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The Formal Development of a Pb-Free Electronics Manufacturing Operation

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Abstract

To successfully navigate the transition from an entrenched Pb-based electronics manufacturing model to a fully integrated Pb-free manufacturing operation will require significant and coordinated modifications to many elements of currently operating electronics manufacturing organizations. Starting with the fact that no "drop-in" replacement for eutectic tin (Sn) - lead (Pb) solder exists, the demands of Pb-free production will alter most facets of the manufacturing organization, from higher temperature processing with more expensive Pb-free alloys, to specifying component and laminate requirements able to tolerate the new constraints, to formulating new approaches for testing, inspection and quality control, to understanding the unknown reliability of Pb-free products. The elimination of Pb from electronic products will impact companies across the entire organization, not just at the manufacturing level. This will include product designers, component engineers, purchasing and quality assurance departments, sales and marketing groups, material vendors, assembly equipment suppliers, original equipment and contract manufacturers, and recyclers. Clearly there is no shortage of work that needs to be done to place our understanding of Pb-free electronics production on the same level as the Pb-based counterpart. This paper discusses the comprehensive experimental approach that Cookson Electronics Division has taken to address the conversion to an integrated Pb-free manufacturing operation. The initial focus has been on materials compatibility for Pb-free processing using statistically based experimental designs. The study investigates compatibility between several Pb-free alloys, board and lead finishes, and flux types for both wave and paste/reflow soldering, including extensive reliability testing of the Pb-free assemblies. The statistical methodology and the results from the study will provide guidance for the implementation of successful and reliable Pb-free processing and serves as a model for how to establish a dedicated Pb-free electronics manufacturing operation.

Introduction

Over the next several years the electronic products industry will take on the challenge of eliminating lead (Pb) from most assembly materials and components used in the production and delivery of electronic goods and services. The inevitable move to Pb-free will impact all aspects of electronics production, especially in the area of materials, including electronic components, printed wiring boards (PWBs), wave solder alloys and surface mount technology (SMT) solder pastes. The exact timing of the conversion to Pb-free manufacturing for any given business will depend on several factors including the targeted product line (e.g., consumer electronics, telecommunications, military applications), the geographic localities where the Pb-free products and services are being introduced, the market drivers for "green" products, and the potential impact of legislation governing Pb in electronic products (e.g., Waste Electrical & Electronic Equipment (WEEE) Regulations in Europe).

The environmental impact of Pb from the electronics manufacturing industry is minimal (less than 0.5% of annual Pb utilization is by the electronics industry) when compared to Pb-bearing products of other industries. However, research has proven that producing and promoting Pb-free electronic products creates a competitive marketing advantage. This is a tangible incentive for the investigation and implementation of Pb-free manufacturing operations.

Impact of Pb-Free Across the Organization

Implementing Pb-free (Pb-free) in an organization can without a doubt be a precarious experience if not well planned. Notice that I stated, "Pb-free in an organization" and not specifically "implementation in manufacturing". Many people don't realize that "getting the Pb out" can have a rippling effect throughout most areas of an organization including: Marketing, Sales, Purchasing, Engineering, Quality Assurance, Manufacturing, Maintenance, Equipment, etc. In a nutshell, you need to consider many facets of the business before you get down to building your product.

Various factors need to be considered that ultimately affect the decisions and costs of running your operations when implementing or converting to Pb-free. From a business standpoint, some thoughts that immediately come to mind are: who should organize the transition?, what does this do to my bottom line?, when is the best time for implementation?, is this here to stay or just a passing fad?

Whether it be printed circuit boards or other manufactured products that normally utilize Pb-bearing alloys, the following items may be relevant.

Marketing & Sales
Promoting Pb-free products may be advisable if your customer base is environmentally conscious. You may have a golden opportunity to sway the "green" or environmentally conscious population to purchase your product over the competition. Especially if you have a nifty marketing promotion that states you've taken great strides to save the environment. Unfortunately, this will only work for a while. You can bet the competition is headed down this path. Sales and marketing will also be tasked with providing information necessary to convince customers that degradation to quality and reliability are not at stake.

Keep in mind that in some regions, certain to increase in the future, the manufacturer may be required to take back the product from the consumer for proper disposition & recycling, especially if it contains Pb or other non-desirable or regulated elements.

Purchasing
Procurement departments will have to be circumspect of components and assembly products that may contain Pb. This will most definitely have an impact on approved vendor and component lists. There may also be higher costs associated with purchasing products that are "guaranteed" Pb-free. And by the way, the criteria used to distinguish what constitutes "Pb-free" have not been nailed down yet. The maximum parts per million (PPM) of Pb acceptable in a component, printed wiring assembly, solder joint, or alloy system has not been determined or standardized. Until global standards are adopted, you can bet this will vary from country to country let alone customer to customer.

Even when purchasing materials such as solder paste, bar solder, and solder preforms, cost and specification issues must be addressed. The densities of Pb-free solder alloys are generally quite a bit less than that of the customary $Sn_{63}Pb_{37}$, $Sn_{60}Pb_{40}$, and $Sn_{62}Pb_{36}Ag_2$ (Pb-bearing alloys). Therefore, when you buy 500 grams of Pb-free solder paste or a kilogram of Pb-free bar solder you're going to get a significant increase in material volume. Hence, this will result in a substantial increase in the number of solder joint interconnects/printed wiring boards that you can manufacture per unit mass of Pb-free alloy. Therefore, you can expect a price increase when purchasing Pb free alloys by mass partially because of the resulting increased volume, as well as raw material cost differentials.

Quality Assurance
These people will certainly have their hands full. Personnel trained for post solder inspection as well as automated optical inspection (AOI) systems are accustomed to bright, shiny, and smooth solder joints that are typical with Sn-Pb alloys. Many of the Pb-free alloys do not exhibit the same wetting and surface appearance. Therefore, new conformance standards, retraining, reprogramming & different vision algorithms are a must. Organizations that typically supply the electronics industry with conformance standards such as the IPC are not quite ready.

Verification by QA departments that the correct alloys were used for primary assembly, hand solder, touch-up & rework is a difficult business. Most people would be hard pressed to tell the difference by sight, touch, or odor. Mixing certain alloys can result in devastating effects relative to reliability making this an important quality issue.

Maintenance
Equipment used for printed wiring board assembly also needs to be considered when implementing a Pb-free process.

Wave solder machines that have stainless steel solder pots and stainless steel parts are subject to premature failures. The primary concern with Pb-free alloys is the high content of tin (Sn). Sn, at elevated temperatures is corrosive to the stainless steel used in some solder pots and modules of wave soldering machines. Without protection, standard 304SST will degrade after one to two years of use.

Most wave solder machines are provided with a solder low temperature protection circuit to prevent the pumps from turning on if the solder is solid. This temperature is set to a few degrees above the liquid temperature of standard tin/lead alloy. With the higher temperature Pb-free alloys, this low level temperature must be raised to represent the higher temperature. If this is not done, there is a chance that the pumps may turn on with the Pb-free solder still solid.

Many equipment manufacturers utilize different types of floats in the solder bath to monitor and control solder level. Generally these floats are made out of solid SST, which floats in $Sn_{63}Pb_{37}$ solder. This is not the case with Pb-free solders. Due to the lower density, stainless steel and steel will sink in the solder bath therefore requiring a different float design.

For reflow equipment, nitrogen (N_2) capability and control may become a critical aspect of some Pb-free assembly operations, thereby impacting reflow oven designs.

In summary, the process of transitioning to Pb-free production in the electronics industry will take on vastly different sizes and shapes for the wide spectrum of players in the electronics industry, and will impact more than just the manufacturing process. Even from the manufacturing perspective, the need will vary quite a bit. For the leadframe manufacturer, for example, the main need may only be to determine the most cost-effective and compatible Pb-free plating formulation to replace Sn-Pb tinning, a process that may only involve a few steps. The more considerable challenge faced by original equipment manufacturers (OEMs) on the other hand, will be to wrestle with the numerous aspects of the transition process to successfully navigate the path to fully integrated Pb-free assembly.

The following experimental design is a scientific approach that was designed to identify qualitative and quantitative interactions of various solderable Pb free surface finishes, attachment alloys, fluxes and components. The soldering processes include solder paste reflow and wave solder operations. All of the materials used in this experimentation (board laminate, solder mask, surface finishes, solder alloys, solder pastes, fluxes, adhesives, etc.) are from the Cookson Electronics product portfolio.

Experimental Strategy

Given the veritable forest of factors that must be considered when considering going to Pb-free, it is important that any organization develop the appropriate strategy to successfully and efficiently navigate through it. It is impossible to attack and optimize for each important factor in sufficient detail all at once, and focusing too narrowly on a small subset of individual factors might cause important behavior or interactions to be missed. To provide general directional vectors aimed at easing this transition, we have developed a broad experimental approach that targets the main issues of surface finish-flux-alloy compatibility, using solderability and reliability/performance testing as the measure of relative success. The results from this large screening study will narrow the choices for final optimization and identify the most problematic material combinations. The effort represents a two-pronged attack on the broad areas of Pb-free wave soldering for SMT and through hole (TH) components and Pb-free paste/reflow assembly with SMT and TH components.

Test Vehicle Design

For these projects the test vehicle was designed to have the following attributes:

- Be large enough to simulate a real-life assembly situation
- Have a range of SMT and TH components of various pitches and geometries
- Have component layout such that soldering defects would be expected in certain areas to give a basis for cross-comparison of results
- Have enough solder joint opportunities to produce a statistically meaningful dataset
- Utilize current off-the-shelf Pb-free materials for fabrication

To satisfy these requirements, the test vehicle is a 12” x 10”, two-sided, four layered, 0.062” thick board comprised of six separate circuits. Each circuit has equivalent SMT component composition such that the board may be later sectioned for distribution into the different environmental test chambers. The board laminate material is a high performance FR-4 with a T_g between 175 to 180° C. The bottom side of the board is used for the wave soldering experiments and the arrangements of components on a single circuit is shown in Figure 1, with the feed direction into the wave indicated by the arrow. The SMT components include SO16s, SOT23s, 1206 and 0805 chip resistors, and fine-pitch QFP80s. Both vertical and horizontal orientations are present for all components, giving rise to so-called “design violations” for wave soldering. It is these areas, more than others, that soldering defects are expected to occur. Based on six replicates of the component arrangement in Figure 1 for each test vehicle, there are 4,416 SMT wave-soldering opportunities per board. The test vehicle also has different types of TH components, including (2) 96-pin connectors, (2) 50-pin connectors, (2) DIP16 chip carriers, (1) PGA 256 socket, and (4) arrays of ten ¼ W axial-leaded resistors. The PGA 256 socket and two of the ¼ W resistor arrays are confined to a separate center panel on the board.

The top side of the test vehicle was used for the paste/reflow experiments, and showed a denser arrangement, and higher variety of components compared to the wave soldering side. It also contains six circuits and the component arrangement for a single circuit is shown in Figure 2.

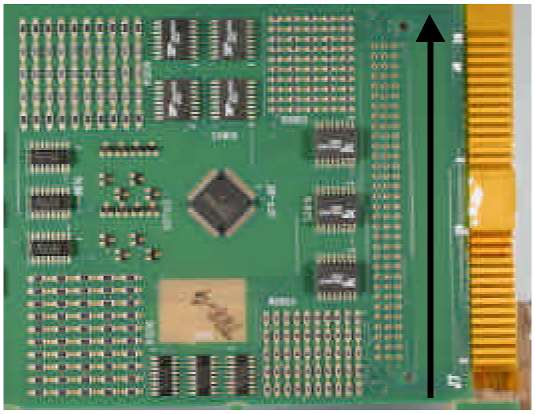

Figure 1 - Arrangement of SMT Components for One Circuit on the Bottom of the Test Vehicle for Wave Soldering Arrow Shows Feed Direction

Each circuit is comprised of an array of normal, fine, and ultra-fine pitch SMT components. This includes chip resistor arrays (1206, 0805, 0603, and 0402) in both vertical and horizontal orientations, (3) QFPs of various pitch, (2) PBGAs and (3) µBGAs, (1) PLCC28, and (1) DPAK. (The TSOP40 component was not used in this study.) The same array of TH components was available for the reflow experiments.

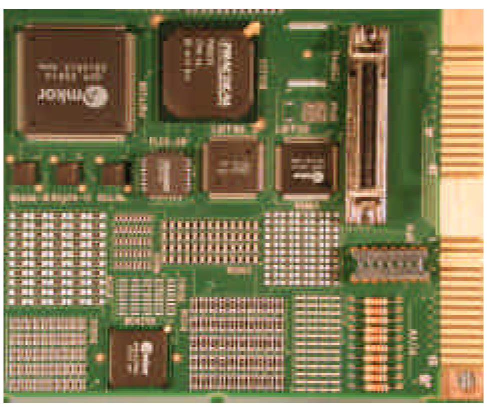

Figure 2 - Arrangement of SMT and TH Components for One Circuit on the Top of the Test Vehicle for Reflow Soldering

Based on six replicates of the component arrangement in Figure 2 for each test vehicle, there are 11,544 SMT reflow-soldering opportunities per board. For both wave and reflow, there are 660 through-hole soldering opportunities per board.

The vast majority of the surface mount and TH components on the board are daisy chained with circuit terminations at the edges of the board (two card-edges connectors per circuit). These edge connections are used for making electrical resistance measurements before and during the reliability tests. The SMT component populations and associated pitches for both wave and reflow are summarized in Table 1.

The test vehicles are treated with five different surface finishes. These are Hot Air Solder Leveling (HASL) (Sn/Pb HASL for $Sn_{63}Pb_{37}$ baseline alloy and Sn-Cu HASL for the Pb-free alloys), Electroless Ni/Immersion Au (ENIG), Immersion Tin (I-Sn), Immersion Silver (I-Ag) and Organic Solderability Preservative (OSP). The I-Sn finish is only tested in the reflow study, not the wave study.

Pb-Free Wave Soldering Project

Test Vehicle Assembly

This wave solder project has a broad scope and is designed to generate statistically meaningful data that will help guide industry choices for wave soldering with Pb-free alloys. The project includes six different alloys, including conventional $Sn_{63}Pb_{37}$ (SP) for baseline control. The five Pb-free alloys being tested are listed below:

- $Sn_{99.3}Cu_{0.7}$ (SC)
- $Sn_{96.5}Ag_{3.5}$ (SA)
- $Sn_{95.5}Ag_{4.0}Cu_{0.5}$ (SAC405)
- $Sn_{96.5}Ag_{3.0}Cu_{0.5}$ (SAC305)
- $Sn_{95.5}$-$Ag_{3.0}$-$Cu_{0.5}$-$Bi_{1.0}$ (SACB)

Two different wave-soldering experiments are described here. For the first four Pb-free alloys above, combinations with four different board finishes and five different flux chemistries will be evaluated. For the SACB alloy, a smaller experiment was designed that involved two surface finishes and three flux chemistries, but included the additional factor of soldering in air versus nitrogen.

The flux formulations are described below:

- Flux A: VOC-Free, No-Clean, Low solids, OA, Water-based vehicle
- Flux B: Low solids, No-clean, Rosin, Alcohol-based vehicle
- Flux C: Low solids, No-clean, OA, Alcohol-based vehicle
- Flux D: High solids, RMA, Alcohol-based vehicle
- Flux E: Medium solids, Rosin, Low VOC, No Clean, Water-based vehicle
- Flux F: Medium solids, Rosin, No Clean, Alcohol-based vehicle
- Flux G: Low VOC, Rosin, Intermediate solids, Alcohol-based vehicle

The two mixed level experiments are summarized in Table 2 below. Experiment W1 has a Mixed Level 5^1 x 4^1 experiment design and Experiment W6 has a Mixed Level 2^2 x 3^1 experiment design. Due to the amount of time required to drain and fill the solder pot, to purge and switch the flux sprayer, and to switch between air and N_2 nozzles, the experimental matrix is blocked by alloy type, flux type and environment, with surface finish condition being randomized during the build.

Table 1 - Summary of SMT Components Used for Wave and Reflow Pb-Free Studies

Top Side Reflow			**Bottom Side Wave**		
Components	I/O	Pitch (mil)	Components	I/O	Pitch (mil)
PLCC28	28	50	SOIC16	16	50
PBGA225	225	59	SOIC16-W	16	50
PBGA256	256	39.4	SOT23	3	--
QFP208	208	19.7	1206 R	2	--
QFP120	120	15.8	0805 R	2	--
QFP168	168	11.8	QFP80	80	19.7
μBGA36	36	31.5			
μBGA56-12	56	19.7			
μBGA36-10	56	19.7			
1026 R	2	--			
0805 R	2	--			
0603 R	2	--			
0402 R	2	--			
DPAK	3	--			

Table 2 - Summary of Experiment Design for Pb-free wave solder studies.

5^1 x 4^1 Experiment Design for W1- Pb-Free Wave Soldering in Air					
Factors	1	2	3	4	5
Alloy	SP	SC	SA	SAC305	SAC405
Flux	A	B	C	D	E
Surface Finish	HASL*	ENIG	I-Ag	OSP	
2^2 x 3^1 Experiment Design for W6- SACB Wave Soldering in Air & N_2					
Factors	1	2	3	4	5
Alloy	SACB				
Flux	E	F	G		
Surface Finish	Sn-Cu HASL	OSP			
Environment	Air	N_2			

* Sn-Pb HASL for $Sn_{63}Pb_{37}$; Sn-Cu HASL for Pb-free alloys.

For the larger experiment, W1, there will be 20 unique processing conditions per alloy tested. Three replicates of each condition will be run, resulting in 60 boards per alloy or 300 boards overall. For each processing condition, there will be a total of 15,228 soldering opportunities (both SMT and TH). The smaller experiment, involving SACB alloy, includes 12 unique processing conditions with two replicates of each condition resulting in 24 boards and 10,152 soldering opportunities per condition.

The wave soldering project has two main stages. The first stage is to accomplish the assembly of the test vehicles using standard SMT assembly equipment to adhere and cure the SMT components to the board, followed by manual placement of the TH components and conventional wave soldering assembly. The numerous controllable and uncontrollable variables attending wave soldering precluded a high level of process optimization for each of the 100 unique processing conditions over all the alloys. Therefore only a “first-level” of optimization is targeted for the assembly process. This “first-level” of optimization includes a single solder pot temperature for each alloy and a consistent set of preheat profiles, conveyor speeds and wave nozzle settings for each flux type following manufacturer recommendations. In doing this, all the boards were processed under nearly identical conditions on a flux basis per alloy tested, thereby allowing an apples-to-apples comparison of the results. One drawback to this approach is that a larger number of defects are expected since many factors are not optimized. However, the relative assembly performance of each alloy-flux-surface finish combination will be evident.

The measure of relative performance, or processability, will be determined by performing 100% visual inspection of the solder joints on all the boards. The solder joint attributes will be evaluated based on J-Std-001C and IPC-610A-C. The defect distribution and total counts will be evaluated and ANOVA analysis will be carried out to determine the statistical significance of the various processing conditions.

Reliability Testing

The second stage of testing involves extensive environmental testing utilizing Air to Air Thermal Cycling (AATC) and Liquid to Liquid Thermal Shocking (LLTS). Following baseline electrical resistance measurements of the daisy-chained circuits, the test vehicles will be sectioned into sixths and distributed among the AATC and LLTS chambers. The exposure range for both chambers will be -55°C to +125°C, which corresponds to Condition B of JESD22-A104-B (Table 1) and Condition C of JESD22-A106-A (Table 1), respectively. The samples will be removed at various intervals for electrical testing and lead-pull testing. Failure analysis will be carried out using a combination of electrical resistance degradation, optical microscopy, X-ray and cross-section analysis. Weibull analysis will be carried out on the failure data. These data will be integrated with the visual inspection data for a full picture of the relative performance of the various alloy-flux-surface finish combinations. The results should provide important guidelines for future optimization for Pb-free wave assembly as well as for development of specialized Pb-free assembly materials.

Pb-Free Paste-Reflow Soldering Project

Test Vehicle Assembly

The Pb-free paste-reflow project is slightly less ambitious than the wave soldering experiments but still covers a broad matrix of conditions. A total of six Pb-free pastes and $Sn_{63}Pb_{37}$ baseline paste will be tested in combination with five different surface finishes. The slate of Pb-free solder pastes to be tested includes SA, SAC305, SAC405, SACB, Sn-Ag-Cu-Sb (SACS), and Sn-Zn-Bi (SZB). Thus the experiment design is a mixed level $5^1 \times 7^1$ and is summarized in Table 3.

For this experiment there are 35 unique processing conditions, including the $Sn_{63}Pb_{37}$ control. Three replicates of each condition will be run totaling 105 boards. For each processing condition there will be a total of 36,612 soldering opportunities.

Similar to the wave-soldering project, the paste-reflow project has two main elements, the evaluation of the process assembly performance and the reliability testing. Like the wave project, it is desirable to be able to compare all the test vehicles on an equal basis for a direct comparison. The assembly process parameters, primarily printing parameters and the reflow profile, will conform to the guidelines of the Pb-free paste manufacturers. Fortunately there is sufficient overlap in the manufacturer's recommended process windows of all the Pb-free products so that a single set of printing parameters and a single reflow profile can be used. The boards will be built on standard SMT assembly equipment thereby simulation a real-life production environment. To gain an understanding of possible printability differences between the Pb-free pastes, paste height and volume measurements will be made on every assembly prior to placement using a 3-D laser profilometer.

Stencil Design

It is imperative to have a robust stencil printing process to accommodate the diverse range of components on the test vehicle. The through-hole components (THC) require upwards of 150,000 cubic mil of solder paste at one extreme and the μBGAs only need about 400 cubic mil (for a 5-mil stencil). A further constraint imposed during the study is to use a stencil having uniform thickness of 5 mil.

Table 3 - Summary of Mixed Level $5^1 \times 7^1$ Experiment Design for Pb-Free Wave Solder Studies

Factor	1	2	3	4	5	6	7
Solder paste	SP	SA	SAC305	SAC405	SACB	SACS	SZB
Surface finish	HASL*	ENIG	I-Ag	I-Sn	OSP		

* Sn-Pb HASL for $Sn_{63}Pb_{37}$; Sn-Cu HASL for Pb-free alloys

To compromise between these extremes, a two-step printing process will be used, using two stencils. A 7-mil thick stencil with overprint apertures for THC only was designed for the bottom side printing. This printing step will deposit about 60% of the required paste for the THCs. The 5-mil thick topside stencil also has THC overprint apertures and collectively they provide the calculated required volume of solder paste for each THC. The topside stencil has all the SMT apertures and the second printing step applies the paste for the SMT components. At 5 mil thickness, three of the SMT components, the QFP168 and both µBGA56s have lower than desired area ratios (<0.66), and are expected to be difficult to print. Both stencils are laser cut and electropolished.

Reflow profile

A single Pb-free reflow profile was developed following the guidelines of the paste manufacturers. It incorporates a target peak reflow temperature 240 ± 5 °C with a 60-90 second soak at 130-160 °C, and a TAL target of 50-70 seconds. The profile was verified using five type K thermocouples attached to different locations on a fully assembled board, the resulting profile being shown in Figure 3. All pastes will be reflowed in air except for SZB, which will be run in N_2. The $Sn_{63}Pb_{37}$ paste will be run using a conventional reflow profile in air, based on manufacturer specifications.

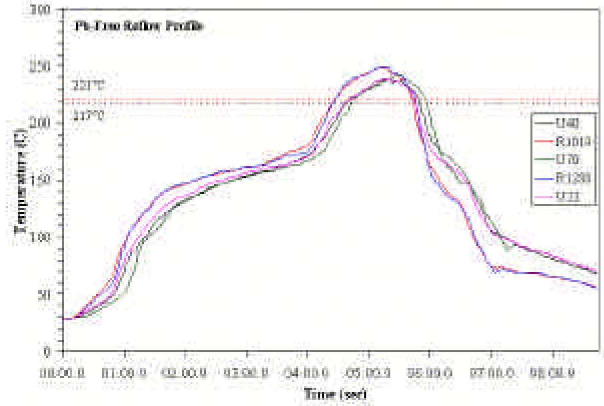

Figure 3 - Reflow Profile Used for all Pb-Free Pastes

Process Flow

The assembly of the Pb-free test vehicles will adhere to the process flow outlined in Figure 4. The measure of relative assembly performance for the Pb-free pastes will be based on visual inspection of the solder joints for solderability defects per industry standards (J-Std-001C & IPC-610A-C) and x-ray inspection of BGAs for voiding following the IPC 7095 standard. The data will be analyzed using ANOVA to assess any statistical differences among the 35 processing conditions for the utilized set of generic processing parameters. This analysis should reveal information related to optimization level and process window for the different Pb-free pastes

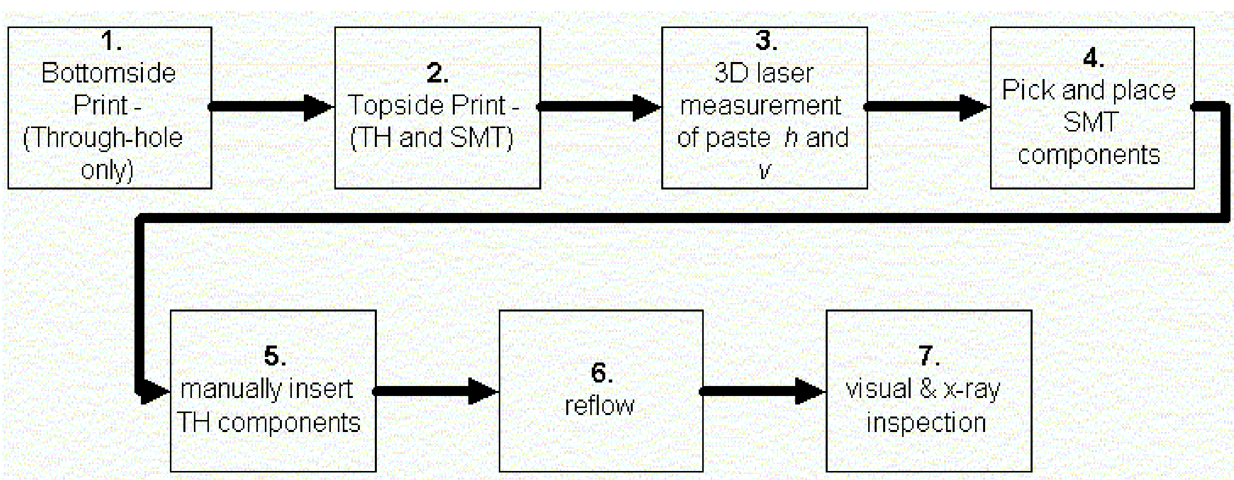

Figure 4 - Process Flow for Pb-Free Paste-Reflow Assembly Process

Reliability Testing

The second stage of testing involves environmental testing utilizing Air to Air Thermal Cycling (AATC), Liquid to Liquid Thermal Shocking (LLTS) and Temperature-Humidity exposure. The exposure range for both cycling chambers will be -55°C to +125°C, which corresponds to Condition B of JESD22-A104-B (Table 1) and Condition C of JESD22-A106-A (Table 1), respectively, which is the same as the wave study. The Temperature-Humidity exposure will be at 85°C-85% RH following JESD22-101-B. Electrical resistance measurements of the daisy-chained circuits will be made prior to and during the stress testing. Samples of each condition will be removed at specific intervals for lead-pull testing. Failure analysis will be carried out using a combination of electrical resistance degradation, optical microscopy, x-ray and cross-section analysis. Weibull analysis will be carried out on the failure data. These data will be integrated with the visual inspection data for a full picture of the relative performance of the various paste-surface finish combinations.

Current Status of Projects

The Pb-free projects described above got underway in early 2001. At the present time all the Pb-free assemblies, both wave and paste-reflow, have been assembled and visual inspections of solder joint attributes have been completed. For the paste-reflow boards, x-ray examination of the BGAs has also been completed. The results from this part of the project are currently in preparation for publication.

Some general observations from the results of the visual and x-ray inspections include:

1. Statistically significant differences are found between different processing conditions in terms of defect production during the wave assembly process.
2. The influence of flux chemistry is considerably stronger on wave assembly than the board surface finish, though some differences due to finish are observed.
3. Defect production is relatively low for the paste-reflow boards, with most pastes showing somewhat similar performance.
4. Generic processing parameters are adequate for a wide range of Pb-free pastes, although additional optimization (e.g., reflow profile) will improve yields for specific combinations.

The reliability-testing program is currently in full swing and the exposure of the Pb-free paste-reflow boards is virtually complete. The electrical failure data are currently being analyzed, and detailed failure analysis is ongoing. The large numbers of wave-soldered boards are currently in the environmental test chambers. Due to the large number of samples, the testing will continue through the first half of 2002, with periodic reports emerging on selected results. It is anticipated that by the end of summer 2002, a comprehensive picture will emerge from these studies that will provide sound directional guidance for the swiftest path to fully integrated Pb-free production. This will include guidelines and recommendations for the higher levels of process optimization as well as indicators to aid in the development of dedicated Pb-free assembly materials.

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