Optimizing Type 7 Solder Paste Formulation and Compatibility with Assembly Technology for Sub-75um System-in-Package Applications

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Abstract

For System-in-Package (SiP) assembly, solder paste printing remains the preferred solder application method of choice. However, as passive components (008004) and next-generation flip-chip components continue to shrink, smaller stencil openings are needed, and these small stencil apertures still need to achieve consistent printing. In addition, as component standoff height continues to decrease for fine-pitch applications, the cleanability of the final SiP build becomes a concern; for many applications that require water-soluble pastes, pure DI water becomes difficult to use when the standoff height lessens. This paper will investigate important parameters from a materials supplier's perspective for meeting the challenges of fine-feature solder paste printing and package assembly.

First, innovations in solder powder technology will be discussed, which allow for consistent solder paste (Type 7) printing at 60um apertures. Next, the effect of stencil technology will be discussed. Many stencil manufacturers are approaching a manufacturing limit both with respect to stencil thinness and aperture size. This paper will discuss two common stencil manufacturing designs, laser-cut and electroform, and present findings on the effect these designs have on solder paste print consistency. Lastly, solder paste cleanability will be discussed; the results of a study investigating novel Type-7 solder pastes for use with semi-aqueous cleaning technology will be presented. Important process considerations with respect to stencil and package cleaning will also be discussed.

Key words

About four to six key words or four phrases in alphabetical order, separated by commas.

I. Introduction

System-in-Package (SiP) assembly is a significant technology driver in the electronics assembly space. There has been continuing demand for innovative electronic devices across industries, including but not limited to 5G, Internet-of-Things (IoT), artificial intelligence, smart devices, and big data. From a manufacturer's perspective, the drivers behind this demand are that these devices need to be high-performing and come to the market quickly. SiP devices (and, by extension, other heterogeneous integration assembled packages) have been established and innovated in high-volume manufacturing environments to meet increased consumer demand.

As the trend toward miniaturization in SiP applications continues, from current 01005 and 008004 components to 0050025 for next-generation packages, the printing performance of solder paste becomes critical. The conventional SMT solder paste printing process using Type 3 or Type 4 powder size has evolved into a more complicated printing process for SiP, using Types 5, 6, 7, or even Type 8 powder size, with much smaller stencil apertures, thinner stencils, and more stringent requirements for allowed paste deposit variability. Solder paste formulation with these powder types needs to be carefully considered; attributes that may be relevant for SMT solder paste may not carry over to solder paste used for SiP assembly.

As packages get smaller and thinner, solder paste manufacturers need to consider attributes of SiP devices when designing an appropriate solder paste. The first of which is that solder interconnections are required to be smaller and tighter. This is driving current soldering materials technology to a different level in order to handle various challenges such as fine aperture printing and small dot dispensing, residue cleaning, and solder joint integrity, with insufficient print deposits being the common failure mode. These smaller print deposits are also being manufactured at a much tighter pitch to accommodate the number of chips that fit into a SiP. An incorrectly formulated solder paste for a tight-pitch SiP will inevitably lead to solder bridging issues. One method that certain manufacturers are using to mitigate this issue is by printing multiple solder deposits on the same pad. Warpage is another factor causing yield loss due to SiP substrates becoming much smaller and thinner. In addition, pressure to reduce costs pushes the industry for more cost-effective methods of assembly. From a chemistry standpoint, much of the advancements discussed in this paper will be focused on a novel solder paste designed for semi-aqueous cleaning processes due to the challenges of cleaning under low standoff height components and tight component pitches.

II. Solder Paste Formulation Advancements

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 [1]. Solder powder Types 3-5 are commonly used for SMT applications. SiP applications typically require powder types 6 and 7, with applications in the future heading toward Type 8 powder sizes. This guideline results from the standard convention that consistent solder deposits should have no more than six solder particles across a given aperture.

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
8	2-8	48	8.1

B. Flux System

In fine-feature applications, flux systems can be classified as no-clean, water-soluble, and ultra-low residue. Ultra-low residue (ULR) 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. For a comparison of these flux systems, see Table 2.

	No-Clean	Ultra-Low Residue NC	Water-Soluble
Flux Residue %	20-60%	0-10%	N/A
Cleaning Process	Solvent Clean or Not Needed	Not Needed	Water Clean
Compatibility with Underfill or Molding Compound	Typically low	Good	Good if completely cleaned

Table 2. Comparison of the mentioned flux systems

Flux homogeneity is also an important advancement that has been made for solder paste applications for SiP devices. Post-processing steps have been developed which remove air bubbles and any additional abnormalities from solder flux, which has the effect of improving the transfer efficiency of the associated solder paste. Any abnormalities in the flux vehicle naturally run the risk of causing defects when the stencil apertures are manufactured on the order of ~100 microns, so ensuring flux homogeneity is key. Figure 1 shows the difference between a homogeneous flux and a non-homogeneous flux.

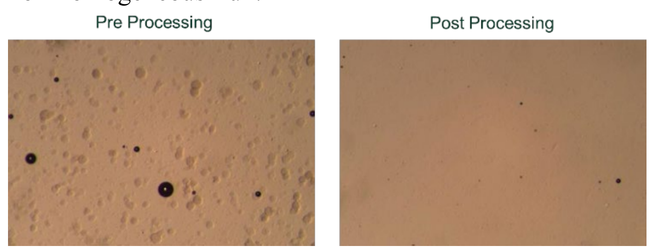

Figure 1. Solder flux with and without impurities

Another advancement in flux chemistry is novel flux chemistries which are designed to be cleaned with semi-aqueous cleaning solutions or saponifier technology. This flux chemistry is an attractive alternative to pure water-soluble chemistries, which are standard in SiP assembly [2]. This is because semi-aqueous cleaning solutions have a lower surface tension than pure DI water. That attribute allows for ease of cleaning on low (~60 micron) standoff height components while maintaining the cleaning benefits of pure water-soluble processes. Novel pastes have been developed for this system, and a Design of Experiment (DoE) is outlined later in the paper.

C. Paste Rheology

The transition from SMT technology to SiP technology also causes changes in 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 [3]. 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 [4]. The paste rheology can be further optimized by varying the metal load and flux rheology for better printability in SiP applications. The fine powder size required for good printability, in contrast, places a burden on the rheology improvement effort.

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. Figure 2 shows an example of a typical response-to-pause experiment which shows the effect of pausing printing for one hour after printing six boards. As shown in the figure, there is no statistically significant change in print performance after an hour pause after the sixth board, showing excellent stencil life at 75um apertures.

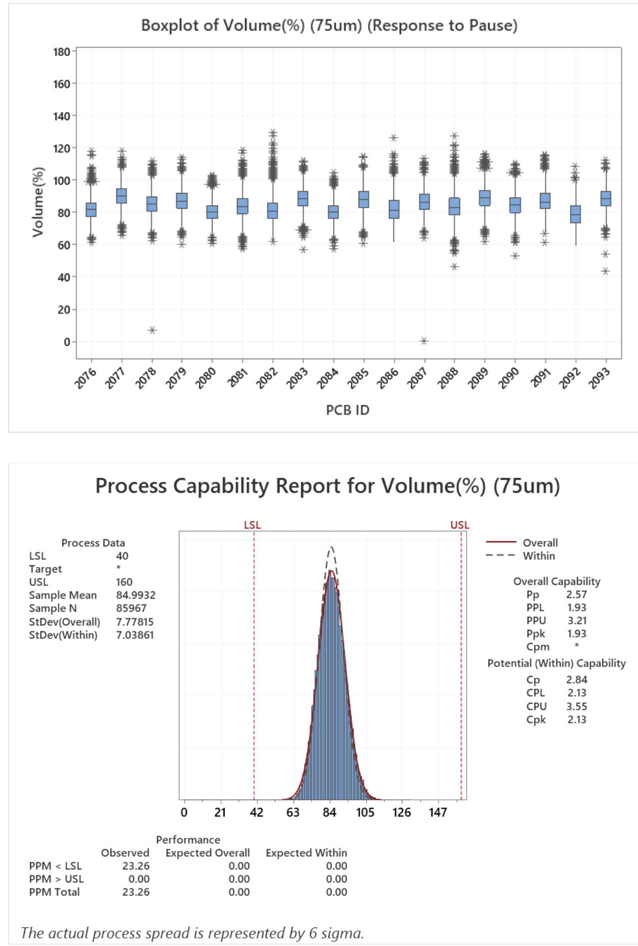

Figure 2. Response To Pause Test of T7 Solder Paste

F. Paste Tackiness

During the solder paste printing process, the paste is required to flow easily during printing, but not to flow at all afterwards. As powder size decreases, the tackiness of a solder paste typically increases. As such, it is important to formulate a solder paste such that the paste is sufficiently non-tacky to be released from the stencil aperture but tacky enough to hold onto the substrate and the components to be placed subsequently onto the paste after printing [3]. In order to meet the requirement of a SiP application, the rheology of solder paste has to be tailored to that application.

Figure 3 shows the comparison of paste tackiness when held at 50% relative humidity for 24 hours. This graph shows the average tackiness of five solder deposits measured at 2-hour intervals. At the beginning of data collection, the tackiness of T7 powder is higher than that of T6. However the values shift over time because of exposure to the humidity. It is important to note that the values remain consistent through 24 hours and do not drastically increase or decrease during this time period, ensuring consistent performance through 24 hours.

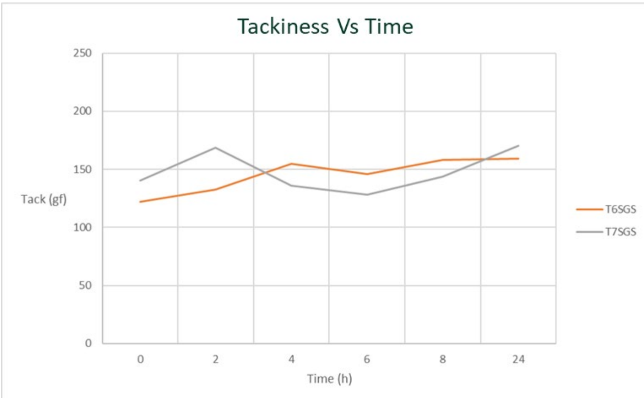

Figure 3. Tackiness over Time of SiP Solder Paste

II. Stencil Technology

In order to properly test solder paste formulated for SiP applications, a study was conducted in order to find the optimal stencil material at fine feature print deposits. Typically, electroform stencils and laser-cut stencils with nano-coating are two common processes used for fine-feature stencil manufacturing. The laser cut stencil process involves (1) processing Gerber data, and (2) cutting images [5, 6, 7]. Electroforming is an additive process [6, 7]. A mandrel is used as a base for the photoresist application and for resolution of the image. The mandrel is then placed in a bath where Ni is plated. The opening will be formed around the photoresist until the desired thickness of the stencil has been achieved.

To determine the optimal stencil material for SiP applications, a solder paste printing study was conducted. Three stencils of different thicknesses were chosen: a 30um laser-cut stencil, a 35um electroform stencil, and a 40um laser-cut stencil. An experiment was conducted where 20 test boards were printed with each stencil, and the resulting process control variables were analyzed. Since the stencils were of different thicknesses, apertures with similar area ratios were compared to each other to measure the transfer efficiency of each stencil. The results of this study are shown in Figure 4.

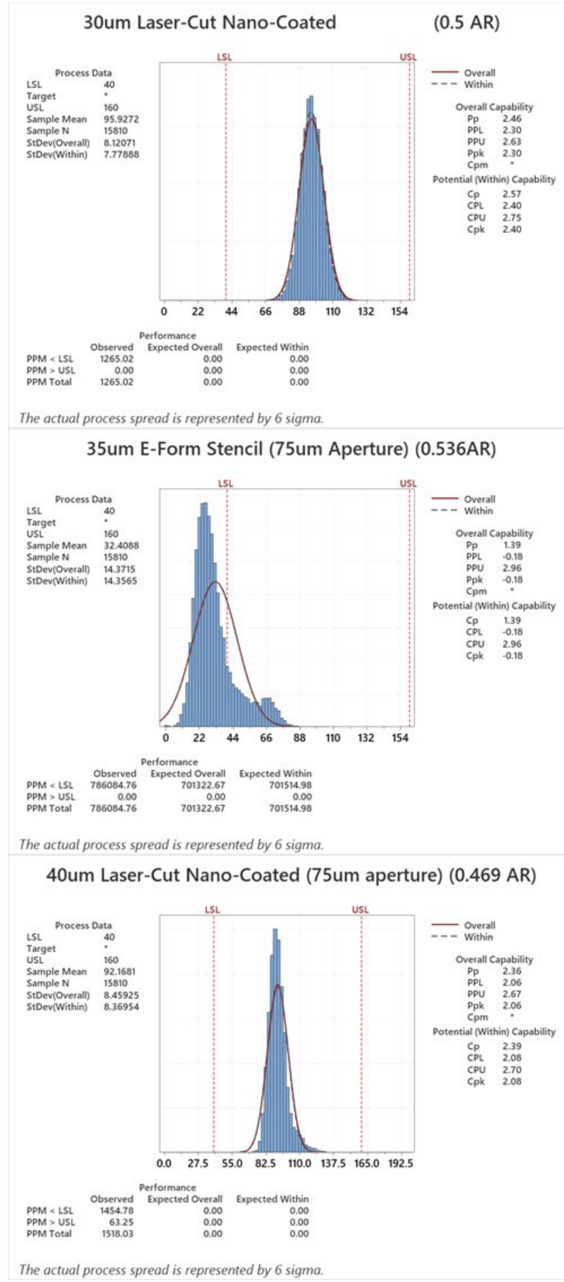

Figure 4. Stencil Comparison at Similar Area Ratios

The results of this study show that at similar area ratios, the two laser-cut stencils outperform the electroform stencil, even though the area ratio for the 40um stencil is much lower than that of the electroform stencil. Naturally, the thinnest stencil has the best performance, although the SPC numbers of the 40um laser-cut stencil are only slightly worse. The results of this study show that 60um aperture printing is feasible with laser-cut stencils, and that the SiP printing process is made more feasible with laser-cut stencils.

III. Type 7 Solder Paste Printing Test

The purpose of this printing test was to validate the printing performance of a novel Type 7 solder paste formulated for cleaning with semi-aqueous cleaning solution technology.

For the forthcoming printing experiments, a test vehicle was designed to accurately mimic a typical SiP assembly substrate. The board size is 200mm in length, 60mm in width, and 0.5mm thickness. This test vehicle has ENIG pads spaced in five sections with pad pitches between 50 and 150 um, with 20,000 total pads on the test vehicle. This test vehicle does not contain solder mask around the pads, as the removal of solder mask allows for improved transfer efficiency from stencil to substrate. Typically, a typical solder mask height for a SiP test board is roughly 25um; even this small height difference can cause transfer efficiency issues when printing with thin stencils and small stencil apertures.

The stencil used for the printing test is a 30um laser-cut stencil with nano-coating to improve transfer efficiency, as outlined in the previous section. The stencil was manufactured in a way to print solder deposits of various sizes on the test vehicle, i.e. 60 and 75um deposits on 008004 pads, and 90 and 105um deposits on 01005 pads.

Equipment
- DEK Horizon Printer
- Koh-Young Meister S SPI
- Juki Pick and Place
- Pyramax BTU 100N Reflow Oven
- Dage Quadra 7 X-Ray

G. *Fine-Pitch Printing Test*

The primary objective of carrying out this fine-pitch printing test is to validate the printability of a solder paste formulated for semi-aqueous cleaning applications. The apertures studied in this printing test are 60um and 90um, typical print apertures used when printing with T7 powder. Each stencil aperture has near 5,000 deposits analyzed. The printing structure of the fine-pitch printing test is to knead the solder paste to allow it to reach equilibrium, print 6 boards, pause 1 hour, and repeat with 6 board intervals and an extra 1 and 2 hour pause. There was an understencil wipe after each print using an IPA solution.

The results of the fine-pitch printing test are shown in Figure 5. Both results show consistent, low standard deviation fine feature printing at 60 and 90um aperture sizes. Of particular importance to highlight is the consistency and high Cpk of the 60um apertures. The rule of thumb “five-ball rule” for choosing an appropriate powder size indicates that the maximum aperture size for T7 powder is 55 (11*5) um. 60um is quite close to that lower limit, and the high Cpk at that aperture size is indicative of the strong printability of this material. Also of note is that at both aperture sizes, there are no “start-up strokes” after the pauses.

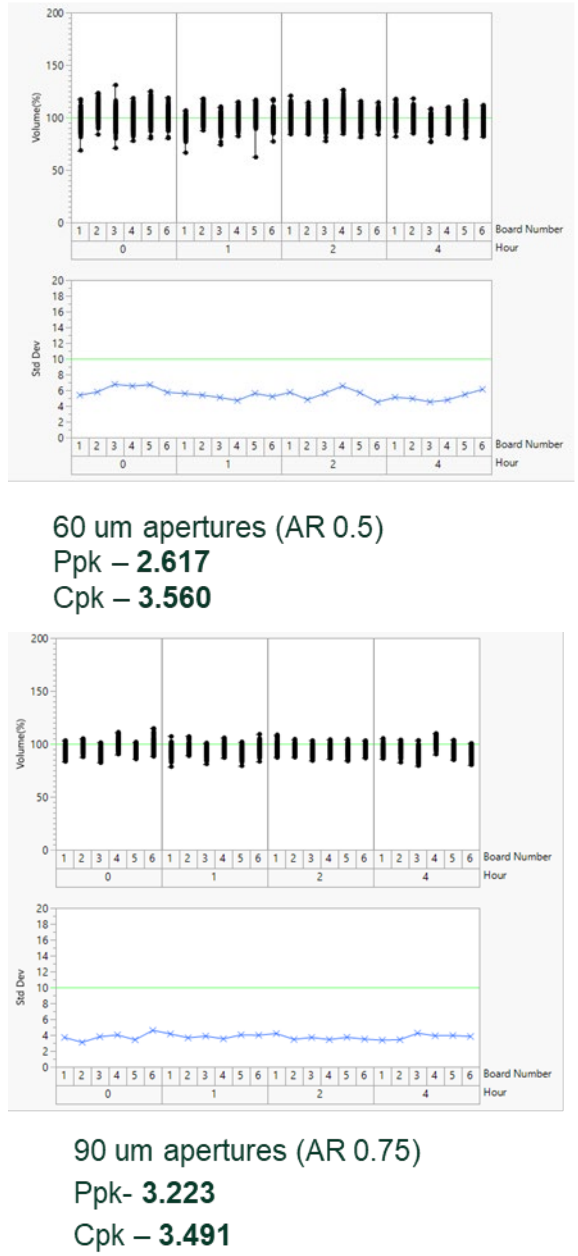

Figure 5. Response to Pause of Novel T7 Solder Paste

H. *Component Bridging Analysis*

In the previous section, no instances of solder bridging across pads at fine pitches were observed. While bridging before component placement is important to consider, component bridging after the component placement and reflow step is equally important. Component to component bridging with passive components can lead to short failures. To study the robustness of the slump resistance of this novel solder paste, a reflow study was conducted to analyze 008004 components and any resulting solder bridging which occurred. The same solder paste was used for this study as in the previous section; however the stencil apertures were modified to be 100% of the 008004 pad size.

The results of this bridging experiment are shown in Figure 6. With the test vehicle outlined previously in the paper, component to component bridging was mitigated down to 50um pad spacing.

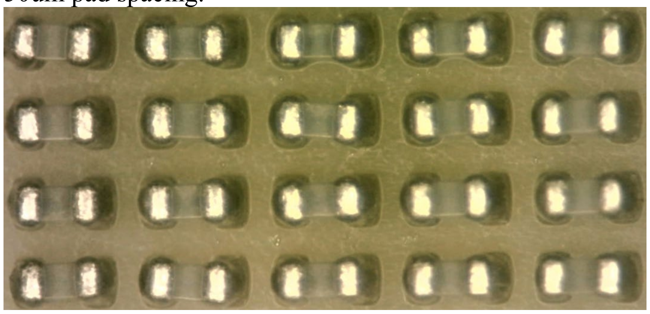

Figure 6. 008004 Components Placed Without Bridging at 100% Pad Size Apertures

I. Cleanability Analysis

The cleanability of this novel solder paste was also analyzed. The benefit of using saponifier technology as a substitute for pure DI water in a water-wash process relates to the standoff height of SiP components. As the pitch of SiP components reduces below 100um and the standoff height of these components reduces below 60um, the reduction limits the ability of cleaning agents to remove water soluble flux residues. Water soluble solder pastes do have benefits, such as strong wetting, cosmetic benefits, as well as the ability to completely remove all contaminants from a substrate post reflow. However, the low standoff height and tight pitch of components is a natural challenge for those assembling fine-feature products. A solder paste that is formulated to be completely cleaned with a semi-aqueous chemistry can be an attractive solution to low standoff height component builds. Figure 7 shows a typical developmental cleaning test to determine the validity of solder paste flux removal. In this test, solder is printed on a 1-inch diameter copper coupon in two patterns and reflowed. The reflowed solder is then sonicated in a solution made of 95% DI water and 5% semi-aqueous cleaning solution at 50C for 7 minutes, then pure DI water for 1 minute. The novel solder paste on the left is shown to leave no flux residue after cleaning, while an improperly formulated paste on the right shows flux residue remaining after the reflow step.

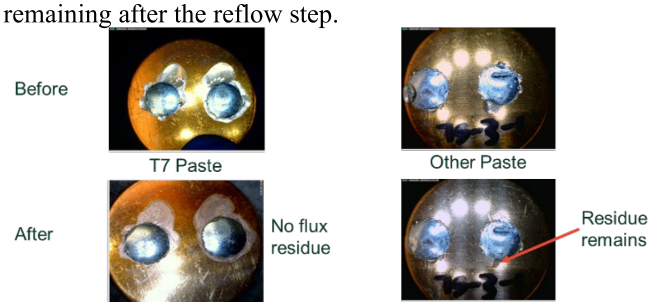

Figure 7. Typical Solder Flux Cleaning Test Results

IV. Conclusion

In summary, a novel solder paste was presented with supporting data as a solution to cleaning challenges in the semiconductor assembly industry. A Type 7 solder paste with excellent printability at small apertures and fine pitches, as well as with low component-to-component bridging was presented. In order to achieve the maximum benefits of this type of solder paste, process setup and tooling selection, such as stencil technology, is just as important as material selection in order to achieve a high-yield process.

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