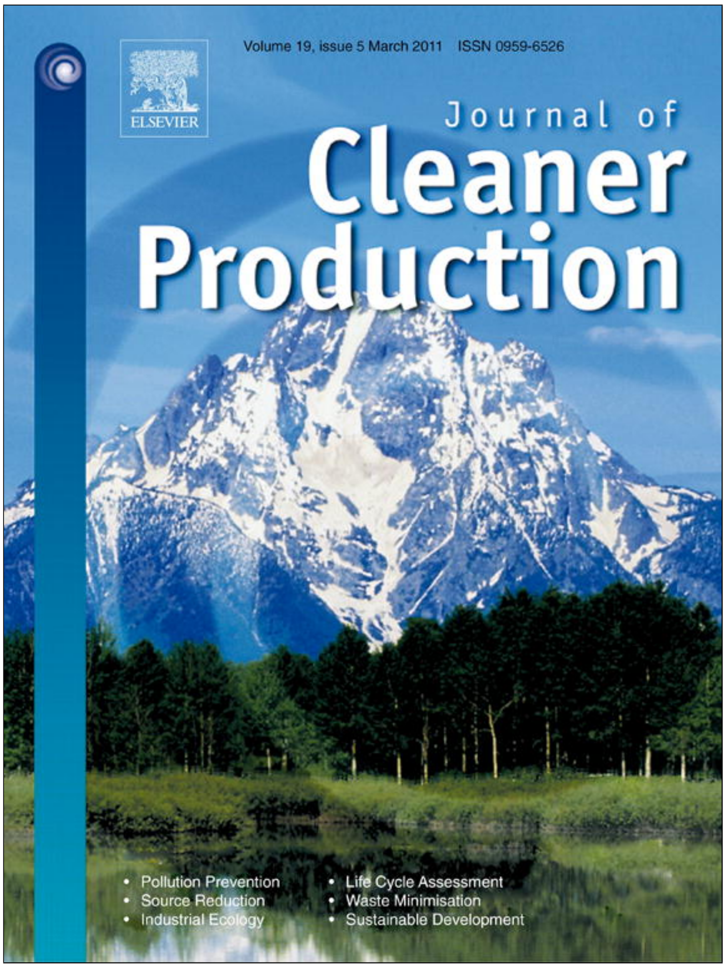

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Supply chain collaboration to achieve toxics use reduction

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ABSTRACT

The use of lead poses significant hazardous occupational exposure to workers in the electronics industry, and also causes environmental challenges at the end of product life. For the past decade, there has been a global effort in the electronics industry to initiate a move towards using lead-free materials for the production of printed circuit boards. However, there are technical and economic challenges, such as long term reliability and rework capability, that remain to hinder the universal implementation of lead-free materials. As a result, many electronics products are still currently manufactured and assembled using materials containing lead.

The costs for investigating and evaluating the various lead-free electronics materials and manufacturing processes can be cost prohibitive for an individual company to undertake alone. Consequently, the New England Lead-free Electronics Consortium was formed as a collaborative effort of New England companies spanning the electronics supply chain to help move the industry towards lead-free electronics. The Consortium is a working collaboration of industry, government, and academia. For the past several years, the Consortium has conducted research and testing for using various lead-free materials for the manufacture of printed circuit boards. The Consortium has been successful in identifying lead-free materials and processes to address the challenges of assembly and rework. The Consortium is currently conducting research to address the long-term reliability challenge of lead-free electronics.

1. Introduction

1.1. *Use of lead in electronics*

Since the emergence of etched printed wiring board technology, lead has been used in a variety of ways for manufacturing printed circuit boards. Lead can be used as a conductive surface finish on printed circuit boards, as a conductive component finish, as solder paste for the assembly of surface mount components, and as bar solder for assembly of through-hole components. Lead is used as a material in electronics because it has many desirable properties such as a low melting temperature and low cost, and also because it forms reliable solder joints (Hwang, 2001).

Printed circuit boards are found in electronics products. The printed circuit board is crucial to the manufacture and sales of approximately $1 trillion in electronic products each year. The printed circuit board is the platform upon which electrical components such as semiconductor chips and capacitors are mounted, and it provides the electrical interconnections between components. In 2003, the United States produced approximately 15% of the world's printed circuit boards (LaDou, 2007).

In the United States during 2003, approximately 13.9 million pounds of lead were used in solder for the manufacture of electronics products (U.S. Geological Survey, 2006).

1.2. *Hazards of lead*

The use of lead materials provides a potential exposure pathway to workers in companies throughout the entire supply chain of the electronics industry. This involves companies involved in transportation, solder and solder paste manufacturing, electronics component manufacturing, circuit board manufacturing, assembly of circuit boards, final product assembly, use and repair of electronic products, recycling of electronics products, and disposal of electronic products.

The acute and chronic toxic effects of lead to humans have been well studied. Brain damage, kidney damage, and gastrointestinal distress result from acute exposure to high levels of lead in humans. The most sensitive targets for the acute toxic effects of lead are the

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kidneys and the hematological, cardiovascular, and nervous systems. Because of the multi-modes of action of lead in biological systems, lead could potentially affect any system or organ in the body. Approximately 99% of the amount of lead entering the human adult body will leave in urine or fecal waste within a couple of weeks, but only about 32% of lead entering a child's body will leave in the waste. Under conditions of continued human exposure to lead, not all of the lead that enters the body will be excreted, resulting in accumulation of lead in body tissues (ATSDR, 2007).

There are a wide variety of chronic health effects for human exposure to lead. Animal studies have reported kidney tumors in rats and mice exposed to lead. The U.S. EPA considers lead to be a Group B2, probable human carcinogen (EPA, Lead and Compounds, 2007). The International Agency for Research on Cancer (IARC) considers lead to be a Group 2B, possibly carcinogenic to humans. (IARC, 2006) Studies on male lead workers have reported severe depression of sperm count and decreased function of the prostate and/or seminal vesicles. Occupational exposure to high levels of lead has been associated with a high likelihood of spontaneous abortion in pregnant women. Exposure to lead during pregnancy produces toxic effects on the human fetus, including increased risk of preterm delivery, low birth weight, and impaired mental development. Chronic exposure to lead in humans can affect the blood and the nervous system. Neurological symptoms have been reported in adults with elevated blood lead levels of greater than 40 μg/dL (ATSDR, 2007).

Human exposure to lead typically occurs through a combination of inhalation and oral exposure. For companies that are involved with circuit board assembly operations, inhalation of lead can occur during soldering processes. The primary solder operations occur during reflow soldering of surface mount components, wave soldering of through-hole components, and manual soldering of reworked components.

The Leadout Project is a European funded initiative to help companies across Europe develop technological solutions for implementing lead-free solution in the electronics industry (Leadout, 2007). A study was conducted by the Leadout Project to measure the occupational exposure to lead during reflow and wave soldering operations. Occupational exposure measurements were performed at three different electronics companies using personal sampling pumps at the breathing zone of workers who were conducting reflow and wave solder operations using tin/lead solder. The action level limit (30 $\mu g/m^3$) was exceeded by two out of the three companies for reflow solder operations, and the permissible exposure limit (50 $\mu g/m^3$) was exceeded by two out of the three companies for wave solder operations. The lead emission results from this study are shown in the Table 1 below (Aguirre, 2006).

During the many and varied processes of electronics assembly, there is considerable handling of lead solder, lead solder paste, components with lead finish, and circuit boards with lead finish. For example, the printing operator must pick up circuit boards with a lead finish, as well as manually apply lead solder paste to the printing machine. The handling of these lead containing materials can result in lead contamination of workers hands and clothing. This contamination of hands and clothing can ultimately cause lead ingestion if proper hand and clothing washing procedures are not conducted. Ingestion of lead can also occur through contact with lead-contaminated hands, food, cigarettes, and clothing. Further, lead contaminated clothing and other objects that are brought into the home environment also represent a potential exposure hazard to occupants in the home, especially to children (NIOSH, 1995).

Table 1
Lead emission measurements (Aguirre, 2006).

Company	Wave solder: lead exposure ($\mu g/m^3$)	Reflow solder lead exposure ($\mu g/m^3$)
IDK (Spain)	68	30
ALCAD (Spain)	18	16
TELCA (Portugal)	115	< 33

The environmental hazards involved with the use of lead solder in electronics often occur during the disposal stage. At the end of life, electronics products often end up at incinerators without proper control technology, or at landfills or dumping areas that are not properly lined to prevent the migration of lead to soil and groundwater. Lead can enter the ambient atmosphere if it is not incinerated with appropriate control technology.

1.3. *Drivers of lead-free electronics*

For the past decade, there has been a global effort in the electronics industry to initiate a move towards using lead-free materials for the production of printed circuit boards. The major types of drivers for moving manufacturers towards lead-free electronics include regulatory and market drivers. A major regulatory driver has been the European Union's Restriction on the use of certain Hazardous Substances (RoHS) Directive that was enacted in 2003. This directive limits the amount of lead and five other substances that are used in electrical and electronic equipment. This directive covers some, but not all, electrical and electronic equipment placed on the European Union market as of July 2006. There are several types of electronics products (e.g. medical equipment, aerospace, etc.) that are either exempt or considered out of scope from this directive.

Even in the absence of regulatory requirements, several companies have responded to market drivers to eliminate lead from their electronics products. Many progressive companies are trying to produce more environmentally friendly and recyclable products, as well as providing a safer working environment for their employees. These efforts can become market drivers for the remainder of the supply chain, as suppliers must provide materials, components, and assemblies that are lead-free, or otherwise risk losing the business of these progressive companies. Another market driver occurs when companies leverage marketing their product as 'green'; this forces competitors to follow suit, or lose market share.

1.4. *Challenges of lead-free electronics*

Despite the environmental and occupational hazards described in the preceding section, there is continued use of lead solder. There are many reasons for this practice, including the presence of technical and economic challenges with transitioning to lead-free materials. A common source for many of these challenges is that the melting temperature of lead-free solders is typically higher than that of tin/lead solder. For example, the melting temperature of tin/lead solder is 183 °C, and the melting temperature of tin/silver/copper solder (a common lead-free solder material) is approximately 217 °C. Therefore, the manufacturing process equipment must be run at higher temperatures. For surface mount components, the reflow oven temperature must be higher when using lead-free solder pastes. For through hole components, the solder pot temperature must be higher for wave solder, selective solder, and rework machines when using lead-free solders.

The elevated temperatures necessary to accommodate lead-free solders pose technical challenges. Most common components and printed circuit board laminate materials are rated for the lower processing temperatures required for a tin/lead electronics assembly environment. Therefore, the increased processing temperatures can cause issues such as printed circuit board delamination and component failure.

During the assembly of printed circuit boards, there is often the need to rework the boards due to failures or defects encountered during the assembly process. This rework involves the removal and replacement of components on the printed circuit board. Also, rework of printed circuit boards can occur anytime during the life of the electronics product. For example, if there are component failures during the use of the product, the printed circuit board may have to be sent back to the manufacturer for rework.

The elevated solder temperatures and solder flow required for rework of through hole components can result in copper dissolution on the printed circuit board. Copper dissolution is the erosion of the copper thickness of the pad and barrel wall for plated through holes. The presence of copper dissolution can result in adverse effects on solder alloy performance, can increase the required frequency for solder analysis, increase the required solder pot maintenance, and potentially compromise the long-term reliability of the printed circuit board.

For rework with lead-free solders, copper dissolution can be a greater challenge than with tin/lead solders. First, the melting temperatures of lead-free solder alloys are often higher than tin/lead solders. Therefore, the solder temperature needs to be higher to conduct the rework with lead-free solders which generates more thermal stress to the printed circuit board. Second, the lead-free solders such as tin/silver/copper alloys do not flow as well as tin/lead solders and need more contact time between the solder and the printed circuit board. This also generates additional thermal stress to the printed circuit board. Another issue with lead-free solders is that they have a higher tin content than tin/lead solders. The tin component of most solders reacts with the copper substrate.

The most challenging technical barrier to the widespread adoption of lead-free electronics is the impact on the long-term reliability of the lead-free products. Lead solder has been used extensively for the past sixty years and there is a large reservoir of reliability data available. It has been proven that electronics products containing lead solder can have operational lives of twenty or more years. However, this reliability data has not yet been generated for lead-free electronics, and consequently there is reluctance to use lead-free materials for products that require a long operational life. Since there are outstanding issues with the long term reliability of electronics products manufactured with lead-free materials, there are numerous electronics product applications that continue to use materials containing lead. This includes electronics products requiring high reliability and long product life such as network infrastructure, aerospace, defense, information technology, and medical applications (Pecht et al., 2004).

There are also economic barriers to the widespread adoption of lead-free electronics. For example, the most common lead-free solder used is a tin/silver/copper alloy that is more expensive than tin/lead solder, mostly due to the silver content. Also, new circuit board laminate materials would have to be purchased to accommodate the higher processing temperatures. These higher temperature rated circuit board materials typically cost more than traditional circuit board materials. Another economic issue is the increased energy requirement that is necessary to operate the processing equipment at a higher temperature to accommodate the lead-free solder. This increased energy usage is approximately 20% higher for a reflow oven processing lead-free assemblies rather than tin/lead assemblies, resulting in a corresponding increase in utility costs that the manufacturer must incur.

1.4.1. *New England lead-free electronics consortium*

The costs for investigating and evaluating the various lead-free electronics materials and manufacturing processes are usually prohibitive for an individual company to undertake alone. The New England Lead-free Electronics Consortium was formed as a collaborative effort of New England companies spanning the electronics supply chain to help move the industry towards lead-free electronics. The Consortium has been sponsored and supported by the Toxics Use Reduction Institute (TURI), the U.S. Environmental Protection Agency (EPA), and the University of Massachusetts Lowell.

The Consortium is a working collaboration of industry, government, and academia. Companies in the electronics industry supply chain include original equipment manufacturers (OEMs), printed circuit board assemblers, electronics component suppliers, and material suppliers. A study was conducted in order to examine the role of partnerships between OEMs and suppliers in improving the environmental performance or manufacturing operations. The results of the study indicate that the closer the relations, then the greater the improved environmental performance through implementing innovative materials and manufacturing processes. It was found that as suppliers learned more about the manufacturing operations of the end product, then they were better able to understand the type of product that best meet the needs of the end customer (Tsoulfas and Pappis, 2006). As a result, significant opportunities exist along the supply chain to reduce a company's environmental impact, including substituting chemicals in order to reduce the generation and management of hazardous materials (Cote et al., 2008).

For the past several years, the Consortium has conducted research and testing for using various lead-free materials for the assembly of printed circuit boards. These efforts were conducted in a collaborative manner by the members of the Consortium. The companies in the New England Lead-free Electronics Consortium that contributed to the current phase of research include:

- AIM Solder
- Benchmark Electronics
- Cobham (M/A-COM)
- Dynamic Details Inc.
- EMC Corporation
- Freedom CAD
- International Rectifier
- Isola
- Enthone Inc. (previously Ormecon)
- PWB Interconnect Solutions
- Raytheon
- Stentech
- Teradyne
- Texas Instruments
- Textron Systems
- Wall Industries
- Yankee Soldering

2. Materials and methods

Based upon the input from the consortium members, the consortium conducted the research in the following three areas.

1. Assembly of test vehicles

The first research area included an evaluation of the assembly of test vehicles using various lead-free materials. The lead-free materials evaluated during the assembly included the component finish, the board surface finish, the through hole component solder, and the surface mount component solder paste. In addition, a nanomaterial based surface finish was also included. The results of the lead-free assemblies were compared against baseline data obtained by assembling test vehicles with tin/lead materials. It is essential that quality lead-free solder joints are achieved during the initial assembly before subsequent research in rework and reliability areas can be undertaken.

2. Rework with lead-free materials

The second area of research was a comparison of rework capabilities for the various lead-free solders and surface finishes for through hole components. This research included the evaluation of three different rework processes using lead-free materials. This research also included the evaluation of a rework nozzle that was specifically designed and fabricated to address the rework challenges encountered when using lead-free materials.

3. Reliability of lead-free electronics

The third research area is an evaluation of the long-term reliability of test vehicles that were assembled using lead-free materials. The long-term reliability testing is based on accelerated testing techniques to assess the long-term product life of these electronic assemblies. The primary testing techniques used for the reliability testing are thermal cycling and internal stress testing. The results of this research will include a comparison against baseline data for test vehicles assembled using tin/lead solder.

The ultimate goal of the combined research in all three areas described above was to attain and publish results in these needed areas of original research. The research results should help to further advance the electronics industry towards the implementation of lead-free electronics for all applications, including those demanding high reliability and long product life. The research for the first two areas (assembly and rework) has been completed and the results are provided in this paper. The research for the third area (reliability) is still in progress and will be published in a subsequent paper.

The equipment and materials required for the research in all three areas were obtained by donations by member companies from the New England Lead-free Electronics Consortium, as well as funding provided by the U.S. EPA. The following Table 2 provides a summary of the types of contributions made by companies to support the research conducted by the Consortium over the past several years. These contributions demonstrate the willingness of the electronics supply chain in New England to collaborate for a common purpose of eliminating the use of lead in electronics.

A key step for providing research that is of value to the electronics industry representatives, is to use industry accepted standards and guidelines for the research conducted in the areas of assembly, rework, and reliability. The Association Connecting Electronics Industries (IPC) is a trade organization dedicated to furthering the competitive success of its members in the electronics industry. IPC has developed industry standards for various electronic assembly activities such as: fabrication, acceptance, assembly, inspection, solderability, and testing of printed circuit boards. Throughout the documentation for this research, these IPC standards were referenced and adhered to whenever possible. This is necessary to ensure that the companies in the electronics industry can accept the validity of these research results.

Table 2
Contributions for consortium research.

Contribution	Value
Production equipment and technical support	$90,000
Analysis and project management	$185,000
U.S. EPA funding	$62,000
Engineering support	$240,000
Testing, inspection, and support	$245,000
Components and materials	$195,000
Total	$1,017,000

2.1. Overview of materials included in the research

The research included numerous types of lead-free materials to be used for assembly, rework, and reliability testing efforts. The consortium members selected materials and components that had appropriate temperature ratings for lead-free electronics assembly. There were thirty different types of surface mount components and ten different types of through hole components included in this research. The research included four different printed circuit board surface finishes. The purpose of the surface finish is to provide solderability protection, a contact surface, and a solder joint interface (Hwang, 2005). The first finish used was electroless nickel immersion gold (ENIG). This surface finish involved using both electroless and immersion technologies to deposit the metallic surface finish. The second finish used was hot air solder leveling (HASL) technology to apply the surface finish to the printed circuit board. HASL is a method that entails dipping a bare printed circuit board that into a solder bath. The excess solder is then removed from the printed circuit board by an air stream (Scimeca et al., 2008). For this research, the HASL surface finish used the tin/copper lead-free alloy was 99.4% tin with approximately 0.6% copper. The third surface finish used an organic protection system for the copper pads on the printed circuit board. This surface finish is referred to as organic solderability preservatives (OSP). The fourth surface finish included for this research was a surface finish using nano materials. The nano surface finish consists of nano silver particles (approximately 4 nm) dispersed in a polymer (polyaniline). The thickness of the nano surface finish applied to the test vehicles is approximately 50 nm. This finish is referred to as an organic metal finish. Ninety percent of the layer volume is organic metal, and silver comprises the remainder (Wessling et al., 2007).

Solder paste is comprised of the solder alloy and a flux that is necessary to clean the surfaces that are to be soldered. This research included the following four different solder pastes for assembly of the surface mount components.

- Tin/silver/copper alloy (SAC 305, 96.5% tin, 3% silver, and 0.5% copper) with no clean chemistry flux (from two different suppliers)
- Tin/silver/copper alloy (SAC 305) with organic acid chemistry flux
- Tin/lead alloy with no clean chemistry flux for baseline purposes

Three different solder alloys were used in this research for the assembly of the through-hole components. The solders used were as follows:

- Tin/silver/copper alloy (SAC 305)
- Tin/copper alloy (99.4% tin, 0.6% copper)
- Tin/lead alloy (63% tin and 37% lead, lead-tin eutectic alloy) for baseline purposes

For this research, the three factors under investigation in the Design of Experiments were surface mount component solder paste, through hole component solder, and surface finish. The Design of Experiments (including solder paste, solder, surface finish, and laminate material) that was used for the 24 lead-free test vehicles is provided in the Table 3 below (Morose et al., 2009).

Table 3
Lead-free test vehicles – design of experiments.

Test vehicle	SMT solder paste	Through hole solder	Surface finish
1	SAC 305 NC-1	SAC 305	ENIG
2	SAC 305 NC-1	SAC 305	ENIG
3	SAC 305 NC-1	SAC 305	LF HASL
4	SAC 305 NC-1	SAC 305	LF HASL
5	SAC 305 NC-1	SAC 305	OSP
6	SAC 305 NC-1	SAC 305	OSP
7	SAC 305 NC-1	SAC 305	Nanofinish
8	SAC 305 NC-1	SAC 305	Nanofinish
9	SAC 305 (OA)	Tin/copper (295 °C)	ENIG
10	SAC 305 (OA)	Tin/copper (295 °C)	ENIG
11	SAC 305 (OA)	Tin/copper (295 °C)	LF HASL
12	SAC 305 (OA)	Tin/copper (295 °C)	LF HASL
13	SAC 305 (OA)	Tin/copper (295 °C)	OSP
14	SAC 305 (OA)	Tin/copper (295 °C)	OSP
15	SAC 305 (OA)	Tin/copper (295 °C)	Nanofinish
16	SAC 305 (OA)	Tin/copper (295 °C)	Nanofinish
17	SAC 305 NC-2	Tin/copper (310 °C)	ENIG
18	SAC 305 NC-2	Tin/copper (310 °C)	ENIG
19	SAC 305 NC-2	Tin/copper (310 °C)	LF HASL
20	SAC 305 NC-2	Tin/copper (310 °C)	LF HASL
21	SAC 305 NC-2	Tin/copper (310 °C)	OSP
22	SAC 305 NC-2	Tin/copper (310 °C)	OSP
23	SAC 305 NC-2	Tin/copper (310 °C)	Nanofinish
24	SAC 305 NC-2	Tin/copper (310 °C)	Nanofinish

The Design of Experiments that was used for the eight tin/lead test vehicles is provided in the Table 4 below. These tin/lead test vehicles provided a baseline for comparison with the lead-free test vehicles.

2.2. Assembly of test vehicles methodology

The Fig. 1 below shows the assembled test vehicle that was used for the basis of this research. The test vehicle thickness is the 0.110 inches, has 20 layers of copper, is 8 inches wide by 10 inches long, and contains both surface mount and through hole components.

There were 886 surface mount components, and 21 through hole components assembled on each test vehicle. The test vehicles were manufactured by Dynamic Details Inc. at their board fabrication plant in Sterling, Virginia. The assembly and inspection of the components to the lead-free and tin/lead test vehicles occurred at the Benchmark Electronics facilities in Hudson, New Hampshire, and Guadalajara, Mexico.

The temperature profile of the test vehicle and surface mount components during passage through the reflow oven is a critical determinant of solder joint quality. The test vehicle used for this research was very challenging to obtain a desirable thermal profile because the test vehicle was thick (0.110 inches) and contained many different types of components with greatly varying thermal masses.

Lead-free solder paste using the SAC 305 tin/silver/copper alloy solder melts at 217–220 °C, and the time that is spent above this temperature while in the reflow oven is called time above liquidus (TAL). All three lead-free solder pastes in this research contained the lead-free tin/silver/copper alloy. The target peak temperature for test vehicles assembled with lead-free solder was in the range of 240–248 °C, and the target time above liquidus is in the range of 60–90 s. The target thermal profile was a ramp to peak method. The actual top side temperature profile used for the lead-free test vehicles can be seen in the Fig. 2 below.

Table 4
Tin/lead boards – design of experiments.

Board	SMT solder paste	Through hole solder	Surface finish
25	Tin/lead NC	Tin/Lead	ENIG
26	Tin/lead NC	Tin/Lead	ENIG
27	Tin/lead NC	Tin/Lead	LF HASL
28	Tin/lead NC	Tin/Lead	LF HASL
29	Tin/lead NC	Tin/Lead	OSP
30	Tin/lead NC	Tin/Lead	OSP
31	Tin/lead NC	Tin/Lead	Nanofinish
32	Tin/lead NC	Tin/Lead	Nanofinish

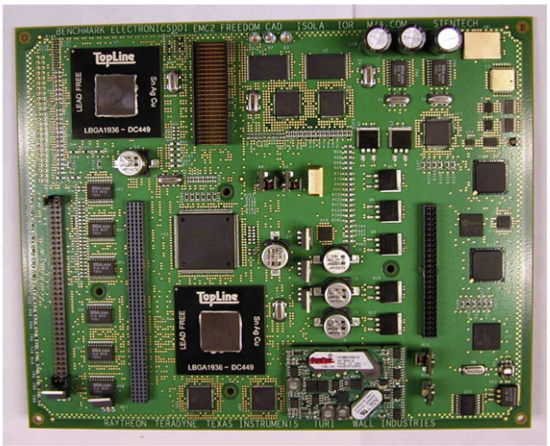

Fig. 1. Assembled test vehicle.

The second temperature profile was for the tin/lead solder paste that melts at 183 °C. The target peak temperature in the reflow oven for test vehicles assembled with tin/lead solder was in the range of 210–218 °C, and the target time for the test vehicles to be above the liquidus temperature was in the range of 60–90 s.

The third temperature profile generated was for the top side of the test vehicles assembled with tin/lead solder paste. The top side of these test vehicles contain ball grid array (BGA) components that contain lead-free solder balls. Therefore, a hybrid temperature profile is needed to melt the tin/lead solder pastes as well as the lead-free solder on the BGA components. The target peak temperature for the hybrid profile is in the range of 222–230 °C, and the target time above liquidus is in the range of 60–90 s (Shina, 2008).

The three major steps for the assembly of the through hole components were: flux application, preheating, and soldering. The flux needs to be applied to each through hole on the test vehicle prior to soldering to help prevent the oxidation of the metal that may occur at the elevated soldering temperatures. The flux was applied automatically to the bottom side of the test vehicle.

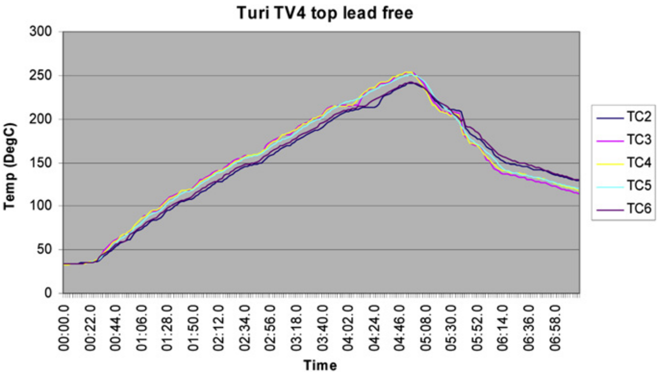

Fig. 2. Top side reflow profile for lead-free test vehicles.

The preheating of the test vehicle was necessary to minimize the thermal stress that occurs when the test vehicle is exposed to the high soldering temperatures. The intent was to gradually raise the temperature of the test vehicle closer to the soldering temperature to minimize thermal stress. However, the preheat temperature cannot be too high or it may burn off the flux before the soldering occurs. For this research, the target preheat temperature was between 110 and 115 °C.

The IPC-A-610 Revision D standard was used as the guideline for conducting the visual inspection for this research. This standard is a collection of visual quality acceptability requirements that is used for electronic assemblies. The standard provides different requirements depending on the classification of the electronics assembly. The visual inspection for this research was conducted to meet the requirements of Class 3: High Performance Electronic Products. This classification was chosen because it covers electronics assemblies that must meet high reliability applications (IPC, 2005). For this research, only soldering related defects were considered.

2.3. Rework with lead-free materials methodology

The rework subgroup established the following three criteria for the rework success of through hole components:

- Meet IPC Class III visual inspection criteria
- No laminate material degradation (e.g. delamination, pad lifting)
- Achieve minimal copper dissolution: primary target is to meet 0.001″ minimum copper thickness at the knee (Class 3), secondary target is 0.0008″ minimum copper thickness (Class 2)

The rework effort was conducted on rework coupons, and not on the actual test vehicles. The panel design included both test vehicles and rework coupons to ensure that the rework research was done on the same laminate material and board stackup as the actual test vehicles.

The through-hole component selected for the through hole rework process was the Samtec 200 pin connector. This component was selected because it would be a challenge to successfully rework this component given the thickness of the rework coupon (0.110 inches). The Fig. 3 below shows the Samtec 200 pin through hole connector mounted on the upper left hand corner at component location J5 of the rework coupon.

The through hole component rework process included the following four surface finishes: OSP, ENIG, lead-free HASL (using the tin/copper alloy), and nano. Nine rework coupons with OSP surface finish were sent to Ormecon to apply the nano surface finish. Applying the nano surface to bare copper is the preferred method by Ormecon, however, the only rework coupons available for this research already had the OSP surface finish applied. Consequently, the OSP finish had to be stripped off by Ormecon before applying the nano surface finish. It is difficult to strip the coupon of its previous surface finish while maintaining an optimal, homogenous copper surface. This could affect the visual appearance of the nanofinish and the solderability of the coupons (Ormecon, 2008).

Two different lead-free solder alloys were used for this experiment: SAC 305 solder and tin/copper solder. Because of time and resource constraints, the tin/lead solder was not included as a baseline measurement for these efforts.

There were twenty-four rework coupons included in the through hole component rework effort. This provided a balanced Design of Experiments for the rework efforts. The rework process took place at Benchmark Electronics in Hudson, New Hampshire. The rework coupons had to undergo two passes through the reflow oven to simulate the thermal stresses that would have been encountered during an actual surface mount assembly process.

The primary machine that was used for the rework efforts was the Premier Rework RW116 machine. There were two types of nozzles used on the Premier Rework machine for the rework efforts. The first was a standard nozzle which is shown in the Fig. 4 below.

The second type of nozzle used for the through hole rework was a hybrid nozzle. The hybrid nozzle was a special proprietary design to address the challenges of copper dissolution during the rework process with lead-free solders. The intent of the design is to minimize solder flow at the surface of the test vehicle, but maintain adequate heat transfer to the solder so that there is not a significant drop in solder temperatures during rework operations. The Fig. 5 below shows the hybrid nozzle with solder flow during actual rework operations.

There were three different rework processes that were used for reworking the through hole components. For each of these processes, a board preheat temperature of 130 °C was used for the rework machine, and Alpha EF2202 no clean flux was used at the component site. These three processes are described below:

Process 1: The Premier Rework RW116 machine was used for initial component installation, component removal and second component installation. This process used the standard nozzle design.

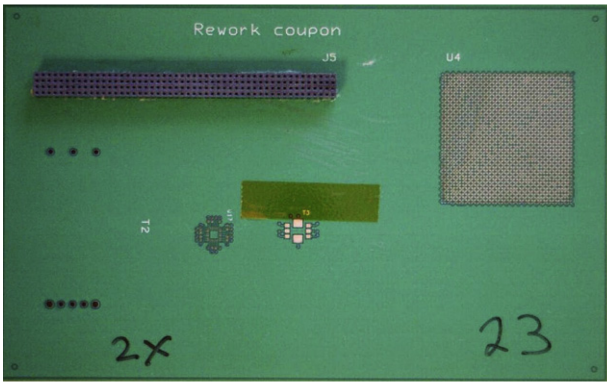

Fig. 3. Rework coupon with through hole connector.

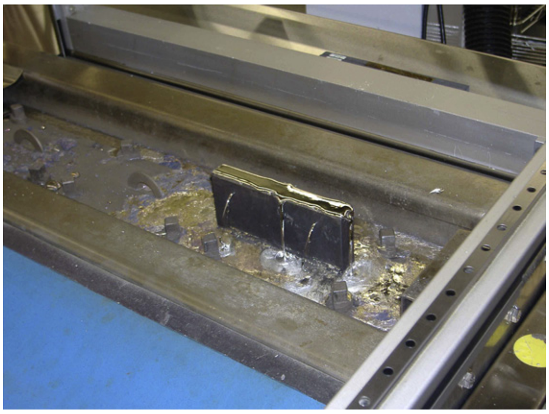

Fig. 4. Standard nozzle during rework operations.

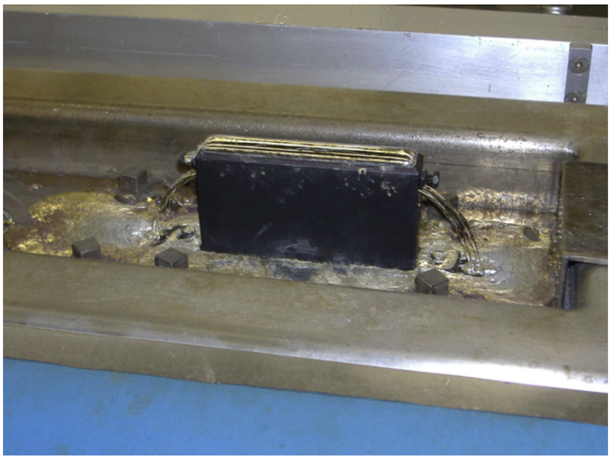

Fig. 5. Hybrid nozzle during rework operations.

Process 2: The Premier Rework RW116 machine was used for initial component installation, component removal and second component installation. This process used the hybrid nozzle design.

Process 3: The Premier Rework RW116 was used for the initial and second component installation. This process used the standard nozzle design for component installation. The Air Vac DRS25 was used for component removal. Previous studies have found that forced convection for component removal together with solder fountain for component installation during rework can have an impact on decreasing copper dissolution rates (Farrell et al., 2007).

The objective was to have a solder pot temperature of 270 °C for the SAC 305 solder. The tin/copper solder has a higher melting temperature than SAC 305, and therefore it is more desirable to use this solder at a higher temperature. Therefore, the solder pot temperature was raised to 287 °C for the tin/copper solder.

For Process 3, the component removal was accomplished by using the Air Vac DRS25XLT machine. The rework coupon was preheated prior to the start of reflow. Once the reflow was complete, the heat nozzle was taken off the component so that the connector could be removed from the rework coupon. The following Fig. 6 shows the use of the Air Vac heat nozzle applying heat to the connector and rework coupon.

Once the connector was removed from the rework coupon, then heat was continuously applied to the rework coupon, and finally the vacuum nozzle was used to remove the solder from the connector holes. The key measurements made during the through hole rework process were contact time and copper dissolution. The contact time when the solder in the nozzle is in contact with the bottom surface of the rework coupon was measured for each step in the rework process. For Processes 1 and 2, this included contact time during initial component installation, component removal, and second component installation. For Process 3, this included contact time during initial component installation and second component installation. Microsectional analysis was used to evaluate the level of copper dissolution. Microsections of the connector and rework coupon were conducted to obtain copper dissolution measurements.

Fig. 6. Air vac machine using heat nozzle.

3. Results

3.1. Assembly research results: through hole components

Two examples of defects identified during the inspection process are provided. The following Fig. 7 illustrates the insufficient solder defect for one of the leads of component Q17 on the top side of test vehicle number 22.

The following Fig. 8 illustrates the solder bridge defect for component J5 on the bottom-side of test vehicle number 28.

For this research, Analysis of Variance (ANOVA) was utilized to understand the relationship between the lead-free materials used and the assembly results. The overall mean for defects per test vehicle for all combinations was 105 defects per test vehicle. The two best performing solders were tin/copper (2) and the SAC 305 solders with 79 and 96 defects per test vehicle respectively. The two lesser performing solders were tin/lead and tin/copper (1) solders with 115 and 131 defects per test vehicle respectively. The two best performing surface finishes were lead-free HASL and ENIG surface finishes with 51 and 84 defects per test vehicle respectively. The two lesser performing surface finishes were the OSP and nano surface finishes with 142 and 143 defects per test vehicle respectively. The results of the main effects are shown in the Fig. 9 below.

The interaction plot reveals that the ENIG surface finish had a lot of variability across the different solder types. The ENIG surface finish had the lowest defect rate when using the SAC 305 and tin/lead solders, however the ENIG surface finish had the highest defect rate when used with the tin/copper (1) and tin/copper (2) solders. The lead-free HASL had the lowest defect rate for the tin/copper (1) and tin/copper (2) solders, and had the second lowest defect rate for SAC 305 and tin/lead solders. This positive result was expected given that the lead-free HASL finish is comprised of the tin/copper solder alloy. The lead-free HASL surface finish is a good choice for

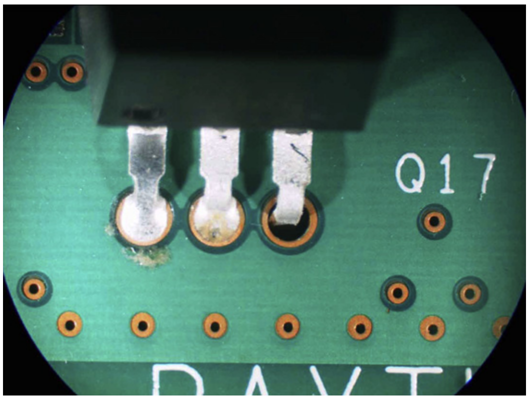

Fig. 7. THT defect on test vehicle number 22.

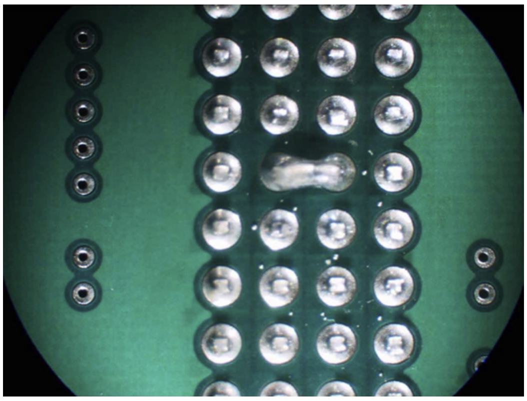

Fig. 8. THT defect on test vehicle number 28.

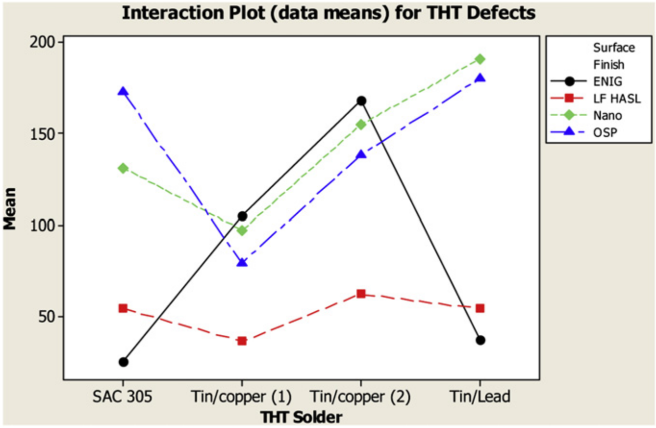

Fig. 10. Interactions plot for through hole component defects.

a company that may use more than one solder type. The performance of the nano and OSP surface finishes were comparable for each of the four solders. The following Fig. 10 illustrates the effect of the interactions for the various combinations.

3.2. *Assembly research results: surface mount components*

Upon review of the mean values and the main effects plot for this research, it was determined that the SAC 305 OA solder paste had a much higher mean defect rate (8.0 defects per test vehicle) than the overall average of 4.25 as well as all of the other three solder pastes. The other three solder pastes (SAC 305 NC-1, SAC 305 NC-2, and Tin/lead NC) had defect rates between 2.75 and 3.25 defects per test vehicle and each had no-clean flux. For the surface finishes, it can be seen that the nano surface finish had the lowest mean defect rate (2.75 defects per test vehicle), while the other three surface finishes had defect rates between 4.0 and 5.5 defects per test vehicle. The following Fig. 11 is the main effects plot for the surface mount components for all solder types.

3.3. *Rework with lead-free materials results*

3.3.1. *Contact time*

Upon review of the means for the main effects and the main effects plot, it was found that the SAC 305 solder had a much lower mean contact time of 65 s as compared to 88 s for tin/copper solder. Process #1 had a much lower mean contact time of 68 s as compared to the mean contact time of 139 s for Process #2. The only difference between these two processes was the type of nozzle used. Process #1 used the standard nozzle and Process #2 used the hybrid nozzle. The contact time required for solder flow through to the top side of the rework coupon was much greater for the hybrid nozzle than for the standard nozzle. Process #3 had the lowest mean contact time of 32 s because there was no contact time during the component removal process when using the Air Vac machine.

The mean contact time for the ENIG (72 s), nano (70 s), and HASL (77 s) surface finishes were all between 70 and 77 s. The contact time for the OSP surface finish was the highest of the four surface finishes with a mean time of 89 s. The Fig. 12 below show the main effects plot for contact time.

Upon review of the interaction plot, it appears that the main effect of the process is predominate over any of the possible interactions. For example, the Process #2 had the highest contact time for all four surface finishes (ENIG, HASL, Nano, and OSP), Process #1 had the second highest contact time for all four surface finishes, and Process #3 had the lowest contact time for all four surface finishes. In addition, Process #2 had the highest contact time for both solders (Tin/copper and SAC 305), Process #1 had the second highest contact time for both solders, and Process #3 had the lowest contact time for both solders. The following Fig. 13 shows the interaction plot for contact time.

3.3.2. *Copper dissolution*

The key measurement used to assess the degree of copper dissolution during the rework process is the thickness of the copper at the knee location of the plated through hole. This measurement was taken during the microsectioning process.

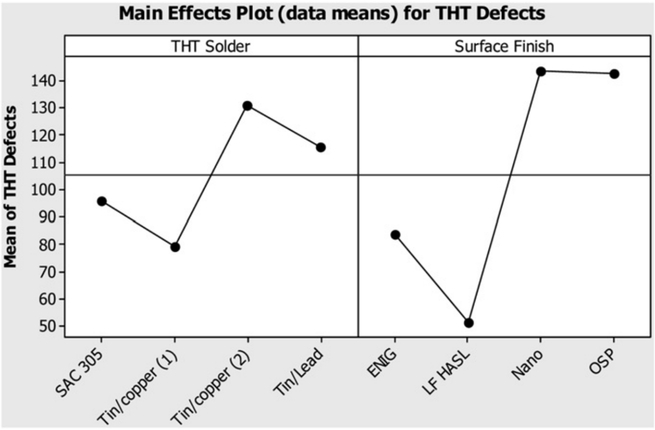

Fig. 9. Main effects plot for through hole component defects.

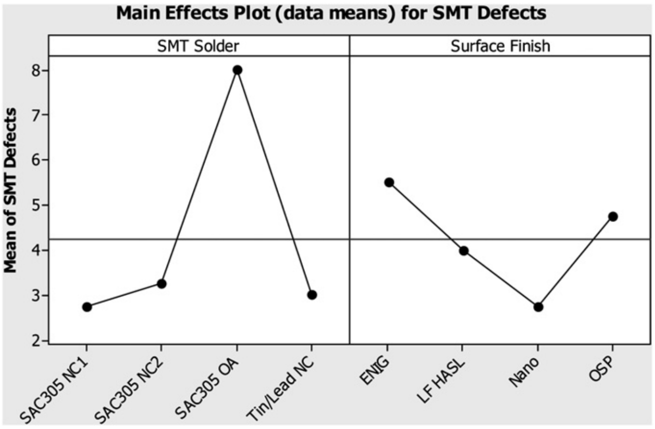

Fig. 11. Main effects plot for the surface mount components for all solder types.

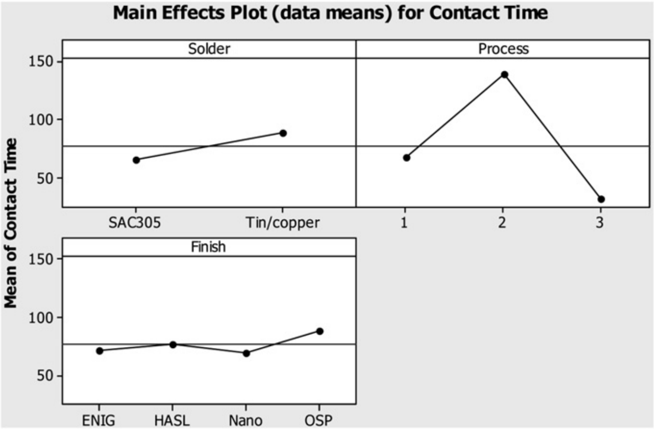

Fig. 12. Main effects plot for contact time.

Microsectioning is a labor intensive process, and only the necessary rework coupons were microsectioned in order to reduce labor needs for this research. Since rework coupons with a ENIG surface finish have a nickel barrier, copper dissolution is typically not considered an issue for these coupons. Consequently, microsections were taken on only two out of the six ENIG rework coupons to validate that this assumption was accurate.

The microsectioning was done at the same location on the 200 pin through hole connector for each of the rework coupons. The plated through hole with the most copper dissolution was selected for cross section pictures and copper thickness measurements.

The copper thickness at the bottom side knee location was considered to be the minimum thickness of the copper for the rework coupon. The bottom side knee copper thickness was compared to IPC 6012B "Qualification and Performance Specification for Rigid Printed Boards" standards for minimum copper thickness (IPC, 2004). The target level for the rework efforts was to achieve a Class 3 level which is a minimum of 1.0 mil copper thickness. The IPC 6012B standards for minimum copper thickness are provided below. There were no signs of thermal degradation to the laminate or the component during the rework process.

- Class 3: minimum of 0.001" copper (1.0 mil)
- Class 2: minimum of 0.0008" copper (0.8 mils)
- Class 1: minimum of 0.0006" copper (0.6 mils)

The Main Effects Plot was generated to show the copper dissolution measurements in relation to the solder alloy used, the rework process used, and the surface finish on the rework coupon.

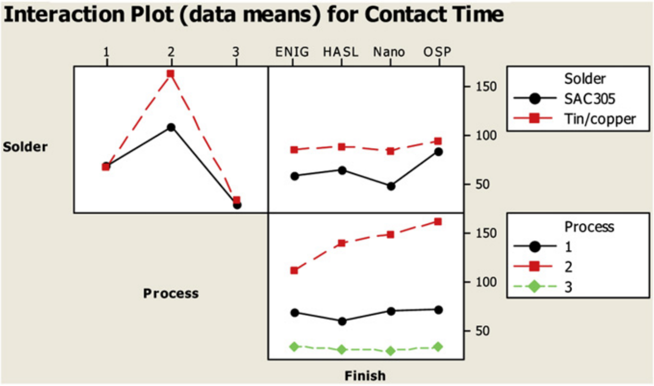

Fig. 13. Interaction plot for contact time.

The following Fig. 14 shows the Main Effects Plot for copper dissolution after completion of the rework process.

Upon review of the Main Effects Plot for Copper dissolution, the following results were obtained.

- Tin/copper solder had 42% less copper dissolution than SAC 305 solder.
- The hybrid nozzle used in Process 2 had 6% less copper dissolution than the standard nozzle used in Process 1.
- Use of the Air Vac for component removal (Process 3) provided 43% less copper dissolution than Process 1.
- ENIG had the lowest copper dissolution, and the nano surface finish had the least amount of copper dissolution for a surface finish without a nickel barrier.

4. Discussion

4.1. Assembly

4.1.1. Surface mount component assembly

The test vehicles assembled with the SAC 305 NC1 solder paste had the lowest defect rate for all the solder pastes evaluated in this research. For test vehicles assembled with lead-free solder pastes, the nano and lead-free HASL surface finishes had the lowest defect rate. For the various lead-free solder paste and surface finish combinations, the combination of SAC 305 NC1 solder paste and the HASL surface finish had the overall lowest defect rate for the test vehicles assembled for this research.

4.1.2. Through hole component assembly

Overall, the test vehicles assembled with the tin/copper (1) solder had the lowest defect rate for all three solders evaluated in this research. For boards assembled with lead-free solders, tin/copper (1) solder had the lowest defect rate, and the HASL surface finish had the lowest defect rate. There was significant variation with the performance of the ENIG surface finish with the various solders. For the tin/lead and SAC 305 solders, ENIG was the surface finish with the least defects, and for both tin/copper solder parameters, ENIG was the surface finish with the most defects. The lead-free HASL surface finish provided the most consistent results as it had either the lowest or second lowest defect rate across all solders.

For through-hole component assembly, the test vehicles assembled with the OSP and nano surface finishes had the highest level of defects. For the test vehicles with an OSP finish,

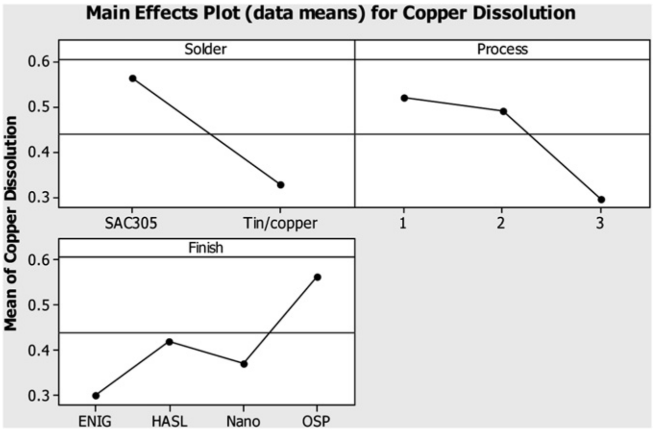

Fig. 14. Main effects plot for copper dissolution.

a contributor to this high failure rate was the time delay between conducting the surface mount assembly and through hole assembly. During this delay, there is potential for degradation of the OSP surface finish that can have a negative impact on subsequent soldering efforts. A key recommendation is to try to minimize the time delay between surface mount and through hole component assembly efforts. Preferably, both procedures should be conducted during the same day.

The best method for applying the nano surface finish to printed circuit boards is to apply it directly to bare copper. However, for the test vehicles used in this research, this method was not followed. Instead, an OSP finish had been previously applied to the test vehicle, then the OSP finish was stripped off, and then the nano surface finish was applied to the test vehicles. The soldering results would most likely be better if the nano surface finish was applied directly to bare copper for further research or assembly efforts.

4.2. Rework

4.2.1. Contact time

Contact time between the test vehicle and the liquid solder in the rework nozzle can be a contributing factor to the generation of copper dissolution. In general, the greater the contact the greater the copper dissolution if all other contributing factors (e.g. solder, surface finish, nozzle design, etc.) are equal. Process #1 had a much lower mean contact time as compared to the mean contact time for Process #2. The only difference between these two processes was the type of nozzle used, where Process #1 used the standard nozzle and Process #2 used the hybrid nozzle. Therefore, the contact time required for solder flow through to the top side of the rework coupon was much greater for the hybrid nozzle than for the standard nozzle.

Process #3 had the lowest mean contact time which can be attributed to no contact time during the component removal process when using the Air Vac machine. The SAC 305 solder had a much lower mean contact time as compared to tin/copper. The contact time for the ENIG was the lowest of the four surface finishes, and the nano surface finish was the lowest of the three other surface finishes without a nickel barrier. The combination of process and surface finish with the lowest contact time was Process #3 with the nano surface finish.

4.2.2. Copper dissolution

The target objective for the rework efforts were to achieve IPC 6012B Class 3 standards for a minimum copper thickness of 1.0 mils or greater. This target was achieved for several rework coupons that underwent rework with lead-free solder and surface finishes. The rework coupons that used the tin/copper solder had greater contact time, but less copper dissolution than the coupons using the SAC 305 solder for the rework efforts. Therefore, the type of solder alloy was a greater contributing factor to copper dissolution than the contact time.

The rework coupons that used Process 2 (hybrid nozzle) had greater contact time but less copper dissolution than Process 1 (standard nozzle). Therefore, the hybrid nozzle was effective at reducing the copper dissolution even though it required additional contact time. The rework coupons that used Process 3 had less contact time and less copper dissolution than both Process 1 and Process 2. The reduction in contact time is attributed to the use of the Air Vac equipment for the component removal. The rework coupons with the ENIG surface finish had the lowest copper dissolution because of the protective nickel barrier. The rework coupons with the nano surface finish had the least amount of copper dissolution for a surface finish without a nickel barrier. Finally, there were no signs of thermal degradation to the laminate or the components during the rework efforts.

5. Conclusions

The cooperation and assistance provided by the members of the Consortium was essential for the ability to successfully carry out this research. From an assembly perspective, the research conducted by the consortium was successful in providing needed information to help companies transition to lead-free electronics assembly. Based on the assembly results achieved by the Consortium, with the careful selection of solder paste and surface finish, it was demonstrated that surface mount and through hole components can be assembled with lead-free materials and achieve equal to or less defects than boards assembled with tin/lead materials. From a rework standpoint, the research was successful in demonstrating that rework with lead-free materials can meet IPC Class 3 standards for minimum copper thickness.

The success of the New England Lead-free Electronics Consortium further demonstrates that the toxics use reduction model can be applied on a supply chain basis. There were benefits from this collaboration to the academic, government, and industry participants. For example, the industry participants were able to have direct input and influence on the type of research that was undertaken. Further, the industry participants were able to share the costs to address a major industry challenge, and as a result were able to derive competitive advantage for early preparedness for transitioning to lead-free electronics.

The academic participants were able to forge collaborative relationships between the university and regional businesses. The research efforts also provided real world learning opportunities for the graduate and undergraduate students that participated at various stages of the research. The government participants were able to reduce the use of a toxic material (lead) which helps create a safer occupational setting and an improved environment. Overall, the government, industry, and academia collaboration was a successful model for applying toxics use reduction principles for a challenging and important application.

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