

Lead-Free Soldering Guide



**Alloys • Chemistries •
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AIM has the RoHS-compliant lead-free products and process knowledge required to help your company in the transition to lead-free soldering in the most logical and economical ways possible.



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Introduction

The issue of lead-free soldering has piqued a great deal of interest in the electronics assembly industry as of late. What was once an issue that seemed too far away to worry about has become a pressing reality. In order to avoid confusion, last minute panic, and a misunderstanding of how the issue of lead-free soldering will affect the industry and individual users of solders, it is necessary for all suppliers and assemblers to become educated in this matter.

Lead-Free Soldering - Why?

The most simple explanation for the tremendous interest in lead-free soldering is FEAR: Fear of Legislation, Fear of Trade Barriers, and Fear of Competition. Most companies do not necessarily *want* to change to lead-free, but rather are motivated by a combination of these three fears.

- The WEEE/RoHS directives in Europe and similar mandates in Japan and other parts of the world have instilled fear that a legislative body will prohibit the use of lead in electronics soldering.
- If a particular country disallows lead in electronics, a trade barrier is created between that country and anyone not capable of providing lead-free electronics solutions. Of course, this also could take place between individual companies.
- Some companies already are producing electronics products with lead-free solder alloys and marketing them as such. This has led to fears of being caught behind commercially.

Resistance to Lead-Free Soldering

Along with the great interest in lead-free soldering has come much resistance to this potential change. The reasons for this change may be divided into two categories: cost and reliability concerns.

As lead is one of the least expensive elements on earth, replacing it with virtually any other metal will raise the price. In addition, incidental costs should not be overlooked; the cost of educating and training company personnel on the use of lead-free alloys and qualifying lead-free parts are not inexpensive ventures.

Reliability issues are also a great concern in the lead-free issue. Although many of the lead-free alloys have demonstrated more-than-adequate reliability characteristics, engineers have developed a certain comfort factor with tin-lead over the last few decades that will not be easy to emulate. In addition, the reliability of assemblies exposed to the higher reflow temperatures of lead-free solders also is of great concern.

Lead-Free Solder Requirements

In response to the aforementioned concerns, a great amount of effort has gone into the development of lead-free solders intended to be "viable" replacements for tin-lead solders. Although each of these alloys has its advantages and disadvantages, some alloys clearly stand out as the likely replacements for tin-lead for the majority of soldering applications.

NOW is the Time to Prepare

Lead-free soldering is not an issue of "if" anymore. In order to be prepared for the inevitable switch to lead-free soldering, companies should begin the search for suitable lead-free products and processes for their unique applications as soon as possible. Only when companies have hands-on experience with lead-free electronics assembly will there be complete confidence in the viability of lead-free soldering and an understanding of what to expect from this dramatic process change.

This guide is intended to guide the future users of lead-free solders to the most appropriate lead-free alloys and processes for their applications. Please feel free to contact AIM at anytime so that we may be of assistance during this transition period. Whether you choose to implement lead-free assembly, sample a lead-free alloy, or simply have a technical question to be answered, AIM is your source for the latest in lead-free soldering technology.

Legislation Update

In January 2003 the EU approved The Waste From Electrical And Electronic Equipment (WEEE) and The Use Of Certain Hazardous Substances In Electrical And Electronic Equipment (RoHS) Directives. It has been decided that four heavy metals (lead, cadmium, mercury and hexavalent chromium) and the brominated flame retardants PBB and PBDE will be banned in new electronic equipment in the European Union from 1 July 2006. Existing national measures on these substances can continue to apply until that date, by which they have to be replaced by the new Community rules.

Following is a summary of the Directives:

Areas Affected

- These directives pertain to products manufactured and imported into European Community member states.

Scope & Coverage of RoHS

- Categories
 - Large household appliances
 - Small household appliances
 - IT & Telecommunication equipment
 - Consumer equipment
 - Lighting equipment
 - Electrical and electronic tools
 - Toys
 - Automatic dispensers
- The exemptions have not been changed. They remain:
 - Lead in high melting temperature type solders (i.e. tin-lead solder alloys containing more than 85% lead)
 - Lead in glass in electronic components
 - Lead in piezoelectric devices
 - Lead in servers, storage and storage array systems (exempt until 2010)
 - Lead in solders for network infrastructure equipment for switching, signaling, transmission as well as network management for telecommunication

WEEE

- The main requirements of the Directive are the collection, treatment, recovery, financing and information regarding waste from electrical and electronic equipment.
- The purpose of this Directive is, as a first priority, the prevention of waste electrical and electronic equipment (WEEE), and in addition, the reuse, recycling and other forms of recovery of such wastes so as to reduce the disposal of waste. It also seeks to improve the environmental performance of all economic operators involved in the life cycle of electrical and electronic equipment and in particular operators directly involved in the treatment of waste electrical and electronic equipment.

RoHS

- States that "Member States shall ensure that new electrical and electronic equipment marketed after 1 January 2006 does not contain lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ether (PBDE).
- Regular reviews for exemptions will occur, as it is stated "Exemptions from the substitution requirement should be permitted if (it is) not possible from (the) scientific and technical point of view...or where scientific evidence demonstrates that their use does not result in any significant risk to health or the environment." Some products already exempted are:
 - Lead in high melting temperature type solders (i.e. tin-lead solder alloys containing more than 85% lead)
 - Lead in glass in electronic components
 - Lead in piezoelectric devices
 - Lead in servers, storage and storage array systems (exemption granted until 2010)
 - Lead in solders for network infrastructure equipment for switching, signaling, transmission as well as network management for telecommunication.
- Member states then have 18 months to pass their own legislation to meet the requirements of the directives. In the case of RoHS, if this remains under Article 95 (Single Market) legal basis member states cannot pass more restrictive laws.

Patent Situation

It is desirable for the industry to find an alloy that is widely available. Therefore, patented alloys have been viewed as undesirable. Although certain tin/silver/copper alloys (such as Sn/Ag3.8-4.0/Cu0.5-0.7) are patent-free and some (such as CASTIN Sn/Ag2.5/Cu0.7/Sb0.5) are patented, a more circumspect view needs to be taken to understand the impact of patents and the true number of sources available for these alloys. As stated above, the Sn/Ag2.5/Cu0.7/Sb0.5 alloy is patented. However, it has been licensed to solder manufacturers with an unlimited number of licensees and no sign-on costs. Currently, the alloy is globally available through several North American, Japanese, and European-based solder manufacturers. Although the Sn/Ag3.8-4.0/Cu0.5-0.7 alloy is not patented, the users of this alloy should be aware that solder joints produced while using this alloy may be patented and the number of electronic-grade solder manufacturers able to sell this product under license in the U.S. is extremely limited.

Alloys such as Sn/Ag3.8-4.0/Cu0.5-0.7 have been recommended to the industry despite the fact that solder joints produced from these may infringe existing patents; it has been assumed that since prior art exists on these systems that they are exempt from the patent. This is wrong, as most of the patents written have both alloy composition and application (solder joint) coverage. Basically, this means that it is allowable for a manufacturer to purchase certain alloys designed to circumvent patents (such as Sn/Ag4/Cu0.5), but using these in manufacturing may result in patent infringement. In other words, the manufacturer has violated that patent and may be subject to legal action.

How can this be? Patents may exist not only for solder alloys, but for solder joints as well. Basically, this means that even if a manufacturer is using an alloy designed to circumvent patents, if during manufacturing the alloy “picks up” base metals (normally copper) and forms an intermetallic that contains the elements covered under a patent, the manufacturer has violated that patent and may be subject to legal action. The most pertinent example of how the above can impact manufacturing pertains to the Ames Lab/Iowa State patent (# US05527628), which covers alloys within the range of tin (balance) / silver (3.5-7.7%) / copper (1.0-4.0%) / bismuth (0-10%) / zinc (0-1%). Research has demonstrated that alloys such as Sn/Ag4/Cu0.5 may be enriched by an additional 0.5% copper during soldering operations. The result: a solder joint that violates Ames’ patent. The violator: the electronics manufacturer. This applies to assemblies made or imported in the U.S. into the U.S.

AIM will provide any alloy that a manufacturer chooses to use. However, manufacturers should be cautious that their alloy of choice will not result in potential patent infringement.

LEAD-FREE ALLOY INFORMATION



AIM offers a broad range of RoHS compliant lead-free alloys for all SMT, wave soldering, hand soldering, and various applications. These alloys include all non-patented alloys, as well as the CASTIN and SN100C alloys. Many of these alloys are compatible with the flux chemistries currently used with tin-lead alloys, while some alloys require special flux chemistries. Other alloys are available upon request.

Alloy	Melting Point °C	Comment	Solder Form Availability					
			Solder Paste	Bar Solder	Cored Wire	Solid Wire	Solder Preforms	Solder Spheres
In52/Sn48	118	Alloy for low temperature applications. Costly due to high indium content. Attention should be paid to corrosion, joint strength and fatigue issues.	Yes	Yes	No	Yes	Some*	No
Sn42/Bi58	138	Alloy for low temperature applications. Attention should be paid to potential embrittlement issues and poor thermal fatigue properties.	Yes	Yes	No	Yes	Some	Yes
Sn42/Bi57/Ag1	138	Similar characteristics to Sn42/Bi58 with improved fatigue characteristics.	Yes	Yes	No	Yes	Some	Yes
In97/Ag3	143	Alloy for low temperature applications. Costly due to high indium and silver contents. Attention should be paid to corrosion, joint strength and fatigue issues.	Yes	Yes	No	Yes	Some	No
Sn91/Zn9	199	Attention should be paid to the very high corrosion and oxidation of Sn/Zn alloys. Requires special flux formulation. Short shelf-life.	No	Yes	No	Yes	Some	Yes
CASTIN® Sn/Ag2.5/Cu.8/Sb.5	217	The lowest melting point and least expensive of the tin-silver-copper family of alloys.	Yes	Yes	Yes	Yes	Yes	Yes
SAC305 Sn/Ag3.0/Cu0.5	217-218	Low-silver tin-silver-copper alloy in line with JEIDA recommendation. Lowest cost pure tin-silver-copper alloy.	Yes	Yes	Yes	Yes	Yes	Yes
SAC387 Sn/Ag3.8/Cu0.7	217-218	Alternative tin-silver-copper alloy. Similar characteristics as SAC305 with slightly higher cost of metals.	Yes	Yes	Yes	Yes	Some	Yes
SAC405 Sn/Ag4.0/Cu0.5	217-218	High-silver tin-silver-copper alloy. Similar characteristics as SAC305 with higher cost of metals.	Yes	Yes	Yes	Yes	Some	Yes
Sn96.5/Ag3.5	221	May not have adequate thermal reliability or wetting and requires higher soldering temperatures than tin-silver-copper alloys.	Yes	Yes	Yes	Yes	Yes	Yes
Sn95/Ag5	221-240	Alloy for high-temperature applications only. Costly due to high silver content.	Yes	Yes	Yes	Yes	Yes	Yes
SN100C	227	Sn/Cu/Ni + Ge alloy available from AIM in North America. Bright solder joints, improved wetting.	Yes	Yes	Yes	Yes	Yes	Yes
SAC-LOW	227	Low-silver, cost effective Sn/Cu/Ag alloy available for wave soldering and rework applications.	Yes	Yes	Yes	Yes	Yes	Yes
Sn99.3/Cu0.7	227	Cost-effective alternative for wave soldering and hand soldering applications. Attention should be paid to poor wetting and fatigue properties.	Yes	Yes	Yes	Yes	Yes	Yes
Sn97/Sb3	232-238	Alloy with similar properties to Sn95/Sb5.	Yes	Yes	Yes	Yes	Yes	Yes
Sn95/Sb5	232-240	Alloy for high-temperature applications only. Poor wetting. Less cost-prohibitive than Sn/Ag.	Yes	Yes	Yes	Yes	Yes	Yes
Au80/Sn20	281	Eutectic die attach alloy. Costly due to high gold content.	Yes	Yes	No	Yes	Some	Yes
Sn97/Cu3	227-300	Alloy for high-temperature applications only.	Yes	Yes	No	Yes	Yes	Yes
Sn/Ag25/Sb10	260-300	High Temperature die-attach alloy. Costly due to high silver content.	Yes	Yes	No	Yes	Yes	Yes
Au88/Ge12	356	Gold die attach alloy.	Yes	Yes	No	Yes	Some	Yes

* "Some" refers to preforms that generally are not available flux filled.

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AIM Lead-Free Assembly Products

AIM has been developing lead-free alloys and researching the subject of lead-free soldering since the 1980s, and we have a great deal of knowledge on lead-free alloys, processes, and the issue in general. We would be happy to work with your company on the implementation of a lead-free process and to share the vast data and experience on lead-free alloys that AIM has accumulated over the years. Please feel free to contact AIM at anytime so that we may be of assistance during this often-complicated transition period.

AIM Lead-Free Assembly Products

AIM has lead-free no clean, water soluble and rosin solder pastes, lead-free bar solders and compatible fluxes, and lead-free cored wire, solid wire, performs and spheres.

Lead-Free Solder Pastes

AIM's lead-free solder pastes are available in a variety of chemistries, alloys (see chart on back page), powder mesh size, and packaging and offer the following features:

- Excellent printability and tack force
- Long tack time and stencil life
- Excellent wetting and solderability
- Low residues
- Easily cleaned residues
- Pass Bellcore and IPC reliability testing

In addition, specific formulas may be requested that offer the following advantages:

- Easily pin probe tested
- High heat and humidity resistance
- Suitable for high-speed printing
- Residues safe to be left uncleaned on RF devices up to 50 gigahertz
- Eliminate solder defects such as voiding and solder beading

Lead-Free Bar Solder

AIM's lead-free bar solder is available in a variety of alloys (see chart on back page), cast (1Kg), extruded (1lb), or margash (10lb) and are manufactured in two different grades:

- Electropure Grade- Very low impurities; Ultra low drossing.
- IPC Grade- Lower cost, Meets IPC-J-STD-006 specifications.

Lead-Free Compatible Liquid Fluxes

AIM's lead-free compatible liquid fluxes are available in a variety of chemistries and packaging and offer the following features:

- Available VOC-Free and alcohol-based
- Ultra-low residues
- Excellent wetting and solderability
- May be sprayed, foamed, dipped, or brushed
- Pass Bellcore and IPC reliability testing

Lead-Free Cored and Solid Wire Solder

AIM's lead-free wire solders are available in a variety of alloys (see chart on back page), diameters, spool sizes, and solid or cored in a variety of chemistries and offer the following features:

- Low fuming and low odor
- Excellent wetting and solderability
- Low Residue
- Guaranteed void-free core
- Pass Bellcore and IPC reliability testing

Lead-Free Preforms and Spheres

AIM's lead-free performs and spheres are available in a variety of alloys (see chart on back page), some flux filled or coated, and the following shapes.

- Spheres
- Segments
- Discs
- Horseshoes
- Rings
- Washers
- Other specialty shapes and sizes as requested

No matter what the application, AIM has the lead-free products and process knowledge required to help your company in the transition to lead-free soldering in the most logical and economical ways possible.

Lead-Free Consultation Services

In order to support the assembly processes in demand by the electronics industry, AIM is pleased to announce its lead-free consultation services. These services take place in the AIM U.S. Technical Applications Laboratory, located in Cranston, Rhode Island, and are supported by AIM applications engineers, metallurgists and chemists.



Engineers are invited to the AIM laboratory to gain first-hand knowledge of lead-free electronics assembly. Alternatively, those considering a lead-free process may send boards to AIM for evaluation per their requirements. Through the use of the laboratory, AIM is able to demonstrate the true ramifications and requirements of implementing a lead-free process and to make recommendations based upon these. All common lead-free alloys are currently available for SMT and hand soldering applications, and a tin/silver/copper alloy is available for wave soldering.

The AIM Applications Lab is heat and humidity controlled and contains high-end assembly equipment, including a fully automated screen printer, a 7-zone forced convection reflow oven, placement equipment, a wave soldering machine, and several rework stations. The lab also is utilized to help customers improve existing manufacturing operations. In addition, the lab is used as a fully hands-on training center. Customers, distributors, representatives, and associates of AIM are able to visit the facility for frequently scheduled soldering training and troubleshooting seminars.

These services are available to all electronics assembly professionals. Interested individuals should contact AIM for additional information.



AIM Lead-Free Validation Program

Bronze Service	Silver Service	Gold Service
<p>1. Visual Examination:</p> <p>General Inspection of boards, components, and solder connections with stereomicroscope and board level microscope.</p> <p>2. Microscopic Examination:</p> <p>4 components are cross-sectioned and analyzed for interfacial reaction layers, microstructural integrity, and identification of general defects</p> <p>3. Reporting:</p> <p>Observations, photographic documentation, interpretation of pertinent findings and recommendations, if applicable, are presented</p>	<p>1. Process Capability Validation:</p> <p>a) General Inspection of boards, components, and solder connections with stereomicroscope versus IPC J-STD solder connection requirements</p> <p>b) 4 components (BGA, chip component, J-lead, and gull wing) from one board are cross-sectioned and analyzed for solder wetting and fillet quality versus industry requirements</p> <p>c) 4 components from one board are cross-sectioned and analyzed for general defects</p> <p>d) Shear testing on 4 component types are run. A comparison report is assembled of leads tested</p> <p>2. Reporting:</p> <p>Observations, photographic documentation, interpretation of pertinent findings and recommendations, if applicable, are presented</p> <p>3. Lead-free process capability validation certificate is issued</p>	<p>1. Process Capability Validation:</p> <p>a) General Inspection of boards, components, and solder connections with stereomicroscope versus IPC J-STD solder connection requirements</p> <p>b) 10 components (BGA, chip component, J-lead, and gull wing) from one board are cross-sectioned and analyzed for solder wetting and fillet quality versus industry requirements</p> <p>c) 10 components from one board are cross-sectioned and analyzed for microstructural integrity with identification of general defects</p> <p>d) Shear testing on 10 components run. A comparison report is assembled of leads tested</p> <p>2. Voiding:</p> <p>2 BGA components from two boards are analyzed for voiding</p> <p>3. SEM EDX:</p> <p>Available for an extra fee as needed</p> <p>4. Thermal Cycling Testing</p> <p>5. Reporting:</p> <p>Observations, photographic documentation, interpretation of pertinent findings and recommendations, if applicable, are presented</p> <p>6. Lead-free process capability validation certificate is issued</p>
\$3000	\$4500	\$9000

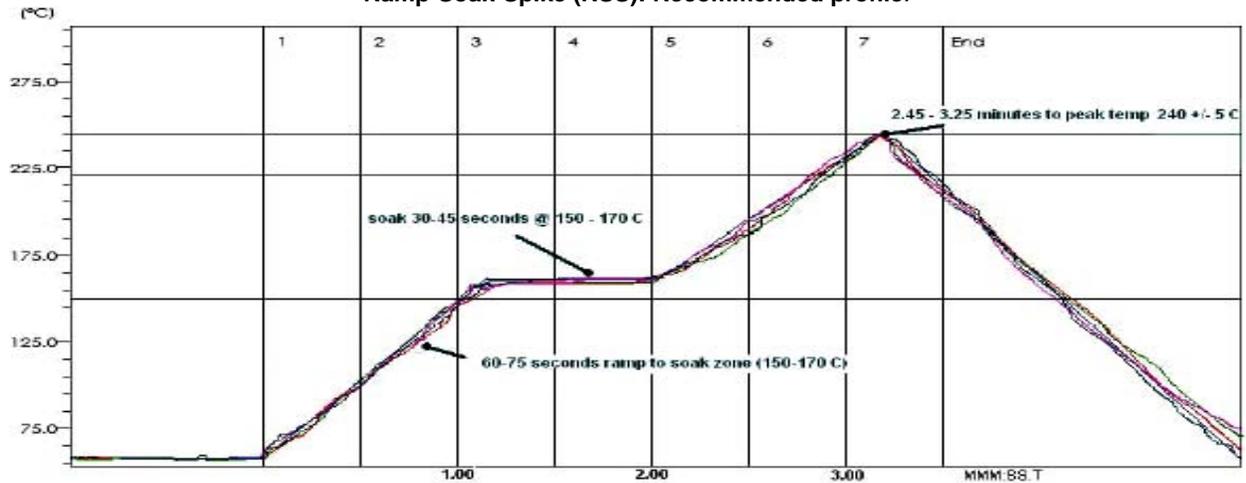


REFLOW PROFILE SUPPLEMENT

ALLOY:

Sn/Ag/Cu

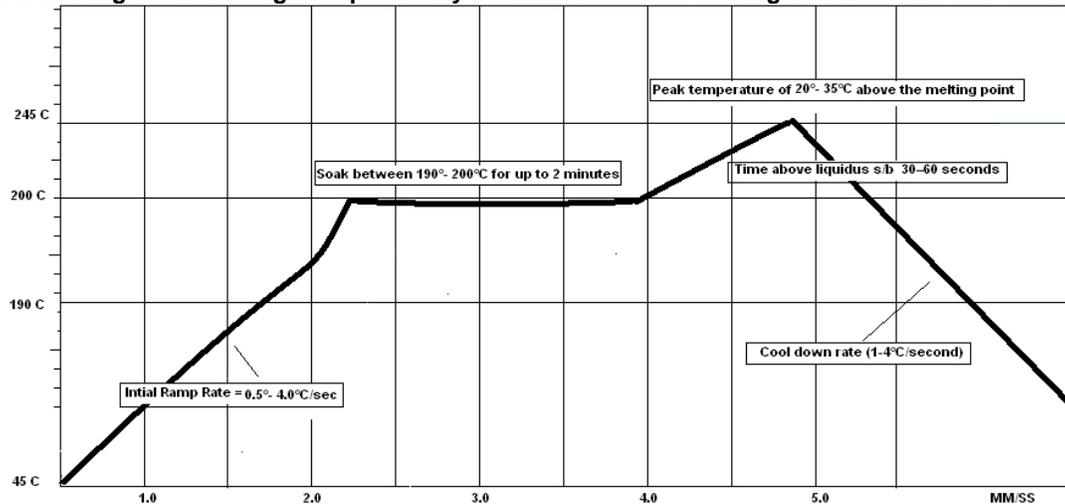
Ramp-Soak-Spike (RSS): Recommended profile.



RSS Profile Guidelines

- The typical initial rate of rise for the RSS profile is 1.4 to 1.8°C/second.
- Ramp up to 150°C and then soak the assembly for 30 to 60 seconds.
- The soak zone should be controlled between 150 -170°C. Above this point the paste will lose its activator.
- Proceed to spike immediately once the PCB has reached thermal stability.
- Peak temperature is 240°C ± 5°C.
- Time above liquidus is 45 ± 15 seconds.
- The total profile length should be between 2 ¾ - 3 ½ minutes from ambient to peak temperature.
- Cool down should be controlled within 4°C/second.

Low-Voiding Profile: Designed specifically to eliminate/reduce voiding with BGA and CSP devices



Profile Guidelines

- The initial rate of rise is 0.5 to 4°C/second.
- Ramp up to 190°C and then soak the assembly between 190 to 200°C for up to 120 seconds.
- Proceed to spike immediately after exiting the soak zone.
- Peak temperature is 238 to 253°C.
- Time above liquidus is 30 to 60 seconds.
- The total profile length should be between 4 ½ - 5 minutes from ambient to peak temperature.
- Cool down should be controlled within 4°C/second.



Lead-Free Wave and Dip Solder Pot Suggested Maximum Levels

Contaminant element	SAC Alloys % by weight	SN100C Alloy % by weight
Ag (Silver)	4.25	0.2
Au (Gold)	0.4	0.4
Al (Aluminum)	0.006	0.006
Bi (Bismuth)	0.1	0.1
Cu (Copper)	1.0	1.0
Fe (Iron)	0.04	0.04
Ni (Nickel)	0.05	0.08
Pb (Lead)	0.1	0.1
Sb (Antimony)	0.2	0.2
Zn (Zinc)	0.006	0.006

Action to Take if Exceeding Dump Limits

Frequent pot analysis is the best deterrent to solder pot contamination. AIM recommends that you keep records of frequent analyses to monitor the increase in contaminants.

If none of the major elements in the alloy increases, you may dilute the solder pot with the same type of alloy to reduce the contaminant level.

If one of the major elements in the alloy does increase, you should dilute the solder pot with the recommended top-off alloy. For example, if a SAC alloy increases in copper, you should dilute the solder pot with tin or tin-silver. If SN100C increases in copper, you should top off the pot with SN100Ce.

Dilution is the first option and best choice for contaminant reduction. If dilution using a top-off alloy is not successful, then a partial drain of the pot may be necessary to reduce the contaminant level.

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A COMPARISON OF TIN-SILVER-COPPER LEAD-FREE SOLDER ALLOYS

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ABSTRACT

As the electronics industry begins to focus upon the tin-silver-copper family of alloys as a viable replacement for tin-lead solders, research needs to be done to determine if any particular alloy is best suited for the broadest range of applications. The tin-silver-copper family of alloys has earned a great deal of positive response from various industry consortia and organizations in recent years and the majority of manufacturers plan on implementing one of these alloys. However, as there are several different alloy formulations within the tin-silver-copper family, background information is necessary to determine which alloy is best suited for the broadest range of applications.

Keywords: Lead-Free, Alloys, Tin-Silver-Copper, Comparison, Cost, Availability, Patents, Printing, Melting Points, Wetting, Reliability.

1. INTRODUCTION

It is inevitable that lead will be eliminated from a great deal of electronics assembly. Whether this will be the result of legislation, marketing pressure, or de facto trade-barriers is not important. The only important aspect of this issue anymore is that it is real, and that it is coming within the next few years. Therefore, electronics manufacturers need to be cognizant of the solder alloy choices available to them, and the fact that not all alloys, including those within the same families, share the same characteristics.

Based on recent industry-wide developments, it appears that the choice of candidate lead-free alloys to replace tin-lead for electronics assembly is narrowing. Despite a confusing patent situation and continuing questions about reliability, the tin-silver-copper family of alloys has earned a great deal of positive response from various industry consortia and organizations in recent years and the majority of manufacturers plan on implementing one of these alloys.¹ In general, this family of alloys demonstrates relatively low melting points, good reliability characteristics, and, depending upon the exact composition, reasonable cost. However, as there are several different alloy formulations within the tin-silver-copper family, background information is necessary to determine which alloy is best suited for the broadest range of applications.

It also should be noted that these (sometimes nominal) varying alloy compositions are confusing to the industry and create an inventory nightmare for solder manufacturers and end-users. The result is a higher cost for the industry. Selecting a "default" lead-free alloy benefits the entire supply chain. This is especially true of EMS providers, who may be forced to stock multiple alloys based upon the requirements of their customers.

2. TIN-SILVER-COPPER ALLOY COMPARISON

The alloys tested are the most promising and popular of the tin-silver-copper alloys: Sn96.5/Ag3.0/Cu0.5, Sn95.5/Ag3.8/Cu0.7, and Sn95.5/Ag4.0/Cu0.5. In addition the Sn96.2/Ag2.5/Cu0.8/Sb0.5 alloy is used in some cases as a low-silver content alternative for comparative purposes. This paper is meant to provide the baseline information for these alloys needed to fairly compare one to another. Objective test methodologies were used to represent

key-criteria in the transition to lead-free electronics assembly. The issues that will affect the broadest range of users of these alloys are addressed in this study. Included in the comparison is availability, cost, solder paste printing, melting, wetting, wave soldering, thermal fatigue and solder joint reliability characteristics. Of course, individual companies are encouraged to perform further tests in order to determine the viability of these alloys for their particular parts, processes, and applications.

3. LEAD-FREE ALLOY ELEMENT TOLERANCES

It should be noted that solder alloys have an acceptable tolerance for each component element. Per IPC-J-STD-006, elements that constitute up to 5% of an alloy may vary by up to $\pm 0.2\%$, while elements that constitute greater than 5% of an alloy may vary by up to $\pm 0.5\%$.

For example, the Sn63/Pb37 alloy may contain between 62.5% to 63.5% tin and 36.5% to 37.5% lead. The Sn62/Pb36/Ag2 alloy may contain between 61.5% to 62.5% tin, 35.5% to 36.5% lead and 1.8% to 2.2% silver.

Below is a chart of various lead-free solder alloy compositions and their potential elemental range. This is intended to demonstrate the likelihood of potential alloy overlap, even when specifying a “unique” alloy. This information pertains to industry standards for alloy tolerances, and not of any particular vendor.

Alloy	Alloy Range
Sn96.5/Ag3.0/Cu0.5	Sn96.0 to 97.0 / Ag2.8 to 3.2 / Cu0.3 to 0.7
Sn95.5/Ag3.8/Cu0.7	Sn95.0 to 96.0 / Ag3.6 to 4.0 / Cu0.5 to 0.9
Sn95.5/Ag4.0/Cu0.5	Sn95.0 to 96.0 / Ag3.8 to 4.2 / Cu0.3 to 0.7

4. ALLOY AVAILABILITY AND PATENT SITUATION

It is desirable for the industry to find an alloy that is widely available. Therefore, patented alloys have been viewed as undesirable. However, the issue is not as simple as it seems. Manufacturers should note that certain patented alloys have been licensed to several manufacturers around the world and are widely available. Conversely, certain solder alloys that appear non-patented may not be completely free of patent coverage.

The issue of alloy patents is complex, with different alloy formulations patented in different parts of the world. In addition, what many do not realize is that most alloy patents cover not only the alloy in solder form, but completed solder joints as well.

Alloys such as Sn95.5/Ag4.0/Cu0.5 and Sn95.5/Ag3.8/Cu0.7 have been recommended to the U.S. industry despite the fact that solder joints produced from these alloys may violate patents. For one, these alloys are covered under patent in Japan, so this limits the export of products manufactured with these alloys.ⁱⁱ Also, it is possible that the use of these alloys could violate Iowa State University U.S. patent # 5527628. Although these alloys do not fall under this patent, these same alloys with 1.0 to 4.0 percent copper are covered. The application claim of this patent states that even a *finished solder joint* is covered by the patent. Therefore, if one of these non-patented alloys is used and during manufacturing the alloy “picks up” copper (which normally does occur) and forms an intermetallic that contains the elements covered under the Iowa State University patent, the manufacturer has violated that patent. Although this will be difficult to enforce, manufacturers should be aware of this potential for patent violation.

Below is a listing of the key patents for tin-silver-copper alloys:

Alloy Elemental Range	Patent #	Patent Holder	Geographic Coverage
Sn/Ag3.5-7.7/Cu1-4/Bi0-10/Zn0-1	5527628	Iowa State Univ.	USA
Sn/Ag0.05-3/Cu0.5-6	N/A	Engelhard & Oatey	(patents expired)
Sn/Ag1.5-3.5/Cu0.2-2/Sb0.2-2	5405577	AIM, Inc.	USA and Japan
Sn/Ag3-5/Cu0.5-3/Sb0-5	05-050286	Senju	Japan

5. COST OF METALS COMPARISON

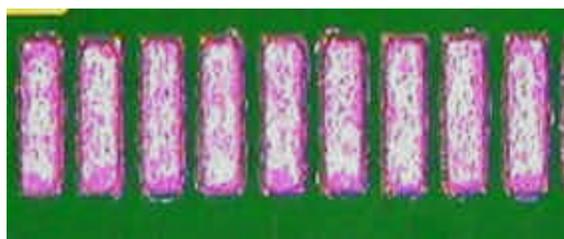
As seen below, silver is the cost element in the tin-silver-copper alloys. The cost difference for the raw metals that make up Sn95.5/Ag3.0/Cu0.5 versus Sn95.5/Ag3.8/Cu0.7 and Sn95.5/Ag4.0/Cu0.5 is US\$1.43/1.30 Euros and US\$1.13/1.03 Euros per kilogram, respectively. This can result in dramatic cost differential for wave soldering and hand soldering operations, as the costs of metals is a key contributor to the final cost of bar solder and wire solder, and can have an impact on pricing for SMT grade solder pastes as well. As with other cost studiesⁱⁱⁱ, included for comparison purposes is the Sn96.2/Ag2.5/Cu0.8/Sb0.5 alloy, which is the least expensive of the tin-silver-copper based alloys and shows still more of a cost reduction compared to high-silver alloys. Also included for comparison purposes are the costs of metals for Sn62/Pb36/Ag2 and Sn63/Pb37, each of which are significantly less costly than the lead-free alloys being discussed.

Alloy	Price Per Kg (July 06)
Sn95.5/Ag4.0/Cu0.5	US\$24.79
Sn95.5/Ag3.8/Cu0.7	US\$24.43
Sn96.5/Ag3.0/Cu0.5	US\$20.90
Sn62/Pb36/Ag2	US\$14.19
Sn63/Pb37	US\$6.34

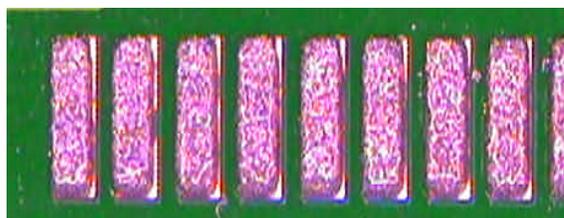
6. SOLDER PASTE PRINTING COMPARISON

Although previous testing has shown little differences between printing lead-free and tin/lead solder pastes^v, it is useful to prove out the similarity of the printing process windows of particular lead-free solder pastes, as this is a key factor when determining the process windows and ease-of-use of various alloys. Testing was performed to mimic manufacturing requirements in order to determine the printing process windows of the Sn95.5/Ag3.0/Cu0.5, Sn95.5/Ag3.8/Cu0.7, and Sn95.5/Ag4.0/Cu0.5 alloys. Each alloy was mated with the same no-clean paste flux chemistry with the same metal load, powder micron size and viscosity.

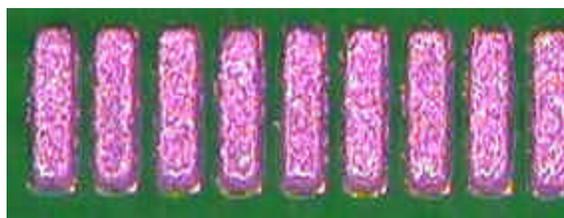
As seen in the images to the right, very little difference is observed in the printing of pads with 12 mil gaps when using any of these alloys. All show good aperture fill, well-formed print deposits, and resist bridging.



Sn96.5/Ag3.0/Cu0.5

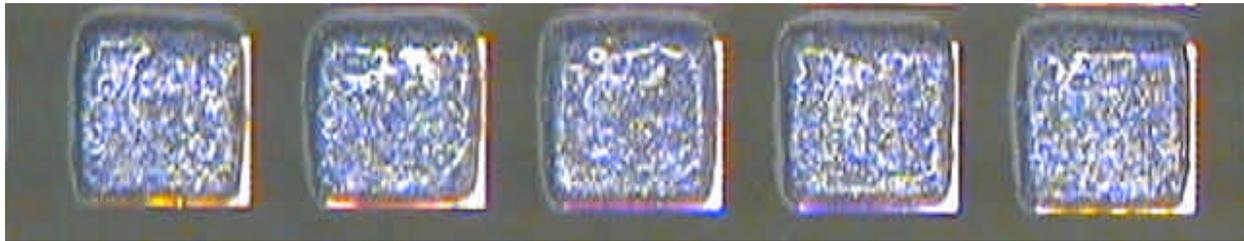


Sn95.5/Ag3.8/Cu0.7

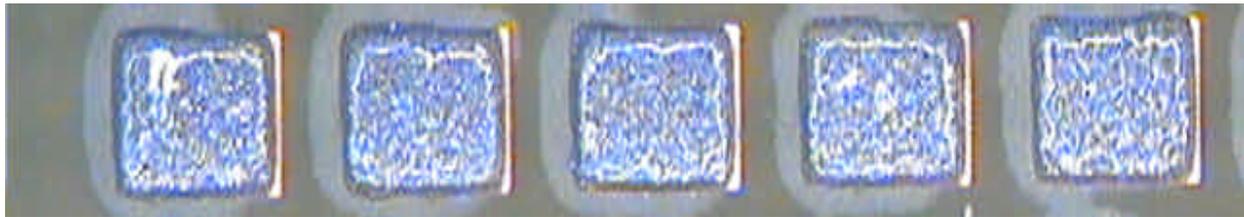


Sn95.5/Ag4.0/Cu0.5

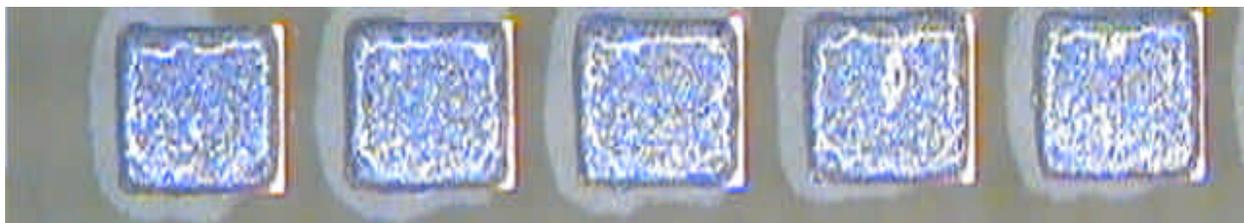
To confirm the above results, square pads with 10 mil gaps were printed using each of the three alloys on a PCB that had not had solder mask applied on it. Once again the print results were very similar and all show good aperture fill, well-formed print deposits, and resist bridging.



Sn96.5/Ag3.0/Cu0.5



Sn95.5/Ag3.8/Cu0.7



Sn95.5/Ag4.0/Cu0.5

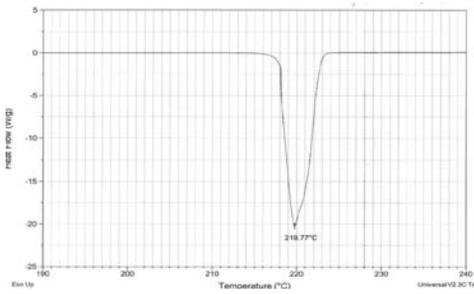
Furthermore, when subjected to subsequent longer-term testing, each of these pastes performed similarly.^{vi} The testing used was performed over several hours and determined that the fine pitch printability, pause to print times, tack life, and the effect of time to solder wetting were acceptable for each of these pastes. Thus, it may be assumed that each of the tin/silver/copper alloys will provide manufacturers with a similar printing process window as tin/lead alloys.

It should be noted that successful lead-free solder paste printing characteristics does depend on if the paste manufacturer has their solder density issues resolved. Lead-free alloys are significantly less dense than tin/lead; up to 17% in some cases. If one experiences a significant difference in printing characteristics for a lead-free solder paste versus the equivalent tin/lead paste, it may be related to the metal loading or flux chemistry of the paste in use. This would typically manifest itself with a solder paste that appears very thick and difficult to print with standard squeegee pressure settings.

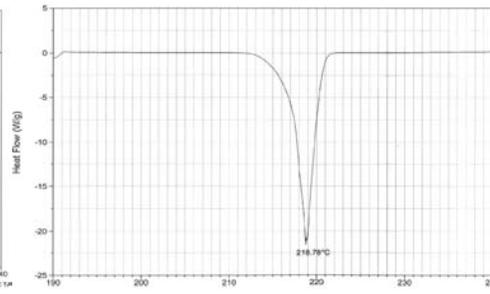
7. MELTING POINTS

DSC testing was used to determine the melting points of the alloys tested. As shown in the DSC diagrams below, the melting points of the alloys tested range from 218-220°C when tested at 2°C per second, with Sn96.5/Ag3.0/Cu0.5 melting at 219.77°C, Sn95.5/Ag3.8/Cu0.7 at 218.78°C, and Sn95.5/Ag4.0/Cu0.5 at 220.23°C. When tested at 10 °C per second the melting points of the alloys remained similar, with less than 2°C separating the alloys.

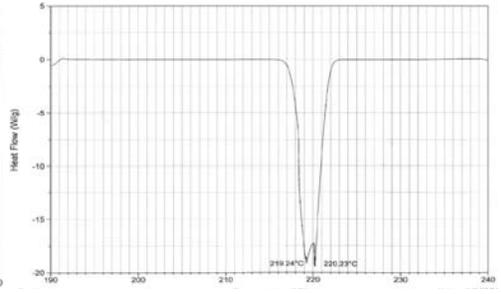
DSC 2°C Per Second



Sn96.5/Ag3.0/Cu0.5

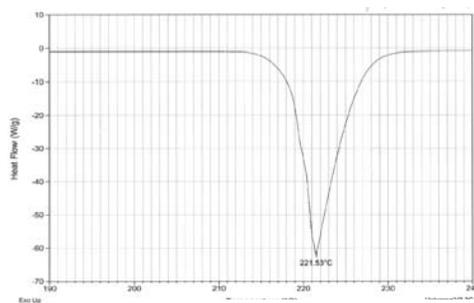


Sn95.5/Ag3.8/Cu0.7

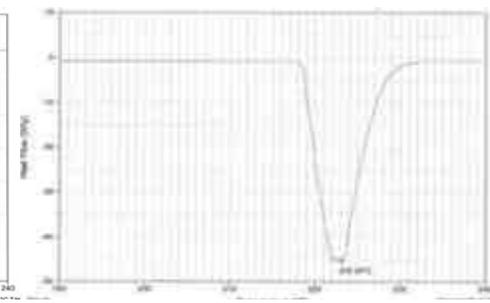


Sn95.5/Ag4.0/Cu0.5

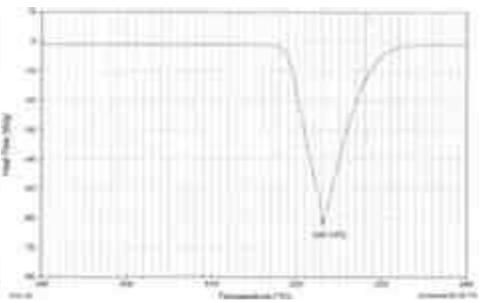
DSC 10°C Per Second



Sn96.5/Ag3.0/Cu0.5



Sn95.5/Ag3.8/Cu0.7



Sn95.5/Ag4.0/Cu0.5

WETTING

In general, lead-free alloys do not wet as well as tin-lead solder alloys. This also is true of the tin-silver-copper family. However, it is possible that different tin-silver-copper alloys will have different wetting characteristics from one another. To determine the wetting capabilities of these alloys, wetting balance testing and spread testing was performed.

7.1 WETTING BALANCE TESTING

In wetting balance testing, the dynamic wetting force of an alloy is measured and graphed versus the time it takes to achieve wetting. In the operation of a wetting balance, the specimen is suspended from a sensitive balance and immersed edge-wise, at a predetermined and controlled rate, and to a specified depth, into the molten solder maintained at a controlled temperature. As a

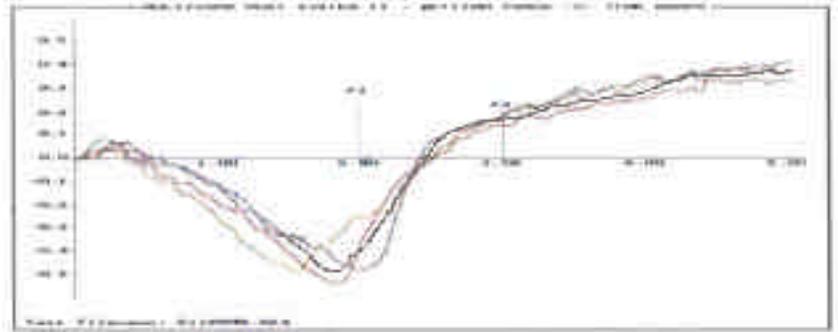
	RMA Flux	No Clean Flux	OA Flux
1% Ag	fair 	very good 	good
2.5% Ag	very good 	good 	very good
3.5% Ag	good 	fair 	good

Previous Tin-Silver-Copper Alloy Wetting Testing

result of the interaction between the molten alloy and the board finish, the wetted coupon is subject to time-variant, vertical buoyancy forces and downward surface tension forces. The forces are detected by a transducer and are converted into an electrical signal, which in turn is recorded by the data acquisition system in a computer.

As shown above, the wetting curves from previous testing demonstrate the superiority of lower-silver tin-silver-copper alloys for wetting time and force when used with a variety of flux types. However, it should be noted that the results indicate a relative similarity between all of these alloys.

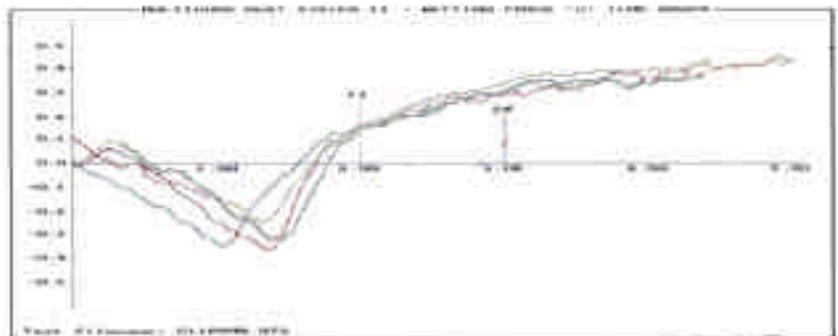
To corroborate the above, globular wetting balance testing was performed on the Sn96.5/Ag3.0/Cu0.5, Sn95.5/Ag3.8/Cu0.7, and Sn95.5/Ag4.0/Cu0.5 alloys. As shown in the graphs to the right, once again wetting time and force for each of these alloys proved similar.



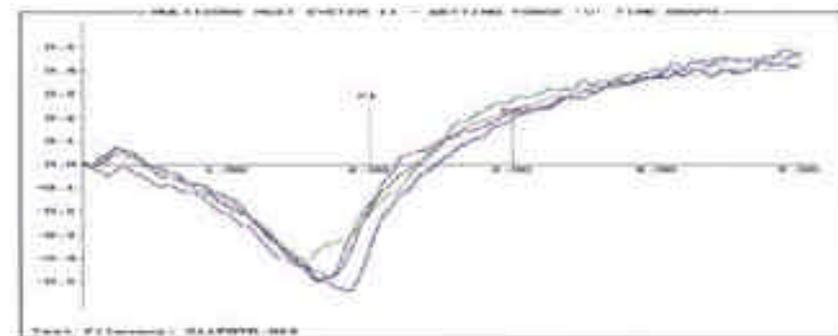
Sn96.5/Ag3.0/Cu0.5

8.2 SPREAD TESTING

Spread testing was performed as a means to gauge the wetting ability of the alloys tested. The figures below were made using the Sn95.5/Ag3.0/Cu0.5, Sn95.5/Ag3.8/Cu0.7 and Sn95.5/Ag4.0/Cu0.5 alloys mated with the same no-clean paste flux chemistry. The pad material was gold over nickel and the assemblies were heated in a convection reflow oven without the use of nitrogen. As can be seen on the following page, each solder paste achieved full spread to all four edges of each pad.



Sn95.5/Ag3.8/Cu0.7



Sn95.5/Ag4.0/Cu0.5

In addition, spread tests were performed on test coupons heated on a hot plate. Although it may be difficult to discern from the images on the following page, spread for each sample was virtually identical and each was considered to be in the acceptable range per IPC test requirements.

From the wetting and spread tests presented here, manufacturers can expect similar wetting with each of the tin-silver-copper alloys, with slightly superior wetting likely with the lower-silver alloys.

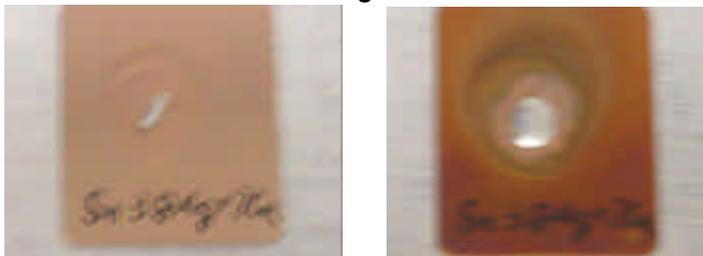
Sn96.5/Ag3.0/Cu0.5



Before

After

Sn95.5/Ag3.8/Cu0.7



Before

After

Sn95.5/Ag4.0/Cu0.5



Before

After

8. LEAD-FREE WAVE SOLDERING CONSIDERATIONS

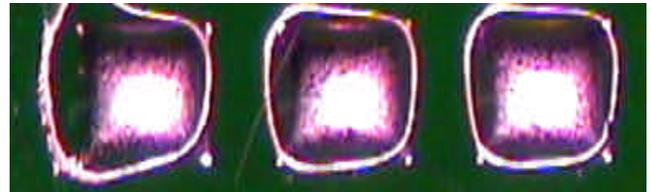
While it can be tempting to concentrate solely on SMT applications when discussing lead-free soldering, it should be remembered that wave soldering continues to remain a viable and popular technology. As lead-free wave soldering becomes increasingly prevalent, questions have arisen about copper dissolution into lead-free alloys and the possibility of additional solder pot maintenance.

Gold Over Nickel Spread Tests

Sn96.5/Ag3.0/Cu0.5



Before

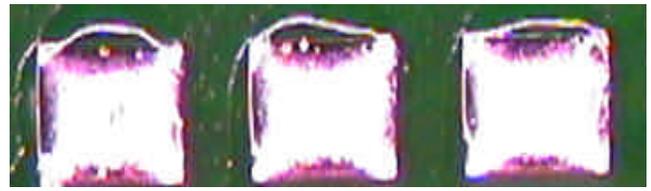


After

Sn95.5/Ag3.8/Cu0.7

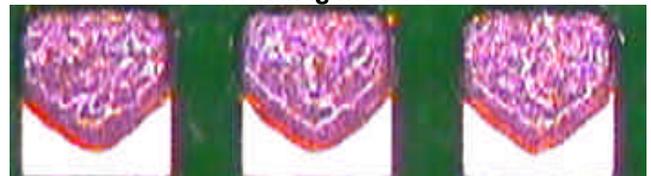


Before

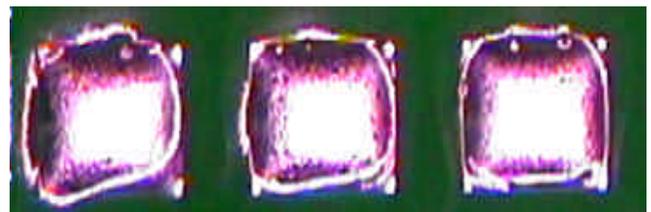


After

Sn95.5/Ag4.0/Cu0.5



Before



After

In a standard Sn63/Pb37 wave pot, as impurities such as copper build up, they form intermetallics with the tin. This intermetallic buildup can be systematically removed by reducing the temperature of the solder pot to 188°C (370°F) and allowing the pot to sit undisturbed for > 8 hours. The density of the Cu₆Sn₅ intermetallic is 8.28, while the density of Sn63/Pb37 is 8.80, allowing most of the Cu₆Sn₅ to float to the top of the pot after a few hours of cooling. After this the top of the pot can be skimmed and new solder added to bring up the level. This typically will maintain copper levels below 0.3% and can maintain the copper level in the 0.15% range. This is a simple gravimetric separation of Cu₆Sn₅.

However, the densities for tin-silver-copper alloys are approximately only 7.4. Therefore, instead of the Cu₆Sn₅ intermetallic floating off and easily being removed as when in Sn63/Pb37, the intermetallics sink and are dispersed through the lead-free alloy in the pot. The end result of this is copper build-up in the pot. This is also true of the Sn99.3/Cu0.7 alloy, which has a density similar to that of tin-silver-copper alloys.

The result and biggest problem of the above is that solder pots may need to be dumped more often, leading to a complete change over of the wave pot. The pot dump specification will most likely be around 1.55% copper, since above this point the alloy becomes sluggish and at 1.9 to 2% precipitation in the pot starts to occur, which can lead to damage to wave pumps and baffles. Attention should be paid to this issue when implementing lead-free wave soldering.

9. SOLDER JOINT RELIABILITY TESTING

For good reason, the issue of solder joint reliability is of great concern to the potential users of lead-free alloys. How an assembly will survive after it has been soldered with a tin-silver-copper alloy must be determined before implementing an alloy for production.

It should also be understood that solder joint reliability is dependent upon several factors other than solder alloy, including solder joint geometry, fatigue severity and soldering surface finish. Furthermore, tin-silver-copper alloy fatigue resistance has been proven superior to tin/lead under certain testing condition, but *inferior* under other conditions. Until the failure mechanisms of the tin-silver-copper alloy systems are better understood, it is recommended to perform accelerated testing that mimics as close as possible the operating conditions of the assembly in question.

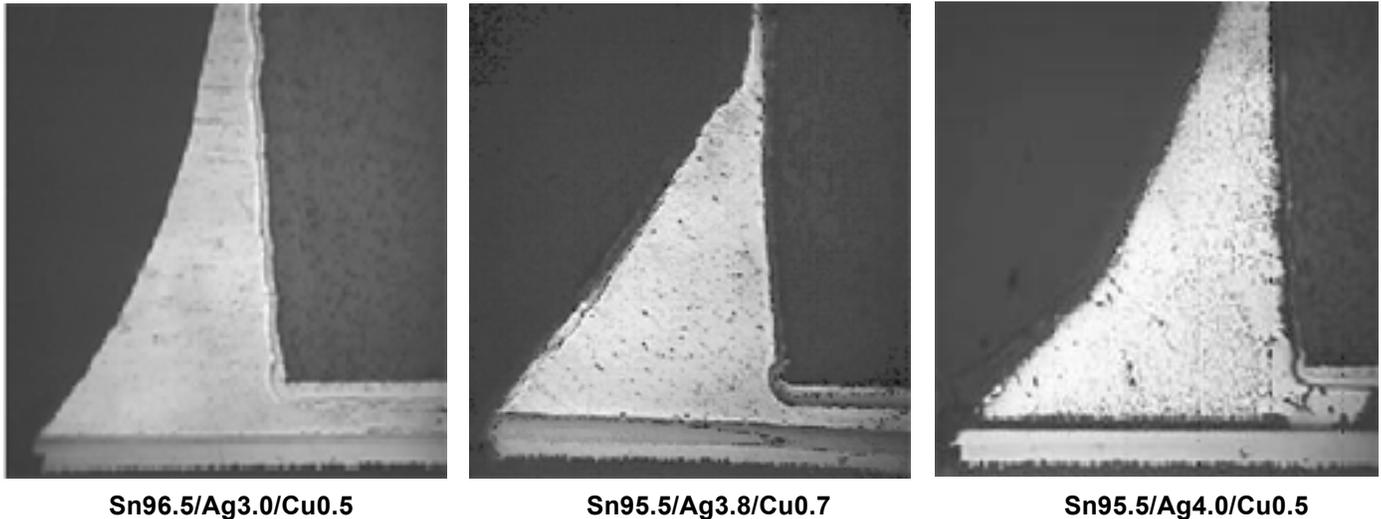
That being said, baseline comparative reliability information for the tin/silver/copper alloys being studied is important as a down-select tool. Several reports have already been published which demonstrate the thermal and mechanical reliability of these alloys^{vii, viii}. However, few comparative tests have been performed on these alloys. Therefore, the following tests were carried out to quickly determine if there are any clear differences between these alloys in terms of reliability.

9.1 THERMAL CYCLING TEST RESULTS

Test boards were built using Sn96.5/Ag3.0/Cu0.5, Sn95.5/Ag3.8/Cu0.7, and Sn95.5/Ag4.0/Cu0.5 solder alloys in conjunction with 1206 thin film resistors. The boards were then thermal shocked from -40° to +125°C for 300, 400 and 500 15 minute cycles. Solder joints were then cross-sectioned and inspected for cracks.

As shown below, none of the alloys tested showed any cracks during testing up to 500 repetitions. However, it should be noted that the Sn95.5/Ag3.8/Cu0.7 and Sn95.5/Ag4.0/Cu0.5 alloys did exhibit some change in grain structure throughout the joint after the thermal shock

testing, especially the latter. Further studies should be undertaken to determine whether this change of grain structure may be indicative of a potential reliability issue.



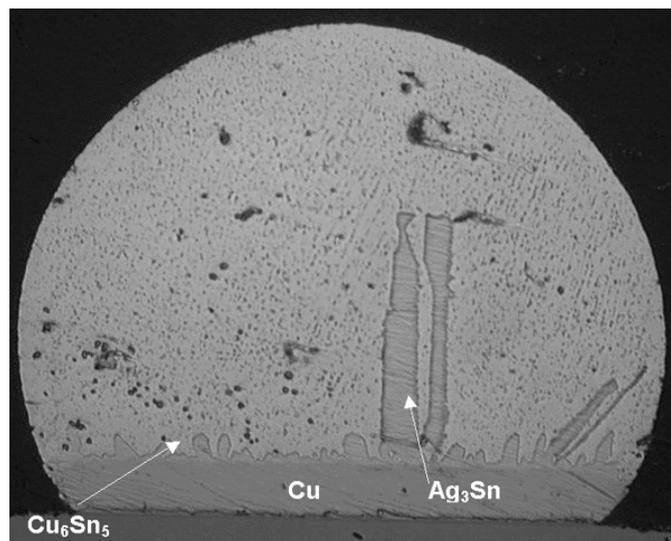
9.2 MECHANICAL STRENGTH- FLEX TESTING

Test boards were built using Sn96.5/Ag3.0/Cu0.5, Sn95.5/Ag3.8/Cu0.7, and Sn95.5/Ag4.0/Cu0.5 solder alloys and were subjected to flex testing.^{ix} Solder joints were then cross-sectioned and inspected for cracks. Again, the alloys tested passed all test requirements. It should be noted that the Sn/Cu alloy did exhibit cracks when exposed to this same testing.^x

9.3 ADDITIONAL TESTING

Previous testing has demonstrated that the high-silver tin-silver-copper alloys can suffer from reliability issues as the result of large, plate-like, Ag_3Sn structures that grow rapidly during the liquid phase of the reflow profile, before the final solidification of the solder joints.^{xi} This testing has shown that when the Sn95.5/Ag3.8/Cu0.7 and Sn95.5/Ag4.0/Cu0.5 solder alloys are exposed to slow cooling rates, large Ag_3Sn plates can subtend the entire cross section of solder joints and can significantly influence the mechanical deformation behavior of the solder joints when they are exposed to the thermomechanical stresses.

The image to the right is of the Ag_3Sn forming as large plates attached to the interfacial intermetallics. This results in plastic strain localization at the boundary between the Ag_3Sn plates and the bounding b-Sn phase.^{xii} Adverse effects on the plastic deformation properties of the solidified solder have been reported when large Ag_3Sn plates are present.^{xiii} It also has been suggested^{xiv} that silver segregates to the interface and weakens it by “poisoning”. The brittle fracture is exacerbated by gold contamination.^{xv}



Studies have shown that tin-silver-copper alloys with a low silver content do not experience the growth of these plate-like, Ag_3Sn structures, regardless of cooling rates. This suggests that low silver content tin-silver-copper alloys may present fewer reliability issues than other tin-silver-copper alloys.

10. CONCLUSION

Evidence from Europe, North America and Japan indicates that the majority of the electronics industry is moving towards the tin-silver-copper family of alloys for lead-free soldering. However, as with any process, care must be taken to select the most appropriate alloy for a broad range of applications. Furthermore, the logistics and economics of specifying a particular alloy must be considered. As pointed out earlier, silver is the cost element in the tin-silver-copper alloys. Since the testing discussed in this paper showed no advantages in terms of processing, reliability, or availability for the high-silver alloys as compared to the low-silver alloys, it is only logical to utilize the less expensive of these for all soldering applications. In fact, the low-silver alloys may have less patent issues associated with them in many parts of the world, as well as superior wetting and fewer reliability issues. As previous reports have shown, it is logical from both a procurement and reliability point of view to utilize the same alloy for SMT, wave soldering, and hand soldering operations.^{xvi} Because the Sn96.5/Ag3.0/Cu0.5 alloy provides manufacturers with the advantages of the tin-silver-copper family of alloys but is less cost-prohibitive than the other alloys tested, individual companies are encouraged to perform further tests in order to determine the viability of this alloy with their particular parts, processes, and applications.

ACKNOWLEDGEMENTS

We would like to acknowledge and thank Kevin Pigeon, International Technical Support Manager of AIM, for PCBA print and reflow test preparations.

A Practical Guide to Achieving Lead-Free Electronics Assembly

Feb 2002

INTRODUCTION

The switch to lead-free assembly affects virtually all aspects of the Engineering function. Engineering personnel will have to pay close attention to design, components, PWBs, solder alloys, fluxes, and the printing, reflow, wave soldering, rework and cleaning processes, equipment and inspection.

DESIGN

Established PCB-design rules may need to change during the transition to lead-free soldering. Currently, industry guidelines govern component lead-pad and land size, track width and spacing, via and through-hole dimensions, and similar factors to ensure manufacturability and reliability. However, the physical characteristics of any solder include subtle factors, such as its ductility and elasticity. In addition, the local heating of component leads and their pads causes some thermal expansion during operation, which tin-lead solder accommodates and matches.

In determining design solutions, Design should try to remain with as many standard parts as possible. This will reduce the unpredictability encountered with atypical parts. In addition, if the assembly is designed to have a long life, factor in the reduced moisture resistance of parts. Furthermore, Design must factor in the higher temperatures required for connectors.

MATERIAL CONSIDERATIONS

The first critical duty is to ensure that the parts to be used will be compatible and reliable for their particular application. Compatibility relates to components, PWBs, solder alloy and flux. Reliability relates to component concerns, which includes such factors as Moisture Sensitivity Level (MSL) Rating, wetting and tin whiskering.

Component Reliability Concerns

The higher melting temperatures of the lead-free solders that are coming into use mandate components that can withstand the increased temperature stresses of the soldering process. Life-test data for many components at these higher temperatures is less comprehensive than it is for tin/lead processes. To maximize reliability, Engineering should start looking now at all critical components, design rules, fabrication processes, component engineering, and reliability records.

A critical factor in the transition to lead-free assembly is the MSL rating of components. To date, industry testing has demonstrated that there is no generic solution for maintaining an IC's MSL with a higher reflow profile. However, it has been demonstrated that degradation of MSL may increase with increasing profile dwell above 200°C and that MSL typically degrades by one level for every 5 to 10°C increase of peak reflow temperature. Therefore, all ICs must be reclassified for lead-free applications and the impact to MSL. This could result in an increased need to pre-bake parts and more stringent storage methods.

As discussed above, several lead-free component lead finishes are available. It should be noted that these different materials have different wetting characteristics and that Engineering should consider wetting when specifying components. Engineering also needs to balance the fact that increased reflow temperatures can improve wetting, but worsen reliability. In addition, Design should be aware of reduced solderability on second-side reflow and through-hole processes.

Another hot topic of discussion is tin whiskering, which continues to be an oft-misunderstood and debated subject. Proponents of matte tin argue that whiskering is a result of the plating process, and not necessarily inherent to pure tin. They demonstrate that whiskering can also occur with Sn/Bi, etc. Others, however, suggest that a dopant is needed to offset the whiskering. Engineering should follow the on-going debate and studies regarding this topic, work closely with component vendors and participate in studies to determine the most suitable lead finish for their applications.

PWBs

Several PWB lead-free surface finish options exist. Many of these, such as OSPs and Au/Ni, have been available for years. Engineering should determine the finish of choice based upon wetting, storage, planarity and cost issues. In addition, it must be ensured that board materials can withstand reflow temperatures without warpage or other damage. For many cases, FR-4 will remain acceptable, but other applications may require a modification.

Solder Alloy and Flux

Unfortunately, despite a great deal of research, comprehensive and comparative data on lead-free alloys is lacking. The list of solder alloy requirements is lengthy and involved. In general, technical requirements include being non-“hazardous”, mechanically reliable, thermal fatigue resistant, good wetting, relatively low melting temperature and compatible with a variety of lead-bearing and lead-free surface coatings. In addition, one must consider logistical issues such as alloy cost, availability and patent issues. While most of the world has settled on the tin-silver-family of alloys, a good deal of debate still exists as to which exact composition is ideal, and of course others will choose alloys from outside of this family. As with all other technical issues, although there has been much consortia work on alloy selection, the alloy of choice will come down to the specific requirements of each unique assembly. Your choice of alloy is dependent upon your application and should be proven out to your standards.

As with alloys, what is a suitable flux (paste, liquid flux and cored wire) for one manufacturer may not be for another. Select flux chemistries suitable for lead-free processing and your particular application. One should consider a flux’s activation temperature, activity level, compatibility with chosen alloy and reliability properties such as SIR, electromigration.

PROCESS CONSIDERATIONS

Once it is confirmed that the parts and materials to be used in lead-free assembly are available, suitable and reliable, it is time to get the processes optimized in order to achieve maximum throughput and reliability. To do so, Engineering must refocus attention to paste handling, printing, reflow, wave soldering, rework & repair and cleaning.

Paste Handling

Shelf-lives with lead-free pastes may be reduced as compared to tin/lead, and storage conditions may be slightly more stringent. However, in general, the same rules as with tin/lead apply. For example, prevent/minimize paste’s exposure to heat and humidity, allow paste to come to room temperature before using and do not mix old and new paste in the same jar. If one follows proper paste handling procedures now and has good results from these, there should be very few issues when transitioning to lead-free paste use.

Printing

In general, no major changes to the printing process should be necessary. That is, lead-free pastes should exhibit similar features on the stencil and the same equipment set points should transition well. One can expect similar performance in terms of stencil life, aperture release, print definition, high-speed print capabilities, print repeatability, etc. However, this depends on the paste manufacturer and if they have density issues resolved. If one experiences a significant difference in printing a lead-free solder paste versus the equivalent tin/lead paste, it may be related to the metal loading or flux chemistry of the paste in use. In this case, Engineering should work with the paste vendor, or try competitive pastes, in order to resolve these issues.

As tin/lead solder alloys tend to have better wetting than most lead-free alloys, some stencil design modifications may be needed to maximize spread of paste and counteract inferior wetting. Engineers should run tests with lead-free alloys on their current stencils to confirm adequate spread and wetting. If wetting is not sufficient and cannot be rectified by other means, stencil design modifications may be in order.

Ovens

Most modern reflow ovens in use today can provide the necessary heat (additional 20 to 40°C) for lead-free soldering. However, whether this equipment can also tightly control the reflow profile parameters (minimize ΔT) should be investigated. This implies that pure IR equipment will probably not be suitable for lead-free processing. Rather than replacement, some oven may simply require retrofitting. For example, some convection ovens currently have the electronics too close to the process chamber, which can lead to overheating. Ovens may also need to be equipped with nitrogen to compensate for difficult-to-wet parts and poorer wetting solder alloys.

Wave Soldering

Depending upon the alloy selected, wave soldering will require a pot temperature of 260-275°C. This increase of temperature and the change in solder alloy will require some additional process changes.

Flux

May require a change in liquid fluxes to compensate for the poor wetting of some alloys and high thermal stresses of the wave process. If changing fluxes, particular attention should be paid to both to operating window it offers and the material's reliability characteristics.

Equipment

Most modern wave solder machines can provide the necessary heat (preheat and wave) for lead-free soldering. However, as shown in figures 3 and 4¹, the high-tin lead-free alloys rapidly dissolve the materials often used in wave solder equipment. Stainless steel pots, nozzles, impellers and other parts will need to be replaced with cast iron and other materials available from wave soldering equipment manufacturers or be covered with an appropriate paint that should protect the parts for 2-3 years. In addition, a nitrogen blanket may be required, depending upon the alloy and flux selected.

Rework and Repair

Materials

Operators must be re-trained for lead-free rework, as the lead-free solders do not flow as well as tin/lead. This could also require stronger cored wire fluxes to be used. As with any change of flux chemistry, if changing wire solders, particular attention should be paid to both to operating window it offers and the material's reliability characteristics. Some wires often assumed to be safe to leave uncleaned are actually classified as rosin fully-activated and could cause field failures.

All rework should use the same lead-free solder alloy as originally used on the solder joint; different lead-free solder formulations should not be mixed on the same joint. If more than one alloy is in use in the production process (i.e., Sn/Ag/Cu for SMT and Sn/Cu for wave soldering), operators should be trained to use the correct wire for each part. For this reason alone, it is advisable to use a single solder alloy for all assembly operations.

Equipment

It is necessary to ensure that the desoldering and soldering stations are suitable for lead-free processing, i.e. can reach the necessary temperatures for lead-free soldering. It should be noted that lead-free soldering can wear out tips at a much higher rate than tin/lead.

Cleaning

In general, studies have demonstrated that post-process flux residues from lead-free applications are still cleanable. Water soluble chemistries may be cleaned in water, no-clean and RMA chemistries with a saponifier or cleaning solvent. However, it has been found that an increase in pressure, cleaning times and/or cleaner concentrations often is necessary. The efficiency of the cleaning equipment, strength of the cleaner, melting point of the alloy being used and thermal stability and propensity of the flux to "char" all affect the cleanability of an assembly.

¹ Pictures courtesy of TWI/UK

MAINTENANCE

The main challenge for maintenance is the additional wear and tear that lead-free assembly puts on assembly equipment. This is especially true of reflow ovens and wave solder machines. This is the result of the higher melting temperatures at which the lead-free solders require the equipment to work and the tendency of the lead-free materials to wear out the materials they come in direct contact with.

Reflow Ovens

As a result of a greater strain being placed on reflow ovens, additional maintenance to oven components, heating elements, etc. will be required. It has been reported that ball bearings of motors without a cooling fan will breakdown far more frequently as a result of lubrication problems. In addition, the higher reflow temperatures and new flux chemistries could create the issue of flux management, which results in flux control units having to be cleaned more often. Furthermore, sealings in nitrogen equipment will need more frequent replacement.

Wave Soldering Equipment

As discussed above, high-tin alloys rapidly dissolve the materials often used in wave solder equipment. If stainless steel parts are not replaced or protected at the onset of lead-free processing, Maintenance can expect these parts to wear rapidly. As with reflow ovens, wave soldering equipment pushed to its limits by lead-free assembly may require additional maintenance to wave components, heating elements, and flux management systems.

QUALITY/INSPECTION

The main challenge for Quality Assurance /Inspection is to recognize the inherent different appearance of lead-free solder joints and flux residues that are not as easily pin probed.

Inspection

Due to inherent physical differences in their grain structures, lead-free solder joints look different than tin/lead solder joints. Whereas tin/lead joints often appear bright & shiny, lead-free joints are generally dull & grainy. In addition, wetting spread may not be as great as with tin/lead joints. However, this does not necessarily mean that lead-free joints are sub-standard or weaker than tin/lead joints. Inspection personnel must be trained on what to look for when inspecting lead-free solder joints. Figure 5 contains examples of lead-free solder joints.

Pin Probe Testing

Current test fixture settings could possibly damage lead-free solder joints. In addition, the higher reflow temperatures may result in charring and make probing through “pin probeable” flux residues more difficult. This could warrant changing flux chemistries or even residue removal in some cases.

Lead-Contamination in Lead-Free Electronics Assembly

Karl Seelig and David Suraski
October 2001

The question of what happens to a lead-free solder joint if it becomes contaminated with lead is important because during the transition to lead-free soldering it is very likely that tin/lead parts will still be used in a great deal of production. In other words, just because one implements a lead-free solder alloy does not mean that tin/lead coated components and boards will disappear immediately. In fact, exposure to lead from boards, components and repair operations could occur for years to come.

Unfortunately, in the past the presence of lead in lead-free alloys has been presumed to be acceptable. The logic behind this was that tin and lead are soluble in a lead-free system. However, what has been overlooked is that the intermetallic crystalline structures in lead-free systems are not soluble and will precipitate at lead boundaries. Thus, when using a lead-free alloy to solder to Sn/Pb coated component leads, Pb can actually create voids in the solder joint that can result in joint failure.

An example of what can also occur is with bismuth-bearing alloys, as bismuth and lead form pockets with a secondary eutectic of 96°C. This could have obvious negative effects on reliability if an assembly is exposed to any thermal stress.

The Dynamics of Lead-Contaminated Solder Joint Failure

It is important to note that lead that contaminates a lead-free solder joint is not distributed uniformly through the joint; rather, the Pb localizes in the last point to cool. This is

similar in dynamics to “zone refining”, a process utilized to refine high-purity elements. In zone refining, a heat source traverses across a billet. As this occurs, the elemental impurities are collected in the liquid phase and are condensed at the last point to cool (the end of the billet), which can then be removed (Fig. 1).

Just as in zone refining, lead as an impurity in a solder joint migrates to the last area of the joint to cool. This occurs under the middle of the component lead at the solder joint-PCB interface (Fig. 2), which is inevitably the area of a solder joint that results in a failure. When this occurs, the joint forms pockets and the

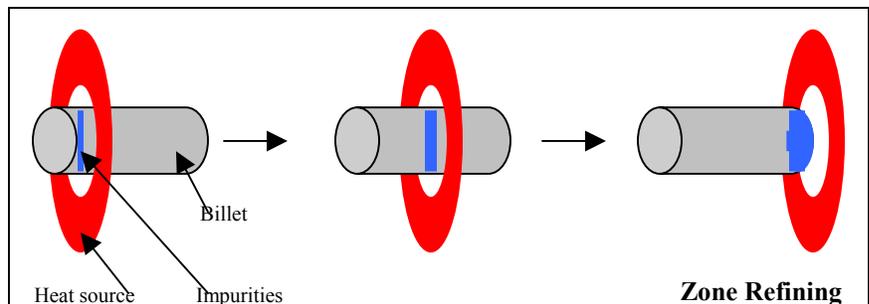


Fig. 1

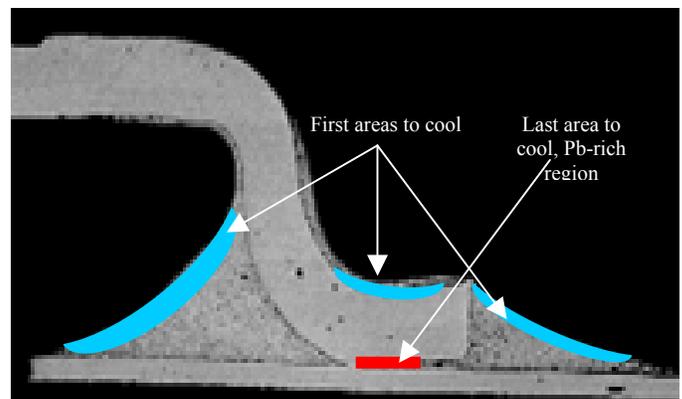


Fig. 2

grain structure is disturbed. These Pb-rich regions are lower in melting temperature and may cause dewetting during soldering.

Fig. 3 illustrates how much of a lead sphere dissolves into a Sn/Ag system during a normal reflow cycle. Fig. 4 is a close-up of Pb pockets that are dispersed through a Sn/Ag system.



This dispersion is a common part of wetting: as the solder wets, the Pb dissolves into the joint. As the Pb starts concentrating in pockets, this starts forming a eutectic of Sn/Pb/Ag with a melting point of 179°C vs. 221°C for Sn/Ag or 217-218°C for Sn/Ag/Cu. This phase occurs during cooling, and the slower the cooling, the larger the pocket of this lower melting temperature alloy will form. In essence, this pocket of alloy acts as a void in the solder joint. As the component heats and cools during its product life, this void will eventually lead to joint failure. Failure rates related to this issue typically occur relatively quickly (in less than 400 thermal cycles).



Fig. 4

Bulk Solder Testing

In order to determine Sn/Ag/Cu alloys' durability when exposed to lead, Sn/Ag4/Cu0.5 was tested for mechanical reliability with a 0.5% and 1% contamination of lead. The test methodology used in this study was simple: the mechanical strength of the Sn/Ag4/Cu0.5 bulk solder alloy without lead contamination was tested under Low Cycle Fatigue Testing in accordance with ASTM E606; then, the alloy was doped with 0.5% lead and tested; finally, the alloy was doped with 1% lead and tested. The samples tested were required to achieve 10,000 cycles without failure in order to pass the test. The results of this testing is summarized below.

Fatigue Test Results

Sample	Cycles to Failure	Result
Tin/Silver/Copper	13,400	Pass
0.5% Pb Contamination	6,320	Fail
1% Pb Contamination	3,252	Fail

As is seen above, Sn/Ag4/Cu0.5 passed the testing requirements. However, when contaminated with 0.5% lead, the alloy lasted only approximately 50% of the cycles as the alloy without lead contamination and failed the test. Furthermore, when contaminated with 1% lead, the cycles to failure were again reduced by 50%, which constituted another failure. The above results are contrary to the presupposition by many in the electronics industry that Sn/Ag/Cu alloys are not negatively affected by lead contamination.

The above reduction in bulk solder strength can impact solder joints as well. Fig. 5 is a magnified close-up of a fracture resulting from Pb contamination in a Sn/Ag/Cu solder joint. This occurred on an in-field assembly and resulted in a field failure. As discussed above, this fracture occurred at the middle of the component lead at the solder joint-PCB interface. Fig. 5 is a magnified view of the lead pockets found in the lead-free solder joint that led to this failure.

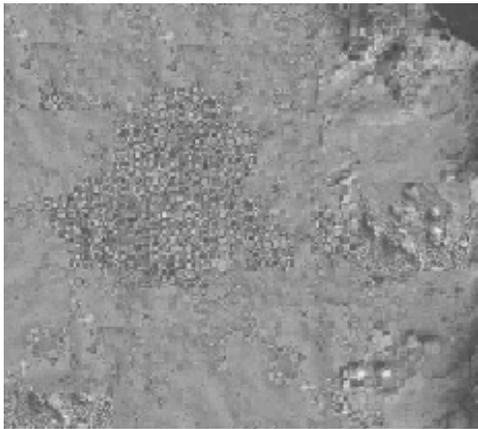


Fig. 5

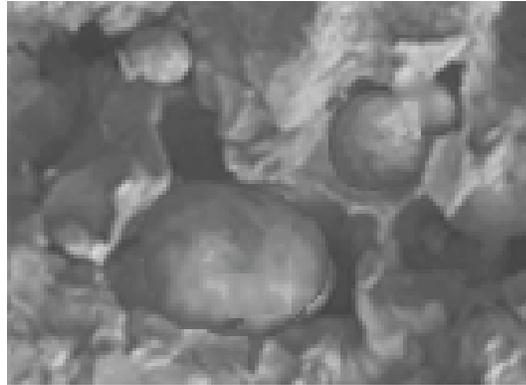


Fig. 6

BGA Thermal Cycling Data

As previous testing has demonstrated¹, potential reliability issues exist when mixing Sn/Pb parts with lead-free solders during BGA assembly. 35 x 35mm 388ld PBGA packages with both Sn/Pb and Sn/Ag/Cu balls were assembled using Sn/Pb and Sn/Ag/Cu pastes. Several failures did occur in -40° to +125°C testing. As indicated in the chart below, the most reliable of these assemblies were those produced with Sn/Ag/Cu balls and paste. (As an aside, this superior thermal fatigue resistance is one reason that the automotive industry has been pursuing lead-free soldering irrespective of legislative or marketing concerns.) However, it is important to note that assemblies that mixed Sn/Pb balls with Sn/Ag/Cu paste fared significantly worse than either the all lead-free or all Sn/Pb assemblies. This data reiterates to potential reduced reliability of mixing lead parts with lead-free solders.

BGA Thermal Cycling Results Summary

Ball	Paste	% Cum Failures
Sn/Pb	Sn/Pb	47%
Sn/Pb	Sn/Ag/Cu	56%
Sn/Ag/Cu	Sn/Ag/Cu	3%

¹ MEPTEC Summit on Lead-Free Solder Implementation, January 10, 2001, “Lead-Free: An Overview of Temperature Cycling, Aging, Bend Testing and Plating Chemical Evaluation Results”, Swaminath Prasad et al.

Field Failures From Lead-Contamination

A leading multinational electronics manufacturing company recently experienced field failures in a product assembled with a tin/silver/copper alloy, and tin/lead coated components and leads. Samples of the failed solder joints were viewed using SEM to determine the possibility of lead or other contamination that could have lead to the failure. EDS was used to determine if there was contamination in the solder joint. As shown in Fig.7, the EDS revealed lead contamination levels ranging from 3% to 10%. In Fig. 8 the mating area of the lead-free alloy and tin-lead parts is shown. The Sn/Ag/Cu alloy is seen in the lighter areas and the darker Sn/Pb areas surround it.

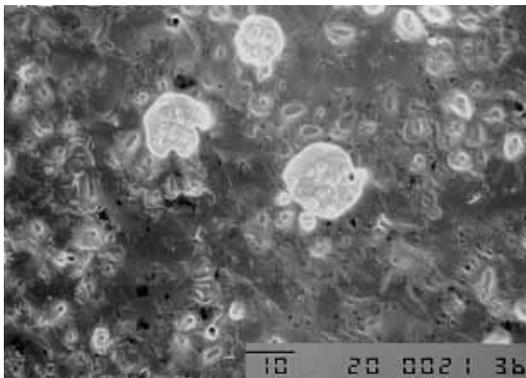


Fig. 8

This intergranular phase exhibits poor adhesion to the lead-free alloy, thus causing the grain separation.

This particular grain boundary interface that led to the failure could be the result of a specific heat cycle being utilized. In other words, utilizing different heating profiles during assembly may minimize, but not eliminate, this problem. To determine this, more joints, processed using different thermal profiles, would need to be investigated.

Conclusion

A tremendous amount of interest exists in lead-free soldering. Much of this is

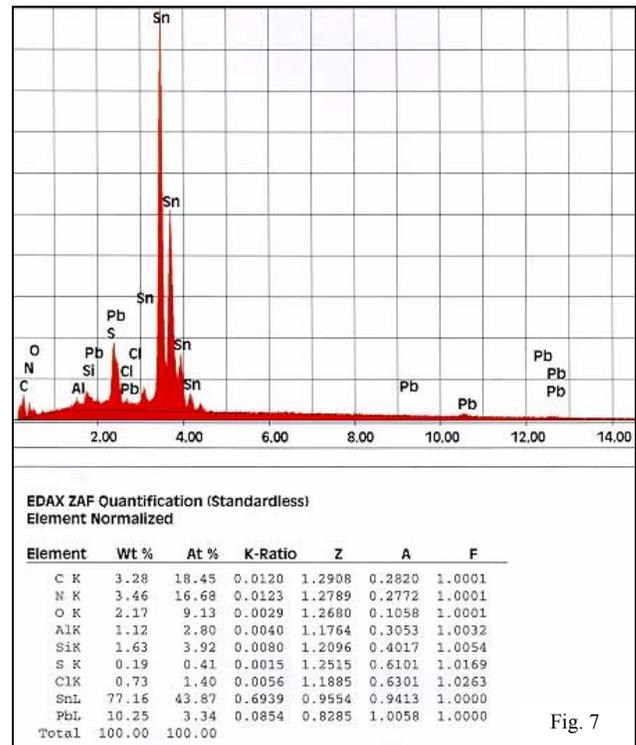


Fig. 7

The failure is an intergranular separation and is being driven by lead in the solder. Figure 9 is a 3500X photo that shows a distinct phase between the normal grains that causes the grains to separate easily. The lead forms a ternary alloy of tin/lead/silver that is trying to go to the eutectic at 179°C. This alloy is surrounding the grains of the lead-free alloy.

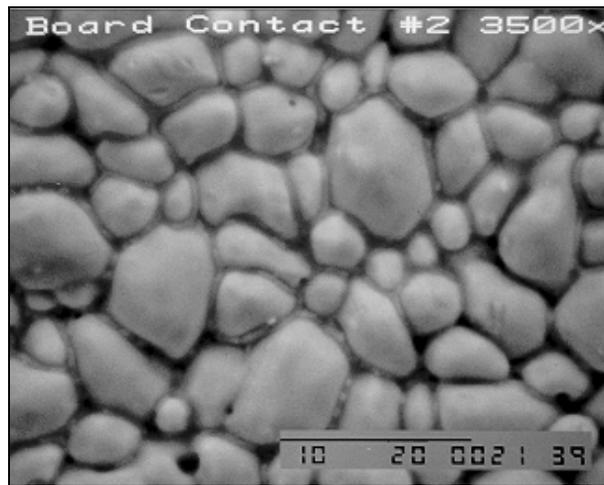


Fig. 9

derived from a fear of legislation and marketing activities. This has spurred a great deal of committee and consortia activity, some of which has been valuable to the industry.

One of the most pressing questions in lead-free soldering pertains to the lead-contamination of lead-free solders and its effects. As the above evidence demonstrates, lead-free alloys can suffer decreased reliability when contaminated with lead. To avoid problems related to this, the most prudent course of action is to reduce the lead-free transition period to as short as possible. In other words, when a company implements a lead-free solder alloy, it should also implement lead-free component terminations and circuit board coatings. If these above guidelines are not followed, the reliability of the solder joint is risked.

For additional information, please contact the authors at 800-CALL-AIM, 401-463-5605 or info@aimsolder.com



Lead-Free Solder Assembly For Mixed Technology Circuit Boards Feb 2006

Several lead-free alloys have been investigated for SMT assembly. The industry has migrated to a family of alloys known as SAC (Tin/Silver/Copper) alloys, and within this group the industry has narrowed its focus to the SAC305 (96.5% tin, 3% silver, 0.5% copper) alloy. The Solder Products Value Council (SPVC) under the guidance of the IPC has completed a million dollar, year-long study that has recently confirmed that SAC305 is the recommended default SMT alloy¹.

However, it is well known that SAC305 can cause negative results in wave soldering, hand soldering and selective soldering applications. For example, due to solder volume and solder joint configuration, SAC alloys often suffer from “hot tears/shrink holes”². These shrink holes can be difficult to distinguish between a “cold” joint and a good joint, thus causing inspection difficulties. In addition, the cost of SAC305, although the lowest of the SAC family, is higher than other alloys due to its silver content. Primarily for these two reasons, the industry is looking for alternative alloys for non-SMT applications. The common alternative alloys are SN100C³, SAC-LOW, and SACX⁴.

The issue of choosing a wave solder or selective solder alloy is more complicated than choosing an SMT alloy because not only do these solders have to form a reliable solder joint, but they also are used in a molten solder bath. How these alloys react to molten solder baths is what differentiates them from one another. The SAC and SACX alloys dissolve most metals they come in contact with over time. For these alloys, new soldering equipment parts are necessary to keep equipment maintenance to a minimum. Contrarily, the SN100C and SAC-LOW alloys contain additives (dopants) to reduce their aggressiveness to the contact parts in the solder pot. Additionally, this also reduces copper corrosion, which is important when running selective soldering for rework applications. The below data clearly demonstrates that SN100C is less likely to remove pads and traces from circuit boards during extended working times.

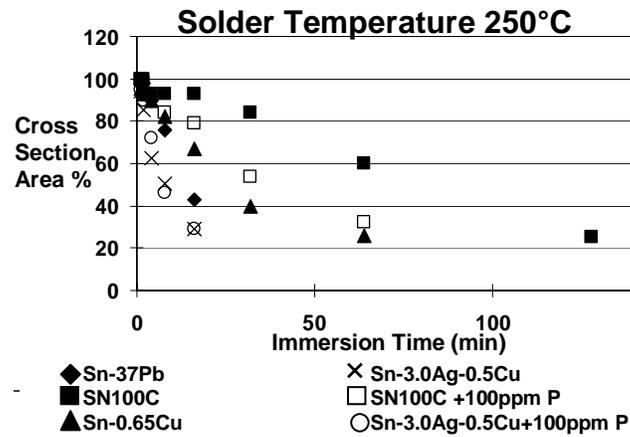
¹ This study is available through the IPC at www.ipc.org

² As referred to in IPC-A-610 Rev D

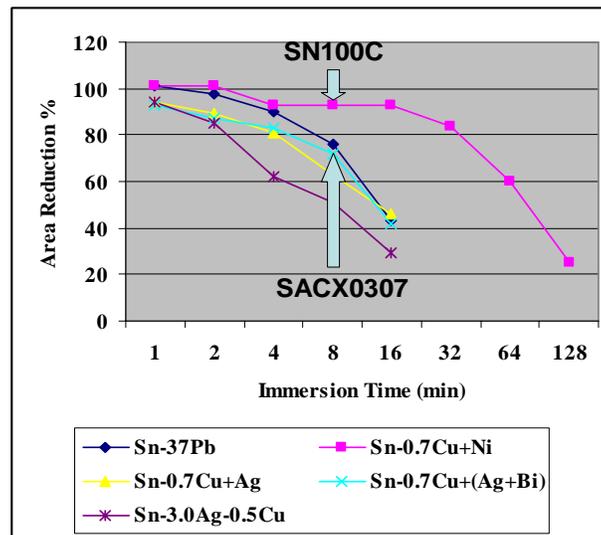
³ Sn/Cu/Ni alloy patented by Nihon Superior

⁴ Sn/Cu/Ag/Bi alloy patented by Alpha Metals

Study of Copper Erosion



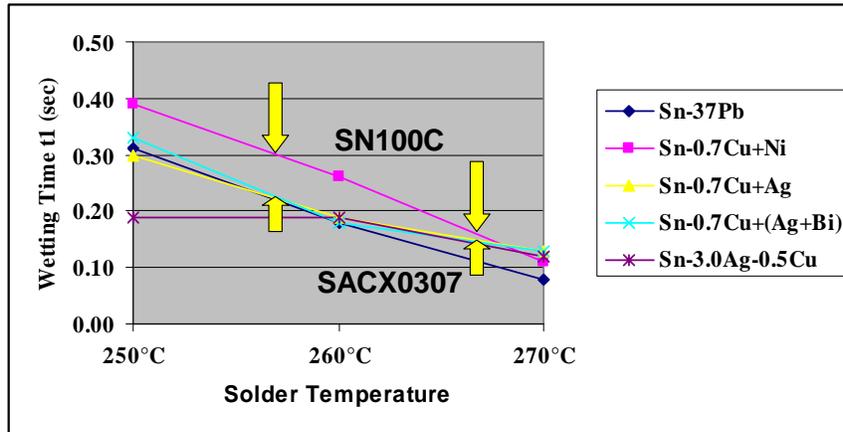
Erosion of Copper at 250° C



Although SACX is similar in composition to SN100C, SACX is more prone to copper erosion during rework or extended soldering times.

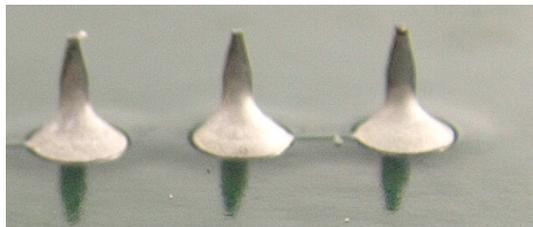
The dopant added to SN100C also slows wetting slightly. The graph below demonstrates how the solder pot temperature affects wetting and solder joint performance.

Wetting time as a function of test temperature

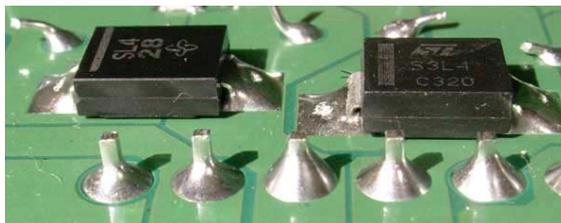


As seen above, when the recommended soldering temperature is used, the wetting is very similar between SN100C and SACX. Wave pot temperatures should be from 265 to 270°C to achieve maximum wetting and, depending on board layout, the dwell time in the wave should be ~5 seconds. This dwell time is longer than conventional tin-lead profiles; however, the extended dwell time will help topside solder fillet formation.

SACX also has a dull appearance and suffers from micro-cracks or the aforementioned “Hot tears/shrink holes”. This also can lead to inspection problems.



SACX

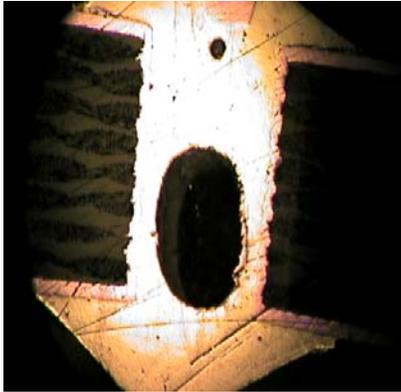


SN100C

Voiding in PTH Joints

Another issue to consider is voiding in the PTH barrels. The SAC alloys are prone to more voiding than alternative alloys. This is typical for a SAC wave soldering application and may or may not cause a reliability issue. In terms of joint strength, SAC alloys have more than ample joint strength, even with the voids. However, if the leads are used for high power, resistance or temperature dissipation might be an issue.

The following pictures are a comparison of ENIG boards soldered with SAC and SN100C. The SN100C solder joint are consistently lower voiding and have very good fillet formation.



SAC



SN100C



SAC



SN100C

In addition to voiding less, SN100C is also less prone to surface cracks that form due to cooling rate along intermetallic grain boundaries. This results in fewer cracks and shinier solder joints and an appearance very similar to tin-lead solder joints.

Lead-Free Alloy “Cross Contamination”

Many assemblers want to use one alloy throughout all soldering processes in order to avoid “cross contamination”. The contamination of lead-free solder joints from exposure to tin-lead can be detrimental and has been documented in “Lead Contamination in Lead-Free Electronics Assembly”⁵ as well as several other publications. Little work, however, has been done on the mixture of different lead-free alloys in the same solder joint. This type of mixture could stem from using the wrong repair solder or board designs that do not allow enough space between SMT and wave pads. Unfortunately, fear of contaminating one lead-free alloy with another has kept manufactures using a one alloy system, despite the fact that SAC may not be the best choice for wave, selective, or hand soldering. This paper addresses the issue of mixed lead-free solders.

During typical SMT assembly, there are few places that solder can cross contaminate other than BGA assembly, in which the solder connection itself is a combination of solder ball and solder paste. As an aside, many of these lead-free BGA balls are a

⁵ This paper may be downloaded at www.leadfree.com

proprietary alloy mixture similar to SAC alloys. The reason that SAC is not used is because these alloys do not have as good as drop shock test properties as tin-lead. Therefore, alloys doped with antimony, nickel, germanium, indium, silicon, and other elements are used to improve this particular characteristic. These solder balls are then soldered with SAC during SMT applications without any issue. However, soldering with SAC to a tin-lead solder ball gives much poorer results due to excessive voiding and a segregated joint that will fail at lower forces than either alloy independently.

PTH Cross Contamination

As the below images demonstrate, the only alloy combination found to be detrimental to solder joint life during the wave soldering test for cross contamination was lead in SAC or any other lead-free alloy.

**Observation of Solder surface.
(Wave solder with SN100C, Manual Solder with SAC
Double side board)**



After Wave Solder



After Manual Solder



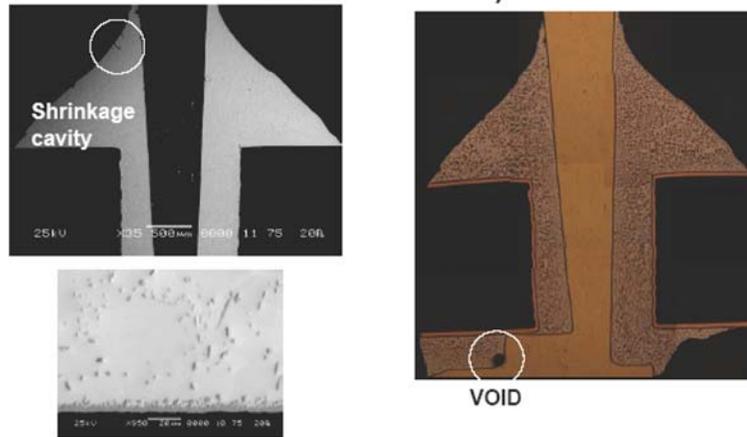
After 500 Heat Cycle



After 10,00 Heat Cycle

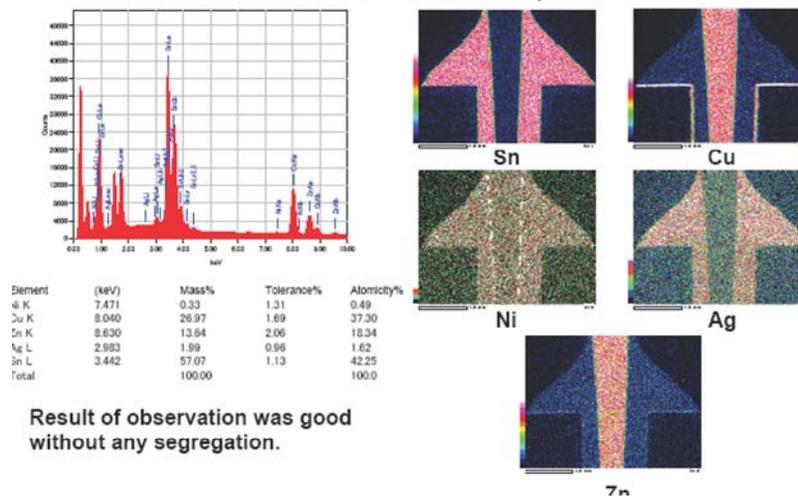
- * After Manual solder with SAC, result of observation was found solder fillet became two sections which was shiny and grainy part.
- * After Heat Cycle, there was shrinkage cavity at shiny part.

**Observation of Cross Section. (After Heat Cycle)
(Wave solder with SN100C, Manual Solder with SAC
Double side board)**



Result of observation was found shrinkage cavity and void.

**Observation of SEM (After Heat Cycle)
(Wave solder with SN100C, Manual Solder with SAC
Double side board)**



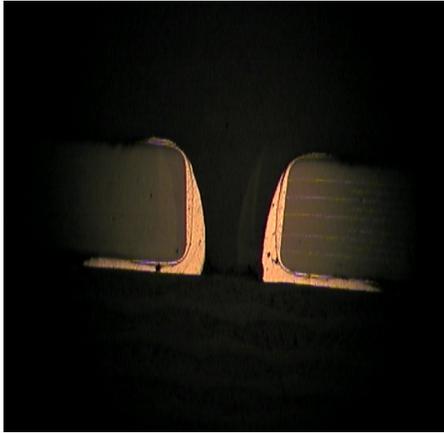
Result of observation was good without any segregation.

From the above pictures and cross sections, SAC and SN100C were found to be compatible with one another when mixed by using a different touch up wire alloy as the alloy used in the wave. Therefore, there would not be any detrimental effect by the accidental mixing of these alloys.

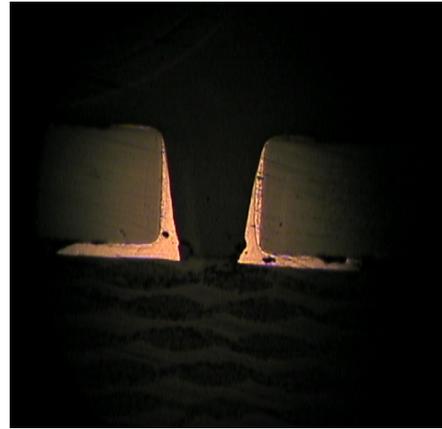
SMT Cross Contamination

Because they are found on both sides of the circuit board and can be soldered with solder paste in an SMT reflow process or glued and soldered in a wave solder process, chip resistors and capacitors are the SMT components most likely to become cross contaminated. If touch up or repair is required, it is likely that these solder joints may

have the wrong solder wire applied to them. To determine if this is a problem, SMT components were soldered with solder pastes comprised of SN100C, SAC305, and an SN100C + SAC mixture. These assemblies were then thermal cycled from 0 to 100°C for 1000 cycles to determine if any of these combinations would cause a failure. The below pictures are of the various solder joints.



SN100C

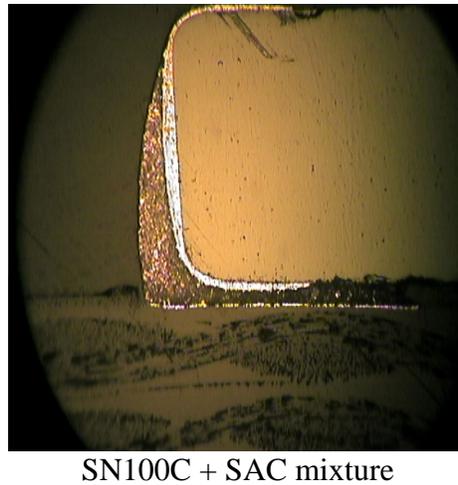
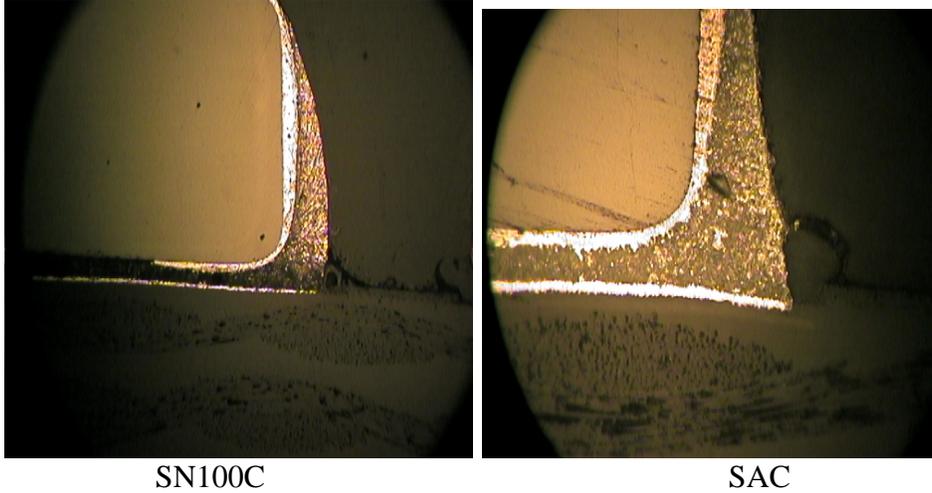


SAC305



SN100C + SAC mixture

The grain structures of the alloys are different and easily distinguishable in an etched cross-section. The grain of the SAC alloy is very large while the SN100C is finer and more uniform. The combination alloy falls between these.



Thermal Cycling Test Results

The SAC, SN100C and SN100C + SAC mixture all performed the same in thermal cycling testing. None of the boards that were assembled and thermal cycled had any solder joint failures. From this initial testing on the SMT joints and the more extensive testing on the through hole joints, it does not appear that the cross contamination between SAC and SN100C alloys has any negative effect on solder joint reliability based on thermal cycles.

The SAC, SN100C and SN100C + SAC mixture were each tested for shear strength of the components before and after thermal testing. The components were tested using a destructive shear test to measure the relative solder joint strengths. The test consisted of a Chatillon TCM 201 SS coupled with a Chatillon DFIS-50 Force Gauge. Downward force speed was 0.25 inches per minute. The results of the shear testing are as follows.

Alloy	0 cycles	1000 cycles
SAC305	15.3 lbs	15 lbs
SN100C + SAC mix	14.1 lbs	14.3 lbs
SN100C	14.2 lbs	14.0 lbs

Sn/Pb	14.8 lbs	14.5 lbs
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The results show that solder joints made with SAC, SN100C and the SN100C + SAC mixture are all comparable to tin-lead solder joints made on the same board. In addition, it was determined that thermal cycling does not seem to degrade these solder joints.

Conclusion

Based on results from this testing, no degradation of the solder joint was found due to mixing SN100C with SAC alloy. Therefore it is believed that a two alloy system can be successfully used for mixed technology boards without compromising reliability.

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