SOLDER PASTE EVALUATION TECHNIQUES TO SIMPLIFY THE TRANSITION TO PB-FREE

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INTRODUCTION

As the July 1, 2006 Pb-free deadline approaches, many electronics assemblers are beginning to fathom the changes and process demands required. The two biggest material concerns involve solder paste and components. This document provides practical recommendations for evaluating Pb-free solder pastes and ensuring that the selected solder paste will deliver assembly yields comparable to, or better than, the incumbent Sn/Pb solder paste.

THINKING STATISTICALLY

Since it is commonly considered that a Pb-free process is more difficult to control (due to more constraints on the printing and reflow), the use of statistics becomes even more essential in the evaluation of solder pastes. Without proper statistical techniques, it is difficult to accurately assess and rank the performance of various solder paste candidates.

Statistics allow the user to adequately characterize variation. There is variation in every process, but operational efficiencies decrease as the variation from the target result increases. Statistics reveal the differentiation between common cause variation, which is controllable and expected, and special cause variation, which is unnatural and not expected. The special cause variation is what typically would result in a defect in the SMT process.

When considering a Pb-free solder paste evaluation, there are a couple of things that need to be defined to enable statistical analysis:

1. Define the part of the process to be evaluated: The smaller and less complicated that the evaluation is, the easier it is to characterize and measure results. It is better to run several small experiments than try one large experiment that tries to characterize a large number of variables. An example would be to evaluate the print performance of the various Pb-free solder pastes.
2. Define the factors to evaluate: In the stencil printing process, one factor is the different Pb-free solder pastes. Other factors include various print speeds, the length of time between prints (response to downtime), etc.
3. Define the response variables: It is essential to know the product attributes that are of the greatest importance to the process. These are the variables that should be measured. In the stencil printing example, solder paste volume is most often studied and is considered the most crucial variable.

Once the experimentation results are collected, the statistical analysis begins. When comparing Pb-free solder pastes, the best paste is the one that provides the process the greatest precision (most consistent results) as well as greatest accuracy (results closest to the targeted values)[i].

ALLOY DETERMINATION

Before embarking on a Pb-free solder paste evaluation, the first important step is to select the most appropriate alloy for the surface mount process. Because of its performance and inherent compatibility with residual Pb (which is an issue with Bi-containing alloys), the Sn/Ag/Cu (SAC) family of alloys is generally considered the best option. However, there are many combinations within that family that are readily available. The SAC alloys with a Ag percentage of 3 – 4% and a Cu percentage of 0.5 – 1% are nearly eutectic, with a melting range of about 217 – 218°C. Within these composition ranges there are some performance differences, especially with respect to voiding and tombstoning.

In research performed by the Indium Corporation[ii],[iii], the two most recommended alloy combinations each have their pros and cons:

1. SAC387 (95.5Sn/3.8Ag/0.7Cu) – Exhibits the best wetting and lowest voiding of SAC alloys.
2. SAC305 (96.5Sn/3.0Ag/0.5Cu) - Exhibits the lowest tendency to tombstone. The reduced Ag content makes it more viable for wave soldering (many manufacturers want to use the same alloy for surface mount and wave to simplify the rework process).

It is important to select the alloy based upon the manufacturing process(es) in which it will be used.

INITIAL SOLDER PASTE SCREENING

Board assembly facilities have limited time to conduct the evaluation. Since there are dozens of Pb-free solder pastes available on the market, it is necessary to narrow the search prior to conducting an extensive physical evaluation. The following elimination criteria are suggested:

1. Solder Paste Lot-to-Lot Consistency: Most solder paste manufacturers will provide potential customers with specific quality documentation for multiple lots (5-10 suggested) of a given solder paste. For Pb-free solder pastes, the most important criteria to investigate would be solder paste viscosity, solder paste metal load, Pb-contamination of the powder, and powder particle size distribution. It is important to understand the material suppliers' specification ranges and actual values for these solder paste characteristics. Since the physical evaluation of material will likely only be with one lot of solder paste from each supplier, it is essential to be confident that each supplier evaluated is able to provide consistency and has quality measures in place to ensure a reliable solder paste supply. Figures 1 and 2 provide examples of the type of data that the solder paste supplier should be able to provide.

Lot#: P7027C3		Lot#: P7028A3		Lot: 7086A3		Lot#: 7026B3	
Element	Average	Element	Average	Element	Average	Element	Average
Ag	3.831	Ag	3.954	Ag	3.718	Ag	3.628
Al	.0012	Al	0.0012	Al	0.0012	Al	0.0011
Bi	.0032	Bi	0.0023	Bi	0.0022	Bi	0.0025
Cu	.6590	Cu	0.6487	Cu	0.6578	Cu	0.5943
Fe	.0028	Fe	≤.0010	Fe	≤.0010	Fe	0.0015
In	.0028	In	0.0018	In	0.002	In	0.0025
Ni	.0010	Ni	0.001	Ni	0.0011	Ni	0.001
P	.0022	P	0.002	P	0.002	P	≤.0020
Pb	.0256 ←	Pb	0.0277 ←	Pb	0.027 ←	Pb	0.0236 ←
Sb	.0085	Sb	0.0062	Sb	0.008	Sb	0.006
Sn	95.462	Sn	95.354	Sn	95.58	Sn	95.737

Figure 1: Example of composition of 4 lots of 95.5Sn/3.8Ag/0.7Cu. The arrows display the Pb contamination in each lot.

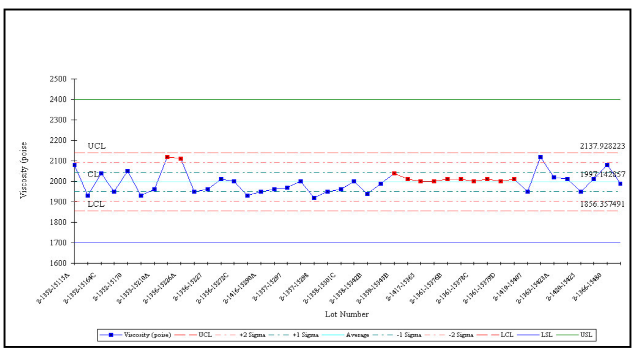

Figure 2: Plot displaying the viscosity trend of 20 consecutive lots of solder paste.

2. Solder Paste Reliability: The solder paste that is ultimately selected for Pb-free assembly must have long-term electrical reliability. At a minimum, all Pb-free solder pastes should meet the IPC/J-STD-004 SIR specification as well as the Telcordia (Bellcore) GR-78 Electromigration requirements.

3. Supplier Service and Support: Since the transition to a Pb-free process is unlikely to be without incident, the solder paste supplier that is selected must have a sufficient support structure to ensure that all issues are addressed and resolved quickly. In addition, a material supplier with strong technical support can aid in the resolution of process issues even if they are not solder paste related.

It should be noted that price was not one of the pre-evaluation criteria. When examining costs, the price of solder paste typically accounts for less than one-tenth of one percent (0.1%) of the cost of a PCB assembly. The typical price differences between solder pastes are almost always negligible compared to the money saved in yield improvements and improved reliability delivered by the top performing product. Solder paste price should only be considered as a deciding factor between solder pastes with equivalent performance.

Once the population is narrowed down to five or fewer products (one of which should be the current Sn/Pb solder paste of choice for use as a control), it is time to develop a test plan that will effectively distinguish the differences in performance between the materials and bring the solder pastes onto the factory floor. The remainder of this document will focus on important solder paste characteristics and practical evaluation techniques that can be performed on the majority of factory assembly lines without the need for highly unique or specialized equipment.

PB-FREE STENCIL PRINTING

It is reported that 50 – 70% of all SMT-related defects are associated with the printing process. Because the flux chemistries of Pb-free solder pastes are significantly different from their Sn/Pb counterparts (to give Pb-free solder reasonable reflow characteristics), it is not a foregone conclusion that they will print as well as Sn/Pb pastes. Therefore, whatever evaluation plan is developed, it is important to assess the following solder paste characteristics:

1. Solder paste stencil life: Any solder paste must print well when it is initially placed on the stencil - as well as when the paste has been on the stencil for several hours. Over time, solder paste viscosity has a tendency to increase as the material is exposed to air. This is primarily due to the evaporation of solvents. As the solvents evaporate, a paste's tackiness will rapidly increase, followed by a dramatic drop. Because of this, measuring a solder paste's change in tack over time can give general idea of the actual stencil life. This is shown in Figure 3. A solder paste with a short stencil life will require frequent adjustment of the stencil printer parameters to ensure a good print.

1. Solder paste response to pause: In the typical manufacturing environment, Pb-free solder pastes are required to handle downtimes of at

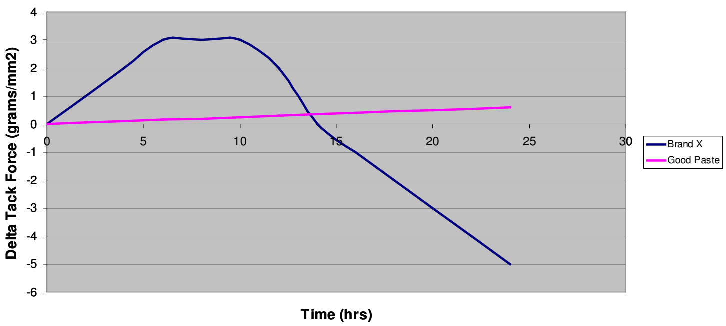

Figure 3: Comparison of tack over time of two different solder pastes. The solder paste represented by the blue line is probably not going to provide as long of a stencil life as the solder paste represented by the pink line.

least an hour while equipment is being repaired or components are being added to the placement machine. The ability of a solder paste to accommodate these downtimes, and print perfectly after the downtime, is termed "response to pause." Figure 4 compares the print volumes between solder pastes that have acceptable and unacceptable "response to pause." It is clear that Paste #3 (indicated by the yellow line) exhibits insufficient print volumes at start up and after downtimes.

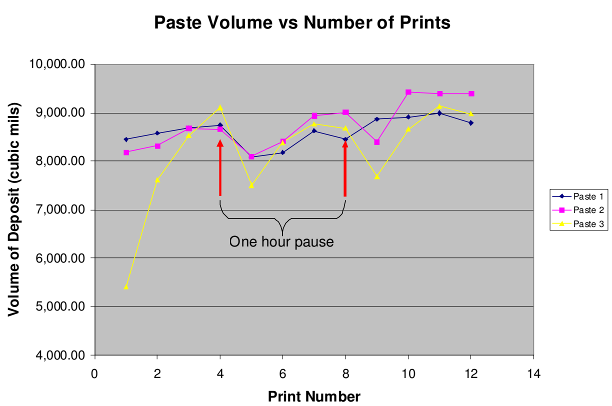

Figure 4: Comparison of print volumes between solder pastes with dramatically different "response to pause." Paste #3 is clearly inferior with respect to this test.

2. Solder paste resistance to shear thinning: Pb-free solder pastes must also be capable of handling high volume manufacturing processes. By design, a solder paste is formulated to "shear thin" (drop in viscosity) as it is being printed. This allows the printed paste to fill the stencil apertures better. Following the print stroke, the viscosity should recover (rise back to its original value) and then drop again during the next print stroke. Some solder pastes are not capable of recovering between print strokes during continuous printing,. This means that the solder paste will continue to decrease in viscosity over time and may eventually result in slumping and bridging in fine pitch applications.

PB-FREE PASTE AND COMPONENT PLACEMENT

Because the formulation differences between Pb-free and Sn/Pb solder pastes can be significant, it is important to determine that the tackiness, or component holding capability, will not be sacrificed. In the IPC/J-STD-005, there is a test method for determining the tackiness of a solder paste. However, Indium Corporation does not believe that the tack value of a solder paste always correlates to the solder paste's ability to hold components. Sending a solder paste through actual component placement equipment will provide the most accurate information on its ability to hold components. A change in a solder paste's properties over time can also affect its ability to hold components.

PB-FREE REFLOW

When transitioning to Pb-free, the reflow process is typically the most heavily evaluated part of the SMT process. The melting point of Pb-free solder is approximately 217°C (about 35°C higher than traditional Sn/Pb solders). Before analyzing the reflow capabilities of a solder paste, a few important decisions need to be made.

First, the surface finish of the test substrates needs to been determined. If the surface finish is already established, this is the finish that should be evaluated. If there are a variety of surface finishes being considered, it would be ideal to evaluate all of them. Since this would extend the evaluation, time constraints may not allow for the evaluation of multiple finishes. In this case, the surface finish that presents the greatest challenge for solder wetting should be considered. The solderability of Pb-free surface finish alternatives is ranked (from best to worst) as follows: 1. Electroless Nickel/Immersion Gold; 2. Immersion Tin; 3. Immersion Silver; 4. OSP.

The second consideration is the temperature constraints that are imposed by PCB or components. Due primarily to these temperature limitations, the reflow process window is likely going to be much narrower in Pb-free assembly. The selected solder paste should be able to perform at low peak reflow temperatures.

Three main elements of a reflow profile should be analyzed. They are: 1. soak time, 2. time above liquidus, and 3. peak temperature. In Pb-free soldering using a SAC alloy, soak time is defined as the length of time between 150°C and 217°C. Figure 5 graphically depicts the 3 main components of a Pb-free reflow profile.

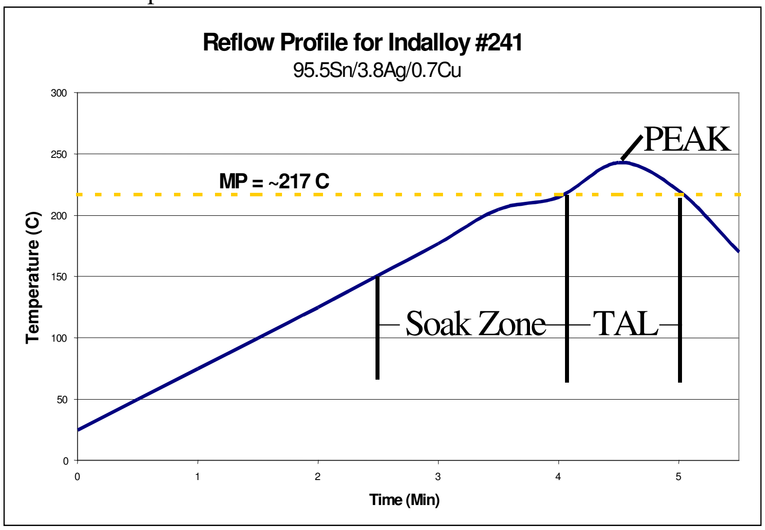

Figure 5: This is a graphical representation of a typical Pb-free reflow profile. The three critical aspects of the profile (soak zone, time above liquidus, and peak temperature) are identified.

A design of experiments (DOE) to evaluate Pb-free solder pastes should combine these three critical variables to determine every solder paste's ability to be withstand required reflow variances to accommodate a wide range of boards and components.

SOLDER PASTE EVALUATION TECHNIQUES

Indium Corporation has developed a Pb-free solder paste evaluation process that takes into account the important printing, placement, and reflow characteristics discussed. This evaluation process is designed to be as simple and practical as possible while ensuring that the best paste for the process will be selected. The proposed evaluation contains four-steps, each offering the opportunity to eliminate poorly-performing materials (thereby simplifying the remainder of the evaluation).

Step #1: Printer Set-up

Assuming that a solder paste pre-screening process was conducted, the first step in a successful evaluation would be to conduct an experiment to ensure that the best printer set-up is used for each solder paste. The key printer variables to optimize are print speed, print pressure, and separation speed (also sometimes called the snap-off speed). It is very likely that each solder paste will have different optimal settings. An attempt to use the same settings for each solder paste may result in the elimination of a product that may be better suited for the process than others that were not eliminated. The number of levels that is evaluated for each factor should be based on production experience, solder paste manufacturers recommendations, and time/resources. The response variable to measure should be print volume.

It may be difficult to look at every factor for each solder paste being evaluated. Therefore, the print parameters evaluated should be based upon specific production requirements or a DOE that reduces the number of profiles needed to obtain meaningful results should be used. Examples of such DOEs are Taguchi or fractional factorial DOEs[iv v].

Step #2: Reflow Window

Since some of the most significant differences between Pb-free solder pastes will be in reflow performance, this should be the second evaluation performed. In this stage, the goal is not to develop the optimal profile, but rather gain an understanding of the reflow robustness of each solder paste. Therefore, an actual DOE is not necessary to achieve the desired results.

Companies, such as Motorola Corporation, have found the greatest challenge for Pb-free solder pastes is the reflow process with a low peak temperature and a short time above liquidus[vi]. Since this type of profile is ideal to accommodate most components and boards, it is crucial to include such a profile when examining the reflow window of the solder paste. Although the exact profiles evaluated should be based on production and product requirements, it would be generically recommended to evaluate the following set-ups based on the profile shown earlier in Figure 5:

	Soak Time	TAL	Peak Temp
Profile #1:	60 Seconds	50 Seconds	230°C
Profile #2:	60 Seconds	60 Seconds	240°C
Profile #3:	90 Seconds	70 Seconds	250°C

Profiles #1 and #3 are meant to test the extremes for recommended profiles, while Profile #2 is a typically targeted Pb-free profile.

Each solder paste being evaluated should be stencil printed onto a board (using the optimized parameters from *Step #1*), components placed and reflowed using each of the 3 profiles. To reduce the opportunity for uncontrolled variables affecting the results, 3 – 5 boards should be run for each paste under each profile. Once the boards are reflowed, they must them be inspected. Developing sound inspection criteria can be a challenge because it is often visual (such as joint shine/smoothness, wetting on components, spread on pads, and number of solder balls). Some of the measurable response variables include number of shorts, number of tombstones, and percentage voiding in area array packages. A ranking process should be developed using the Sn/Pb as a control.

It is very possible that some of the potential candidates could be eliminated at this stage to simplify the remainder of the evaluation. If a certain material does not adequately coalesce/wet under certain profiles, it is probably not one that would be considered for Pb-free implementation. *Figure 6* shows two Pb-free solder pastes after reflow. One of the materials exhibits extremely poor coalescence, while the other shows adequate solderability and wetting.

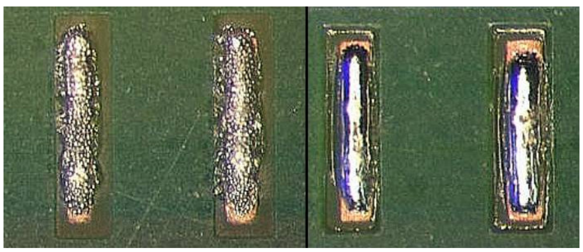

Figure 6: Poor coalescence vs. good coelescence

Step #3: Twelve Board Evaluator

The third step in the evaluation is the first step that actually evaluates the solder paste performance across the entire SMT process. Indium Corporation has developed the 12-Board Evaluator (shown in *Figure 7*) to investigate several response variables using a straightforward and easy technique.

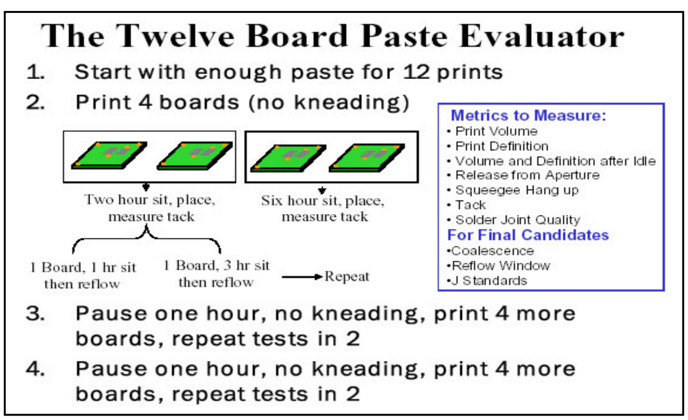

Figure 7: Stencil printing technique for evaluating the stencil life and response to pause of solder pastes.

The key advantage to the 12-Board Evaluator is that it simulates many of the challenges of a true production environment while requiring only a minimal amount of production line time. From a logistical standpoint, it is reasonable to expect that the stencil printer will be occupied for about 4-hours. The placement equipment and oven will need to remain set-up for a longer period to simulate various levels of downtime. The 12-Board Evaluator will characterize the Pb-free solder paste's stencil life, response to pause, tack stability, and reflow performance after downtime. The best response variables to measure would be paste deposit volumes, components lost during placement, visual assessment of the solder joint quality after reflow, and overall number of defects.

Step #4: Resistance to Shear Thinning

The evaluation technique in *Figure 7* does not address a solder paste's resistance to shear thinning because only a limited number of boards are printed. To really understand a solder paste's resistance to shear thinning, it is essential run the solder paste through a high number of print strokes. Oftentimes, it is not practical to run a high volume of boards during an evaluation since it could impact actual production demands. However, it is also extremely detrimental to evaluate a solder paste without determining its resistance to shear thinning. Finding this issue after the solder paste is implemented in production could result in significant production downtime. Indium Corporation developed a test procedure that can adequately evaluate a solder paste's resistance to shear thinning but also minimize any interruption to production. This suggested technique is:

1. Place fresh paste onto stencil (Repeat for all pastes being evaluated)
2. Set printer to run 30 knead strokes, wipe the underside of the stencil.
3. Print one board
4. Set printer to run 50 knead strokes, wipe the underside of the stencil.
5. Print one board
6. Set printer to run 100 knead strokes, wipe the underside of the stencil.
7. Print one board
8. Measure response variables on each printed board

By running knead strokes instead of actual prints, the actual volume of boards run through the printer can be minimized and the paste is still sheared as if in a high volume production run. As with the previous evaluation step, the most common response variable to measure is the print volume. As the solder paste is sheared, the actual volume deposited can change significantly. Additionally, shape of the deposit will be less clearly defined. This is a sign that slumping and bridging could be an issue with a particular paste in a relatively high volume environment.

SUMMARY
Implementing Pb-free solder pastes in inevitable. Properly evaluating Pb-free solder pastes is essential. The proposed 4-step evaluation process provides a systematic approach, while also minimizing the time and resources required. This effective and concise approach allows for complete assessment of the solder paste performance and ensures that the best solder paste is selected. Since 50 – 70% of all post-reflow defects can be attributed to the stencil printing process, a significant amount of time for the evaluations should be spent on that process. Selecting the best Pb-free solder paste for a given process will ensure the highest yields and provide the best opportunity for a successful Pb-free transition.

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