Lead-Free Selective Soldering: The Wave of the Future

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The European perspective on waste management and recycling as described in the European Union's Waste of Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (ROS) strongly suggests that lead-free electronic assemblies will be mandatory in Europe by 2008. Japan is moving toward voluntary compliance by 2003 with a lead-free initiative that focuses on environmental marketing of new products such as mobile phones, consumer electronics and automotive electronics (with the exception of recycled lead-acid storage batteries).

The viewpoint concerning lead-free electronic assemblies in the U.S. is somewhat different since lead usage in electronic solder comprises less than 1.0% of total lead consumption. Despite this fact, technological obsolescence of end-of-life (EOL) electronic products resulted in 21 million used computers being dumped into the solid-waste recycling process in 1998.[1]

An additional concern is that although the electronic solder contained in electronic products represents less than 1.0% of total lead consumption, 28.5% of all lead bearing materials going into municipal solid waste (MSW) in the U.S. is from associated cathode ray tubes (CRT's) contained in television sets and computer monitors. If lead-acid storage batteries could be 100% recycled and thereby removed from MSW, electronic solder and CRT's would represent more than 83.7% of the remaining lead bearing source material.[2]

LEAD-FREE REQUIREMENTS

Lead-free soldering of surface mount technology (SMT) has been studied extensively over the past several years while lead-free flow soldering of through hole (TH) components has received little attention. However, in order for an electronic assembly to be considered as truly lead-free, every step of the assembly process must utilize lead-free materials including SMT reflow, TH soldering, rework, field repair and EOL recycling infrastructure.[3]

Wetting balance tests can be used to determine the solderability of any solder alloy. Wetting is an essential prerequisite for flow soldering of TH components, either by wave soldering or site-specific selective soldering, and is a function of fluxing, preheating, solder temperature, contact time, wave formation and nitrogen inerting.

Alloy Selection

Lead-free solder joints have been proven to be reliable based on a comprehensive series of accelerated thermal cycling (ATC) and failure analysis tests.[4] However, the majority of lead-free alloys available for TH flow soldering exhibit poorer properties and higher surface tension than traditional SnPb alloys which requires that they be processed at higher temperatures as shown in Table 1.

Alloy	Melting Point	Advantages	Concerns
Sn0.7Cu	227° C	Lower cost	Higher temperatures
Sn3.5Ag	221° C	Better thermal fatigue	Silver toxicity
Sn3.0Ag0.5Cu	217° C	Higher tensile strength	Silver toxicity
SnAgCuSb	217° C	Increased reliability	Toxicity and four part alloy

Table 1: Comparison of Lead-Free Flow Solder Alloys

This is especially true when flow soldering TH components on more challenging printed circuit boards (PCBs) that have a high thermal demand due to either complex ground planes, heat sinks or inter-layers.

The intermetallic compound layers formed by the majority of lead-free solder alloys during soldering and subsequent aging are similar to those present with equivalent SnPb interfaces.[5] The difference being that lead-free alloys do not contain a lead-rich region between the solder and the intermetallic layer that is typical with a lead bearing alloy after aging. Intermetallic compound growth rates are statistically no different from those of traditional SnPb alloys.

Flux Requirements

Since the wetting characteristics of lead-free alloys are less than that typically exhibited by SnPb alloys at lower process temperatures, the selection of a good flux is mandatory to assure good solderability. The flux selected must be able to withstand exposure to the higher process temperatures required for lead-free alloys. In general, fluxes used for lead-free TH flow soldering must be able to withstand topside PCB preheat temperatures as high as 130C and solder temperatures as high as 280C for a minimum of 3 seconds of contact time or longer.

The major difference between SbPb and lead-free flow soldering is the higher melting point required by the lead-free alloy. Because lead-free alloys require higher preheat temperatures, thermal shocking of components as they enter the liquidous wave should not exceed 100C. For most applications, VOC-free, water-based fluxes, applied with a spray fluxer or inkjet drop fluxer, are recommended since they can withstand these higher processing temperatures.

Thermal Aspects

In order to form quality solder joints, the flow soldering process irregardless whether wave soldering or site-specific selective soldering is used, must: 1) raise the temperature of the base metals high enough to allow sufficient wetting, 2) provide adequate contact time for capillary action to take place, and 3) provide adequate thermal energy to create an intermetallic layer.

While lead-free solder alloys require higher processing temperatures due to the nature of their wetting properties, TH components can be damaged if their internal threshold temperature is exceeded by either rapid heating or excessive heating of the PCB assembly during the soldering process.[6] This is especially true in lead-free flow soldering since the process temperatures are typically 30-40C higher than traditional SnPb alloy process temperatures for which most TH components were designed. Figure 1 shows a typical thermal process window for a TH component in which a minimum dwell time is required to promote wetting of the through-hole component lead while a maximum dwell time should not be exceeded that could result in damage to the component. Likewise, a minimum temperature is required to make the solder liquidous while exceeding a maximum temperature could cause internal damage to the component.

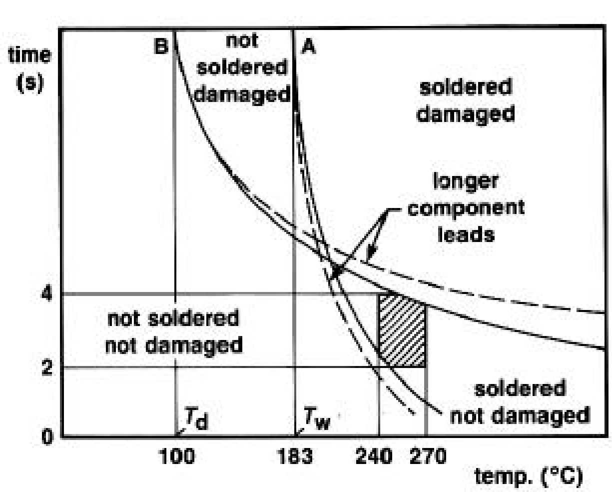

Figure 1: Processing Temperatures

The significant difference between SnPb and lead-free flow soldering thermal profiles are the increased preheat and solder temperatures shown in Figure 2. For most lead-free flow soldering applications, the topside PCB temperature will increase by as much as 125% to approximately 110-130C to limit the thermal shock as the PCB contacts the higher temperature of the lead-free liquidous solder. The ideal method is to heat up the PCB as quickly as possible to 100C and continue to heat the PCB with forced hot-air convection preheating for optimal evaporation of the water medium from the water-based flux.[7] This method of sustained preheat is also recommended for high-volume production or when soldering thermally challenged PCB assemblies.

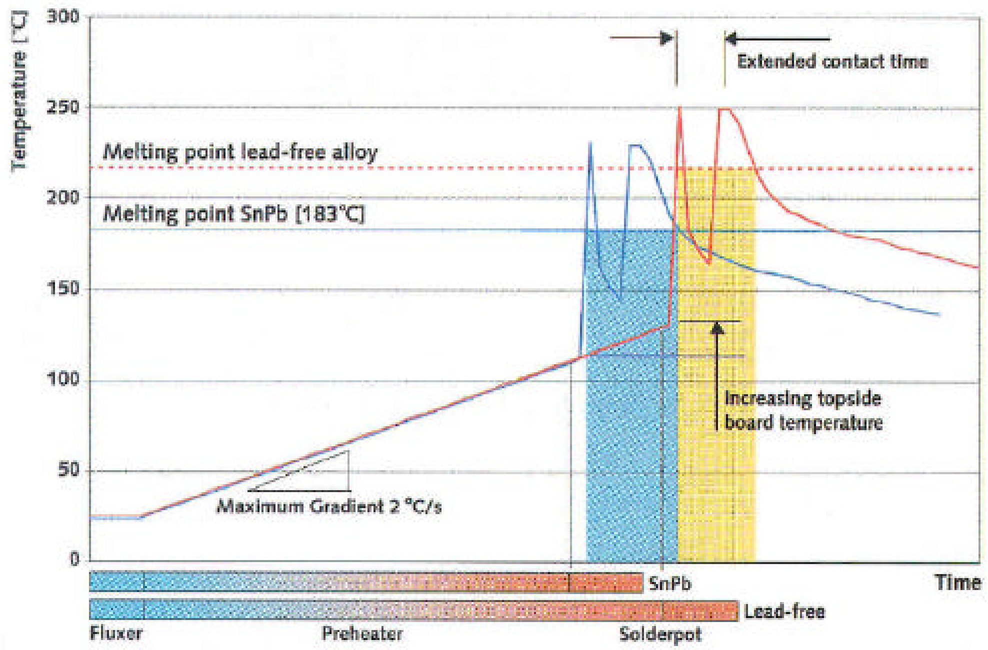

Figure 2: Preheat Temperatures

Due to the higher melting point of lead-free alloys, the temperature of the solder pot will also increase to improve solderability and shorten contact times. For AgSnCu with a melting point of 217C, the solder pot temperature will be between 250-270C or as high as 260-280C for SnCu.

Dross Formation

Lead-free alloys oxidize more rapidly than SnPb solder when the alloy is liquidous and at a high processing temperature. Dross is comprised of cells of solder metal enveloped by an oxide skin. A new oxide layer forms on a liquidous solder bath immediately after the oxide skin is removed. Oxides formed on lead-free alloys are more evident than SnPb solder since lead-free alloys contain as much as 95% tin content compared to only 63% for 63/37 SnPb solder. This higher tin content results in a more rapid formation of tin oxides, in the presence of tin-oxygen (SnO) and (SnO2), while the higher solder bath temperature accelerates the oxidation process. The behavior of tin oxide is predicable with SnPb solder in that the oxide layer breaks up easily and allows for straightforward removal of the dross. The oxide layer formed by a SnAg or SnAgCu lead-free alloy is more tenacious and does not break up into smaller particles making dross removal more difficult. The use of nitrogen inerting is highly recommended when implementing lead-free flow soldering since it not only improves wetting, but also minimizes the formation of tin oxide and dross.

Metals that contact the liquidous solder will dissolve in solder baths of lead-free alloys which are more aggressive than SnPb solder. The dissolution rate is dependent upon the base metal, the alloy composition, the temperature of the solder bath and the flow velocity of the solder. The dissolution rate will be higher for those metals that are not already present in a lead-free alloy. The major sources of contamination for lead-free alloys are lead (Pb) from components leads pre-tinned with SnPb or hot air solder leveled (HASL) PCB's, copper (Cu) from PCB pads or component leads, and iron (Fe) from internal elements of the solder pot. Due to the high tin content of lead-free alloys such as SnCu and SnAgCu, solder pot elements made from 304 stainless steel should not be used since dissolution of the stainless steel results in leaching of iron particles contaminating the solder bath.[8] It is recommended for lead-free applications that the internal elements of a solder bath be fabricated of high-grade 316 stainless steel which reduces dissolution since it contains 10-18% chromium (Cr) and 10-14% nickel (Ni). To further prevent leaching, elements fabricated of 316 stainless steel should receive a corrosive resistant coating or surface pacification treatment.

A common method for generating flow of the solder that comes into contact with the PCB in a wave solder machine or selective soldering system is the use of impeller based solder pumps. Impeller based pumps have a disadvantage in that they produce a vortex that draws oxides and dross formed on the surface into the solder bath. Electromagnetic solder pumps as shown in Figure 3 have the benefit of pumping solder without producing a vortex and therefore reducing the intermixing of oxides and dross throughout the solder bath.[9] Electromagnetic pumps work on the principle of inducing an electrical current though magnetic coils inducing a magnetic field which generates the necessary pumping action to force the solder through the nozzle without any moving parts which is vital to reducing maintenance costs since maintenance of lead-free solder baths is more critical than traditional SnPb solder baths.

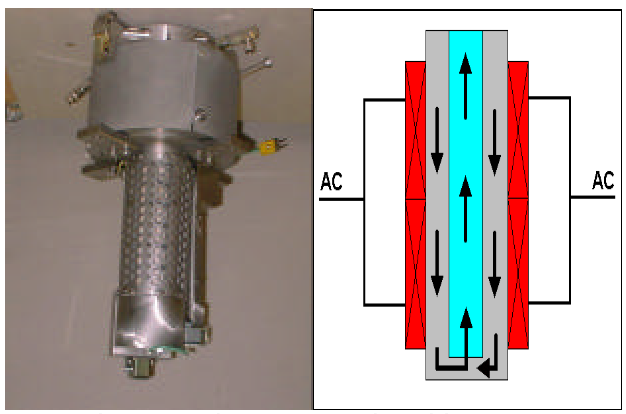

Figure 3: Electromagnetic solder pump

With the introduction of higher cost lead-free solder alloys, electromagnetic solder pumps have generated renewed interest due to their ability to reduce dross. In Japan where lead-free implementation is ahead of the U.S., electromagnetic solder pumps are in widespread use for lead-free flow soldering applications for both new wave solder machines as well as lead-free upgrades to existing machines due to their ability to minimize dross formation.

SOLDERING TECHNIQUES

The use of double-sided SMT and double-sided TH components mounted on both sides of complex mixed technology PCB's typically necessitates two or three unique solder processes. Mass reflow is typically utilized to solder minimalistic and SMT components. A combination of wave soldering utilizing aperture pallets to shield fine-pitch SMT components from immersion in liquidous solder, or a combination of intrusive reflow and manual soldering is used to solder TH components in complex PCB assemblies.

Intrusive Reflow

Paste-in-hole (PIH) or intrusive reflow is commonly used to solder TH components in complex mixed technology PCB's because of the distinct advantage of eliminating secondary operations such as wave soldering or manual soldering. Although paste-in-hole is widely utilized at present, its use will be limited with lead-free applications due to the higher reflow temperatures involved.   Many TH components that are presently soldered with the traditional SnPb PIH process, will no longer be thermally compatible with exposure to the higher peak reflow temperatures of 260C required for lead-free alloys which is greater than the current thermal tolerance of 235-240C for many electronic components.

Wave Soldering

Of the traditional flow soldering methods used to solder through-hole components in complex PCB assemblies, aperture wave pallets are one of the most widely used methods due to their common process compatibility with conventional wave soldering. Although the use of aperture pallets is a generally accepted practice for SnPb applications, several disadvantages result when utilized for lead-free soldering of complex double-sided assemblies since the use of aperture pallets places a higher thermal demand on the wave solder machine and may result in slowing the conveyor speed and decreasing throughput. Aperture pallets also require higher wave heights that result in greater generation of dross that adds an economic disadvantage when using higher cost lead-free alloys.

Selective Soldering

Just as SMT continues to evolve, TH components still appear in many complex mixed technology PCB assemblies. The remaining TH components in these assemblies generally consist of connectors, pin-grid arrays and thermally challenged non-standard TH devices. Many of these components are incompatible with intrusive reflow due to thermal restrictions or are not feasible for aperture pallets due to excessive height limitations. Several methods of selective soldering are available that address the necessity for site specific TH soldering including fountain solder systems and programmable selective soldering.

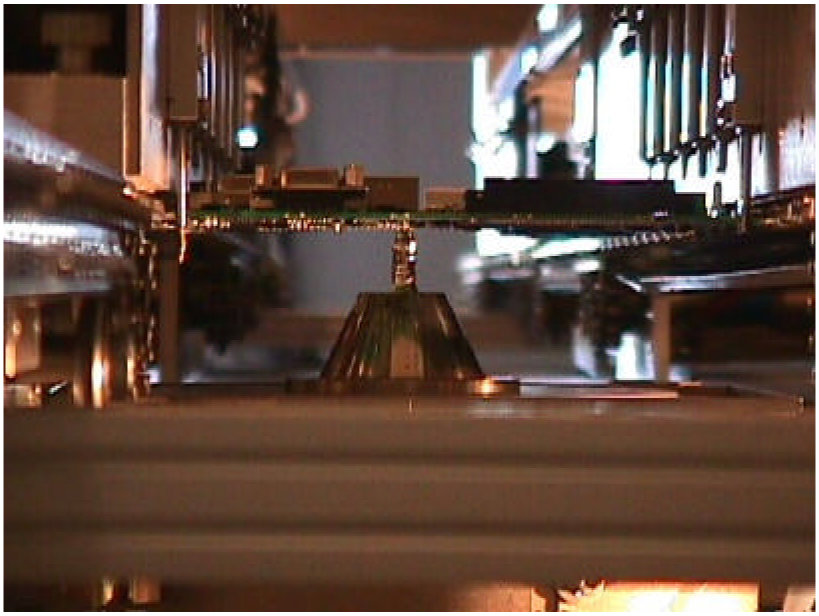

Figure 4: Programmable selective soldering system

Programmable selective soldering systems shown in Figure 4 use a software-controlled multi-axis environment to control flux deposition, preheating and solder application. These systems have the advantage of optimizing the contact time for each solder joint and limiting component thermal exposure and flux residues on the PCB since flux application and liquidous solder does not contact the entire board but only in programmable site specific locations.

The use of selective soldering for lead-free TH soldering applications offers several advantages over intrusive reflow and wave soldering in terms of component reliability. During the selective soldering process the body of a TH component is limited to lower thermal exposure during sustained preheat and soldering that results in the elimination of potential internal thermal damage, moisture sensitivity levels and degradation of plastics.

COST CONSIDERATIONS

The operational costs for a selective soldering system are considerably less than a traditional wave soldering machine due to its site specific nature as compared to a mass soldering method. The consumption of consumables is a major cost for a typical wave soldering operation. Table 2 details a comparison between the principle consumables and major plant utilities for a selective soldering system and a wave soldering machine using aperture pallets for an eight hour shift. The operational comparison for both SnPb and SnAgCu alloys is shown.

Obviously the higher cost of the SnAgCu lead-free alloy directly affects both the cost of replenishment solder as well as dross. The difference in energy consumption can be attributed to the higher melting point and processing temperatures required for the SnAgCu alloy that results in both longer heat up times for the solder pot as well as higher preheat temperatures.

Soldering Method	Selective	Selective	Wave	Wave
Solder Alloy	SnPb	SnAgCu	SnPb	SnAgCu
Solder Pot Temp.	250° C	275° C	250° C	275° C
Time to Setpoint	1.5 hrs	2.5 hrs	3.5 hrs	5.5 hrs
Power Consumption to Setpoint	5.1 kWh	5.1 kWh	34.0 kWh	34.0 kWh
Power Consumption at Setpoint	3.5 kWh	3.5 kWh	5.0 kWh	5.0 kWh
Consumables:				
Solder	$5.88	$10.20	$70.50	$119.00
Dross	$1.60	$3.00	$20.00	$36.00
Nitrogen	$2.33	$2.57	$36.23	$42.53
Flux	$1.80	$1.80	$10.80	$10.80
Electricity	$2.32	$2.65	$10.34	$14.76
Total Cost	$13.92	$20.22	$147.86	$223.08

Table 2: Comparison of Operational Costs/8 hr Shift

The true cost of ownership extends far beyond the initial purchase price of capital equipment. Despite the fact that most programmable selective soldering systems have a higher purchase cost than a wave soldering machine, the cumulative effects of lower material requirements and energy savings results in a favorable economic impact for selective soldering as compared to wave soldering using aperture pallets.

QUALITY ANALYSIS

The TH wetting properties of SnAgCu alloy are less than the wetting properties of traditional SnPb solder but for most PCB assemblies meets the IPC-A-610 requirements.[10] Since it is known that solder defects are directly related to wetting, and that wetting of SnAgCu alloy may not meet the acceptable limits determined by the IPC standard when more thermally challenged PCB's are soldered, a series of tests were conducted using a selective soldering system.

A range of TH components were used for this selective soldering process development study with both SnPb and lead-free component lead plating materials as shown in Table 3A.

Type	Plating	Lead Dia.	Hole Dia.	Solder Joints/PCB
DC/DC Converter	SnPb	0.55 mm	0.75 mm	28
DC/DC Converter	SnPb	2.00 mm	2.15 mm	8
12-pin Connector	Sn	1.00 mm	1.20 mm	48
24-pin Display	NiAu	0.90 mm	1.05 mm	96

Table 3A: Components used in Selective Soldering Study

Rather than designing a special test vehicle, two production PCBs were used representing both an industrial product application and an automotive electronics application. These PCB's had a variety of solder pad finishes as shown in Table 3B.

PCB	Dimensions	Thickness	Pad Finish
1	304 x 406 mm	.090"	OSP over bare Cu
2	194 x 249 mm	.062"	HASL

Table 3B: PCB's used in Selective Soldering Study

The results of the study of PCB #1 as shown in Table 4A found that increasing preheat temperature and increasing preheat duration improved wetting and the formation of destination side solder fillets. It was also determined that an increase in preheat temperature produced more significant improvement than increasing contact time. This was especially true for the high thermal mass DC/DC converters.

Parameter	Test 1	Test 2	Test 3	Test 4
Bottom Preheat Temp.	90° C	90° C	110° C	110° C
Bottom Preheat Time	80 sec	80 sec	90 sec	90 sec
Top Preheat Temp.	100°C	100° C	135° C	140° C
Top Preheat Time	80 sec	80 sec	90 sec	90 sec
Top Preheat Temp.	150° C	150° C	150° C	150° C
Top Preheat Time	120 sec	120 sec	120 sec	90 sec
Solder Pot Temp.	260° C	260° C	260° C	260° C

Table 4A: Matrix for Selective Soldering Process Study – PCB #1

The results of the study of PCB #2 as shown in Table 4B found the opposite results to be effective in improving solder quality. It was determined that decreasing bottom-side infrared (IR) and topside convection preheat temperature and duration during the initial preheat phase, plus increasing the temperature of the solder pot, improved wetting and destination side solder fillets. It was determined that decreasing IR preheat temperature eliminated burnt flux on the bottom-side of the PCB and therefore improved solder filling since this automotive electronics PCB was soldered at a much faster cycle rate.

Sufficient preheating of the PCB and TH components is critical to evaporate the solvent from the capillary between the barrel and component lead and to assure complete barrel fill and formation of solder source side and destination side solder fillets. Convection preheating not only evaporates the solvent but also helps to minimize the temperature differential between the components and the PCB.

Parameter	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Bottom Preheat Temp.	110°C	110°C	100°C	90°C	90°C	90°C
Bottom Preheat Time	90 sec	90 sec	90 sec	90 sec	90 sec	80 sec
Top Preheat Temp.	140°C	140°C	120°C	110°C	110°C	110°C
Top Preheat Time	90 sec	90 sec	90 sec	90 sec	90 sec	80 sec
Top Preheat Temp.	150°C	150°C	150°C	150°C	150°C	150°C
Top Preheat Time	90 sec	90 sec	90 sec	90 sec	90 sec	90 sec
Solder Pot Temp.	260°C	260°C	260°C	260°C	275°C	275°C

Table 4B: Matrix for Selective Soldering Process Study – PCB #2

It was found that sustained convection preheat of the PCB during the soldering process greatly improves the wetting action of lead-free alloys. It has been determined that with the use of sustained convection preheat throughout the selective soldering process, the temperature of the solder pot can be decreased from 320-350C to 260-280C. Operating the solder pot at a lower temperature produces less thermal burden on the components and PCB, reduces oxide and dross generation and conserves energy.

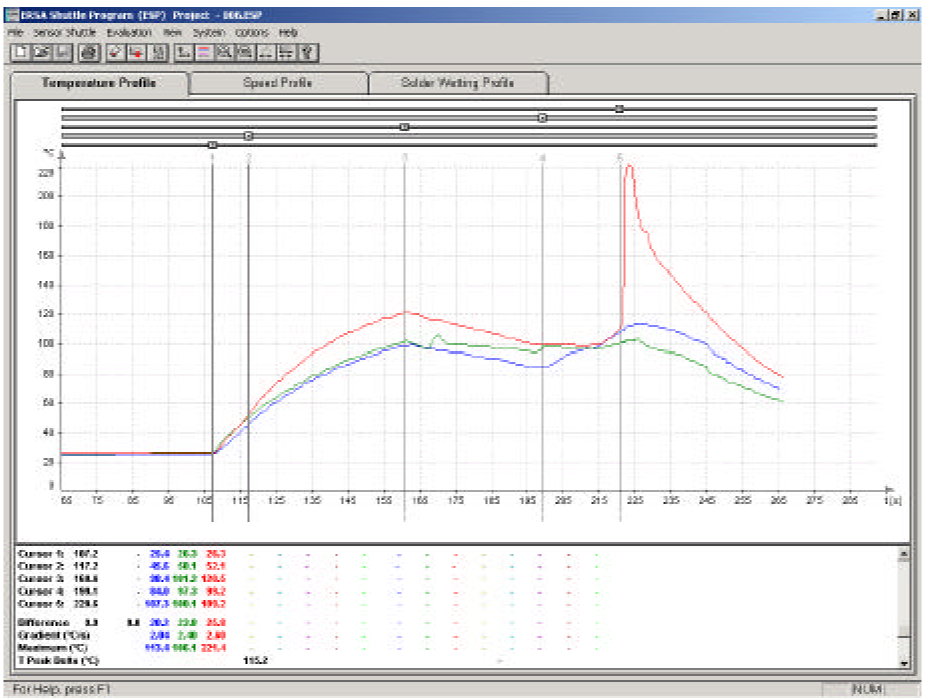

Figure 5: Selective soldering thermal profile

In order to study the effects that sustained convection preheat has upon the selective soldering process additional tests were conducted. Figure 5 shows the thermal profile that was achieved when selectively soldering PCB #2 without the use of sustained convection preheat. In this test the PCB was heated using only bottom-side preheat and the latent heat of the solder pot. Bottom-side short-wave infrared preheating was used which is an excessive heating method resulting in rapid heating and a corresponding decrease in topside PCB temperature prior to soldering.

A cross-section study was conducted of the PCB's that were soldered without the use of sustained topside convection preheat during the selective soldering process. Figures 6 through 8 show these results. Figure 6 shows an incomplete filling of the capillary between the component lead and PCB barrel with a noticeable lack of wetting caused by rapid heating and too short of a warm-up time. This non-wetting condition resulted in the development of a visible separation between the solder alloy and the Cu barrel of the PCB when the solder joints were exposed to mechanical stress as shown in Figure 7. It was determined that this separation resulted from excessive intermetallic compound thickness that decreased the long-term mechanical strength of the solder joint due to rapid heating as shown in Figure 8.

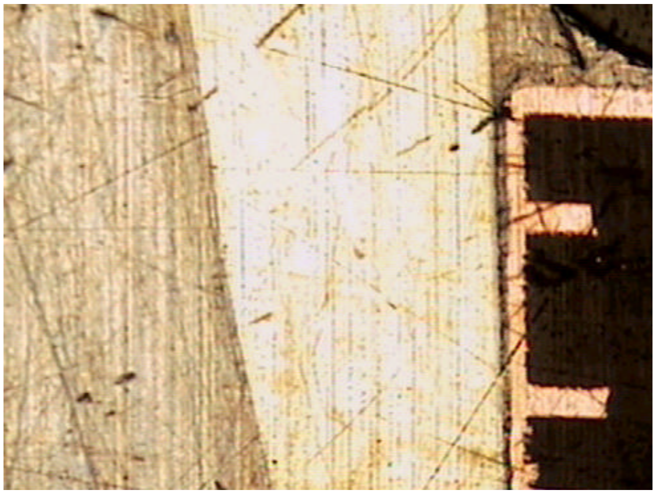

Figure 6: Incomplete Filling

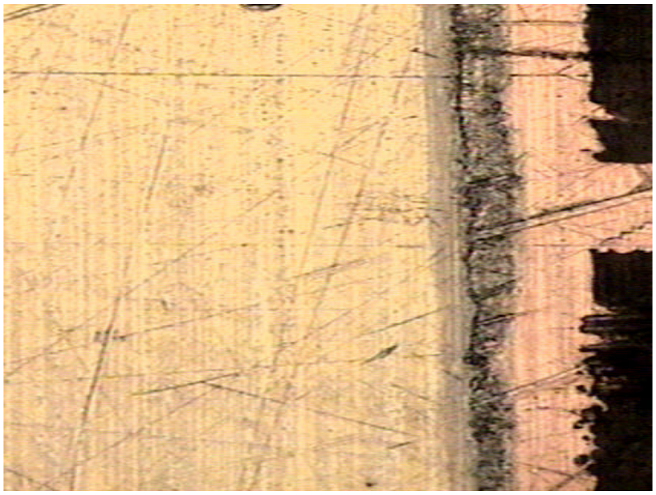

Figure 7: Non-Wetting

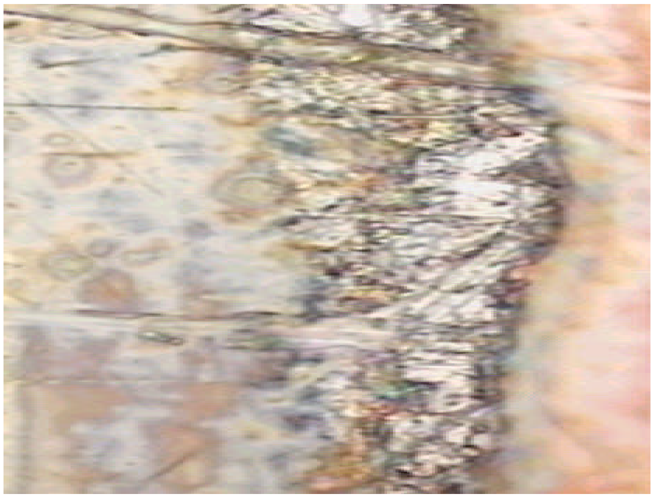

Figure 8: Excessive intermetallic thickness

Figure 9 shows the thermal profile that was achieved when selectively soldering PCB #2 using sustained convection preheat. In this test the PCB was heated from both the top and bottom using bottom-side preheat as well as sustained topside convection preheat throughout the selective soldering process. Sustained convection preheat is an asymptotic heating method that maintains a uniform topside PCB temperature without a decrease in the topside temperature prior to soldering.

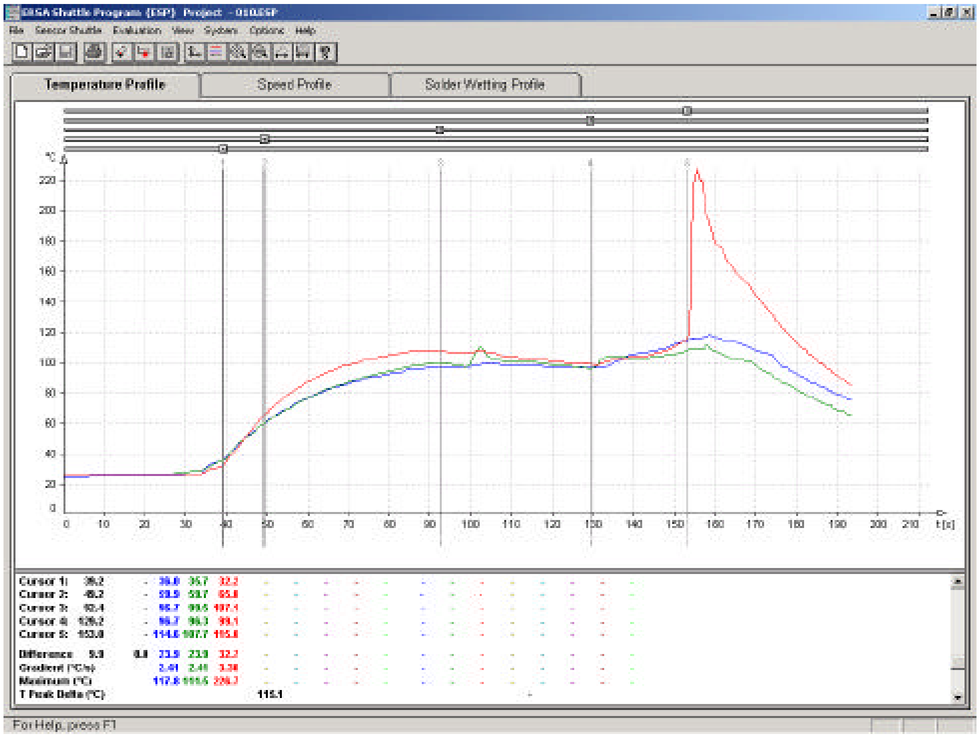

Figure 9: Selective Solder Thermal Profile

A cross-section study was conducted of the PCB's that were soldered using sustained topside convection preheat during the selective soldering process. Figures 10 through 12 show these results. Figure 10 shows a complete filling of the capillary between the component lead and PCB barrel with complete wetting action. Complete wetting resulted in no visible separation between the solder alloy and the Cu barrel of the PCB after exposure to mechanical stress as shown in Figure 11. It was noted that the intermetallic compound thickness produced by the asymptotic heating method had ideal chemical diffusion as shown in Figure 12.

Figure 10: Complete filling

Figure 11: Complete wetting post mechanical stress

Figure 12: Acceptable level of intermatallic

CONCLUSION

Selective soldering is a viable, cost effective alternative to wave soldering for lead-free soldering of TH interconnections in complex mixed technology PCB assemblies. Confirmation tests have established that sustained topside convection preheat throughout the selective soldering process results in improved solder joint quality.

This asymptotic heating method results in the elimination of solder defects especially pronounced when soldering with higher melting point lead-free alloys at high conveyor or throughput speeds. The use of electromagnetic solder pumps furthermore reduces the formation of dross with lead-free solder alloys.

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