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The Use of SAC Solder and Pb-Free Lead Materials in the Repair Scenario

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Abstract
Much work has been done involving the introduction of RoHS and WEEE Directives across the European Union and the world. Although the use of Pb is limited in new products and equipment, older Pb-containing materials can continue to be used for repair of existing systems. As time progresses, these older Pb-containing materials will need to be repaired using Pb-free components and solders. This paper addresses the concerns of repair centers, which must rework these boards using Pb-free components and materials.

Introduction
Europe, China, individual states within the USA, and several countries in South America are implementing, or have implemented, stringent limits on the use of certain hazardous substances in electronic assemblies. The most well known of these, perhaps because it is so far along in implementation, with a deadline of July 1, 2006 is the European version of the Restriction of the use of Certain Hazardous Substances in electrical and electronic equipment, or RoHS.[2] The restrictions in these markets may drive the elimination of these hazardous substances in electronic assemblies throughout the world.

With few exceptions, this law drastically reduces the amount of several hazardous materials, compounds, and chemicals in electronic assemblies. It limits the amounts of Lead (Pb), Hexavalent Chromium (Cr^{+6}), Polybrominated Biphenyls (PBB), Polybrominated Diphenyl Ethers (PBDE), and mandates stricter limits on Mercury (Hg), and Cadmium (Cd). The most difficult of these laws to comply with from a manufacturing perspective is the limits on Lead (Pb). It has now become necessary to ensure that the Lead (Pb)[2] is eliminated from the electronic components in order to comply with these new laws going into effect in the world.

In the electronic assembly industry SnPb eutectic (or near eutectic) solders have been used as an agent to provide both structural strength and electrical conductivity in electronic assemblies for the past 40 years. In addition high temperature SnPb solders with high Pb concentrations have been used for die-attach in components and subassemblies to ensure that they do not melt during a standard reflow process.

An exact drop-in replacement, with the structural integrity, melting point, and workability for SnPb solder has not been found. Recently industry in the USA has adopted an alloy of Tin (Sn), Silver (Ag) and Copper (Cu). Two formulations have been forerunners in these choices, a tin-based alloy with 3.5% silver and 0.5% copper, (SAC305) and a tin-based alloy with 4.5% silver, 0.5% copper (SAC405).

For this paper we utilized an alloy containing 96%Sn, 3.5%Ag, and 0.5%Cu (SAC). This solder has a higher melting point than SnPb eutectic solder. It is not a true eutectic solder and has a small melting point range of 217°C to 220°C. Between these temperatures both molten and solid areas can coexist. This is termed the "plastic stage" of the solder.

This solder melts about 30°C higher than SnPb solder. Some "standard" components developed for SnPb soldering conditions may not withstand the higher reflow temperatures of the SAC solders. The IC encapsulants and polymers used for connectors in particular may decompose or deform during the reflow process. Additionally, it has been reported that all polymeric products exposed to the SAC processing temperature could be more prone to the water absorption. However with proper care most of these problems can be overcome during production scale operations. During our field trials using SAC solder and SAC reflow temperatures, we found no appreciable drop in manufacturing yield or short-term reliability when components designed for SnPb reflow soldering conditions were used at the higher temperatures required for SAC solder. However, our results were limited both in the scale of our testing and the number of components tested.

The component industry has not been complacent in looking forward to the implementation of RoHS. Just as the assembly industry has been examining replacement solders for SnPb, component manufacturers have been examining replacement coating for leads and new formulations for the polymers used in their components. Some component vendors are taking two steps to meet the Pb-free requirements. First, they will provide component leads that do not contain Pb. These initial components will not be guaranteed to withstand the higher reflow temperatures necessitated by SAC solders. Then, the component supplier will implement high temperature polymers, coatings and materials that will withstand the higher reflow temperatures.

Several methods have been developed to insure that the leads remain easy to solder. Both gull-wing and J-leaded packages use a base metal such as copper as the lead material. Clean copper is solders will, but left exposed to the air, copper will oxidize rapidly forming a tough coat that is difficult to remove. SnPb was used in the past to protect the leads. This coating because a portion of the solder ensuring a good connection. Today different coatings have evolved to replace the Pb in the earlier coatings. Tin is used to coat the copper leads. Sometimes the tin is placed over a barrier layer of nickel. Other coatings that have been noted are palladium over nickel plated on the copper. Gold over a nickel barrier layer has also been used. Of all these methods, the use of tin alone, or tin over nickel are the most economical. Both gold and palladium are precious metals and expensive.

Some vendors have changed to a matte tin, a matte tin over nickel plate, or a gold, palladium, nickel, coating over the lead. Both tin and gold are easily wetted by either SnPb or SAC solder.[4] During the investigation portion of this experiment we found that several component suppliers had already eliminated Pb from the lead coatings, utilizing either matte tin plating or a nickel-palladium-gold sandwich plating.

We are presently working with our Repair Facilities to make sure they will be ready to use Pb-free solders well in advance of the RoHS deadline. We foresee a day in which most assembly houses will only work with non-Pb solders, and the easily available components will also be Pb-free. Ultimately there will be little or no added Pb in the assembly at all. During the transition, there will be a time in which both Pb-bearing components and Pb-free components will coexist in the manufacturing facility. Manufacturing facilities will be switching from SnPb to SAC solders. It is possible that all combinations of component lead finishes and solders will be able to be found for a short period of time.

The European laws permit the replacement of Pb-containing PWBs with Pb-containing PWBs to maintain or repair equipment, which had been in the market before July 1, 2006. Equipment development companies that maintain existing equipment will have the option of replacing an existing Pb-bearing PWB with another Pb-bearing PWB. We will see the necessity of repairing a PWB or assembly originally built with SnPb solder using Pb-free components and SAC solders.

We wanted to examine what problems may occur when a Pb-free component is soldered using Pb-free solder to an existing PWB that has originally been built using SnPb solder. The repair centers we utilize generally use hand soldering to replace individual components such as Gull-wing and J-lead devices. We utilized gull wing devices and hand soldering operations during this examination. Table 1 summarizes the existing and future possible rework scenarios.

Table 1 - Properties of Eutectic Pb-Sn and SAC305 Solders[3]

Characteristic	Eutectic SnPb Solder	SAC Solder (96Sn:3.5Ag:0.5Cu)
Liquidus Temperature	183°C	221°C
Solidus Temperature	183°C	221°C
Suggested Reflow Temp.	220°C	240°C - 250°C
Resistivity	14.5µΩ·cm	13µΩ·cm
Tensile Strength	40 N/mm^2*	48 N/mm^2*
Thermal COE	$24.6x10^{-6}/K$	No Reference Noted

Experimental Procedure

Test Coupons for Cross sectioning and Thermal Aging

We obtained test coupons by cutting the solder pads containing a SnPb soldered component from a scrap PWB. These PWBs were scrapped because the functions they performed had been eliminated or updated. They were not scrapped because of failure. The cuts were made far enough from the existing IC that neither it nor the pads were damaged.

We carefully removed the selected components from the PWB coupons using a METCAL MX-500P-11 System with a 600°F (316°C) tip (METCAL Series 600 Tip). We used the METCAL system because the tip has a lower and more stable temperature than standard soldering iron tips. Both component removal and reattachment were accomplished using this system.

After removing the existing ICs from the individual coupons, the pads were cleared of the remaining SnPb solder using a no-clean flux impregnated copper braid. This process left a thin layer of SnPb solder on the pad which has been ignored in the past because the new, added solder had essentially the same composition. This will no longer be the case. This experiment is designed to examine the differences in the quality of the solder bond caused by the remaining Pb-containing solder on the pad and any Pb-containing coating on the component lead. There is an intermetallic layer of approximately 1µm to 2µm with about a 1μm SnPb coat left on the pad. Figure 1 shows a cross section of a pad after cleaning. Note the thin layer of intermetallic compound and solder left on the pad at the top of the image.

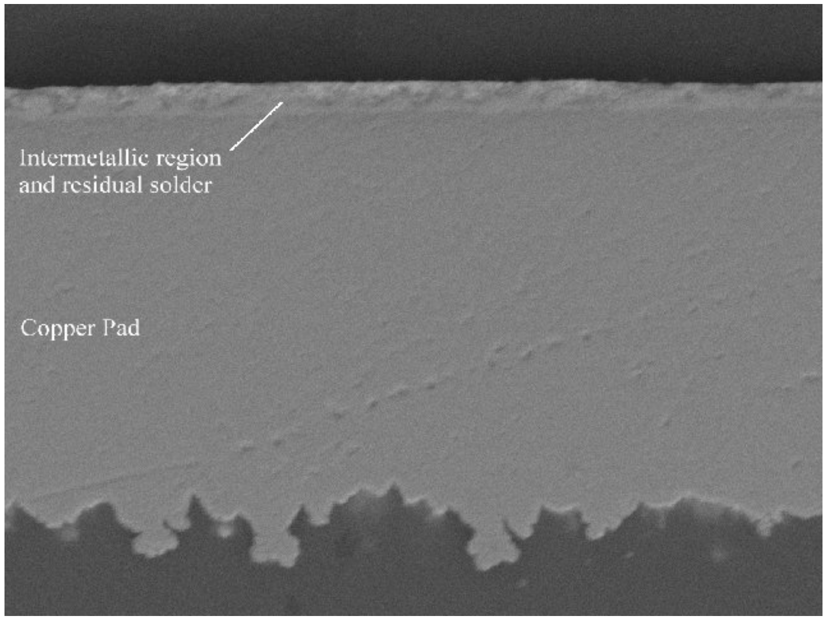

Figure 1 - Thin layer of SnPb solder left on pad after cleaning and leveling and prior to component placement
Magnification 1500X

Table 2 - Possible Rework Scenarios

Rework	Component	Solder
Existing Procedure	Pb-Containing	SnPb
Near Future Procedure	Pb-Containing	SAC
Future Procedure	Pb-Free	SAC

All replacement ICs were resoldered to the pads using SAC305 cored solder containing a no-clean flux. Two groups of components were formed as shown in Table 2. Group 1 is the non-reworked (original) group. Group 2 contains Pb-free components. Thermal damage to the body of the IC is not a concern during this kind of rework. The component's body does not either reach SnPb or SAC reflow temperatures, because the heat energy is applied directly to the leads and not to the entire component as in a reflow oven.

After attachment of the components, the coupons were segregated into two groups. One group, containing both SnPb coated components and Pb-free components, was placed into a thermal chamber at 150°C for 500 hours. The second group was placed in a dry box at room temperature for 500 hours to simulate a fresh solder joint. At the end of the aging period samples of both groups were cross-sectioned and polished for analysis.

Both SEM and mapping EDX analysis were performed to determine the location of the various layers within the solder connections. Areas of copper pad, copper-tin intermetallic, SAC solder, and lead coatings and base material were identified and mapped. Pb from the residual solder was found mixed throughout the entire solder connection, which indicates that the residual layer mixed well with the additional solder used in making the connection.

Data from Cross-Sectioning

The intermetallic layer consisting mainly of copper and tin had grown to about 4.2μ in thickness during the thermal soak at 150°C for 500 hours. No significant differences in the intermetallic layer thickness were noted between the SnPb coated leads and the matte tin coated leads. The intermetallic layer thickness consists mainly of tin and copper. It is more dependent upon the time and temperature than it is upon the addition of lead to the solder. Figures 2 through 4 show a SEM image of the intermetallic layer along with the copper and tin maps of the image. The elemental maps clearly show the copper – tin intermetallic layer. The large bright circles above the intermetallic layer are areas composed mainly of Pb.

This is to be expected because in SnPb solder alloys, the Sn and Pb are not uniformly mixed at the micro level. The alloy is, in reality, a mix of tin rich areas and Pb rich areas in contact with each other, not a uniform mixing of Sn and Pb.

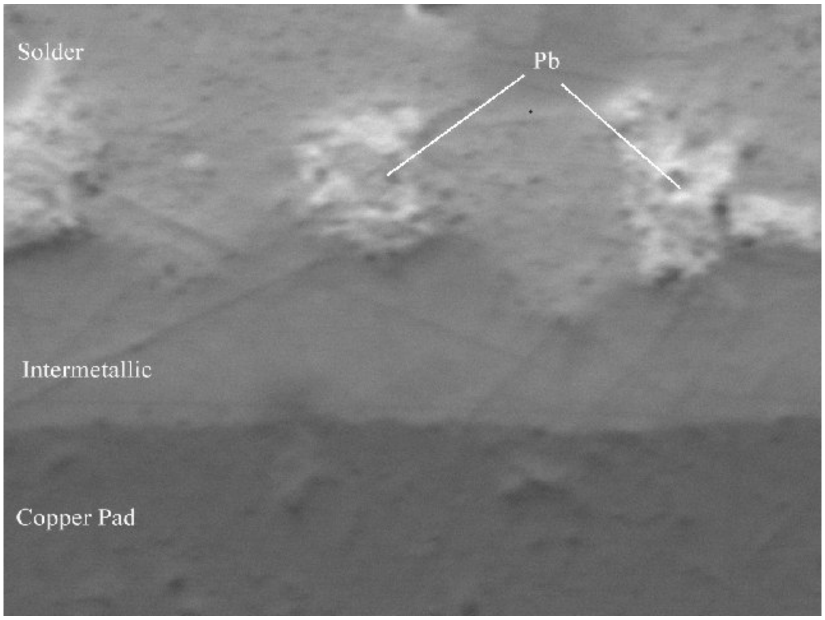

Figure 2 - SEM SEI Image of Intermetallic Layer Magnification 5000X

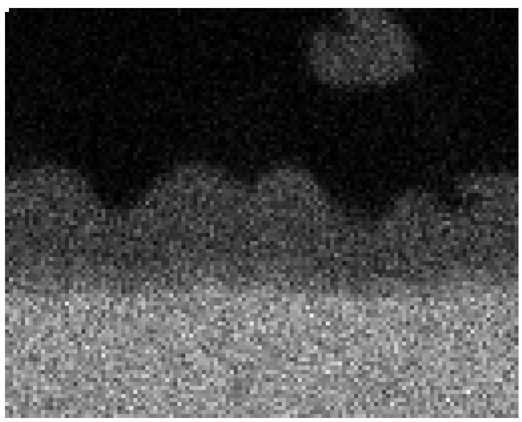

Figure 3 - Copper EDX Map

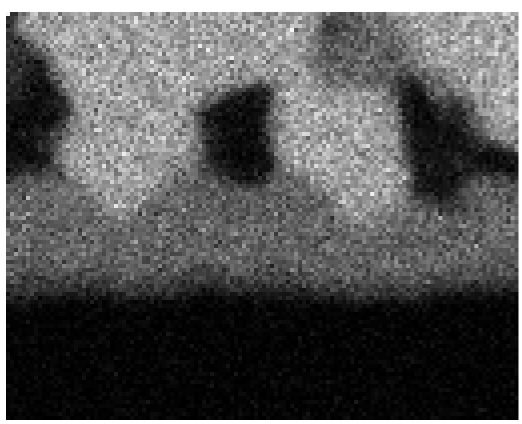

Figure 4 - Tin EDX Map

The intermetallic thickness of a sample aged at 150°C for 500 hours varied between 2.8µm and 5.7µm, with an average thickness of about 4.2µm across the sample. Non-aged samples have an intermetallic thickness between 1µm and 3µm with an average thickness of about 1.5µm.

Bond Pull Strength Testing

Pull testing of the bonds was performed to assess the strength of the bonds before and after the thermal aging. Table 3 shows the average and the standard deviation of the bond pull strength testing of the samples, along with that of original SnPb solder connections for comparison.

The average force required to break the bonds was not significantly different between the Non-Reworked bonds and the New SAC solder. The differences may be due to the soldering technique rather than the solder itself. However, after 500 hours of aging there was a drop in the bond strength as well as an increase in the standard deviation of the sample. This reduction is due to the amount of intermetallic formed at the copper-tin interface. With leads that are coated only with tin the intermetallic will form and increase in thickness at both the pad to solder interface, but also at the lead to solder interface. This may result in greater loss of bond strength over time. A nickel plate over the copper lead (and over the pad) will result a thinner intermetallic because nickel does not form an intermetallic with tin as fast as copper does.

Table 3 - Results of Bond Pull Testing

Group	Average	Standard Deviation	N
Non Reworked PbSn Bond	34.27 N	4.31 N	20
Non-Aged Matte Tin IC	32.74 N	5.85 N	20
Aged Matte Tin IC	28.57 N	7.89 N	20

Board Selection for Operational Reliability Testing

We began the experiment using existing PWBs built with standard components, and SnPb solder. We carefully selected a PWB that had several similar components for which we could readily obtain Pb-free parts from the supplier (in sample quantities at least). The four matching components were removed from four PWB assemblies. Two Pb-coated components and two Pb-free components were resoldered to the PWBs. Each PWB was tested for correct operation before and after the replacement using a standard factory test for that particular PWB.

One other modified PWB was then placed into a thermal chamber and cycled between -35°C and 125°C with a 10-minute dwell at each temperature. About one cycle per hour was made over this temperature range. This profile has been shown to accelerate the growth of tin whiskers. The effect of the heat on the leads of the ICs during reattachment with respect to whisker growth is an unknown factor. Matte tin has been shown to have less whisker growth after a high temperature soak to redistribute the stresses within the layer.

The PWB was electrically tested and visually examined for whisker growth at 25 and 50 cycles. The PWB was electrically non-functional after 50 cycles. No attempt was made to determine the source of the failure. Although individual components can withstand many more cycles to these extremes, this is a very harsh thermal cycle for a PWB assembly. The reworked areas were carefully examined for damage, broken or lifted bonds. None were detected.

No whiskers could be detected using a 100X microscope. The PWB was then cycled in groups of 100 cycles and examined. No whiskers had been detected after 500 cycles. We did not detect any whisker formation on either the original or reworked solder connections or the component leads associated with them. The remaining PWBs continued to remain fully functional at room ambient temperatures for more than 1000 hours.

Conclusion

The lead coating now used, and those proposed will wet well enough with SAC solders to pose no wetability problems. The pull strength of the solder bonds is comparable for both solder types. High temperature operation will age either type of solder bond, increasing the intermetallic thickness and reducing the pull strength of the bond. It is possible that the use of a nickel plate under the matte tin finish may slow the degradation of the pull strength. Also, nickel barrier layers have, according to some authors helped to reduce the possibility of whisker growth on the tin lead. We detected no unknown or unsuspected problems associated with the use of SAC solder in the repair of assemblies originally manufactured using SnPb solder.

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References

1. DIRECTIVE 2002/95/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, Official Journal of the European Union, 13.2.2003, L 37/19

2. In this paper we will use the chemical symbol for Lead (Pb) so we won't be confused when we talk about the lead coated leads (Pb coated leads) in a package.
3. Siewert, Thomas, Liu, Stephen, Smith, David R., Madeni, Juan Carlos, Properties of Lead-Free Solders Release 4.0, National Institute of Standards and Technology, & Colorado School of Mines, 2002
4. At concentrations above 3-5% gold can lead to a brittle solder joint, but the 5 to 10µin coating of gold usually does not provide enough material to cause embrittlement. At these elevated concentrations gold has been shown to initiate fractures through the joint.

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RoHS and WEEE

Now

- Pb (Unlimited)
- Cr+6 (Unlimited)
- PBB (Unlimited)
- PBDE (Unlimited)
- Hg (Limited amounts)
- Cd (Limited amounts)

Future

- Pb (<0.1%)*
- Cr+6 (<0.1%)
- PBB (<0.1%)
- PBDE (<0.1%)
- Hg (<0.1%)*
- Cd (<0.01%)

* Exceptions Allowed

Pb Availability

Now	Future
Components Pb coated	Components No Pb
Solder SnPb	Solder SAC/X-Free

No Direct Replacement

- SnPb Solder
  - Low Cost
  - Long History
  - Reliable
  - “Low” Melting Point
  - Good Conductivity
- SAC Solder
  - Higher Cost
  - Short History
  - Reliability ?
  - Higher Melting Point
  - Good Conductivity

Higher Melting Point

- Higher Soldering Temperature
- Not “True” Eutectic
- Components More Moisture Sensitive
- Encapsulant May Be Affected
- Polymer May Be Deformed
- New Fluxing Agents

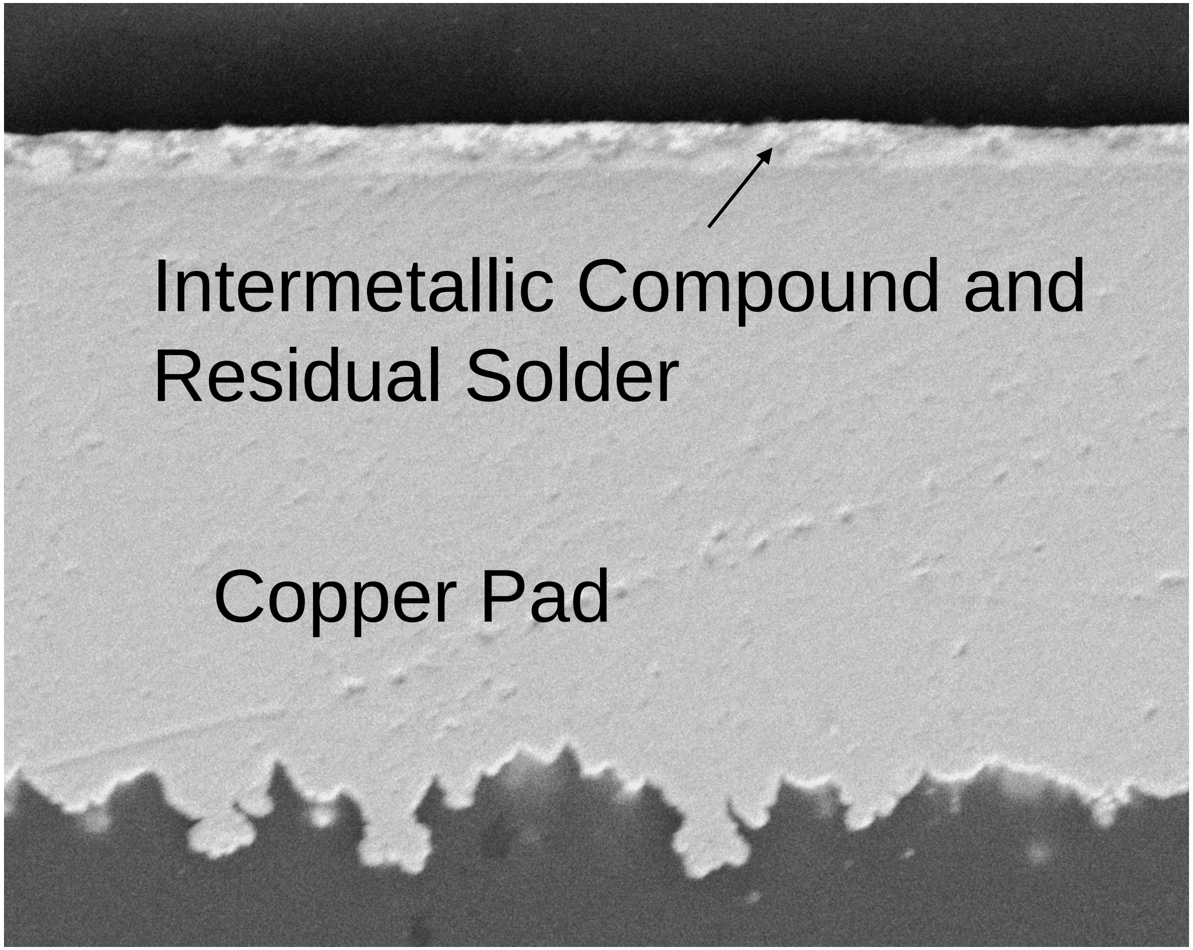
Two Step Changeover

1. Remove Pb from leads
   1. Matte Tin
   2. Ni:Pd:Au
   3. Ni:Au
2. New Encapsulant Materials for High Temperatures

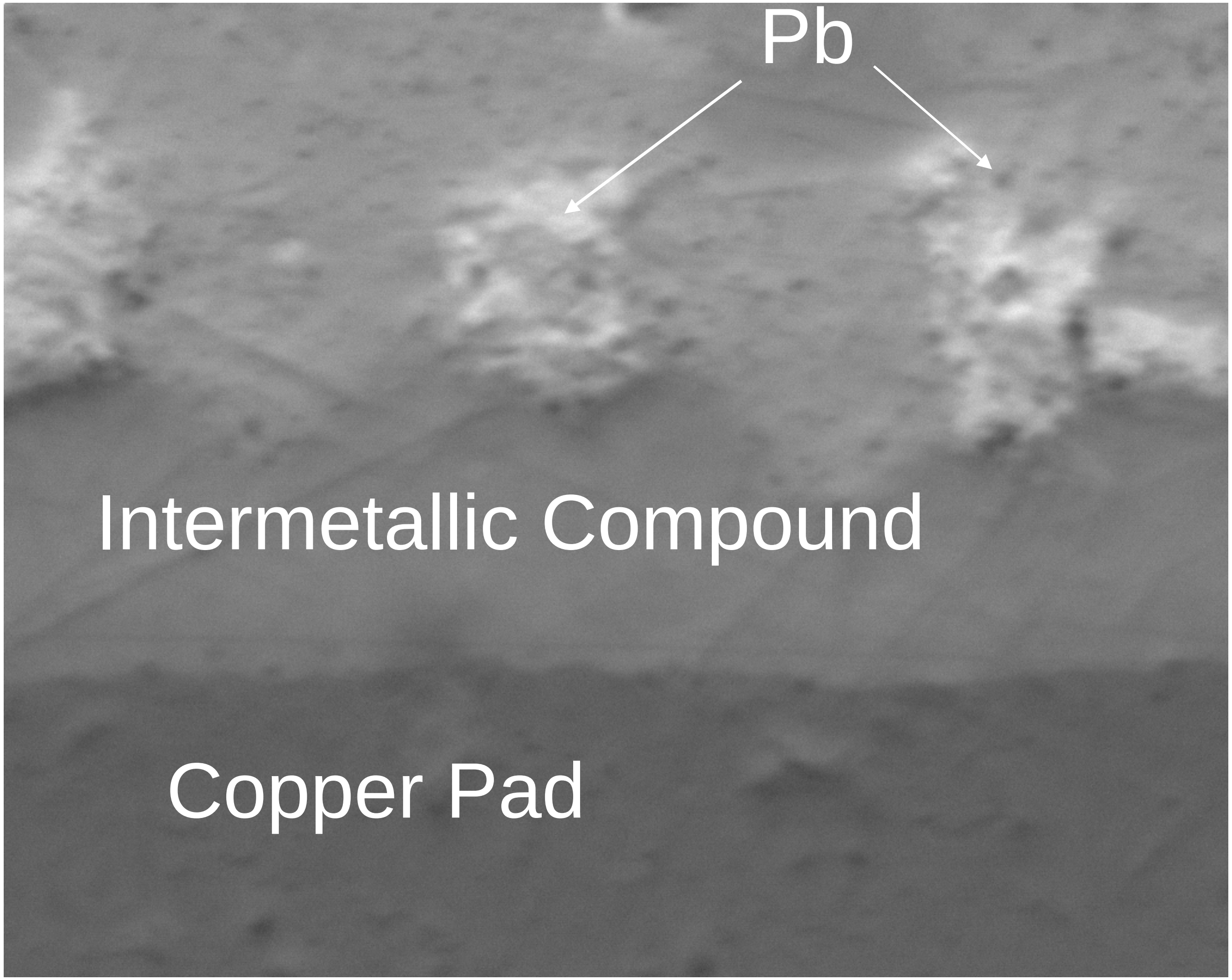
Repair Work

- Repaired PWBs Can Be Used for Replacement / Repair may contain Pb
- Today:
  - SnPb Containing Components
  - SnPb Solder
- Future
  - No Pb Containing Components
  - SAC Solder

Prepared Pad



Intermetallic Growth



Pull Test Data (N=20)

Group	Average	Std. Dev.
SnPb Bond	34.27N	4.31N
New SAC	32.74N	5.85N
Aged SAC	28.57	7.89N

Operation and Whiskers

- No difference in operating characteristics
- No Whisker Growth (-35C to 125C)

Conclusions

- All Lead Coatings Tested Work with SAC Solder
- Pull Strength is not Different
- High Temperature Degrades Both Types of Solder Connections
- No Problems Using SAC Solder and Pb-Free Components to Repair Assemblies

Acknowledgements

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  - Jessica Elzea
  - Matt Gilhousen
  - J. Erin Evans