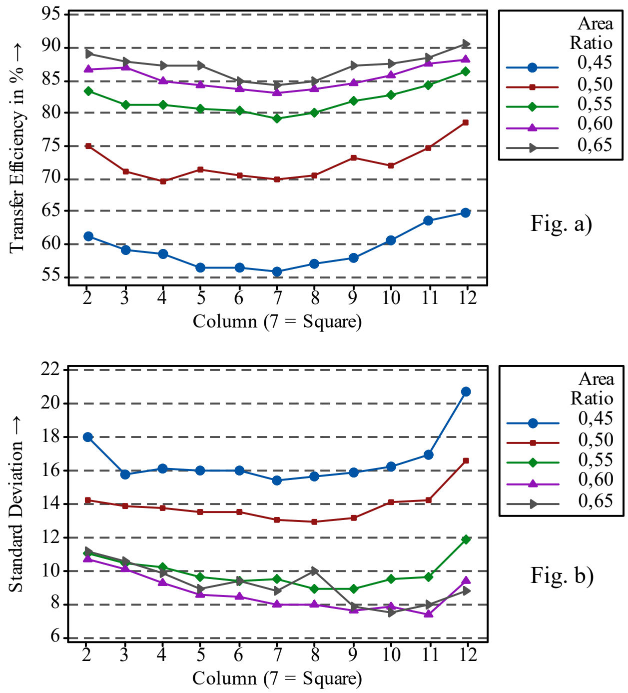

Figure 6. Influence of the aperture shape and the orientation for Solder Paste Type 5

The standard deviation is more evenly distributed using solder paste of Type 5 and shows less variance compared to a solder paste of Type 4. The solder paste Type 5 shows that the transfer efficiency of the 0.45 area ratios raises about 5.4 % for north-south orientation and about 9.1 % for east-west oriented apertures compared to squares.

Stencil Thickness

Following industry accepted area ratio principle, thinner stencils are considered to provide better release behavior for miniaturized structures. While use of reduced stencil thickness raises the area ratio for identical apertures, this stencil design strategy also subtracts volume capacity from the aperture. Within our investigations three stencil thicknesses are examined.

The effect of the 80 µm stencil thickness is illustrated in Figure 7. The graphs in general show a consistent behavior of the transfer efficiency. The measured values rise along with higher area ratios. Apertures with east-west orientation again show higher transfer efficiencies. Against the overall view, the effect seems to have a maximum for columns 5 and 9 at area ratios of 0.5 and above. AR of 0.45 shows a continuous trend to higher transfer efficiencies with a decrease in the outer shapes. The analysis of the standard deviation for the 80 µm stencil thickness shows the clear trend for more unwavering distributions at higher area ratios. Again the rectangular aperture shows a reduced standard deviation but against the overall view no significant variance in the outer columns occurs.

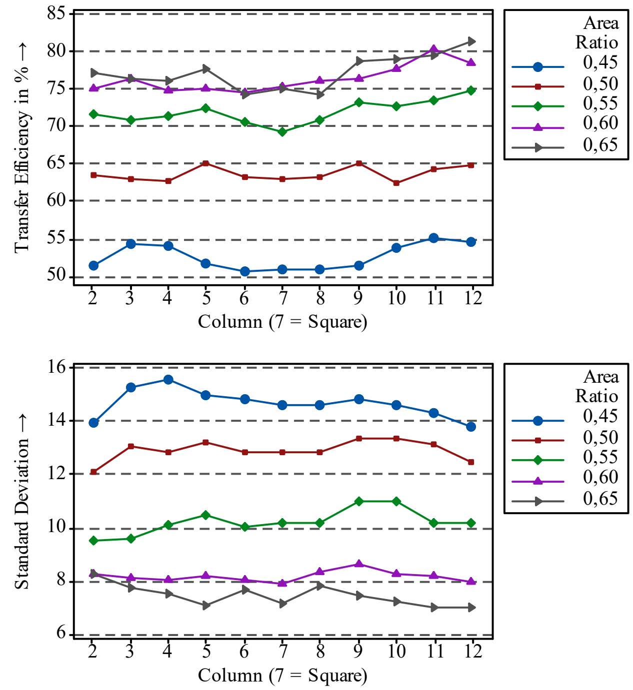

Figure 7. Influence of the aperture shape and the orientation for the 80 µm stencil

The analysis of the measured data for the 100 µm stencil thickness shows significant differences in the transfer efficiencies, as shown in Figure 8. Area ratios above 0.55 consistently print above 75 % transfer, while a strong decrease is observed for the area ratios 0.5 and especially 0.45. Compared to the 80 µm thickness no significant decrease of the transfer efficiency can be observed. Excluding the area ratio 0.5 data, all others have the common trend where the highest aspect ratio rectangles track lower in transfer efficiency relative to neighboring data points.

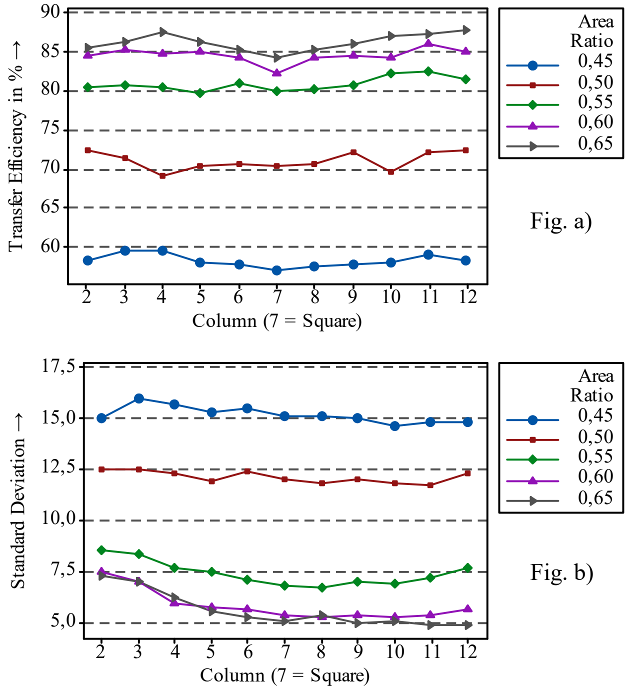

Figure 8. Influence of the aperture shape and the orientation for the 100 µm stencil

The standard deviation of the 100 µm stencil follows the overall trend with higher deviations for the area ratios 0.45 and 0.5. Area ratios above 0.5 show the minimum for the variance in the area of the rectangular shape. A strong influence is detected for north-south orientated apertures resulting in higher values for the standard deviation towards column 2.

The average values of the 120 µm stencil show the highest transfer efficiency of all stencils and it seems to be the stencil with the highest ability to perform the prints. The increase of the transfer efficiency for the east-west aperture orientation is clearly recognizable as illustrated in Figure 9.

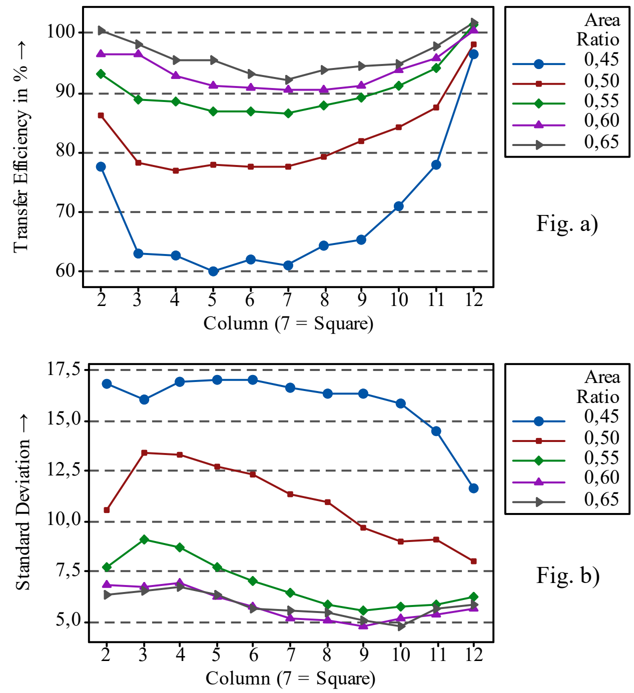

Figure 9. Influence of the aperture shape and the orientation for the 120 µm stencil

Similar to the trends shown in Figure 4 the two smallest area ratios have marked transfer efficiency differences between the two aperture orientations, particularly at high aperture aspect ratio. Conversely, the transfer efficiencies produced by the north-south aperture orientation for the two smallest area ratios are less sensitive to changes in aspect ratio. In general the rectangles with the east-west orientation typically achieve the highest transfer efficiency, especially at low area ratios.

In comparison to the other stencil thicknesses the course of the graphs show some deviation especially concerning the effect of the orientation. One reason might be the difference on the absolute size of the aperture and the different shapes of the aperture depending on the stencil thickness. Thereby the 120 µm stencils occupies the biggest apertures with distinctive differences in their shapes.

The course of the standard deviation has all the same remarkable points in common. The trends in Figure 9 show a decrease of the standard deviation starting at the square and following the east-west orientation before they undergo a rise in columns 11 and 12 for area ratios of 0.55 and above. Area ratios show an ongoing decrease also for apertures with lowest values of the standard deviation in column 11 and 12. In contrast the vertical apertures in north-south orientation have a higher standard deviation than a square. Overall the course of the graphs for the 120 µm stencil thickness is not consistent and no general trend can be observed.

DISCUSSION

The results of the experiments comparing the aperture form show the influence on the stencil printing process especially for small area ratios below 0.6. The upcoming discussion introduces some ideas for the integration of the results in present standard rules.

The first insight of the experiments shows that a rectangle shape leads to better results than the square. Combined with the analysis of the influence of the stencil thickness it is known that the effect depends on the size of the aperture. All stencils have the same area ratio, which also means that the absolute size of each aperture is not identical. Combining the aspect ratio with the transfer efficiency, a higher aspect ratio might lead to higher transfer efficiency. Transferring this point to the orientation of the aperture evidence of printing improvement under test conditions can be found where the wide side of the aperture faces the squeegee.

Continuing with the aperture orientation analysis it was found out that there are differences between the performance of the east-west and the north-south directions. This leads to the idea to extend the common calculation of the area ratio. The analyzed data has shown the orientation and form of the aperture influences the printing results, particularly at small area ratios where unexpectedly high average paste transfer occurred. To include this thesis in the area ratio calculation a levelling factor (short: NF) will be introduced.

Under the present condition it raises the real area ratio to a higher level by including the form and orientation of the aperture. Thereby a new area ratio is calculated, which could serve as the new decisive area ratio. To develop the levelling factor the slope of the average improvement of the transfer efficiency was calculated. For this experiment a nearly linear coherence can be determined. The idea is to use the determined slope, which was calculated on a transfer efficiency base and transfer it to calculate the area ratio. The slope will be multiplied with the difference of the length of the smaller side of the square and the aperture, to include the form of the aperture. Based on the results, the NF-factor can be calculated as:

$$NF = 1 + \frac{0.15\left(B_{square} - B_{aperture}\right)}{100}$$

To calculate the new area ratio the NF-factor will be added to the common area ratio calculation:

$$AR = \frac{area\ of\ aperture\ opening}{area\ of\ aperture\ walls} * NF$$

$$= \frac{A * B}{2 * T * (A + B)} * \left(1 + \frac{0.15\left(B_{square} - B_{aperture}\right)}{100}\right)$$

This extended formula applied to conventionally low area ratio east-west oriented apertures is considered to improve accuracy of area ratio specification for such aperture designs. While the apertures with north-south direction still show better transfer efficiency results compared to squares, the correction by the NF implementation reduces such bias. This exercise serves as a first idea to rethink common rules and consider new requirements provoked by miniaturization to find new ways of achieving more process adapted stencil designs.

CONCLUSION AND OUTLOOK

This paper discussed the effect of the aperture shape and orientation on solder paste printing performance. For the experiments three different stencil thicknesses (80 µm, 100 µm and 120 µm), two different solder paste types (Type 4 and 5) and two manufacturers were used.

For apertures with identical area ratios a strong influence is induced by a varying aspect ratio and the orientation of these structures to the printing direction. The results focusing on the transfer efficiency and the standard deviation show, that the shape of a rectangle and an east-west orientation achieve the best results, as illustrated in Figure 10. Furthermore the solder paste type can have an influence, especially when relatively narrow apertures are printed. Based on the boundary conditions of the PCB layout within the printing tests the thicker stencils have the higher aspect ratios and achieve better printing results.

In general the printing results show that also area ratios lower than 0.66 can be quite regularly printed above 75 % transfer efficiency, with dependencies on the shape of the apertures. This leads to the idea to extend the current calculation of the area ratio by introduction of the leveling factor NF. Using NF for the calculations, the present assumed design limitations are extended to regard the orientation and shape of the stencil apertures.

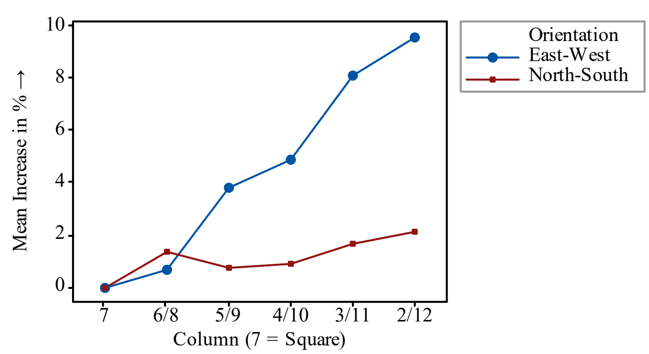

Figure 10. Mean increase of the transfer efficiency in relation to the aperture shape and orientation

Additional research has to be done to find proof for the ideas given in this paper. Different types of solder paste and stencil thicknesses extend the data basis and help to refine the first introduced modeling. This could also lead to non-linear correlations that have to be included for more precise calculations. New materials as finer grained solder paste types, stencil technologies and stencil coatings shift the limits for obtaining a well controlled stencil printing process. Additionally, new calculations based on fundamental printing tests contribute to understand printing behavior of miniaturized structures to achieve a robust solder paste printing performance.

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