

DESIGN AND PROCESS DEVELOPMENT FOR THE ASSEMBLY OF 01005 PASSIVE COMPONENTS

J. Li¹, S. Poranki¹, R. Gallardo², M. Abteu², R. Kinyanjui², Ph.D., and K. Srihari¹, Ph.D.

¹Watson Institute for Systems Excellence
State University of New York
Binghamton, NY, USA

²Technology Development Center
Sanmina-SCI Corporation
San Jose, CA, USA

ABSTRACT

Growing demands for smaller electronic assemblies has resulted in reduced sizes of passive components, requiring the introduction of newer components, such as the 01005 devices. Component miniaturization presents significant challenges to the traditional surface mount assembly process. A successful assembly solution for these 01005 devices should be repeatable and reproducible, and should include guidelines for (i) the selection of solder paste and (ii) appropriate stencil and substrate pad design, and should ensure strict process control standards.

During the first phase of this study, different stencil types, aperture designs, pad layouts and process parameter settings were evaluated with the goal of achieving a high-yield assembly solution for 01005 components. Printed circuit board assemblies are populated, usually, with both large active devices (often surface mount packages), along with much smaller passive components (such as 01005s). Consequently, it was decided to use a 4 mil thick stencil along with a type 4 solder paste. Based on these process and design conditions, several stencil aperture shapes were evaluated using metrics, such as transfer efficiency and variance in volume of the deposited solder. These two criteria help determine solder volume adequacy and consistency. In addition, different pad layouts were studied vis-à-vis their ability to promote (or inhibit) component self alignment during the solder reflow process.

The results of the first phase of this study indicated that an electroformed stencil performed much better than a laser cut stencil in terms of transfer efficiency. However, considering the relatively higher cost of an electroformed stencil, a follow up (second) study focusing on the use of a laser cut stencil was considered essential. The objective of this study was to develop a process that provides higher yields while ensuring cost effectiveness. Aperture designs were adjusted to increase the area ratio. The results showed that it was possible to develop a robust 01005 assembly process with the use of 4 mil thick laser cut stencil in concert with a type 4 solder paste.

Key words: Surface Mount Assembly, 01005 Passive Components, Stencil Design, Transfer Efficiency, Volume Variance, Laser-cut Stencil

INTRODUCTION

The electronics manufacturing industry is continuously facing demands for smaller, lighter and more powerful devices. This demand has led to the introduction of 01005 passive components. The sizes of 01005 components range from 0.10mm (0.004") × 0.304mm (.012") to 0.20mm (.008") × 0.40mm (.016"), which are very small and almost invisible to the naked eye [5]. The use of such miniature components could result in a dramatic challenge to the current surface mount technology (SMT) assembly processes. In order to successfully assemble these extremely small passives, it is important to carefully select the right solder paste, adopt an appropriate stencil design, and have tight control of the assembly process. It is not only important to focus on the 01005 component assembly, but it is equally essential that the tool set design and assembly process be able to accommodate large components, assembled concurrently with the 01005 passives on the same board.

Extensive research, particularly focusing on stencil design and solder paste selection, has been carried out to develop the new tool sets and assembly processes for 01005 passives [1, 2, 3, 4]. It has been demonstrated that 5 mil thick stencils and type 3 solder paste, which are typically used in assemblies, cannot ensure adequate printing results for 01005 component assembly. Thinner stencils (3-4 mils) combined with finer paste types (type 4 or type 5) are necessary in order to guarantee sufficient and consistent paste deposition.

Current published results do not provide sufficient guidelines for the assembly of 01005 passive components, which can be applied for mass production of these devices. This necessitates further study, particularly from a design and process control point of view. The objectives of this study include: (i) providing the optimal stencil solution, which can accommodate both 01005 passives and large components, resulting in better solder paste printing outcomes; (ii) providing optimal pad design in a PCB, which can improve the self-alignment capability of a component during reflow, reducing tombstoning and misalignment defects.

BACKGROUND INFORMATION

Stencil Design

Appropriate stencil design plays a critical role in the surface mount solder paste printing process and directly affects the overall SMT assembly yield [6]. The primary concern in stencil design is transfer efficiency, which represents how much of the solder paste can be released from the stencil aperture and printed onto a pad. Three major factors of stencil design determine the transfer efficiency and dramatically impact the printing performance: (i) area ratio, (ii) fabrication type, and (iii) aperture shape.

Area ratio refers to the ratio between the area of the aperture opening and the area of the aperture walls. An area ratio of 0.66 or higher is recommended for laser-cut stencils to achieve acceptable volume control according to the IPC stencil design guideline. For 01005 passives, meeting this requirement is a challenge, due to their extremely small stencil opening area. In order to increase area ratio, the thickness of the stencil has to be reduced. However, this reduction may result in insufficient paste deposition for larger components. Consequently, in this study, it was decided to use a 4 mil thick stencil along with type 4 solder paste. Based on this condition, different design solutions were evaluated and compared with the goal of improving the printing performance.

Stencil fabrication type can be another factor that affects transfer efficiency. The smoothness of the surface of the aperture sidewall is a function of the fabrication technique used. When compared to a laser-cut type, an electroformed stencil provides a much smoother surface (Figure 1). The smooth finish can help release the paste from the aperture and provide a consistent volume. On the other hand, the price of an electroformed stencil is typically higher than a laser-cut stencil. Consequently, a detailed study is necessary that can help reach a cost effective solution.

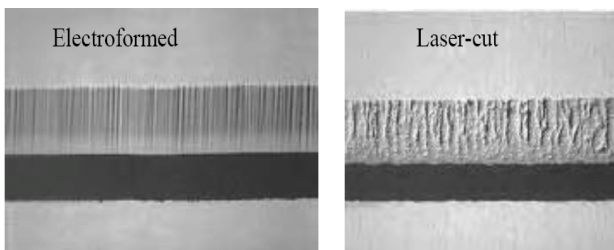


Figure 1 Typical Sidewall Image of Types of Stencil Fabrication

Additionally, literature states that the aperture size along with the aperture shapes influence the release of the solder paste [3, 7]. In order to optimize the aperture design, this study compared different aperture shapes based on printing performance.

Pad Design

The pad size can impact the self-alignment ability of components during reflow, which is critical to reduce skewing and tombstoning defects [5]. Furthermore, it was also observed that appropriate spacing between two adjacent pads, i.e., pitch, is also critical for production yield. Finer pitch ensures a consistent deposition;

however, it can create bridging issues. In this study, four different pad designs were compared based on the assembly yield after reflow.

Printing Process Setting and Reflow Process

Print parameters, such as print speed, print pressure, and stencil release speed, can also affect print performance. Several studies have investigated the 01005 printing process by optimizing the printing parameters [1, 2]. The results showed that typically slower print speeds coupled with quicker stencil release provide for better printing related outcomes. Since the print parameters were not a focus of this research initiative, all the experiments used same print settings.

TEST VEHICLE

In this study, an 8" × 10" × 0.062" PCB was used. The test vehicle used is shown in Figure 2. The PCB pads were coated with ENIG surface finish. Passive components (01005) were populated on each board in the highlighted area as shown in Figure 2.

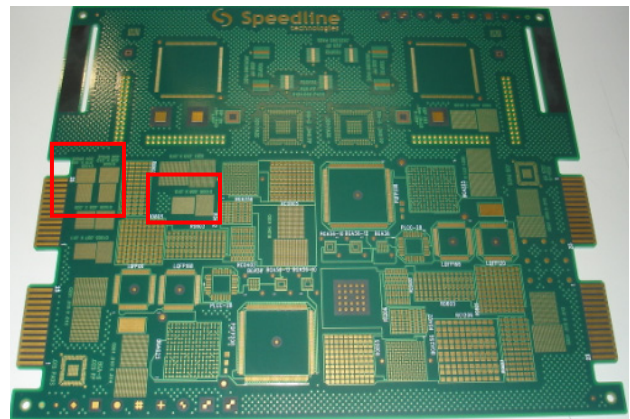


Figure 2 Test Vehicle

DESIGN OF EXPERIMENT (DOE)

A full factorial design was applied in this study to investigate the effects of stencil types, aperture shapes, component orientations and pad designs on the printing performance. As shown in Table 1, two stencil fabrication types, laser cut and electroformed, were used in this experiment. The stencil aperture design consisted of square, circle, home plate, and radiused home plate as shown in Figure 3. Both 0 and 90 degree orientations of components to the print direction were included. Four pad designs were investigated in this study:

- D1 (7×11 mils with 4 mils spacing)
- D2 (9×9 mils with 4 mils spacing)
- D3 (8×10 mils with 4 mils spacing)
- D4 (8×10 mils with 6 spacing)

EXPERIMENTAL PROCEDURE

Solder paste printing was carried out using a Speedline MPM Accela printer. The print force was 8 kg while the print speed was 50 mm/sec. Paste volume was measured by a KohYoung KY-3030, which is a 3D in-line solder paste inspection system. A Fuji-NXT with H12S head was applied for placement. Post-reflow inspection was conducted by a Dage XD 7500VR. The flowchart of the experiment is shown in Figure 4. A total of 14 boards

were assembled and 800 passive components were populated on each board.

Table 1 Full Factorial Design

| Factors | # Levels | Description of Levels |
|---------------------|----------|---|
| Aperture Shape | 4 | Square, Circle, Home plate, Radiused home plate |
| Pad Size & Spacing | 4 | D1, D2, D3, D4 |
| Pad Orientation | 2 | Horizontal, Vertical |
| Stencil Fabrication | 2 | Laser cut, Electroformed |

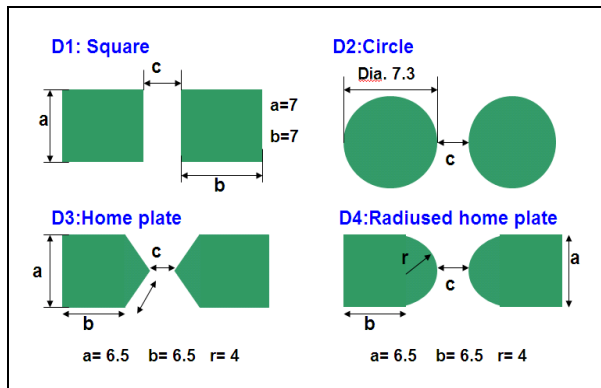


Figure 3 Stencil Aperture Design

Experiment Procedure

Equipment & Settings

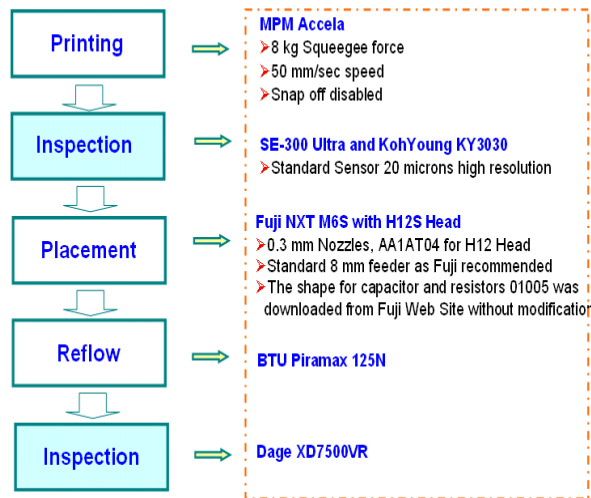


Figure 4 Experimental Procedure and List of Equipment

ANALYSIS

The evaluation included two phases: (i) post-printing and (ii) post-reflow evaluation. Post-printing evaluation was based on the measurement of deposited paste volume to compare different aperture designs on the stencil. Post-reflow evaluation was carried out by identifying yield and defect analysis.

Evaluation 1: Post-printing Evaluation

For a printing process, ensuring both sufficient and consistent paste volume is essential. Sufficient paste volume is necessary for good solder joint formation. An

equally important factor is obtaining a consistent amount of solder paste on each pad. Inconsistency in solder paste deposit heights and volumes can result in defects such as shorts, bridges, tombstoning, and skewing. Therefore, two criteria were used for printing evaluation: (i) volume variance, which indicates the consistency of deposited volume; and (ii) transfer efficiency, which indicates the volume of solder paste printed on a pad. Transfer efficiency is calculated as follows:

$$\text{Transfer efficiency} = \frac{\text{Actual Volume of Paste}}{\text{Expected Volume}} \times 100..(1)$$

Evaluation Criteria 1: Volume Variance

The confidence level was set at 95%, i.e. $\alpha = 0.05$. Table 2 shows MINITAB® 15.0 Analysis of Variance (or ANOVA) results, identifying the probability value (P-value) of the main effects and the interactions. Since the P-value ≤ 0.05 (see Table 2), it can be suggested that the aperture shape, pad design, pad orientation, stencil fabrication, and interactions between aperture shape and pad orientation were significant factors (for $\alpha = 0.05$).

Table 2 Output of Analysis of Volume Variance

| Significant factor | P-Value |
|----------------------------------|---------|
| Aperture Shape | 0.000 |
| Pad Design | 0.001 |
| Pad Orientation | 0.024 |
| Stencil Fabrication | 0.000 |
| Aperture Shape * Pad Orientation | 0.013 |

From the main effects plot (Figure 5), it can be seen that the circular aperture shape has the lowest volume variance, while the electroformed stencil resulted in much smaller volume variances as compared to the laser cut stencil. For pad design, design 3 (D3) exhibited the best performance, and vertical orientation led to better results than the horizontal orientation.

As per the interaction analysis between aperture shape and pad orientation, the effect of pad orientation on volume variance was dependent on the aperture shape (Figure 6). For circular apertures, the effect of pad orientation was negligible. For square and home plate apertures, vertical orientation could lead to a smaller volume variance. On the other hand, for the radiused home plate shape, horizontal orientation showed better results.

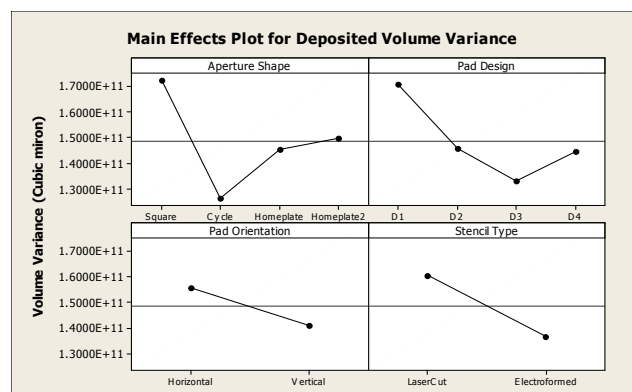


Figure 5 Main Effects Plot for Volume Variance

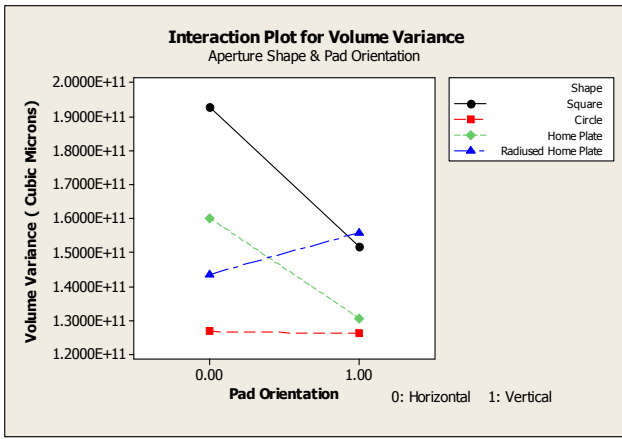


Figure 6 Aperture Shape and Pad Orientation Interaction Plot for Volume Variance

The interaction between aperture shape and stencil fabrication type was another significant factor to determine volume variance. According to Figure 7, irrespective of the aperture shapes, it can be clearly seen that the electroformed stencil outperformed the laser cut type in terms of volume variance.

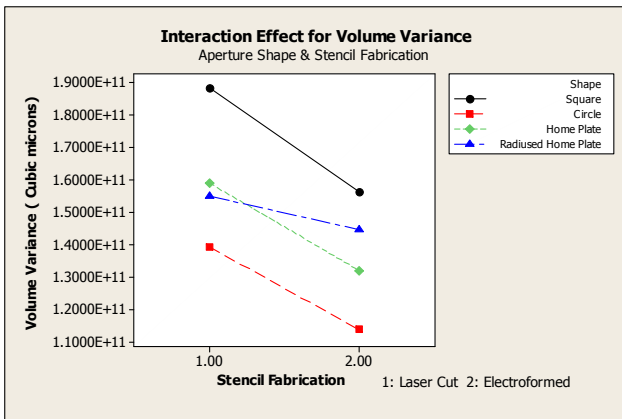


Figure 7 Aperture Shape and Stencil Fabrication Interaction Plot for Volume Variance

The interaction between aperture shape and pad design was statistically important as shown in Figure 8. Overall, pad design 1 performed the worst under all types of aperture shapes. Pad design 2 and 3 performed equally well combined with circle as the aperture shape.

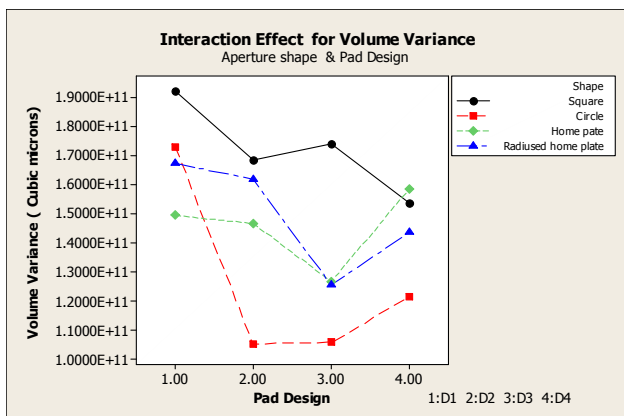


Figure 8 Aperture Shape and Pad Design Interaction Plot for Volume Variance

Evaluation Criteria 2: Transfer Efficiency

According to the statistical results, aperture shape, pad design, stencil fabrication and interaction between aperture shapes and pad orientation were significant factors for transfer efficiency at a confidence level of $\alpha = 0.05$.

Table 3 Output of Analysis of Transfer Efficiency

| | P-Value |
|-----------------------------|---------|
| Aperture Shape | 0.000 |
| Stencil Fabrication | 0.006 |
| Pad Design | 0.000 |
| Aperture Shape * Pad Design | 0.000 |

From the main effects plot (Figure 9) it can be concluded that the circular aperture performed the best and resulted in highest transfer efficiency. Additionally, the electroformed stencil performed much better than the laser cut stencil. The transfer efficiency of laser cut was about 65%, which indicated insufficient paste volume and possible clogging of the stencil.

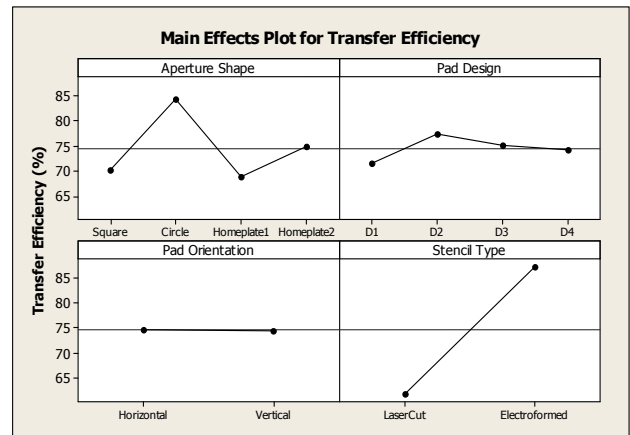


Figure 9 Main Effects Plot for Transfer Efficiency

The interaction between aperture shape and pad design was statistically important with respect to its ability to impact transfer efficiency. For the circular aperture, pad designs 2, 3, and 4 did not show significant differences in terms of transfer efficiency (see Figure 10).

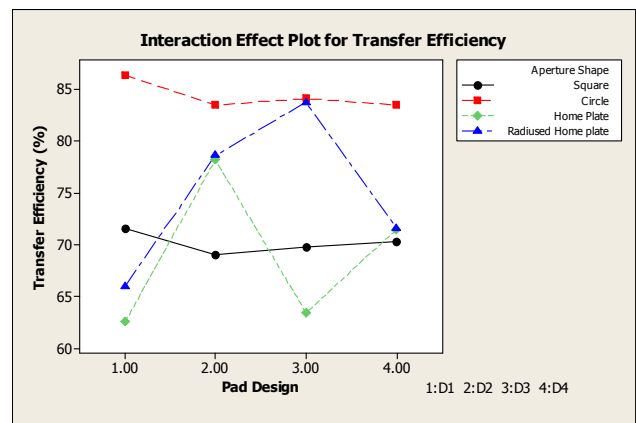


Figure 10 Aperture Shape and Pad Design Interaction Plot for Transfer Efficiency

Based on the aforementioned criteria of volume variance and transfer efficiency, the best design solution should be: electroformed stencil with circular aperture and pad design D2 (or D3). The appropriate design combinations, according to aperture shape, are summarized in Table 4. The order of combinations follows the rank of performance.

Table 4 Design Combination

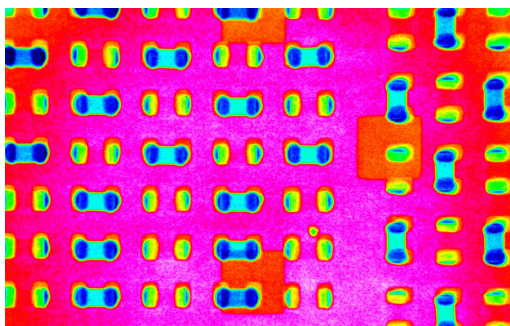
| Rank | Aperture Shape | Pad Size & Spacing | Pad Orientation | Stencil Fabrication |
|------|---------------------|--------------------|-----------------|---------------------|
| 1 | Circle | D2 or D3 | - | Electroformed |
| 2 | Radiused home plate | D3 | Horizontal | Electroformed |
| 3 | Home plate | D2 | Vertical | Electroformed |
| 4 | Square | D4 | Vertical | Electroformed |

Evaluation 2: Post-reflow Inspection

Post-reflow inspection focused on assembly yield and defect analysis. Defects, such as tombstoning and skewing, are mainly caused by unequal forces at the two ends of components. As mentioned above, it is important to deposit equal volumes of solder paste to reduce such unbalanced forces. Meanwhile, appropriate pad design can also help reduce the defects by enhancing the self-alignment ability. Consequently, this phase focused on evaluating the four pad designs by detecting defects after assembly.

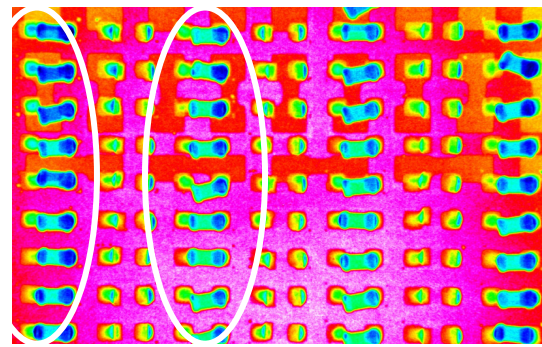
In addition, the evaluation was combined with four offset conditions of the placement machine to investigate the maximum offset tolerance for placement. Inspection was conducted by a Dage XD 7500 VR X-ray machine. Offset conditions were set as: Condition 1: X=0 mils Y=0 mils; Condition 2: X=3 mils, Y=3 mils; Condition 3: X= 4 mils, Y=4 mils; and Condition 4: X=4.5 mils, Y=4.5 mils.

When placement offset equaled zero, no defect was detected among the four pad designs. When the offsets in x and y direction were 3 mils and 4 mils respectively, pad design 2 showed some skewing defects. When the offsets were equal to 4.5, pad designs 1, 2, and 4 showed skewing defects. No defect was generated with pad design 3, which indicated that this design provided the best self-alignment ability.



(1) Placement Offset = 0 mils

Figure 11(1) Post Reflow Inspection



(2) Placement Offset = 4.5 mils

Figure 11(2) Post Reflow Inspection

**SUMMARY
Stencil Design**

In this study, a 4 mil thick stencil was selected to ensure that other large components have sufficient paste. A 4 mil thick stencil combined with type 4 Pb-free paste was used, which led to a successful 01005 assembly process. In addition, four aperture shapes were evaluated based on printing performance. The circular aperture had the best performance in terms of volume variance and transfer efficiency. The comparison between electroformed stencil and laser stencil showed that the electroformed stencil performed much better than laser-cut stencil. Transfer efficiency with a laser cut stencil was only around 65%, which indicated insufficient solder deposition volumes and possible clogging of the stencil.

Pad Design

In this study, four different pad designs were studied. Under certain intentional offset conditions, a rectangular shape generated far fewer skewing defects than a square shape, indicating that better self-alignment could be achieved by pads with a rectangular shape. Among the four designs, a pad design with dimensions of 8x10 mils with 4 mils spacing showed the best performance without any defect, even with a placement offset of 4.5 mils.

2nd PHASE STUDY - IMPROVING THE PERFORMANCE OF LASER CUT STENCIL

In the first phase of this study, it was found that an electroformed stencil performed much better than a laser-cut stencil, in terms of transfer efficiency. A laser cut stencil had only 65% transfer efficiency, which resulted in insufficient solder paste being deposited. Consequently, it was concluded that a laser-cut stencil was not adequate for 01005 applications. However, considering the fact that the cost of an electroformed stencil could be four times the cost of a laser-cut stencil, it would be interesting to find out whether it is possible to improve the laser-cut stencil performance by altering the current designs. Eventually, perhaps a cost-effective assembly solution can be provided to 01005 passive assembling processes using laser-cut stencils. Therefore, the objective of this follow-up study is to improve the printing performance of a laser-cut stencil by adjusting the design and modifying it for the 01005 assembly process.

As mentioned above, from the stencil design viewpoint, the ability to release paste from the inner aperture walls to the pad depends primarily on three major factors: (i) area

ratios / aspect ratios for the aperture design; (ii) the aperture side wall geometry, and (iii) the aperture wall finish.

Since this study uses laser-cut stencils, the focus of improving design primarily focused on determining (i) the means to increase the area ratio and (ii) the best aperture geometry. As seen in Figure 12, in this study, the proposed aperture design adopted an aperture size that was as large as possible, given the pad area. In addition, design 4 used a size that was 10% greater than the pad's design size. As compared to the aperture designs in the previous study, the area ratios increased because of the enlarged aperture size. Consequently, higher transfer efficiency was expected. In addition, it was found in the previous study that the designs with any sharp angle (e.g. rectangular apertures) were not performing as well as those with smoother shapes (such as circular apertures). Therefore, in this study, sharp angles were avoided in all the designs. As shown in Figure 12, Designs 1 and 4 used circular apertures, while Design 2 used an oval aperture and Design 3 used a rounded rectangular aperture.

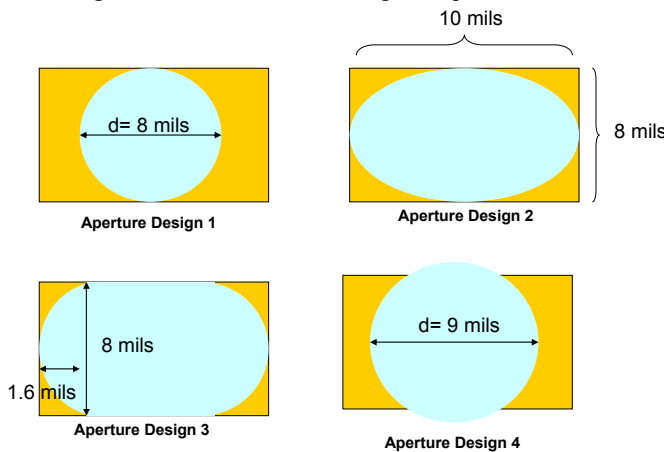


Figure 12 Aperture Design

DESIGN OF EXPERIMENTS & PROCEDURES

A full factorial design was used to investigate the effects of aperture shapes and related orientations on the printing performance. As shown in Table 5, the stencil aperture designs consisted of circle, oval, corner rounded rectangular, and over-sized circle. Both 0 and 90 degree orientations of components to the printing were included.

Table 5 Full Factorial Design

| Factors | # Levels | Description of Levels |
|-----------------------|----------|---|
| Aperture Shape | 4 | Circle, Oval, Corner rounded, Over-sized Circle |
| Component Orientation | 2 | Horizontal, Vertical |

Similar to study 1, post-paste printing and post-reflow inspection were performed for evaluation. Test vehicles, experimental settings and equipment were all kept the same as Study 1.

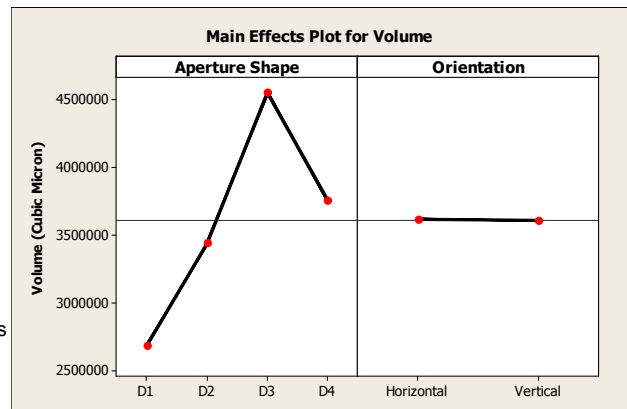
ANALYSIS

For post-printing evaluation, three criteria were applied: (i) deposited volume, which showed the amount of the

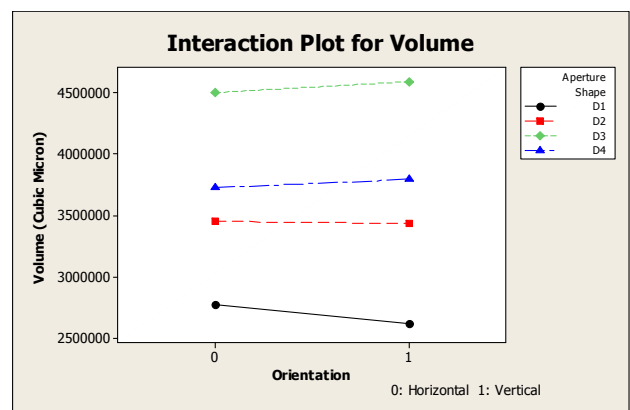
volume printed; (ii) volume variance, which indicated the consistency of deposited volume; and (iii) transfer efficiency, which indicated the ability of the paste to release from the aperture with a particular aperture shape. An ANOVA was conducted using MINITAB® 15.0, and the confidence interval was set at 95%, i.e., $\alpha = 0.05$.

Evaluation Criteria 1: Deposited Volume

From the main effects plot (Figure 13), the aperture Design 3 (corner rounded) generated the highest volume as compared to other aperture designs. Orientation was not a significant factor vis-à-vis the amount of paste printed. The effect from the interaction between aperture shape and orientation was not statistically significant either.



(a) Main Effects Plot

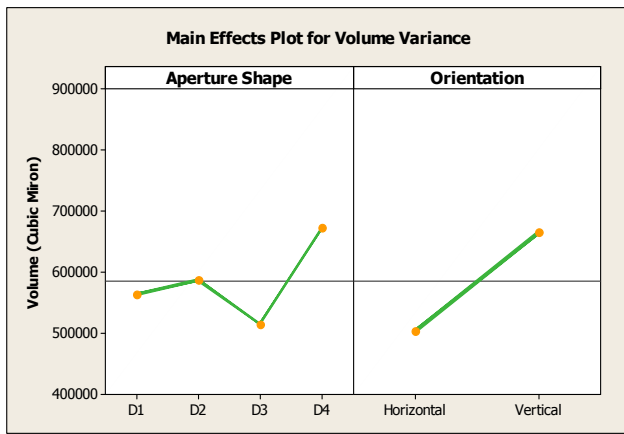


(b) Interactions Plot

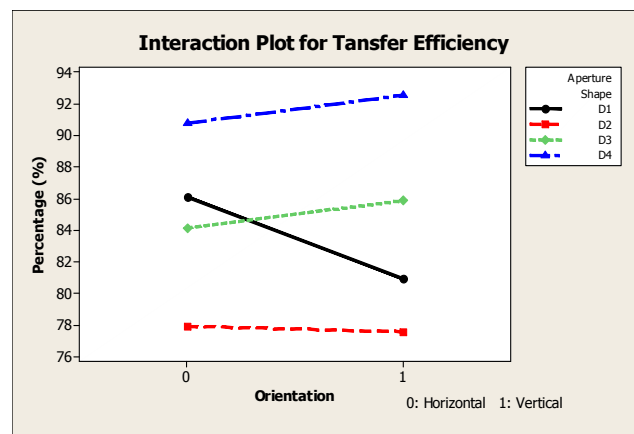
Figure 13 Results Plot for Deposited Volume

Evaluation Criteria 2: Volume Variance

According to the main effects analysis (see Figure 14), both aperture shape and orientation can be considered as significant factors in determining volume variance. The over-sized circle design resulted in relatively higher volume variances. Aperture Design 3 was still the best in terms of deposited variance among all the designs considered. The interaction between aperture shape and orientation was also a significant factor to determine the variance. It showed that the horizontal direction could lead to better printing performance than the vertical direction.

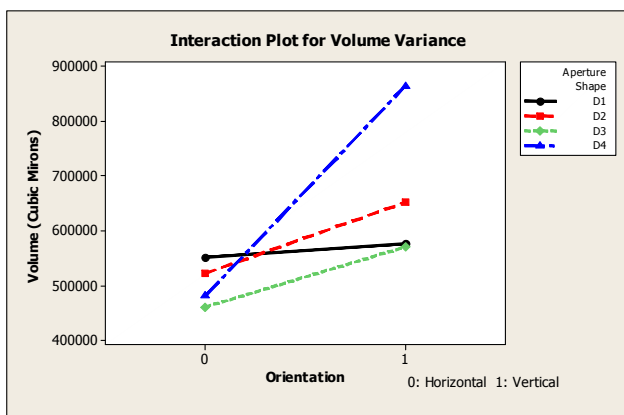


(a) Main Effects Plot



(b) Interactions Plot

Figure 15(b) Results Plot for Transfer Efficiency

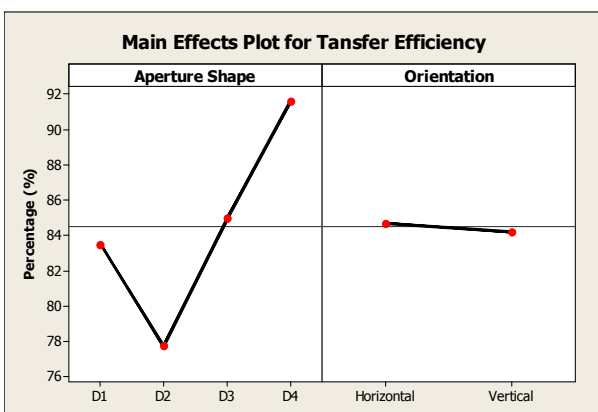


(b) Interactions Plot

Figure 14. Results Plot for Volume Variance

Evaluation Criteria 3: Transfer Efficiency

For transfer efficiency, there was a huge difference among the designs. As seen in Figure 15, Design 2 had a very low transfer efficiency when compared with other designs. The transfer efficiency of Designs 1, 3 and 4 were all around or above 85%, which was comparable with the performance of an electroformed stencil, according to Study 1. The horizontal direction resulted in a slightly better performance than the vertical direction. According to the interaction plot, for Design 3, the best design so far, the horizontal direction could help to improve the transfer efficiency.



(a) Main Effects Plot

Figure 15(a) Results Plot for Transfer Efficiency

CONCLUSIONS

By increasing the aperture size, the performance of laser-cut stencil was significantly improved. Transfer efficiency increased from 65% to more than 85%, which is comparable to the electroformed stencil used in the first phase of the study. Based on this follow-up study, it was shown that laser-cut stencil can be used for 01005 assembling process. Among the four proposed aperture designs, Design 3, corner rounded rectangular, performed the best in terms of deposited volume, volume variance and transfer efficiency. The information of suggested stencil design is summarized in Table 6.

Table 6 Design Solution for 01005 Passives Assembling

| Stencil Design Based on Laser-Cut Type | |
|--|---------------------------------|
| Aperture Shape | Rectangular with corner rounded |
| Aperture Size | As shown in Figure 12 |
| Aperture Orientation | Horizontal |
| Pad Design | |
| Dimension | 8 × 10 mils |
| Spacing Distance | 4 mils |

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