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Perspectives on Repaired Lead-Free Solder Joints

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Abstract
The use of lead-free (LF) solders as a replacement for traditional tin-lead (SnPb) solders in military and high reliability applications has a number of technical challenges unique to the industry. The need for a metallurgically stable solder joint under harsh environmental conditions, high stress and shear loading, and long term storage presents a set of requirements that are significantly different from most commercial applications. It is well documented that processing conditions during soldering can significantly affect the microstructure and reliability of the joint. Due to the low volume and long life cycle of military and aerospace electronic assemblies, repair of components is widely employed. While methods for repairing assemblies using SnPb solders are well established, limited data is available for re-work and repair of LF solder processing, especially when the resulting joint is a combination of SnPb and LF solders. In this study the influence of repair processing conditions on the microstructure of LF solders was investigated. Processing parameters such as soldering conditions and solder composition were used to simulate manufacturing operations. Temperature cycling of components soldered to printed circuit boards between -55°C and +125°C with SnPb, LF, and mixtures of SnPb and LF solders was performed. Analyses of the phases present, chemical composition and microstructure of the solder joints before and after temperature cycling were conducted using optical and electron microscopy to correlate processing conditions to the resulting microstructure. Shear testing of surface mounted capacitors prior to and after temperature cycling demonstrated a significant drop in shear strength after temperature cycling. Implications of processing conditions on the reliability and long term stability of the solder joints will be discussed.

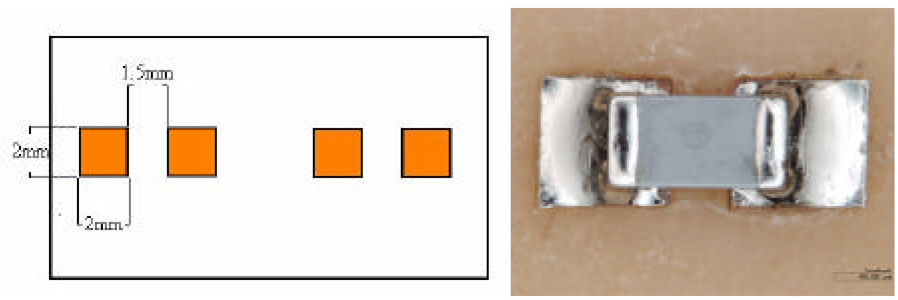
Introduction
The global transition to lead-free (LF) is having a significant impact on the electronics industry in many facets, including aerospace. Even though the aerospace industry is specifically excluded from the mandates of European Union's RoHS[1] directive, the industry will still feel deleterious effects from the transition. This is due partly because many aerospace products are designed and produced by suppliers who supply to worldwide customers and/or commercial customers. For various economic reasons, those suppliers may deliver LF products to all of their customers, regardless of RoHS exclusions. Therefore, aerospace prime contractors will be forced to use products that contain LF solder alloys in their military or commercial aircraft.[2]

This brings up several important issues with which the aerospace industry needs to be concerned. One critical concern is the area of rework and repair. Aerospace electronics, both commercial and military, are unique from the consumer electronics market in that rework and repair are critical to maintaining the aircraft. In addition, the operating conditions for the assemblies are harsher from an environmental and mechanical standpoint. For instance, the shear stress on a solder joint is very high during take off of military aircraft, especially for naval aircraft from a carrier deck. Products used in military or commercial aircraft are expensive and must be repairable. Also, the timeliness of rework and repair is critical. Because of this, the capability to do rework and repair is normally on-site at a base or shipboard and is usually limited, not only in terms of space but also in the amount of materials and equipment that can be present. The rework/repair issues concerning long-term reliability, supportability, and maintainability must be approached because of the very strong possibility of mixing LF and tin-lead (SnPb) solder alloys during the rework and/or repair process.

A number of studies have been conducted that investigated the influence of the incorporation of Pb into LF solders.[3-5] However, most of those studies focused on the incorporation of Pb into LF solders as a result of having both types of solders on the same assembly. This approach results in a small amount (few percent) of Pb in the LF solder but does not investigate the conditions present during a repair operation in which a significant amount of SnPb solder is present on an existing board or component. Therefore, the objectives of this effort were to study the soldering processes and resultant metallurgies of various mixed LF and SnPb solder alloys under rework and repair conditions. The metallurgical microstructure, composition, and strength of mixed LF and SnPb solder joints were also studied in order to begin correlation to real-world aerospace conditions. This work is a single project within a much larger program and collaboration between the University of Missouri – Rolla (UMR) and Boeing-Phantom Works for the Center for Aerospace Manufacturing Technologies (CAMT) housed at UMR. The results presented in this paper are from the initial part of a multi-year collaboration between UMR, Boeing Phantom Works, and the Air Force Research Laboratory under CAMT.

Experimental Procedures

One SnPb and one LF solder was used in the investigation. A 63Sn37Pb solder wire of 0.032" diameter with an integrated no clean flux was used as the standard. The LF solder was a commercially available Sn-Ag-Cu (SAC) no flux wire with a composition of 3.0% Ag and 0.5% Cu and the balance Sn. Mixtures of the two solders were done on the board using hand soldering. Preheating of the soldering iron prior to processing was 200°C for SnPb alloy and 235°C for the SAC alloy. A rosin flux was used with the SAC alloy and excess solder was removed with a solder sucker in all cases. Residual SnPb solder was left on the board to simulate a repair process. Typically, the amount of SnPb solder in the final mixture was between 5% and 10%. There were two different types of test boards used in the study. The first was a custom made FR4 based board with 2mm x 2mm copper pads 1.5 mm apart that were suitable for hand soldering of 1206 surface mount capacitors (Figure 1a and 1b). A cross sectional view of a typical hand soldered joint is given in Figure 2. The other type of board used was an RF module test kit sample with through hole devices and eutectic SnPb solder joints. Removal of the solder present in the through hole was performed using a soldering iron heated to 210°C and a solder sucker. During a repair operation these holes were filled with SAC or SnPb solder.



a) b)

Figure 1 – a) Surface Copper Land Pad Design and b) Hand Soldered 1206 SMT Capacitor

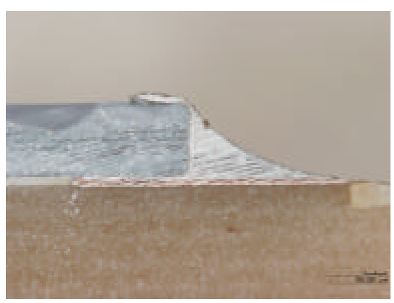


Figure 2 – Optical Image of 1206 Surface Mount Capacitor with a Hand Soldered Snpb Joint

After assembly, boards were subjected to further test and evaluation by various means. A Thermotron ATS-320-V-10-705-CO2 system was used to temperature cycle boards between -55°C and +125°C with a transition time of approximately two seconds and a 10 minute soak at either extreme. Samples were pulled after 100, 300, 625, and 805 temperature cycles. Shear testing of the surface mount capacitors was done using a Romulus IV Universal Testing system outfitted with a shear test module. The programmed load rate during shear testing was 8 lbs force per second but the actual time shear the component to failure was approximately 5 seconds. This equates to a net load rate of approximately 2 lbs per second. Chemical and microstructural characterization of the solder joints was done using optical and scanning electron microscopy (SEM) of polished cross sections. The microscopes used were a Hitachi S-570 LaB_6 filament and a Hitachi S-4700 field emission SEM each equipped with energy dispersive spectroscopy (EDS) units for chemical analysis. A Hirox digital video-microscope imaging system was used to record the optical images.

Results and Discussion

Shear Testing

Results from the shear testing of the as prepared and temperature cycled surface mount 1206 capacitors with the different solders are presented in Table I. It is worth noting that since these assemblies were soldered by hand, to simulate repair, the amount of solder on each component was not the same. Care was taken to try to achieve as consistent a solder volume as possible but variations did occur. The as prepared (0 temperature cycle) samples required 12 to 15 lbs of shear force to remove them from the test boards, with the standard SnPb joints the strongest. These results are comparable in value to the data reported by Warwick.[3] The standard deviation of the test data was approximately 2-4 lbs and the limited data set prohibits meaningful statistical analysis, but generalized data trends can be discerned. The SnPb shear strengths were typically the highest value of the three solders. If the samples after 100 temperature cycles are excluded, shear strength decreased with an increase in the number of cycles. The reason for the low values after 100 cycles is under investigation. The SAC solder results are less consistent with temperature cycling but were usually the lowest value of the three. The data suggests that a mixture of the SnPb and LF solder is preferred over a LF only solder joint. From a repair perspective this implies that complete removal of the existing SnPb solder may not be desirable from a shear strength perspective as the presence of SnPb in the joint appears to strengthen the shear of the solder. An optical image of a through hole after removing most of the original SnPb solder indicated that a thin layer of solder was still present (Figure 3). Therefore, the interface between the copper and the solder after repair with SAC would most likely contain intermetallic compounds along the interface from the original SnPb solder joint, leading to higher shear strength compared to SAC solder joints. Obviously there are many other considerations and more extensive testing is required but preliminary data indicates a benefit from residual SnPb in the joint.

Table I –Shear Strength Test Results (lbs_f)

	Solder Type		
# of Temp Cycles	SnPb	SAC	SnPb + SAC
0	14.7	13.3	12.3
100	6.7	5.2	6.0
300	8.8	10.8	9.5
625	8.3	4.3	8.1
805	7.1	4.8	7.0

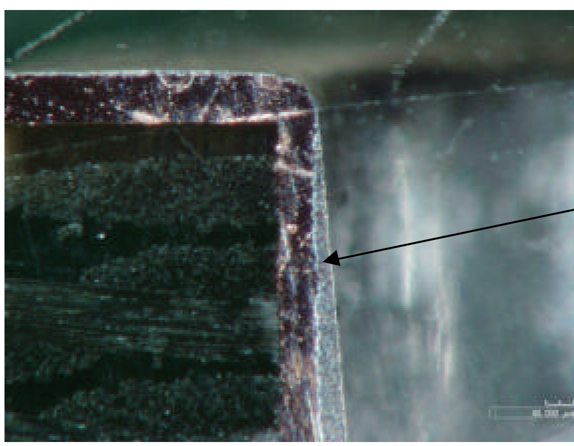


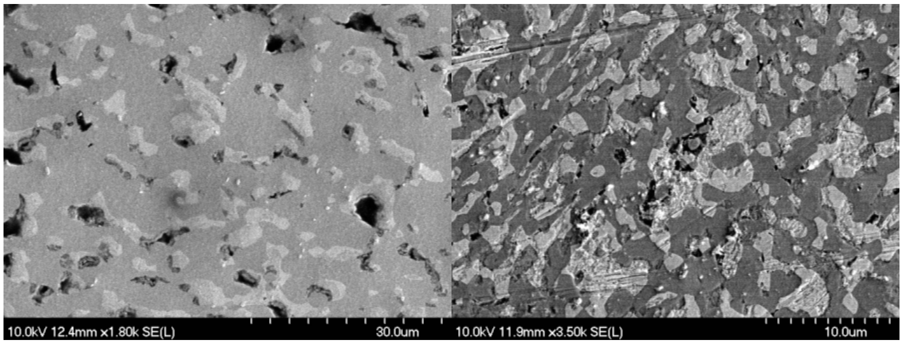
Figure 3 – Optical Image Of Through Hole after Removal of Most of the SnPb Solder

Microstructural Analysis

Characterization of the microstructure and chemical composition of the solder joints was done to identify similarities and differences in the various solder compositions, as well as evaluating the effectiveness of the repair operations. In order to be as systematic as possible in analyzing a process that relies on human operations, the solder joints were examined after each step of the process. This was done for the SnPb and the SAC alloys as well as the mixture of the two solders. Another variation that was included in the study was repair of the original SnPb solder joint with the same composition of SnPb solder. The repair of SnPb solder with SnPb solder provided a means of characterizing the hand soldering process and served as a reference microstructure.

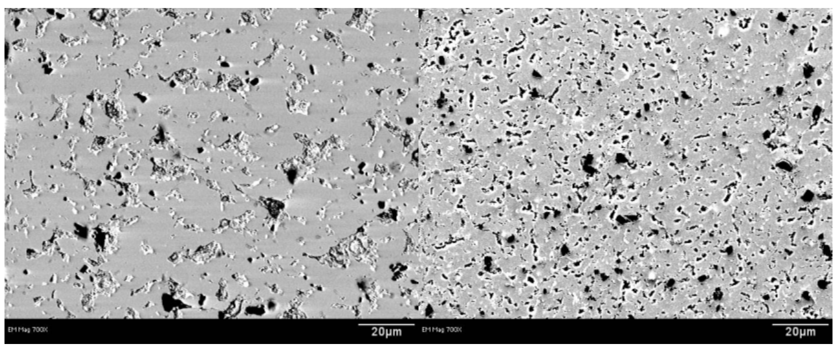
SnPb Solder

As would be expected, the original eutectic SnPb and “repaired” SnPb solder microstructures were very similar in appearance (Figure 4). In the images the light colored areas are Pb-rich regions. After temperature cycling, the euctectic lamellae were no longer observed (Figure 5). The chemical composition of the solder, as measured by EDS, was much more homogeneous after temperature cycling.



a) b)

Figure 4 – SEM Images of SnPb Solder: A) Original Microstructure and B) After A Repair Procedure with SnPb



a) b)

Figure 5 – SEM Images of SnPb Solder after 625 Temperature Cycles: a) Original Microstructure and b) After A Repair Procedure with SnPb

SAC Solder

An even more pronounced lamellar microstructure was evident in the SAC eutectic alloy prior to temperature cycling than was observed for the SnPb solder (Figure 6). Due to difficulties in preparing samples, a microstructure for the SAC alloy after temperature cycling was unable to be obtained but efforts to get a usable sample continue. Inspection of the interface between the SAC alloy and the copper on the board indicated that the Cu/Sn intermetallic compound was discontinuous (Figure 7).

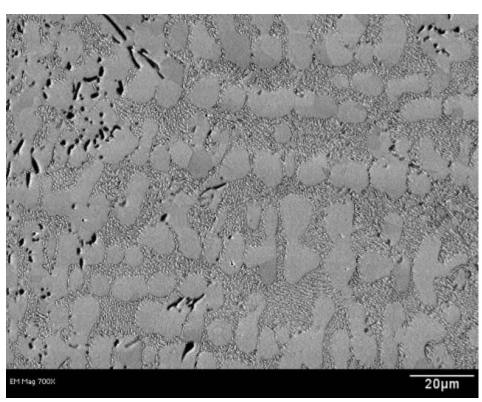


Figure 6 – SEM Images of SAC Solder Microstructure Before Temperature Cycling.

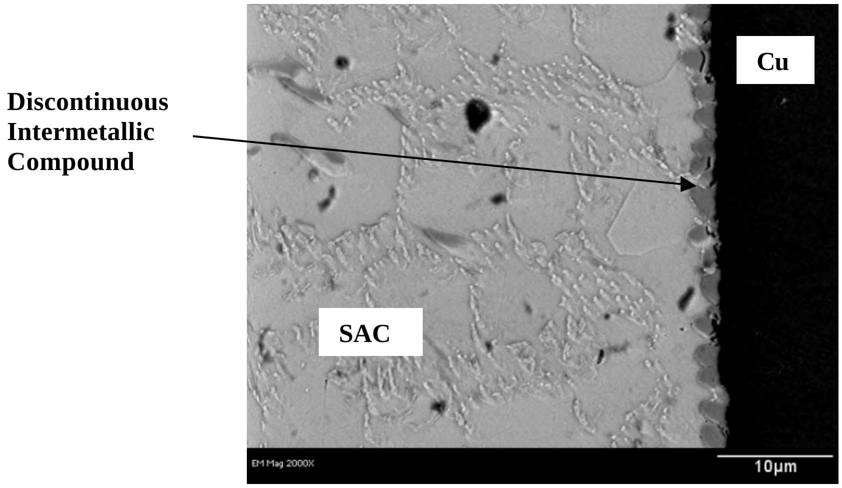
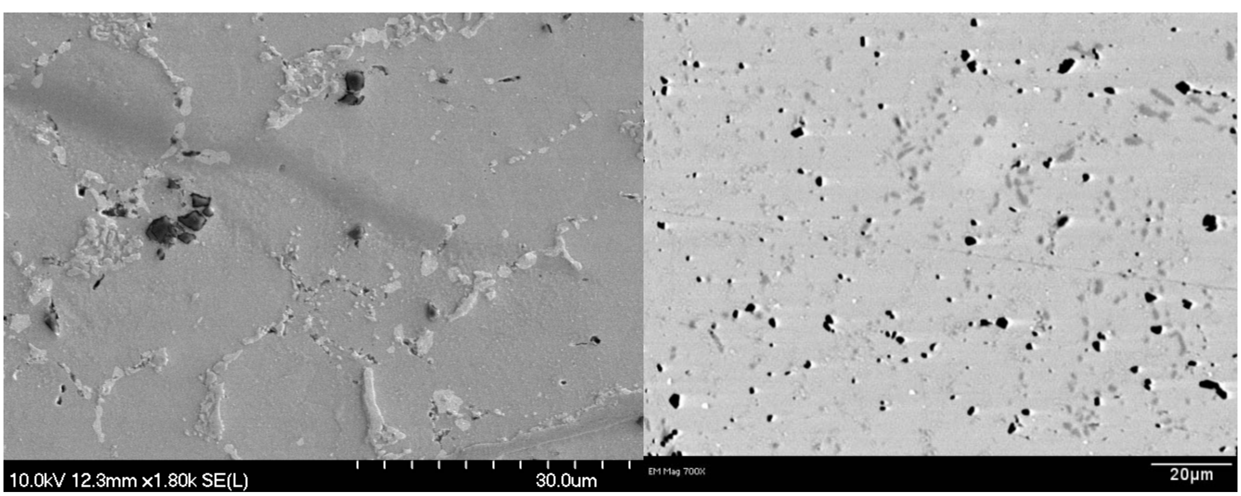


Figure 7 – SEM Image of SAC Solder Joint along the SAC/Cu Interface

Mixed SnPb + SAC Solder

A number of different samples of a mixed SnPb/SAC solder alloy were analyzed since that combination reflects the most likely scenario to be encountered in an actual aerospace repair operation, i.e. residual SnPb solder on the board or component that is repaired or replaced with a LF solder. Two distinct areas were investigated. One was the center of the joint that should contain mostly SAC solder and the other area was near the interface where the residual SnPb solder would interact with the SAC. The center of the repaired joint before temperature cycling did not appear to have the lamellar microstructure that each of the unmixed alloys exhibited (Figure 8a) but the microstructure after temperature cycling was very similar to the SAC solder (Figure 8b). The distribution and size of the secondary phases in solder did not appear to be significantly different than the SAC (only) solder.

Characterization of the center of the solder joints did not reveal any information that could be used to adequately explain the higher shear strength measured with a mixed SnPb/SAC solder alloy composition compared to the SAC alloy. Investigations of the interface of the SnPb + SAC solder with the copper on the board did, however, show a difference. As shown in Figure 9a and 9b for two areas from the same repaired component repaired using a SAC alloy after removal of excess SnPb solder, there is a fairly continuous Cu/Sn intermetallic compound reaction along the interface. Although there are areas that may have a thicker intermetallic compound layer or the intermetallic compound may not be as dense (which was evident by the contrast of the phases), there did not appear to be a break along the interface. It is believed that the residual SnPb alloy on the surface of the copper was a barrier to direct reaction of the SAC repair alloy with the copper substrate. As a result, the shear strength of the joints of a SnPb surface that were hand repaired with SAC was higher than the SAC (only) joint. Additional work is needed to verify the validity and reproducibility of this result. However, the preliminary data indicates that incomplete removal of the SnPb solder during repair with a LF solder may actually be beneficial to the reliability of the joint.



a) b)

Figure 8 – SEM Images of SnPb + SAC Solder a) Before and b) After 625 Temperature Cycles

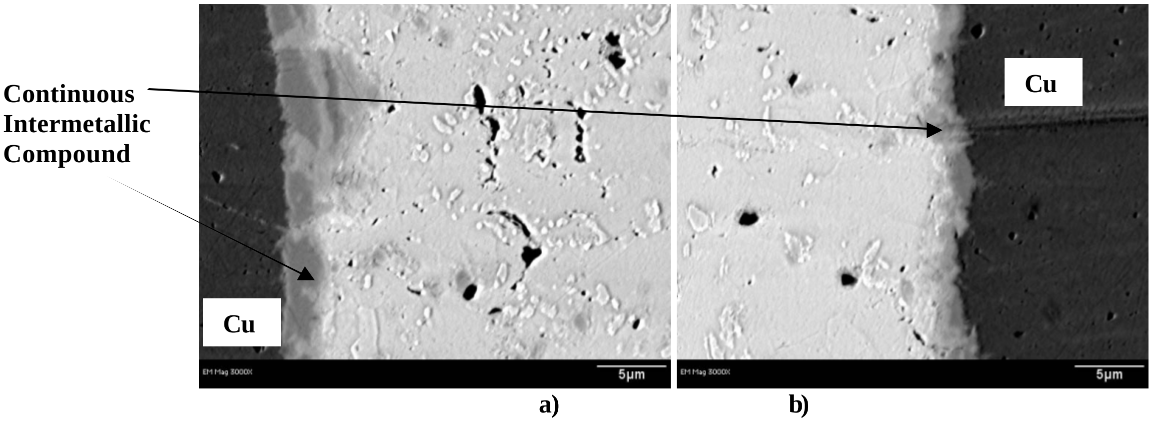


Figure 9 – SEM Images of two Different SnPb + SAC Solder Joints Interfaces with Cu Interface After 100 Temperature Cycles

Summary

An investigation into the repair of SnPb solder joints with LF Sn-Ag-Cu (SAC) solder was done as part of an on-going effort to look at manufacturing related issues in the aerospace industry. Due to the life cycle of aircraft spanning over decades, multiple repair and replacement operations are expected, many of which will be done by hand. The transition from the existing SnPb systems to LF solders will result in mixed alloys with unknown physical and mechanical properties. Preliminary experiments were conducted to investigate the influence of processing parameters and temperature cycling between -55°C and +125°C on the shear strength and microstructure of SnPb, SAC, and SnPb + SAC solders. The shear strength of 1206 surface mount capacitors was, in general, highest for the SnPb solders and lowest for the SAC solders. Mixed SnPb and LF alloys had a shear strength in between the individual alloys. Shear strength decreased with an increase in the number of temperature cycles, as has been previously reported. Examination of the solders before and after temperature cycling indicated that the eutectic microstructure before temperature cycling was eliminated during thermal excursions. The higher shear strength of the mixed SnPb + SAC alloy after repair was attributed to preserving the original Cu/Sn intemetallic layer along the solder/copper interface. Additional work is needed but preliminary results indicate that incomplete removal of the SnPb solder in contact with the copper prior to hand repair with LF solder may be beneficial to the strength of the joint.

Acknowledgements

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