Evolution and Applications of Fine-Feature Solder Paste Printing for Heterogeneous Integration

Evan Griffith, Sze Pei Lim
Indium Corporation
301 Woods Park Drive
New Hartford, NY 13413 USA
Ph: 315-893-4900
Email: egriffith@indium.com

Abstract

The semiconductor industry is quickly adopting heterogeneous integration as a solution to allow a large number of dies to be packed onto smaller components, improving cost-performance while expanding functionality. As such, the printing of solder paste formulated for System in Package (SiP) applications is becoming more difficult, with many depositions designed at one point as extremes during testing becoming the norm in industry. This paper will first briefly discuss the evolution of soldering material for heterogeneous integration, as some aspects of solder paste manufacturing, such as powder size, differ significantly from larger scale soldering applications. The objective of this study is to illustrate critical parameters for the printing of SiP paste. Multiple parameters that are important for SiP paste printing applications will be discussed, such as the metal load optimization, paste rheology, and metal powder size, type, and quality.

Key words

SiP, slump, solder paste, solder paste inspection, 008004

I. Introduction

The need for Heterogeneous Integration stems from the observed abating of Moore's Law. With both physical and economic constraints having become more evident with regard to process nodes, a number of innovations have been developed to keep up with the pace Moore's Law has set since the invention of the integrated circuit. System-in-Package (SiP) is one of these innovations; a version of the package on a package (PoP) packaging method where components such as logic and memory chips are stacked on top of each other in one package. SiPs can be compared to System on a chip (SoC) solutions, the contrast being that SiPs are not constrained to a single semiconductor die.

One of the primary driving factors of SiP devices are market trends in connected electronic devices, such as in wearables and "smart" technology including internet of things (IoT) and the ever-evolving mobile communications field. These factors include devices in the automotive market, as vehicles become increasingly connected due to infotainment advances as well as the advances that have arisen towards automatic driving vehicles. All of these new technologies require advanced technology to meet consumer needs, and SiP technologies are one of the many ways which electronics manufacturers are able to meet those needs.

As electronic components have evolved and have trended towards miniaturization and more complex package designs, so too has soldering material evolved to fit these needs. With respect to printing applications, which is the focus of the printing study in this paper, we can differentiate printing technologies between newer processes for SiP applications, and older processes for surface mount technology (SMT) applications. The clearest observation to make is that as electronic components have decreased in size and increased in complexity, the corresponding solder deposits need to be smaller as well. This leads to much smaller stencil apertures than are commonly used in SMT technology, both in diameter and area ratio. For SMT technology, a common metric was that in order to achieve consistent printing, the area ratio of an aperture must be greater than 0.66 [1]. However, for SiP applications, thin stencils and small apertures decrease the area ratios of apertures further, with area ratios commonly measuring in the 0.4-0.5 range [2]. Thus, an appropriate small powder size and flux chemistry for a solder paste must be chosen in order to both fill the aperture, and provide enough force to release from the stencil with such a small amount of solder on the deposit.

II. Solder Paste

A. Solder Powder

Solder powder is classified by type according to IPC J-STD-005A, with the relevant powder types for SMT and SiP shown in Table 1 [2]. Solder powder Types 3-5 are commonly used for SMT applications; SiP applications typically require powder types 6 and 7. This guideline results from the standard convention that consistent solder deposits should have roughly six solder particles across a given aperture; smaller apertures therefore require smaller solder particles.

Table 1. Powder Sizes

Powder Type	Powder Size (um)	Minimum Stencil Aperture (um)	Approximate Surface Area Ratio
3	25-45	270	1.0
4	20-38	230	1.2
5	15-25	150	1.9
6	5-15	90	3.7
7	2-11	66	5.6

B. Flux System

In semiconductor applications, flux systems can be classified as no-clean, water soluble, and ultra-low residue. Ultra-low residue flux is particularly attractive for SiP applications, as cleaning between increasingly small solder deposits becomes naturally more difficult. ULR flux systems also provide the benefit of removing costs associated with cleaning and the chemical processes associated with that cleaning.

C. Paste Rheology

The transition from SMT technology to SiP technology also causes changes with solder paste rheology with respect to particle size. As particle size decreases for fine-feature printing, the viscosity of solder paste increases due to its thixotropic nature. Solder paste rheology is the driving factor behind the ability of solder paste to fill an aperture, the ability for solder deposits to release from the aperture onto the substrate (transfer efficiency), and solder deposit shape. It has been shown that using finer solder powders can improve the transfer efficiency of a solder paste, but many factors need to be considered, such as the shape of the pad and the presence or lack thereof of solder masks [3].

D. Slump Behavior

Slump refers to an expansion of a solder paste deposit in the x-y direction caused by gravitational forces after a print. Slump is directly affected by the paste's metal load; a low metal load will cause the paste deposit to slump while a high metal load will give the paste a very high yield stress and prevent it from properly filling and releasing from the aperture. Metal load optimization is therefore a very important parameter when conducting a printing experiment.

E. Stencil Life

It is important for a solder paste to have a long stencil life is important to ensure print-to-print consistency. High-volume manufacturing environments typically require a solder paste to have a 4-8 hour stencil life. It is important to note that decreasing the size of the solder powder for use in SiP applications can reduce the stencil life of a paste. Smaller powders naturally have more surface area, leading to increased oxidation reactions in the solder paste. Oxidation thickens the solder paste, leading to potentially clogged apertures and the solder paste sticking to the squeegee blades. Flux formulations are made with this oxidation in mind to slow the rate of oxidation.

III. Printing Experiment

In this study, several combinations of solder paste and aperture sizes were studied. Two flux vehicles each with three different powder distributions were studied; these solder paste specimens were then compared against a baseline powder with a third flux chemistry. Concurrently with this printing experiment, a separate experiment was conducted in order to investigate the effect of parameter changes on the Koh Young SPI used to measure solder deposit volume percentages.

A. Test Vehicle and Stencil Design

A test vehicle was chosen to quickly and easily analyze pads of different sizes. A test board from the manufacturing services company Jabil was used in this study. The pads of interest in this study are all adjacent to each other with pad sizes varying by 1 mil (25.4 microns) across a region. Pad regions are arranged in horizonal and vertical positions to mimic different squeegee wiping patterns. The pad surface finish is Cu OSP (Organic Solderability Preservative) and pads are both solder mask defined (SMD) and non-solder mask defined (NSMD). Both pad types were chosen for this study to analyze the effect of solder masks at small aperture sizes.

The stencil used in this printing experiment is a 50 um-thick laser-cut stencil with 1-to-1 openings for the Jabil test board. The aperture sizes and corresponding area ratios are shown in Table X.

B. Solder Paste Specimens

Three flux vehicles were chosen in this printing test: two no-clean fluxes and one water-soluble flux. The two no-clean fluxes were mixed with type 6 powder; however, three different paste distributions were used in this study: these distributions will be referred throughout this paper as Type 6 (T6) [powder distribution] 1, 2, and 3. Text about difference between the three. The two no-clean flux formulations were compared against a water-soluble flux with one powder distribution: T6 2.

For each powder distribution and flux vehicle combination, the optimal metal load was chosen based on results from previous studies. Changes in powder distribution alter the viscosity of a solder paste sample, thus previous work was referenced to optimize the metal load of the pastes. A table illustrating the paste specimens can be seen in Table 2.

Table 2. Paste Specimens and Associated Metal Loads and Viscosities

Flux Vehicle	Powder Type	Metal Load	Viscosity (Poise)
A	1	87.5%	1,643
	2	87.0%	1,946
	3	87.5%	1,981
B	1	88.0%	1,682
	2	87.5%	1,875
	3	88.0%	1,921
WS	2	89.0%	3,217

C. Printing Parameters

Print speed was chosen for each paste specimen so that the minimum pressure needed to wipe the stencil clean was required for each print. The corresponding print parameters are shown in Table 2. It is important to minimize printing pressure when printing for fine-feature apertures as excessive pressure can cause movement of the printing surface during a stroke. Additionally, stencil thicknesses for fine-feature printing are becoming thinner and thinner, excess pressure can cause stencils to wear faster, potentially causing avoidable operations delays and costs. Cleaning frequency was set to each board, with a cleaning mode of wipe/vacuum/dry (W/V/D).

Table 3. Printing Parameters for Each Paste

Flux Vehicle	Powder Type	Squeegee Pressure (kg)
A	2	5.5
	3	6
	1	5
B	2	5.5
	3	5.5
	1	5.5
WS	2	8

D. Equipment and Tooling Setup

Printing was conducted using a DEK Horizon Printer with a 12" squeegee blade at a 60-degree wiping angle. Printed boards were analyzed with a Koh Young SPI.

It is important to note that with thinner stencils and smaller solder prints, the margin of error with the parameters of the Koh Young SPI becomes much smaller. The two main parameters that are often adjusted to obtain the most accurate printing data on the SPI are threshold height and extended region of interest (ROI). Threshold height is the height which the SPI sets as the upper limit for solder deposits; a deposit exceeding this height runs the risk of being measured as having excessive volume percentage. The extended ROIs are the areas around each pad that the Koh Young actually inspects when measuring a solder deposit. These are usually set to be squares, but can be modified based on the pad dimensions.

The Koh Young comes with recommended settings to use for both threshold height and extended ROIs for a given stencil height. However, with fine feature printing on stencils that extend below 75 um, these recommended settings can cause issues with reading excessive prints. The reasons for this require more study, but a potential reason might be small differences between the positions of the solder mask and the rest of the test vehicle in the z-direction. If the copper mask sits below the surrounding board material, there may be issues that arise when the Koh Young goes through its Bare Board Teach process regarding where the height of a solder deposit is measured from. For thick stencils, this discrepancy may not matter as many studies have been conducted with expected results. However, for thin stencils, following the recommended parameter settings for a given stencil thickness leads to excessive prints being measured even if the solder bead visually looks acceptable. For this study, the same program was used for each solder specimen in order to generate meaningful data and to compare these specimens to each other in a vacuum. Further work is needed to ensure proper inspection is being done with regards to parameter optimization and test vehicle design.

E. Slump Test Experiment

To compare the effects of slump for each of these pastes, a slump analysis was conducted in accordance with IPC standards. Paste was printed using a 60 um stencil thickness in a pattern in accordance with the IPC-A-21 and IPC-A-20 slump patterns. Boards were then either left at room temperature for 20 minutes or baked at 180 C to simulate both cold and hot slump. Each pattern was then observed and all gaps at which bridging occurred were noted.

IV. Results and Discussions

A. Comparison of different solder pastes

The following figures in this section show the comparison of different solder pastes both to each other and to the water-soluble baseline. The solder pastes will be differentiated in this section by letter (i.e. Paste A and Paste B for no-clean fluxes 1 and 2) and by number (i.e. Paste 1, 2, and 3 for the different powder distributions).

Figures 1 and 2 show the deposit volume comparisons of the different paste for different area ratios. The area ratio in Figure 1 was chosen to match the area ratio of an 008004 pad for a 50-micron thick stencil. It is clear to see that the A-series of fluxes perform better than both the B-series and the baseline water-soluble paste. There are very few insufficient deposits at this pad size with the A-series pastes. Among the A-series pastes, pastes A1 and A2 show the tightest distributions, while paste A3 has a slightly larger distribution and shows insufficient prints. Figure 2 moves down 25 microns in pad size. The improvement of the A-series pastes is still prevalent at this pad size over the B-series pastes and the baseline paste. Insufficient deposits start to appear with paste A1, while paste A2 still shows no insufficient prints at this smaller pad size.

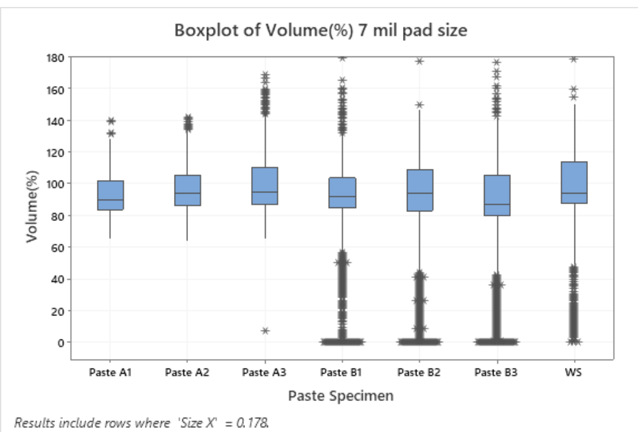

Figure 1. Paste Comparison for 7 mil Pad Size

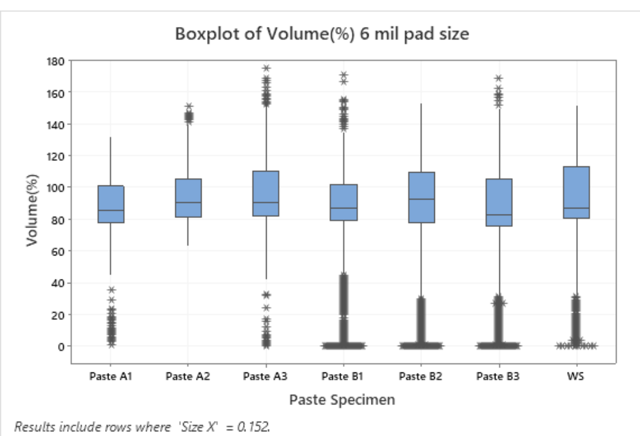

Figure 2. Paste Comparison for 6 mil Pad Size

Figures 3 and 4 show a response to pause experiment between pastes A1 and A2. Six boards were printed from a cold printer startup with no kneading done on the paste. Printing was then placed on a 1-hour pause before printing 20 additional boards. It is difficult to draw conclusions with respect to printing consistency with this chart, however it is important to note that paste A1 printed more consistently at startup than paste A2, even though paste A2 showed fewer insufficient deposits at the same pad size.

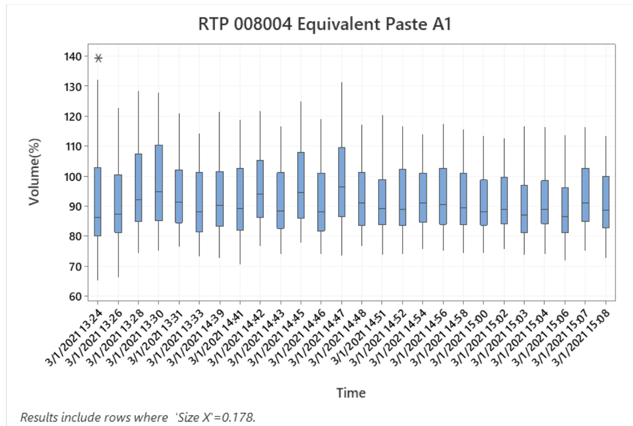

Figure 3. Response to Pause for Paste A1

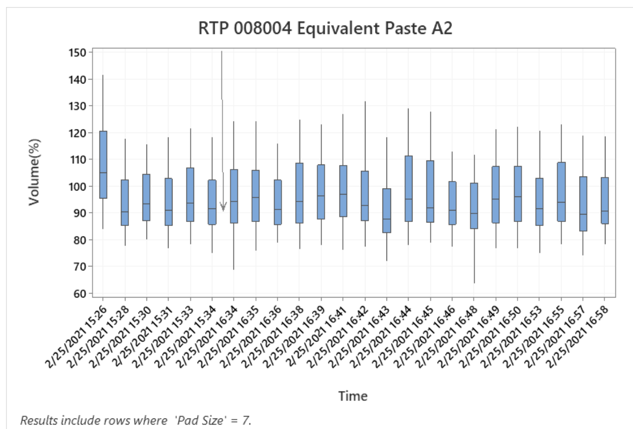

Figure 4. Response to Pause for Paste A2

B. Effect of Koh Young Parameters

The previous results clearly show the importance of choosing a correct flux system and solder powder formulation for achieving consistent printing for SiP applications. However, it is important to note that these experiments were conducted in a relative setting to easily compare specimens. Further work needs to be done with respect to SPI programming and test vehicle design to achieve results which may be more applicable to high-volume manufacturing settings.

Figures 6 and 7 show results of a separate printing test which fed one printed board into multiple Koh-Young programs which varied two parameters, threshold height and extended ROIs. It is important to note that this program had different parameters than the program which produced the printing data in the previous sections, so one cannot compare the differences in volume % between this printing test and the previous printing test.

In Figure 6, there is a clear trend that shows the Koh Young measures a smaller volume % as you increase the threshold height. This is reasonable because as you increase the height beyond which the Koh Young would read an excessive height value, the calculated volume would decrease from the lower read height. For a 50 micron stencil, the recommended threshold height is 20 microns.

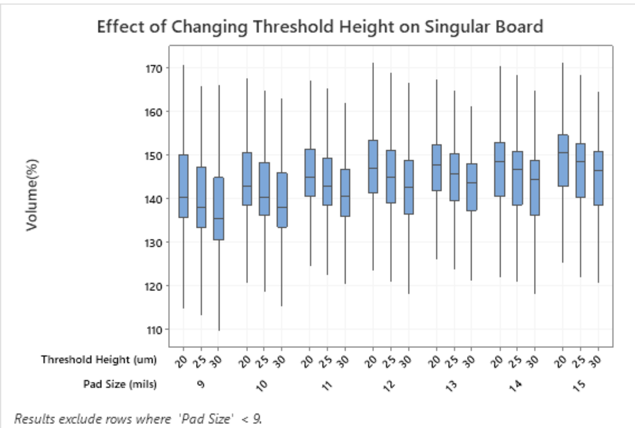

Figure 6. Effect of Varying Threshold Height on Single Board

In Figure X, the results are shown for varying the extended ROI parameters on the Koh Young. The interesting trend here is for smaller pads, decreasing the area which the Koh Young inspects tightens the spread of volume %, but that trend reverses once pad size increases beyond 9 mils. As the Koh Young decreases the extended ROIs, solder deposits on larger pads may extend beyond the ROI limit and are not captured by the SPI, explaining the larger variance for small ROIs and the fact that the IQR extends to lower volume percentages. When printing for SiP applications, it is important to consider the extended ROIs with respect to the size of the pads; shrinking the ROIs for SMT applications for larger pad sizes may not necessarily improve results.

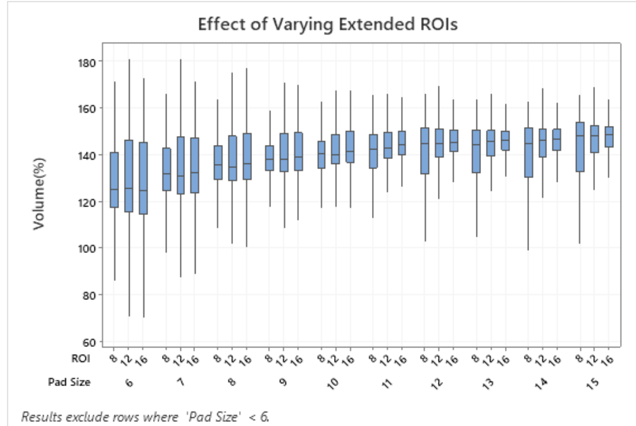

Figure 7. Effect of Varying Extended ROIs on Single Board

C. Process Capability Study

Cp, Cpk, and Ppk values were calculated using Minitab software with a reference specification of 50%-150%. Table 4 shows process capability of all pastes using various pad sizes.

Table 4. Cpk, Ppk, and Cp of Different Pastes

Flux Vehicle	Powder Type	Pad Size (mil)	Cp	Cpk	Ppk
A	2	6	1.24	1.07	1.04
		7	1.52	1.40	1.35
	3	6	1.01	0.93	0.91
		7	1.27	1.24	1.20
	1	6	1.22	0.95	0.92
		7	1.56	1.33	1.30
WS	2	6	0.83	0.72	0.61
		7	1.00	0.97	0.85
B	2	6	0.62	0.45	0.44
		7	0.75	0.59	0.58
	3	6	0.63	0.43	0.43
		7	0.67	0.48	0.48
	1	6	0.9	0.69	0.68
		7	0.98	0.83	0.81

D. Slump

Table 5 shows the results of the slump test. The largest gap at which bridging occurred for each flux and powder combination is noted. While data was collected for both horizontal and vertically oriented patterns, only horizontal data is shown as the most interesting trends were noticed at this orientation. All paste specimens either exhibited no bridging or only one gap bridged at the time of printing.

The points which the paste failed the slump tests are in bold in Table 5; the only pastes which failed were Paste B1 and the water-soluble baseline paste. Paste A shows relative consistency across all three powder types. This is interesting to note because Paste A1 shows a lower viscosity than Pastes A2 and A3, which in theory could negatively impact slump, however there was no large impact on slump. Paste B2 shows similar slump performance to the A-series of pastes, however Pastes B1 and B3 both perform much worse with hot slump than the aforementioned pastes. This trend is also apparent with the water-soluble baseline.

Table 5. Slump Comparison

Flux Vehicle	Powder Type	Temperature	Pitch/Pad Size	Orientati	Largest Bridged Gap (mm)
A	1	25 C	0.63mm/0.33x2.03mm	Horizonal	0.15
			0.40mm/0.20x2.03mm	Horizonal	0.125
		180 C	0.63mm/0.33x2.03mm	Horizonal	0.15
			0.40mm/0.20x2.03mm	Horizonal	0.15
	2	25 C	0.63mm/0.33x2.03mm	Horizonal	0.15
			0.40mm/0.20x2.03mm	Horizonal	0.125
		180 C	0.63mm/0.33x2.03mm	Horizonal	0.15
			0.40mm/0.20x2.03mm	Horizonal	0.15
	3	25 C	0.63mm/0.33x2.03mm	Horizonal	0.1
			0.40mm/0.20x2.03mm	Horizonal	0.125
		180 C	0.63mm/0.33x2.03mm	Horizonal	0.15
			0.40mm/0.20x2.03mm	Horizonal	0.15
B	1	25 C	0.63mm/0.33x2.03mm	Horizonal	0.15
			0.40mm/0.20x2.03mm	Horizonal	0.15
		180 C	0.63mm/0.33x2.03mm	Horizonal	0.2
			0.40mm/0.20x2.03mm	Horizonal	**0.2**
	2	25 C	0.63mm/0.33x2.03mm	Horizonal	0.15
			0.40mm/0.20x2.03mm	Horizonal	0.125
		180 C	0.63mm/0.33x2.03mm	Horizonal	0.15
			0.40mm/0.20x2.03mm	Horizonal	0.125
	3	25 C	0.63mm/0.33x2.03mm	Horizonal	0.1
			0.40mm/0.20x2.03mm	Horizonal	0.1
		180 C	0.63mm/0.33x2.03mm	Horizonal	0.2
			0.40mm/0.20x2.03mm	Horizonal	0.175
WS	2	25 C	0.63mm/0.33x2.03mm	Horizonal	0.15
			0.40mm/0.20x2.03mm	Horizonal	0.125
		180 C	0.63mm/0.33x2.03mm	Horizonal	**0.25**
			0.40mm/0.20x2.03mm	Horizonal	0.2

V. Conclusion

In order to achieve consistent fine-feature prints for SiP applications, there are several attributes that need to be considered. These include both paste attributes such as powder size and distribution, flux vehicle, and slump behavior, as well as non-paste attributes such as printer parameters and SPI programming. SPI programming is of particular importance as SiP technology continues to evolve and component sizes get smaller; test vehicles and SPI parameters need to be properly suited for SiP applications as parameters for SMT applications may not carry over for SiP applications.

Acknowledgment

Special thanks to Indium Corporation's Clinton Simulation Lab and David Sbiroli for his help and support with performing the solder paste printing tests in their lab.

References

[1] Ed Briggs, Ron Lasky, "Best Practices Reflow Profiling For Lead-Free SMT Assembly", *SMTAI*, San Diego, October 2009.

[2] Sze Pei Lim, Kenneth Thum, Andy Mackie, "Fine Feature Solder Paste Printing for SIP Applications," *CSTIC*, March 2017.

[3] Briggs, "Meeting Future Stencil Printing Challenges with Ultrafine Powder Solder Pastes," *International Conference on Soldering and Reliability*, May 2014.