Investigating the 01005-Component Assembly Process Requirements

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Abstract
In 2006 we conducted two formal detailed experiments on the 01005-component assembly process. Two of the most significant findings from those experiments were that a 0.003" thick stencil is required to achieve an acceptable solder paste release percentage and that nitrogen is required for complete reflow of the very small volume of solder paste. For the most part, several other researchers had concluded the same for 01005 component assembly experiments.

Both the potential requirement to use nitrogen for the reflow soldering process and the use of a 0.003" thick stencil will be a major issue for high volume manufacturers. Introduction of Nitrogen will increase the cost and the use of a 0.003" stencil may cause insufficient solder paste for larger components on the same board.

The focus of this study is to discover methods to avoid the use of nitrogen in the reflow soldering process and to allow the use of a 0.004" thick stencil in the solder paste printing process. The questions that will be answered are:
- Can any available stencil technologies and solder paste product/type provide sufficient solder paste release to allow the use of a 0.004" thick stencil for 01005 components?
- Can we develop reflow profiles that will completely reflow 01005 components in an air atmosphere and/or are the solder paste suppliers developing new products that will allow the extremely small volumes of solder paste printed for 01005 components to be reflowed in an air atmosphere?
- If the use of nitrogen is required what is the optimum oxygen level to get complete reflow?

Key Words: Stencil technology, Aperture shape, 01005 passives assembly, Nitrogen reflow, Lead free assembly, SMT. Transfer Efficiency (TE)

Introduction
The continuing demand for smaller, lighter, and more functional hand held devices, such as cellular phones and PDAs, are driving the need for robust process development of miniature components assembly. One of the miniature component packages that are being used for resistors and capacitors is the 01005-chip component package. This component has a few different sizes ranging from 0.10mm (.004") X 0.30mm (.012") to .20mm (.008") X .40mm (.016") depending on the supplier and the type of component, such as resistor or capacitor.

The use of these miniature package sizes poses a number of challenges to the Surface Mount Technology (SMT) assembly process. The first challenge is to develop a cost effective screen-printing process using existing, proven, screen-print technology. The primary objective of this step is to develop reliable, high yield process, by transferring adequate amounts of paste to the board with minimum paste volume variation. Factors effecting the paste transfer operation are solder paste type (powder size), paste characteristics (flux type, lead in paste, etc.), printed circuit board pad design, stencil thickness, technology and aperture design along with printing parameters such as print speed, pressure, separation methods etc. Other factors that may also influence the paste transfer are flatness of the circuit board and the method of supporting the PCB during stencil printing.

A literature search in this area shows that there is not a significant amount of prior working the public domain regarding the 01005 assembly process, even though some assemblers have started using these tiny components. Most likely, the leading edge assemblers have done or are working on some in-house proprietary 01005 assembly process that is not public knowledge yet.

Our previous work[1,2,3] along with a few other published works indicated that a 0.003" thick stencil is required to achieve an acceptable solder paste release percentage and that nitrogen is required for complete reflow of the very small volume of solder paste. Clearly, this finding has some cost implications that need to be further investigated for a more cost effective solution. Keeping this in focus, the current experimental work explores different stencil technologies along with several aperture sizes & shapes for more consistent paste release. In addition, this study also explores the effect of enclosed pump head vs. standard squeegee blade printing for paste conservation.

Stencil Technology
The stencil plays an important role in the SMT printing process and is a major factor in the overall SMT assembly process yield. Since one major focus of this study is to understand the effect of stencil technologies on the overall paste release characteristic, further explanation of this subject will help the reader get a better understanding of the experimental approach.

The function of a stencil is to deliver a known and controlled volume of solder paste to device pads on the PCB. The printing process involves two-steps: (1) the aperture fill process, where solder paste fills the stencil aperture, and (2) the paste transfer process, where solder paste is transferred from the stencil aperture to the PCB pads. The fill process depends largely on solder paste, squeegee blade, solder paste roll, print speed, and aperture orientation with respect to print direction.

Paste transfer depends on the stencil technology and its wall smoothness, the stencil aperture design as related to the area ratio (ratio of the area under the aperture opening receiving the solder paste divided by the area of the inside aperture wall), solder paste, and the board separation speed from the stencil. The paste transfer process can be viewed as a competing process where the pad on the PCB below the stencil aperture is pulling the solder paste out of the aperture while the aperture sidewalls are holding the solder paste inside the aperture. When thinking of the paste transfer process in this manner, it is easy to understand why the area ratio and aperture sidewall smoothness have such a dramatic influence on paste transfer. Typical sidewall pictures for Electroform, Laser, and Laser with Electropolish and Nickel plate are shown in figure 1. As it can be seen from this figure, Electroformed stencil provides a much smoother wall compare to laser cut and Nickel plated. For standard stencil thickness, one would predict that the Electroformed stencil to perform (release characteristic) better than any other stencil technologies. One of the goals of this experiment is test out the theory for very thin stencil such as a 0.003” stencil.

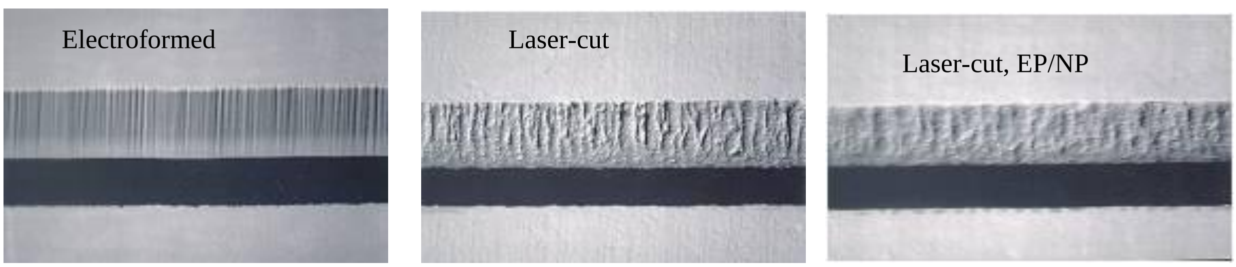

Figure 1. Typical sidewall image of various types of stencil technologies

Enclosed Pump Head
Enclosed print heads have been in use by board assemblers for the past several years as an alternate technology to conventional squeegee printing. By design, enclosed print heads offer several advantages one of which is isolating the solder paste from the ambient environment thereby stabilizing the rheology of the paste for longer periods. In addition, enclosed print heads decouple print speed from the pressure within the paste allowing for better control during the print operation.

With conventional metal blade printing, only two print parameters can typically be controlled: squeegee speed and squeegee pressure. The speed cannot be set so high that the paste does not roll as it moves across the stencil or too low so the print cycle time does not keep up with the manufacturing line. The squeegee pressure is usually set so that no paste remains on behind the stencil after a print stroke. Too high a pressure will damage the stencil by either coining the edges of the image or breaking the fine webs between small pitch apertures. Too low a pressure will cause insufficient paste transfer. Figures 2 and 3 show the difference between a conventional squeegee blade and enclosed pump head print process.

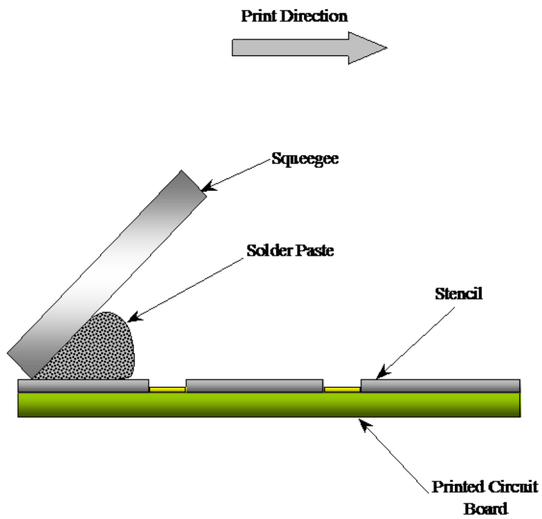

Figure 2. Squeegee blade printing

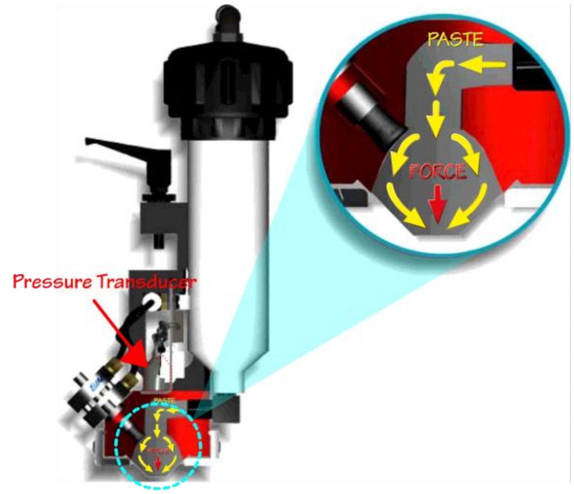

Figure 3. Cross-section of MPM's Rheopump

In an enclosed pump head, such as MPM's rheopump, system solder paste is fully contained and consequently not exposed to environmental conditions that typically shorten the life of the paste. This becomes very important when working with expensive paste such as type IV or V. In addition to cost saving by extending paste life, the enclosed pump head also provides enhanced printing capability. A fundamental difference between squeegee and enclosed printing resides in the fact that in squeegee printing, the pressure driving the paste in the aperture is a function of squeegee speed and downward pressure applied to the squeegee. In the enclosed print head, the same pressure is decoupled from the print speed allowing better control of the printing process. Given these facts one would predict better, more consistent paste transfer with an enclosed pump head.

Experimental Approach

For the sake of simplicity and manageability, the experimental part of this study was divided into three parts. Stencil screening, printing and reflow. Detail description of each part is given below. Figure 4 shows the standard Speedline test vehicle, which was used for all three experiments. A detail description of the test vehicle can be found else where[1]. Based on the results from a previous study[1, 2], the aperture design for the stencil was slightly modified to learn its effect on the overall paste release characteristic. Figure 5 shows the aperture layout for the 0^0 pad orientation for 01005 component pads and figure 6 shows the location of each aperture on the 0^0.

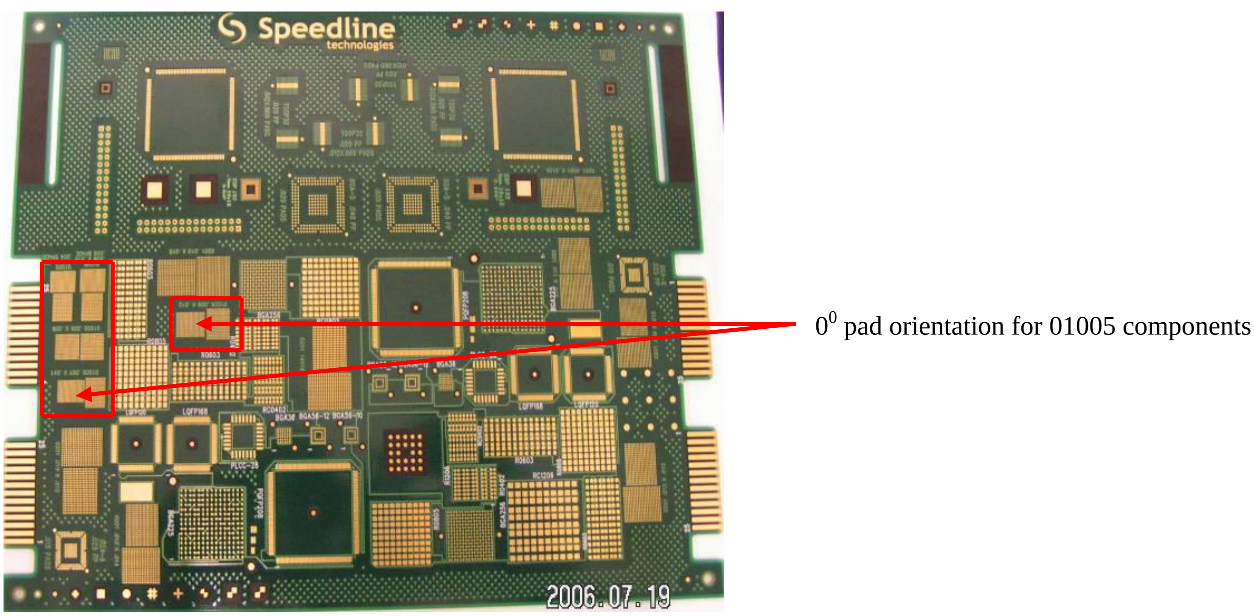

Figure 4. Test Vehicle

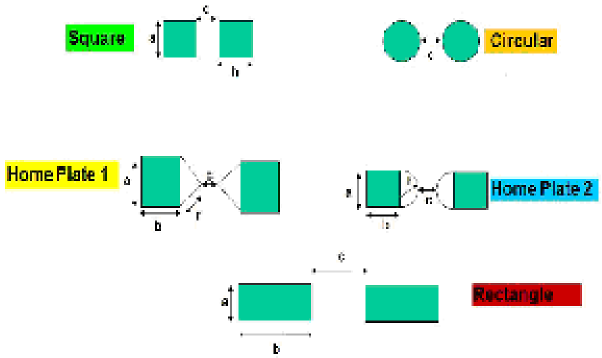

Figure 5. Five different aperture shapes

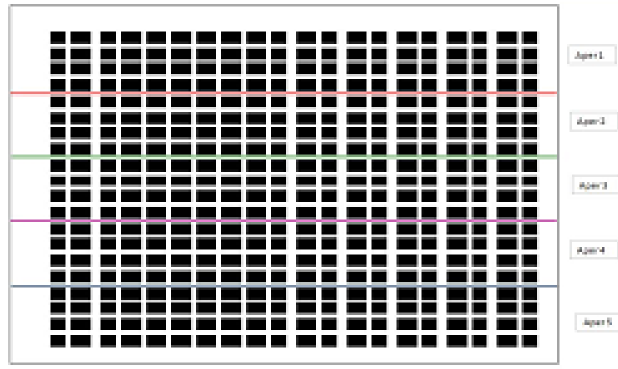

Figure 6. 0 degree pads divided horizontally

All three experiments were conducted using an MPM Accela printer, Electrovert Reflow oven, Juki Pick&Place, Indium type 3 and type 4 pastes, CyberOptic SE300 SPI. Prior to the start of the experiment, a gage repeatability study was conducted on SE300 to ensure solder paste inspection capability. A P/T (Precision to Tolerance) ratio of <10% was achieved for height, area and volume measurements. The detail of the gage study can be found elsewhere[3].

Stencil Screening

The primary objective of the stencil screening experiment was to understand the influence of stencil technologies, such as laser cut, E-fab, Ni coated, and stencil wipe method on the paste release characteristics. The ultimate goal was to choose two stencil technologies and one wipe method that will be included in the printing experiment. Based on the results from previous study[1], the best stencil thickness (3mil) and paste (type 4) combination was chosen for this screening experiment. To reduce noise in the experiment, 2 boards were printed per stroke direction per stencil type. The experimental matrix for the stencil screening experiment is shown in table 1.

Table 1. Experimental matrix for stencil screening experiment

Stencil type	Stroke direction	# of boards	Wipe method
Laser	F to R	2	With solvent
Laser	R to F	2	W/O solvent
E-Fab	F to R	2	With solvent
E-Fab	R to F	2	W/O solvent
Ni plated	F to R	2	With solvent
Ni plated	R to F	2	W/O solvent

The response was chosen to be the volume of the stencil printed "brick'" as measured by CyberOptic SE300 SPI system. The absolute volume measured by the SPI system was then converted to "transfer efficiency" using the equation below:

TE (Transfer Efficiency) = Measured Volume/Theoretical Volume of the Aperture * 100

Results from location 1 (8 x 10 mil pad with 4 mil spacing) and 5 (8 x 12 mil pad with 8 mil spacing) are presented in figures 7a and 7b respectively. As it can be seen from these figures, for most all aperture shapes, laser cut stencil provided slightly higher paste transfer than E-fab and Ni coated. We also observe that the circular aperture provides better paste transfer followed by the rectangular aperture compare to square or home plate apertures. When advance statistical analysis was conducted on a home plate 1 aperture design, which is common to all pad locations, the result showed that there was no statistically significant difference between laser cut and E-fab, while the Ni plated stencil showed a significantly different result. This result is shown in figure 8. This is somewhat unexpected, since the popular belief is that E-fab has significantly better release characteristic than laser cut stencils. For the current experimental set up with 3mil stencil and type 4 paste, this was clearly not the case. Further analysis is under way to better understand the effect of stencil technology on miniature component stencil printing and will be publish at a later date. Based on this result, laser cut and E-fab stencil were chosen to be included in the print experiment. Within the confinement of this experiment, wipe method showed no significant effect on the paste transfer. Based on this result solvent wipe method was chosen to ensure complete cleaning after each print stroke.

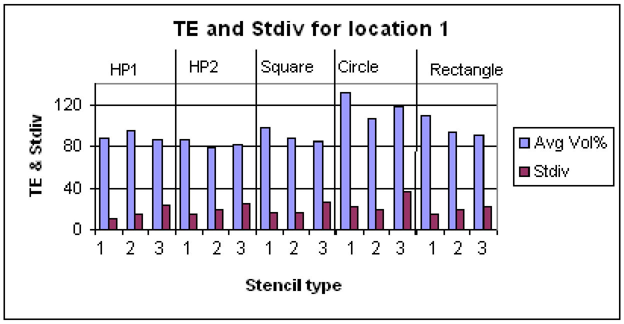

Figure 7a. TE and Std dev of volume for location 1

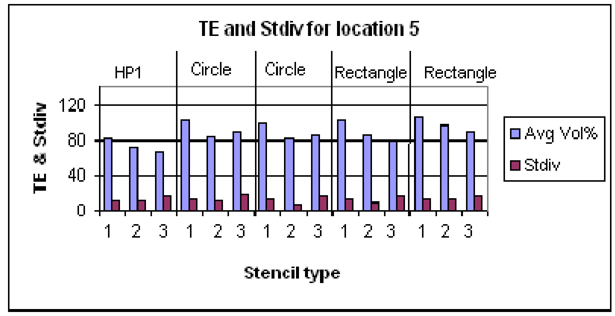

Figure 7b. TE and Std dev of volume for location 5

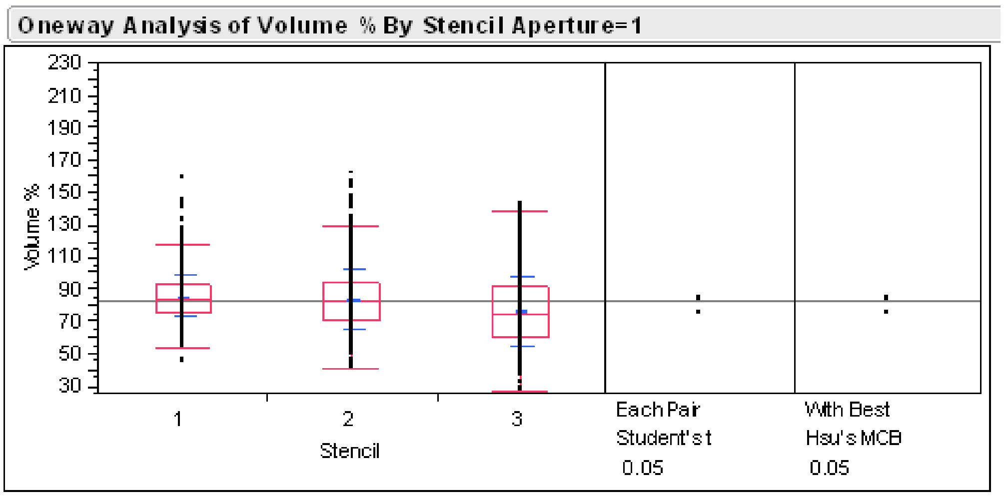

Figure 8 One way analysis of volume % for HP1 aperture shape

Printing Experiment

The paste transfer efficiency part of the experiment was a factional factorial design as shown in table 3. This experiment was design very similar to the previous study[1] with the exception of two new print variables, squeegee type and separation method. The hypothesis here was that the enclosed pump head and enhanced separation method may improve paste release characteristics. The factors and level setting for the print DOE are shown in table 2 and the standard order experimental design is shown in table 3.

Table 2. Factors and level setting for print DOE

		Levels		
Factors	Parameter	(-)	(+)	Comments
SQT	Squeegee Type	Blade	Pump	10 inches
PT	Paste Type	Type 3	Type 4	Indium Paste
ST	Stencil Technology	Laser	Efab	Laser /Electroform
STK	Stencil Thickness	3 mil	4 mil	3 mil / 4 mil
SM	Separation Method	No Snap off	Stepped	
PS	Print Speed	1.5 ips	3.0 ips	ips

Table 3. Standard Run Order Table for Print DOE

Qty	Treatment	RO	SQT	PT	ST	STK	SM	PS
4	3	1	-1	-1	1	-1	1	1
4	4	2	-1	-1	1	1	-1	-1
4	2	3	-1	-1	-1	1	1	1
4	1	4	-1	-1	-1	-1	-1	-1
4	6	5	-1	1	-1	1	-1	1
4	7	6	-1	1	1	-1	-1	1
4	8	7	-1	1	1	1	1	-1
4	5	8	-1	1	-1	-1	1	-1
4	10	9	1	-1	-1	1	1	-1
4	12	10	1	-1	1	1	-1	1
4	9	11	1	-1	-1	-1	-1	1
4	11	12	1	-1	1	-1	1	-1
4	14	13	1	1	-1	1	-1	-1
4	13	14	1	1	-1	-1	1	1
4	16	15	1	1	1	1	1	1
4	15	16	1	1	1	-1	-1	-1

Printing Experiment Result

DOE analysis was conducted using JMP statistical software with Transfer Efficiency (TE) and standard deviation as the response variable. Even though the experiment included various locations on the board, aperture shape and two different pad orientations, presenting the entire analysis within the restriction of this paper is impractical. For sake of simplicity, HP1 aperture shape along with 0^0 pad orientation will be the focus of this discussion.

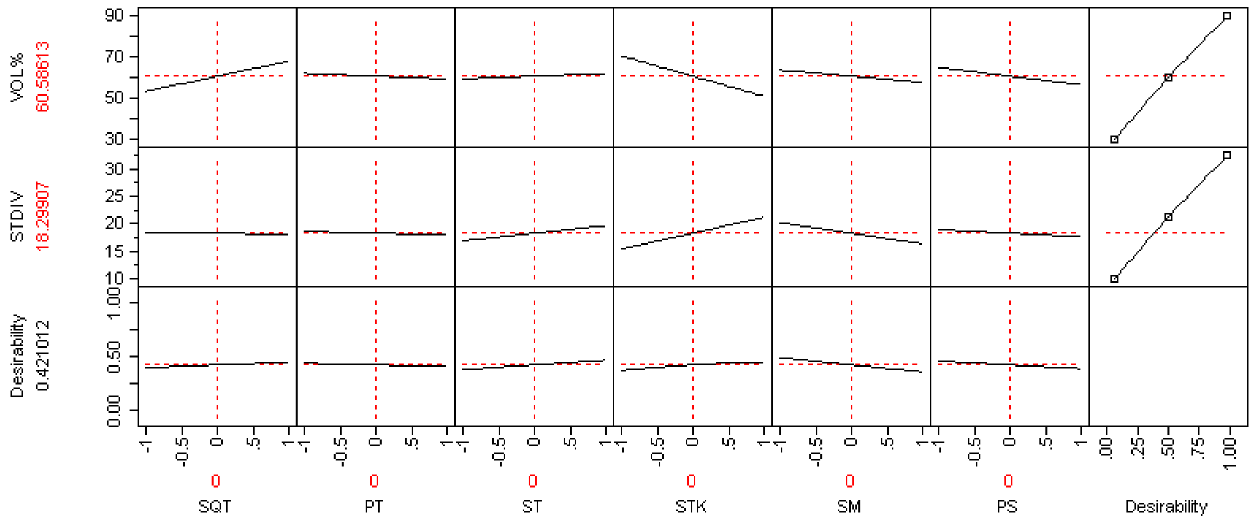

Figure 9. Main effect plot for HP1 aperture shape

The main effect plot shows that stencil thickness has the most significant effect in respect to paste transfer and standard deviation. We see here that the 3mil stencil provides higher paste transfer with a lower standard deviation which agrees with our previous finding and conclusions by other researchers[4, 5]. Squeegee type also appears to have a significant effect on the paste transfer. As it was expected, enclosed pump head definitely provides better paste transfer than the conventional squeegee blade. Other factors show little to no significant effect on paste transfer or standard deviation.

Both Pareto and normal probability charts confirms the main effect plots conclusion. In addition, it shows that there is no significant interaction-taking place between the factors. This result is shown in figure 10 and 11.

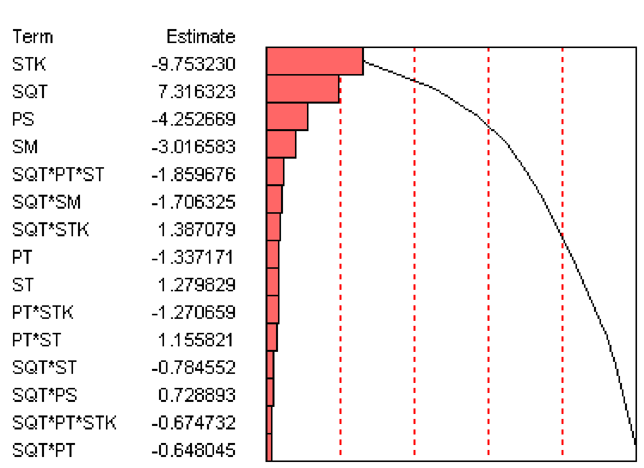

Figure 10. Pareto chart for TE

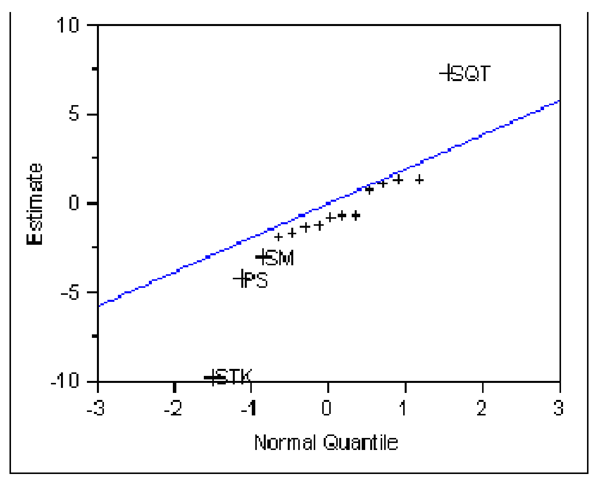

Figure 11. Normal probability plot for TE

Reflow Experiment

The reflow part of the experiment included 4 factors, out of which one was printing related and three were oven related. Stencil thickness (3mil), paste type (type 4) and squeegee type (blade) was held constant through out the reflow experiment. The experimental matrix is presented in table 4a and 4b. Similar to the print experiment, a fractional factorial DOE was developed for this experiment. The primary focus of this study was to understand the effect of the reflow environment and temperature profile on the reflow characteristic of the paste. Two boards per treatment combination were printed and reflowed without any component placement. This approach was chosen due to high cost of 01005 components. A subsequent experiment is under way to learn more about the factor influence in combination with the component placement. The two temperature profiles used in this experiment are shown in figure 12a and 12b.

Table 4a. Factors and level setting for reflow DOE

		Levels		
Factors	Parameter	(-)	(+)	Comments
RP	Reflow Profile	Ramp	Soak	
RA	Reflow Atmosphere	Air	Nitrogen	
PT	Paste Type	Type 3	Type 4	Indium Paste
OC	Oxygen Content	50 ppm	500 ppm	ppm

Figure 4b. Standard order design table for reflow DOE

Qty	Treatment	RO	PT	RP	OC	RA
2	2	1	1	-1	-1	1
2	4	2	-1	-1	1	1
2	8	3	1	1	1	1
2	5	4	-1	1	-1	1
2	1	5	-1	-1	-1	-1
2	6	6	1	-1	1	-1
2	3	7	1	1	-1	-1
2	7	8	-1	1	1	-1

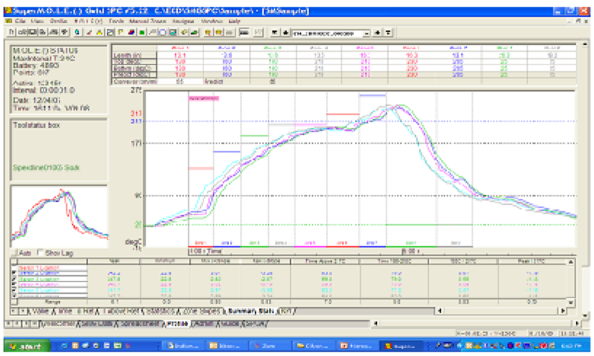

Figure 12a. Soak profile

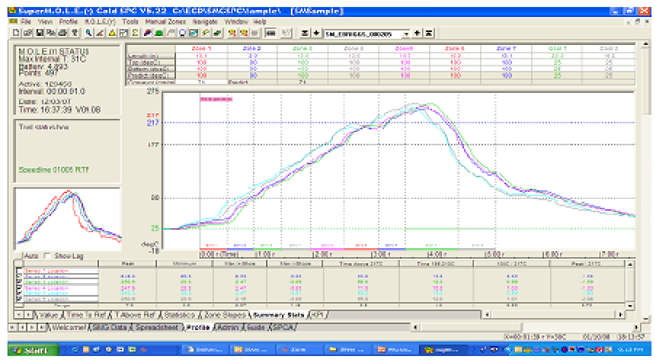

Figure 12b. Ramp profile

Reflow Results

Quantitative results from the reflow experiment are shown in figures 13-14. Figures 13a and 13c show the typical examples of the board reflowed at 50ppm (nitrogen environment) oxygen with ramp profile and soak profile respectively. Figures 13b and 13d show boards reflowed at 500 PPM (nitrogen environment) oxygen with ramp and soak profile respectively. As it can be seen from these four images, all solder reflowed completely without any significant difference. However, the boards reflowed in an air atmosphere showed different results. Figures 14a and 14b show boards reflowed in an air atmosphere with ramp and soak profiles respectively. As it can be seen from figure 14b, the soak profile in air produces very poor results, including evidence that the solder balls in the paste did not reflow.. The ramp profile produced better results than the soak profile,, although it showed dull appearance with some evidence of non-reflowed solder balls (not shown in the image).

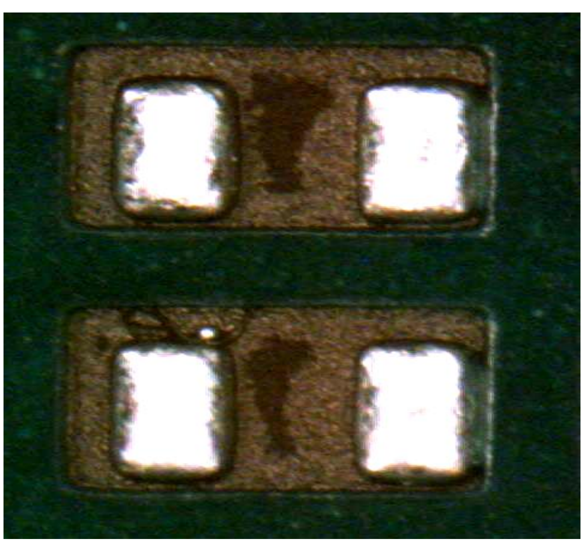

Figure 13a. Ramp profile with 50 PPM of Oxygen

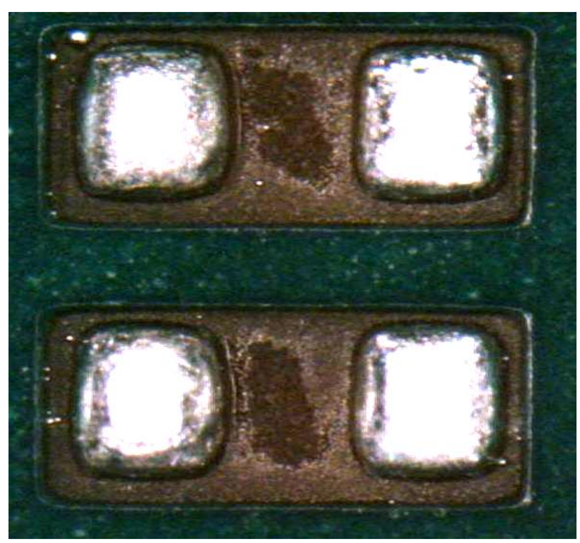

Figure 13b. Soak profile with 500 PPM of Oxygen

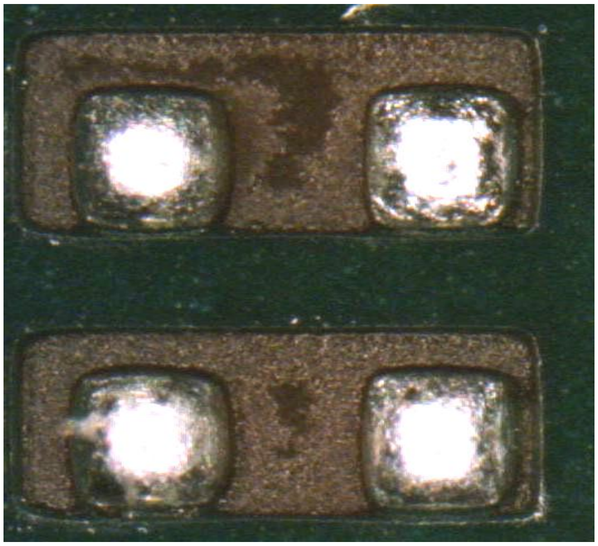

Figure 13c. Soak profile with 50 PPM of Oxygen

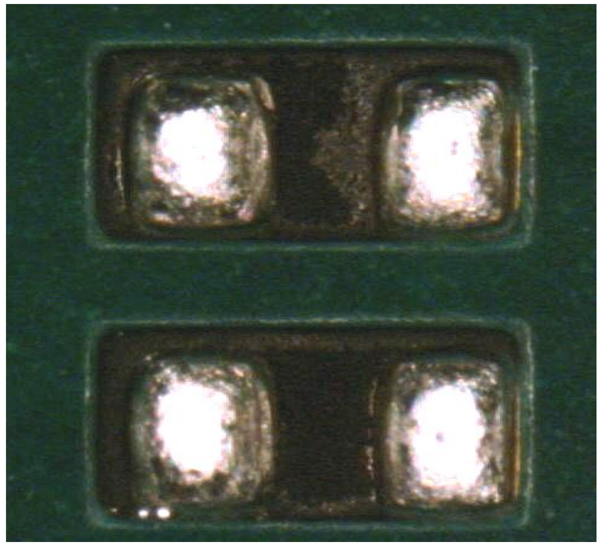

Figure 13d. Soak profile with 500 PPM of Oxygen

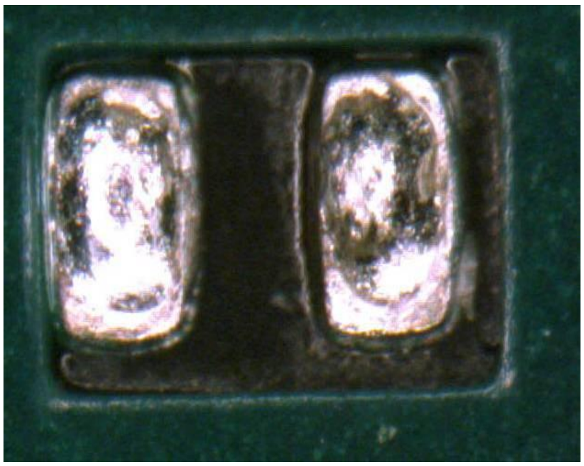

Figure 14a. Ramp profile in Air

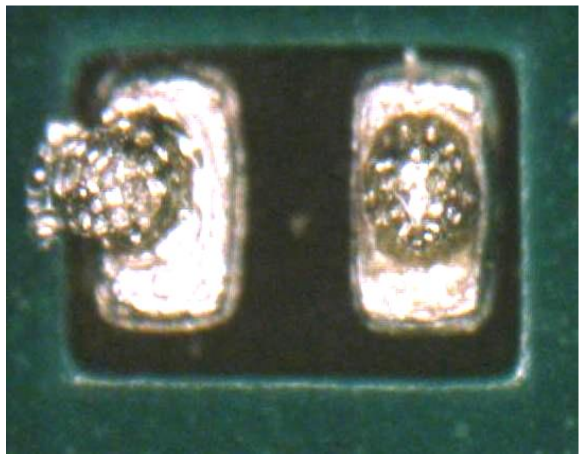

Figure 14b. Soak profile in Air

Summary and conclusion

Multiple DOE's were performed to further understand the effect of various printing and reflow factors on the overall assembly process of 01005 passives. Various statistical analyses were performed to determine the best stencil technology and aperture shape combination to provide best paste transfer. It was found that 3mil stencil and type 4 paste, laser cut and E-Fab stencils performed at a comparable level while Ni plated stencils were somewhat inferior. We also observed that circular and rectangular shape aperture, regardless of stencil technology, performed at higher transfer efficiency level than any other aperture shape.

Similar to previous observations, this study found stencil thickness to be the dominating factor in paste transfer, regardless of stencil technology and aperture shape. Through standard deviation analysis it was observed that 3mil stencils not only provided higher paste transfer but also had lower standard deviations. This indicates 3mil stencils provide a more stable transfer process compare to 4mil stencils. Another significant factor in respect to paste transfer was determined to be the type of paste delivery system. An enclosed pump head consistently provided higher paste transfer compare to a standard squeegee blade. It was encouraging to see that solder paste type (i.e. 3 or 4) had no significant effect of the paste transfer efficiency as the cost of type 4 paste is typically higher.

The reflow part of this experiment was somewhat limited as it was performed without any components. Regardless, the results suggest (similar to other findings) that nitrogen definitely improves reflow characteristics of the solder paste. The results also suggest that there might be a "sweet spot" (reflow profile) that can provide reflow characteristics similar to nitrogen environment. This is evident in results for reflow under air at different reflow profiles. Further investigation is necessary to confirm this observation.

Acknowledgements
First and foremost, the "authors" would like to thank Ed Briggs from Indium Corp. for his countless hours of contribution to this project. Ed was instrumental in running the experiment and making very valuable suggestions in data collection and analysis. The authors would also like to thank Paul Haugen from CyberOptics Corp. for providing the Solder Paste Inspection (SPI) system and countless hours of support in collecting and understanding SPI output. Without the help of Ed and Paul, this project would not have been possible.

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