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Copper Tin Intermetallic Crystals and Their Role in the Formation of Microbridges between the Leads of Hand Reworked Fine Pitch Components

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Abstract
Wave soldering is a mature manufacturing process that metallurgically joins component and PWB termination features by passing them together across the flowing surface of a molten solder reservoir. During this exposure, copper from through holes, surface mount lands, and component leads, continually dissolves into the molten solder. Unless the solder in the reservoir is regularly changed, the dissolved copper eventually reaches a point of saturation, and orthorhombic Cu_6Sn_5 crystals begin to precipitate out of the molten solder, causing it to become gritty and sluggish. Solder drawn from such a saturated wave solder pot can solidify into joints whose surface finish exhibits many needle like metallic protrusions. These protrusions are in fact orthorhombic Cu_6Sn_5 crystals. Recently, BAE Systems has determined that this same phenomenon is responsible for the formation of nearly invisible intermetallic microbridges between fine pitch surface mount component leads. They form when a solder bridge from a surface mount paste reflow operation is hand reworked with a soldering iron and copper desoldering braid. This paper documents several short circuit failures caused by this phenomenon, the investigation that identified the root cause of the problem, and the rework techniques that can be used to prevent its occurrence.

Introduction
BAE Systems' Fort Wayne, Indiana facility manufactures electronic hardware for use in both commercial and military avionics applications. The hardware typically contains surface mount assemblies, which are made with one of two solder paste alloys: Sn63/Pb37 and Sn62/Pb36/Ag2. Both paste types are commercially available, and are stencil printed and hot air reflowed using equipment and profiles common to the domestic avionics industry.

Within the past year, several test engineers responsible for verifying the electrical performance of these surface mount assemblies alerted the manufacturing organization to a series of inexplicable short circuit failures. The actual fault sites were confined to the adjacent leads of fine pitch gull wing devices (i.e. 0.64 millimeters or less), and exhibited failure mode behavior that ranged from a few tens of ohms to a fraction of an ohm. Initially, visual examinations performed at low magnification failed to identify an external cause for these short circuit faults. Yet if one of these components was removed from its assembly, the short circuit condition inevitably cleared from both the affected component leads and their associated PWB solder lands. Eventually, higher power visual examination revealed the presence of extremely fine metallic bridge structures at these short circuit fault sites. Several examples were subsequently submitted to the failure analysis lab, where the root cause of their formation was finally diagnosed.

The Investigation
The first confirmed visual verification of the phenomenon occurred on a finished assembly, where three separate short circuit failure sites were found beneath a layer of acrylic conformal coat. The actual fault sites were found in the 0.24 mm gaps between 0.64 mm pitch gull wing leads associated with three separate but identical plastic small outline integrated circuits (SOICs). The fault paths were somewhat difficult to make out because they were embedded in conformal coat material. In fact, the optical distortion of the conformal coat cast some doubt as to whether or not the identified short circuit path material was actually metallic. However, an x-ray radiogram of one short circuit path confirmed that it was indeed comprised of materials at least as dense as the nearby copper leads, copper PWB lands, and the assembly's Sn63/Pb37 solder joints (see Figure 1).

The next assembly submitted for investigation had also been assembled with Sn63/Pb37 solder paste, but had not yet been conformal coated. Its short circuit fault site was located in the 0.2 mm gap between two adjacent 0.5 mm pitch gull wing leads on a quad flat pack (QFP). The actual short circuit path material was difficult to see at low magnification, but was clearly visible at 50X magnification. It was metallic in appearance, and consisted of two straight needle like segments that were mere microns in diameter. They met at a slight angle in the gap between the two gull wing leads, and each terminated in a shallow cone shaped base on the surface of its respective gull wing solder joint. An additional needle like structure, which was otherwise isolated from the two intersecting segments, also protruded out of one of these cone shaped bases (see Figure 2).

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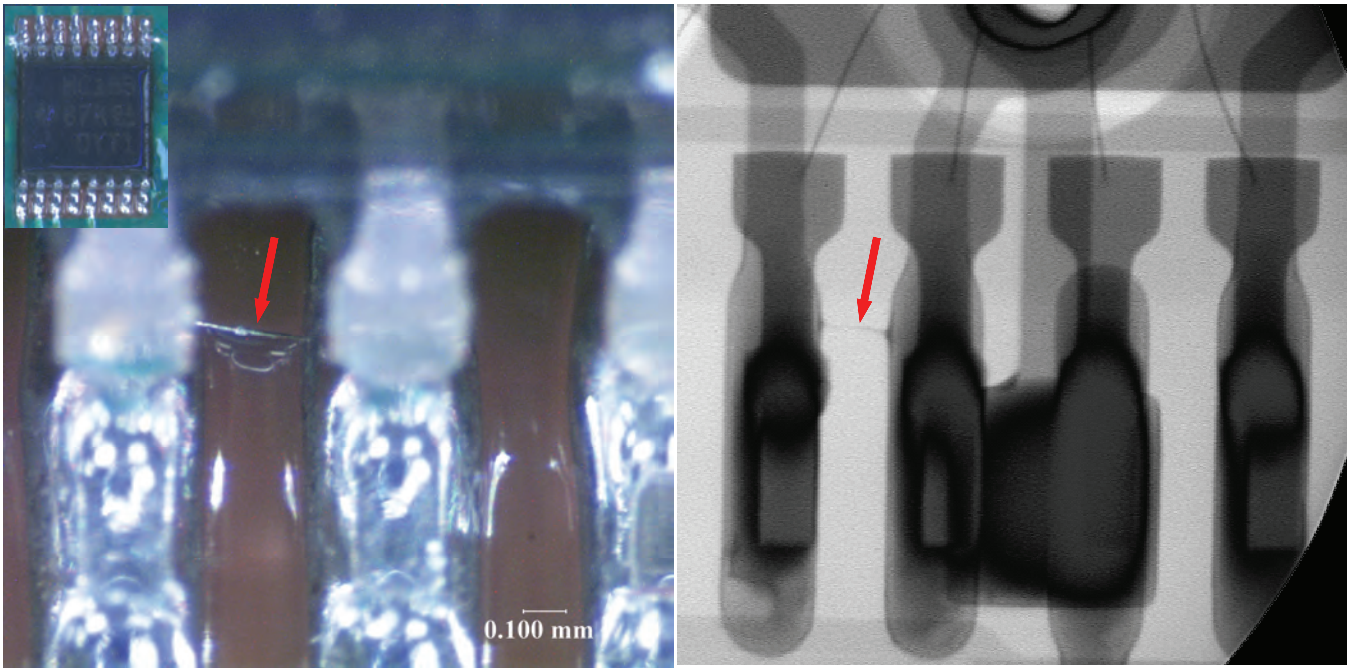


Figure 1: This microbridge (red arrow left) was embedded in conformal coat material within the 0.24 mm gap between two 0.65 mm pitch gull wing leads (actual device upper left). The microbridge was clearly visible during an x-ray examination (red arrow right), indicating it was metallic in composition. Fine gold wire bonds measuring just 0.025 mm in diameter, and seen fanning out from the center of the plastic integrated circuit at the top of the x-ray radiogram, were noticeably larger than the microbridge.

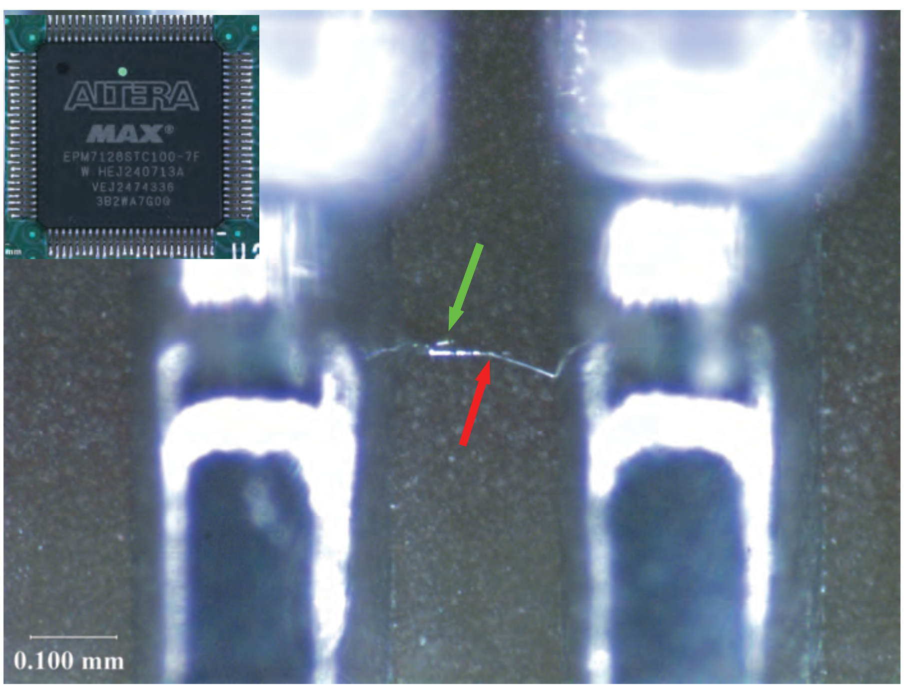


Figure 2: This microbridge (red arrow) was found on an assembly that had not yet been conformal coated. It consisted of two needle like segments that met at a slight angle near the middle of the 0.2 mm gap between 0.5 mm pitch gull wing leads (actual QFP device at upper left). A green arrow highlights a smaller needle like protrusion that extended out of the cone shaped base on the left end of the microbridge.

The test engineer responsible for identifying this first QFP short circuit site reported that the same device had also registered additional short circuit faults between several nearby lead pairs. Again, no visible short circuit path had been noted in production. However, the additional fault sites had been cleared by running the tip of a fine multimeter probe between the affected leads. The submitting engineer indicated that this was becoming a relatively common practice to clear these invisible short circuit fault sites. A detailed examination of the cleared sites confirmed what the test engineer had reported. Probe scratch marks were found on the printed wiring board surface between several of the QFP's nearby lead pairs. The remnant of a cleared short circuit path was found next to one of these probe scratch marks (see Figure 3). Its physical appearance was virtually identical to the intact short circuit path that was currently being studied (see again Figure 2).

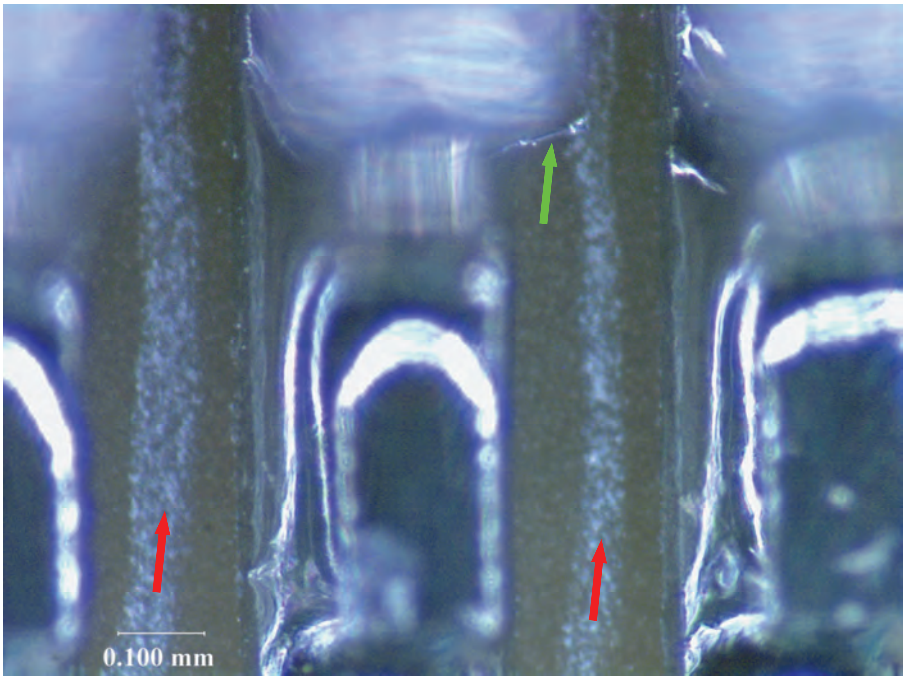


Figure 3: Two red arrows highlight probe scratch marks in the printed wiring board surface in the 0.2 mm gaps between 0.5 mm pitch QFP gull wing leads. These scratch marks were found on the same component, and just a few solder joints away from, the microbridge shown in Figure 2. The green arrow highlights the remnant of a microbridge broken by the probe tip.

Further examination of the QFP's solder joints revealed one additional observation: all of its short circuit sites could be found between solder joints that had been hand reworked. A review of automated inspection records confirmed the existence of solder bridges between several of the QFP's solder joints coming out of the paste printing and hot air reflow operations. Those that had been hand reworked were relatively easy to identify. The hand reworked solder joints were bright and shiny, whereas the reflowed solder joints had a slightly crusty and oxidized appearance (see Figure 4). All of the QFP's short circuit fault sites were located between bright and shiny solder joints that had been hand reworked.

With the discovery of this association between the nearly invisible short circuit paths and reworked solder joints, suspicion immediately fell on one of the key materials used during the rework process: copper desoldering braid. Copper desoldering braid has been used extensively to rework solder joints for decades. It consists of individual strands of fine copper wire that have been coated with a fluxing agent, and woven into a flat narrow ribbon. It is specifically designed to soak up excess molten solder. In a typical rework operation, the copper braid is placed in contact with the rework site, and heat is applied to both with the tip of a soldering iron. When the excess solder at the rework site melts, it is soaked up by the hot braid, which is then removed.

Taking into account the link between the QFP's short circuit paths and its reworked solder joints, it was hypothesized that a few loose strands of this fine copper wire, having been wetted with solder from a rework site, separated from the desoldering braid. Several of these loose strands then settled into place between adjacent fine pitch gull wing leads to form the observed short circuit failure sites. A check with the surface mount repair team confirmed that it was indeed using copper desoldering braid to remove excess solder from surface assemblies coming out of the solder paste print and hot air reflow operations. The material of choice was identified as Chemtronics brand 80-3-5 copper desoldering braid, and a sample of this product was obtained from stock. A single strand of copper wire was pulled from this material, and examined next to the QFP's remaining short circuit failure site. However, this comparison confirmed that even an isolated strand of the copper braid material was far too large to act as the underlying structural basis for the observed short circuit path (see Figure 5).

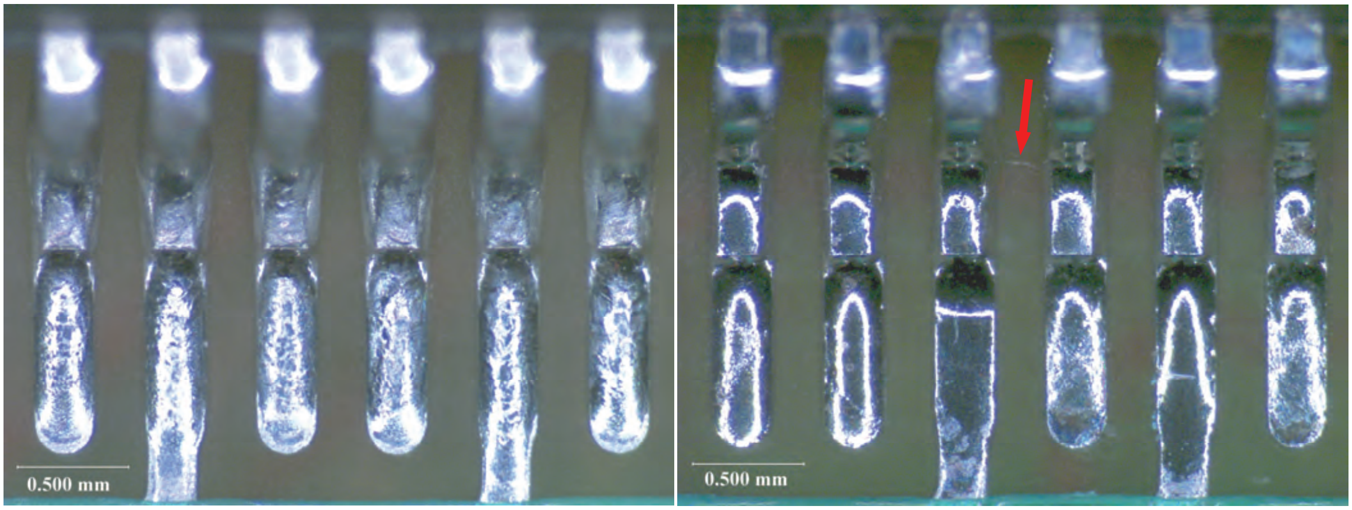


Figure 4: Hot air reflowed QFP solder joints (left), and hand reworked QFP solder joints (right). The red arrow highlights the microbridge shown in Figure 2. The solder joints from the paste reflow process were slightly duller, and had a crusty patina. The hand reworked solder joints were uniformly smooth, bright, and shiny.

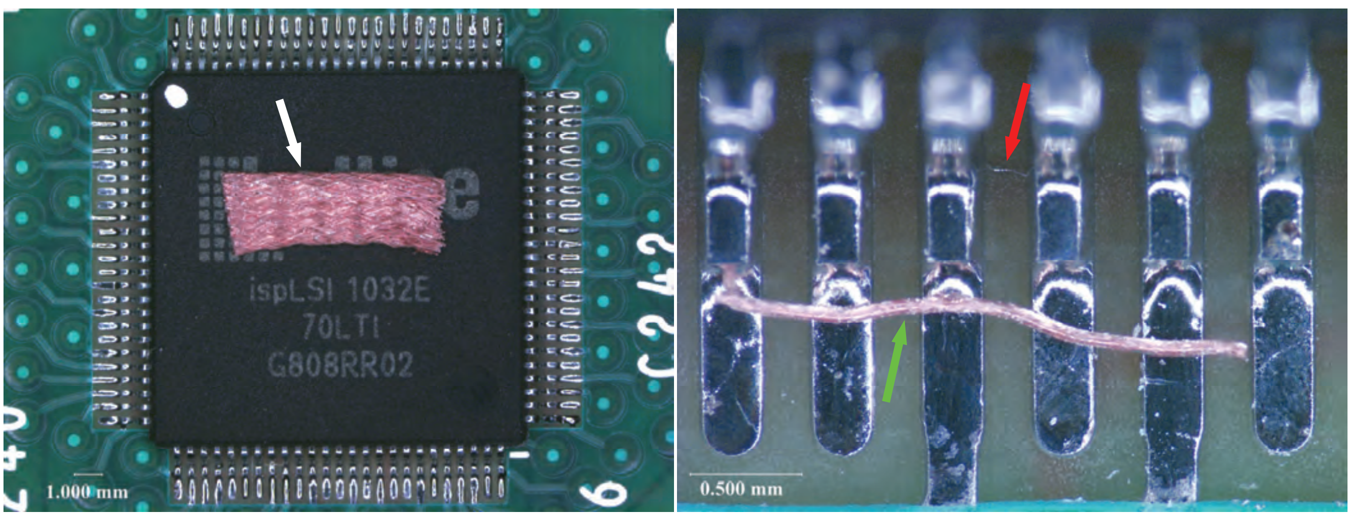


Figure 5: At left is an overall view of the QFP device whose solder joints are shown in Figures 2 - 4. A freshly cut length of Chemtronics 80-3-5 copper desoldering braid (white arrow) was placed on the QFP's marking surface for size reference. A single strand of the same copper desoldering braid (green arrow) appears next to the QFP's microbridge site on the right. Even a single strand of the copper braid was far too large to form the structural basis of the identified microbridge (red arrow).

Having eliminated the copper desoldering braid as the source of the QFP's short circuit failure sites, the investigation refocused on determining the elemental composition of the one remaining short circuit path. It was still intact and free of conformal coat material. Unfortunately, there was no possibility of performing an *in situ* analysis. The cost of the assembly precluded a destructive excision of the component that would include both the underlying PWB material and the intact short circuit failure site. As such, the failure site material had to be separated from the assembly before it could be analyzed.

The path material was excised with a fine Circon scalpel. During the cutting process, it was noted that the path material did not stretch or bend. Instead, it exhibited brittle fracture characteristics, and shattered into a number of smaller fragments. The largest of these fragments remained attached to one of the short circuit path's conical bases, and it was this fragment that was eventually captured and mounted on an aluminum stub that had been covered with double sided carbon tape. The mounted specimen was then placed in a scanning electron microscope, where its surface characteristics were examined and documented, and its elemental composition was analyzed using energy dispersive spectroscopy (EDS).

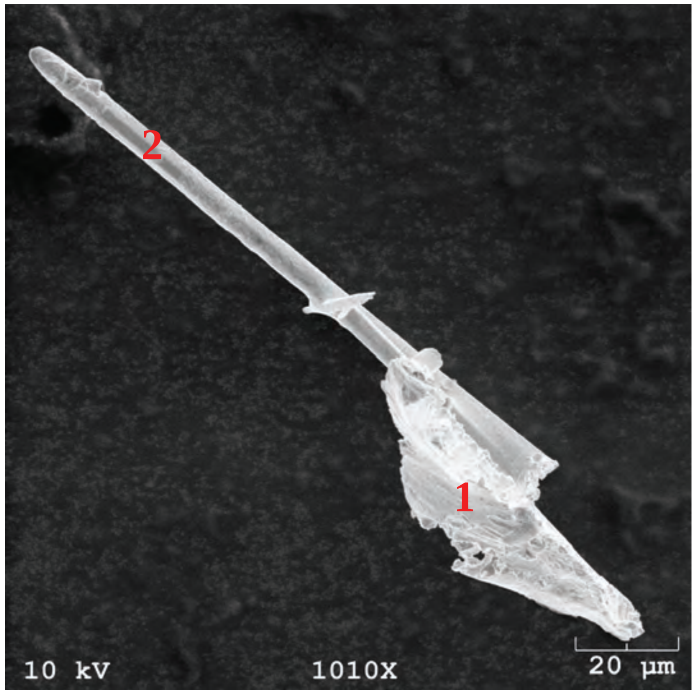
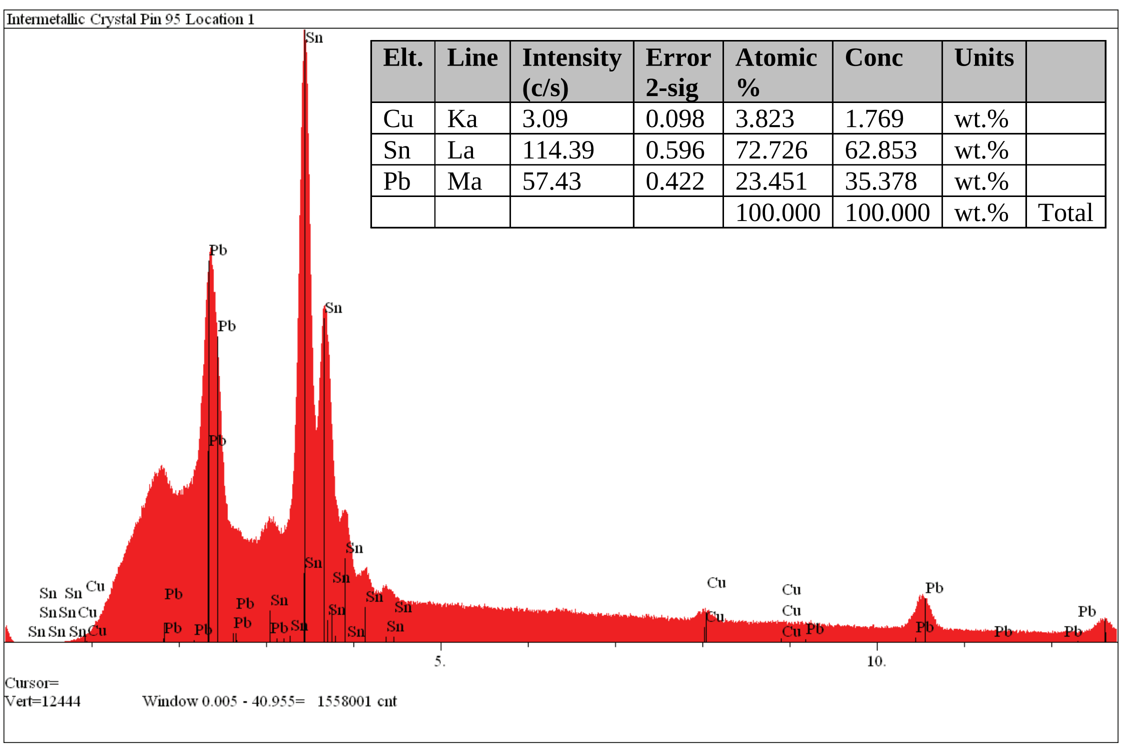
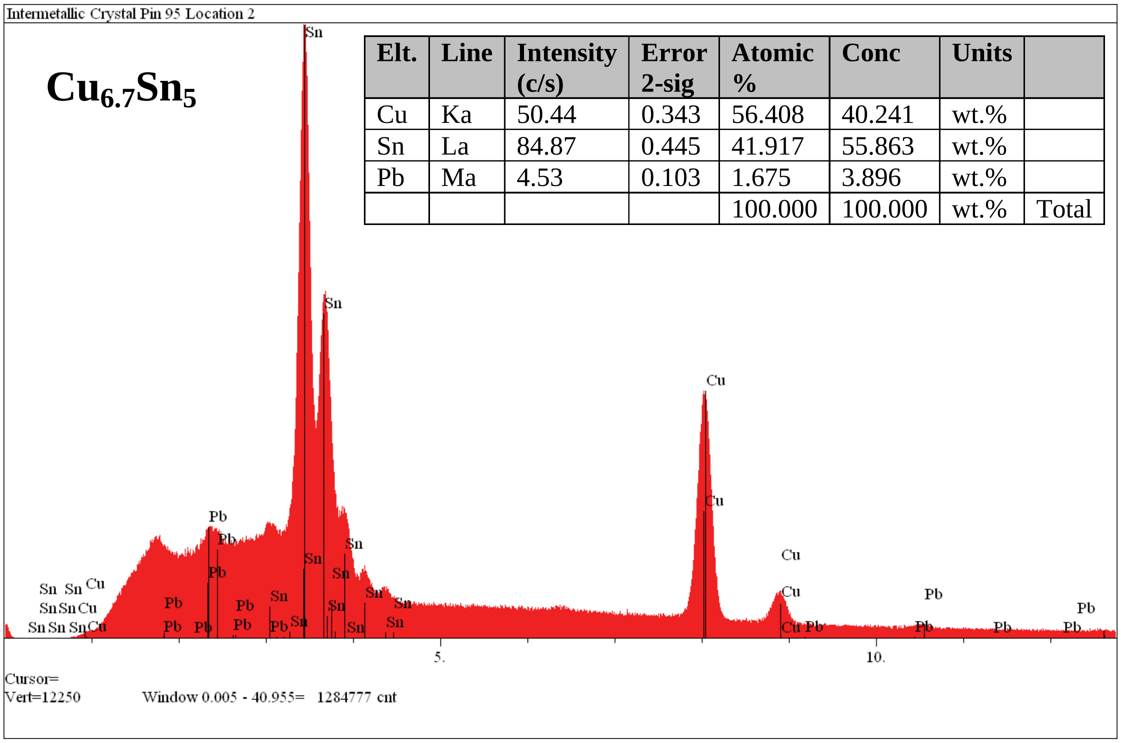


Figure 6: Scanning electron micrograph of the microbridge fragment retrieved from the short circuit site shown in Figure 2. Note that the portion of the fragment labeled with the "2" has a distinct needle like shape. The irregular mass of material marked by the "1" at the lower right was part of the conical base that joined the needle like segment to one of the two solder joints. EDS spectra obtained from the two labeled locations are shown in Figures 7 & 8.



Elt.	Line	Intensity (c/s)	Error 2-sig	Atomic %	Conc	Units	
Cu	Ka	3.09	0.098	3.823	1.769	wt.%	
Sn	La	114.39	0.596	72.726	62.853	wt.%	
Pb	Ma	57.43	0.422	23.451	35.378	wt.%	
				100.000	100.000	wt.%	Total

Figure 7: EDS spectrum obtained from Location 1 in Figure 6. This material from the conical base of the microbridge was composed mainly of tin (Sn) and lead (Pb). The weight percents of these two elements approximated the values expected for the Sn63/Pb37 solder that had been used on the assembly. The remainder of this material, nearly 1.8% by weight, was copper (Cu).



Elt.	Line	Intensity (c/s)	Error 2-sig	Atomic %	Conc	Units	
Cu	Ka	50.44	0.343	56.408	40.241	wt.%	
Sn	La	84.87	0.445	41.917	55.863	wt.%	
Pb	Ma	4.53	0.103	1.675	3.896	wt.%	
				100.000	100.000	wt.%	Total

Figure 8: EDS spectrum obtained from Location 2 in Figure 6. This material from one of the needle like segments of the microbridge was composed primarily of copper (Cu) and tin (Sn), with only a trace of lead (Pb). The stoichiometric ratios of the copper and tin, which are shown at the upper left, closely approximated the atomic formula for Cu_6Sn_5, a known copper/tin intermetallic compound with an orthorhombic (i.e. needle like) structure.

The material associated with the conical base of the fragment was irregular in shape and had the appearance of cut solder. It produced an EDS spectrum consistent with that of eutectic Sn63/Pb37 solder that had absorbed a significant amount of copper (see Figures 6 and 7). By contrast, the material associated with the short circuit path's center span had a distinct needle like shape. It had a uniformly smooth surface, with a diameter of 10 microns and a length of 120 microns. The EDS spectrum obtained from this structure indicated that it was composed almost entirely of copper and tin, with only trace amounts of lead (see Figures 6 and 8). The stoichiometric ratios of the copper and tin were 6.7 to 5 respectively. This was a close match for Cu_6Sn_5, a recognized intermetallic copper/tin compound with an orthorhombic morphology, and a familiar pot contaminant to those who have worked with wave soldering processes.

Test engineers soon submitted additional examples of these nearly invisible short circuit failure sites for analysis. They were being found on assemblies made with both Sn63/Pb37 and Sn62/Pb36/Ag2 solder pastes, and despite these paste differences, exhibited the following common properties:

- The short circuit paths were always located between fine pitch gull wing leads that had been hand reworked for bridged solder after solder paste print and reflow operations.
- The actual path material was difficult to see if examined at less than 30x magnification, and generally consisted of one or more brittle needle like segments.
- The needle like segments were comprised almost exclusively of copper and tin in stoichiometric ratios that approximated the atomic formula for known intermetallic compound Cu_6Sn_5.

It was at this stage of the investigation that the term "microbridge" was coined to differentiate this new phenomenon from the more common type of solder bridge that was its apparent precursor. Left unanswered was the role that Cu_6Sn_5 intermetallic crystals evidently played in the formation of these microbridges. For while Cu_6Sn_5 intermetallic crystals are a common contaminant in wave soldering and hot air leveling operations, they are not normally associated with paste reflow and hand rework operations.

To better understand the relationship between Cu_6Sn_5 intermetallic crystals and microbridges, it is first necessary to review the conditions that cause Cu_6Sn_5 intermetallic crystals to form in the first place. Within the context of this discussion, they commonly form in molten tin/lead solders that have been saturated with copper. Figure 9 illustrates this process using the example of a solder pot. A copper rod, which is suspended within the pot's molten solder, dissolves slowly over time. A thin layer of Cu_6Sn_5 intermetallic compound initially forms on the rod's surface when it contacts the molten solder, and it is from this intermetallic surface layer that copper atoms dissociate into the molten solder. As copper atoms enter solution from the surface of the intermetallic layer, additional copper atoms from the surface of the rod combine with tin that has diffused through the intermetallic layer to form fresh intermetallic compound. Thus, while the concentration of copper atoms in the molten solder steadily increases, the diameter of the copper rod correspondingly decreases. If the rod is sufficiently massive, and is immersed for a long enough period of time, the molten solder in the pot eventually saturates with copper. At this point the dissolution of copper into the molten solder essentially stops. However, when the molten solder is cooled, the copper in solution becomes super saturated, and combines with tin to precipitate out as Cu_6Sn_5 intermetallic crystals. These crystals can either grow on the copper rod's existing layer of Cu_6Sn_5 intermetallic, or undergo homogeneous nucleation within the cooling mass of the liquid solder (i.e. form free floating crystals).

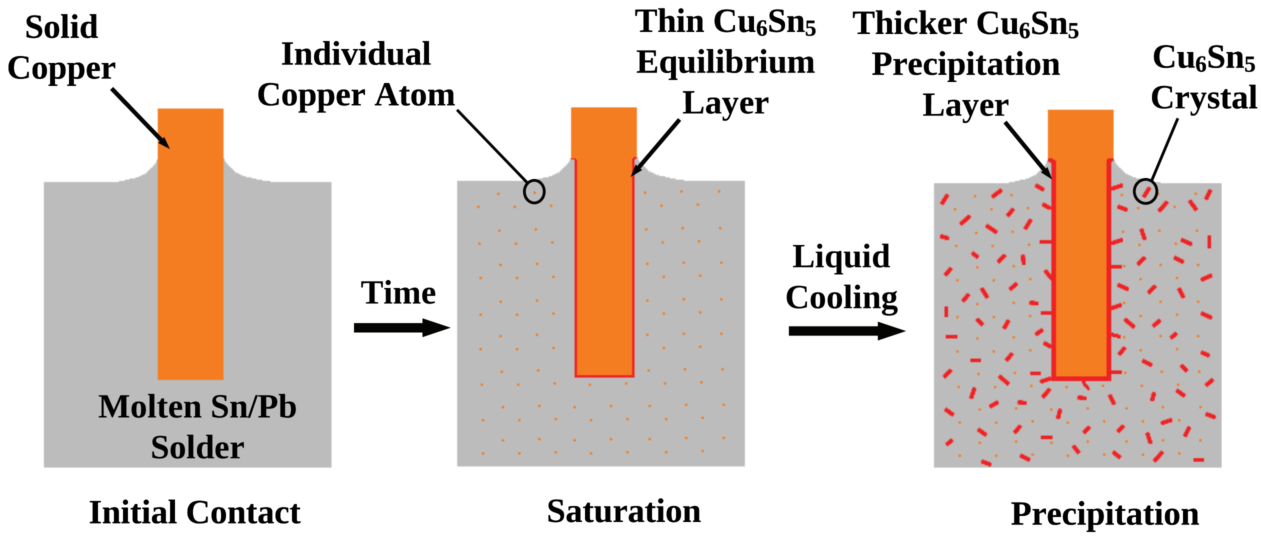


Figure 9: Illustration of the mechanism by which Cu_6Sn_5 crystals form within a volume of molten solder. Given enough contact time, copper atoms from an immersed copper structure will dissolve into the molten solder and saturate it. Cu_6Sn_5 crystals will then precipitate out at the copper interface, and within the solder itself, as the saturated solder cools.

For tin-lead solders, copper holding capacity generally increases with temperature. Thus a 230˚C mass of molten solder will hold less copper, and precipitate fewer Cu_6Sn_5 crystals upon cooling, than will a comparable 250˚C mass of solder. Howard Manko has described these relationships in some detail as they pertain to both wave and hot air solder leveling processes[1].

Actual crystal size depends on several factors, but as with most crystallization processes, slower cooling produces larger crystals. For liquid tin/lead eutectic alloys with relatively low copper concentrations (e.g. ~2 percent), the Cu_6Sn_5 intermetallic phase is in equilibrium with the liquid solder over a temperature range of 182°C to 325°C [2]. Under static conditions with low liquid solder volume, such as those found in solder paste reflow processes, Cu_6Sn_5 intermetallic rods may grow to considerable size (e.g. 10 microns in diameter and 100 microns in length)[3].

After reviewing this background information, it was hypothesized that copper from the desoldering braid was dissolving into the solder bridges between fine pitch gull wing leads during the rework process. This would imply the copper braid itself was the sole source of the copper in the intermetallic crystals found in the microbridges. The high surface area of the copper in the desoldering braid relative to the amount of solder in a typical fine pitch bridge would seem to support this conclusion. However, a lab experiment designed to prove out this hypothesis failed to reproduce the microbridging phenomenon.

The aforementioned experiment was conducted on a scrap assembly with simulated solder bridges. The simulated solder bridges were created with a Metcal soldering iron that was equipped with a No. 137 soldering tip. This was used to melt 0.25 mm diameter rosin cored Sn63/Pb37 solder wire, and fill in the 0.2 mm gaps between adjacent 0.5 mm pitch gull wing leads. The resulting simulated solder bridges were then reworked as follows. First, several drops of Alpha RF-800 no clean rosin flux were applied to the bridge site, after which a short length of desoldering braid was applied with the same No. 137 soldering tip. A substantial number of these simulated solder joints were reworked, employing variations in the size of the initial bridge, the location of the desoldering braid, the position of the soldering tip, and the tip application time. None of these variations produced a single microbridge. Yet despite this initial failure to reproduce microbridges in the lab, examples of the phenomenon were still regularly appearing on hand reworked production assemblies (see Figures 10 - 12). Thus, while it was now apparent that Cu_6Sn_5 intermetallic crystals were playing a key role in the formation of these microbridge structures, the initial lab investigation indicated that the source of their copper was not solely the desoldering braid.

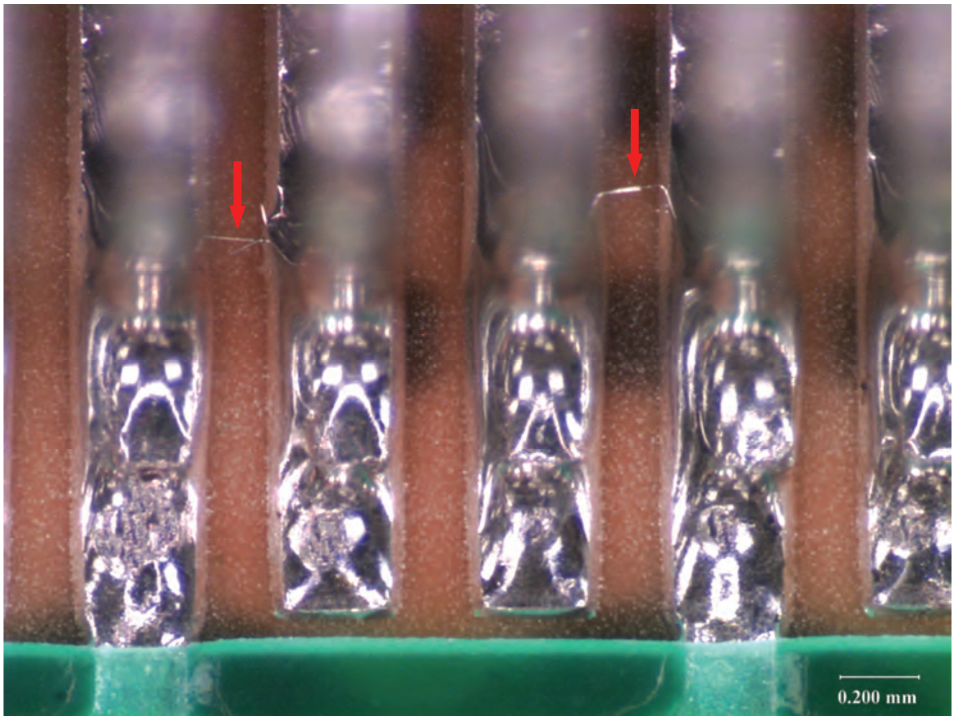


Figure 10: Production microbridges (red arrows) consisting of single needle like segments found in the 0.15 mm gaps between 0.5 mm pitch gull wing leads on an Sn62/Pb36/Ag2 paste assembly. The above solder joints were hand reworked.

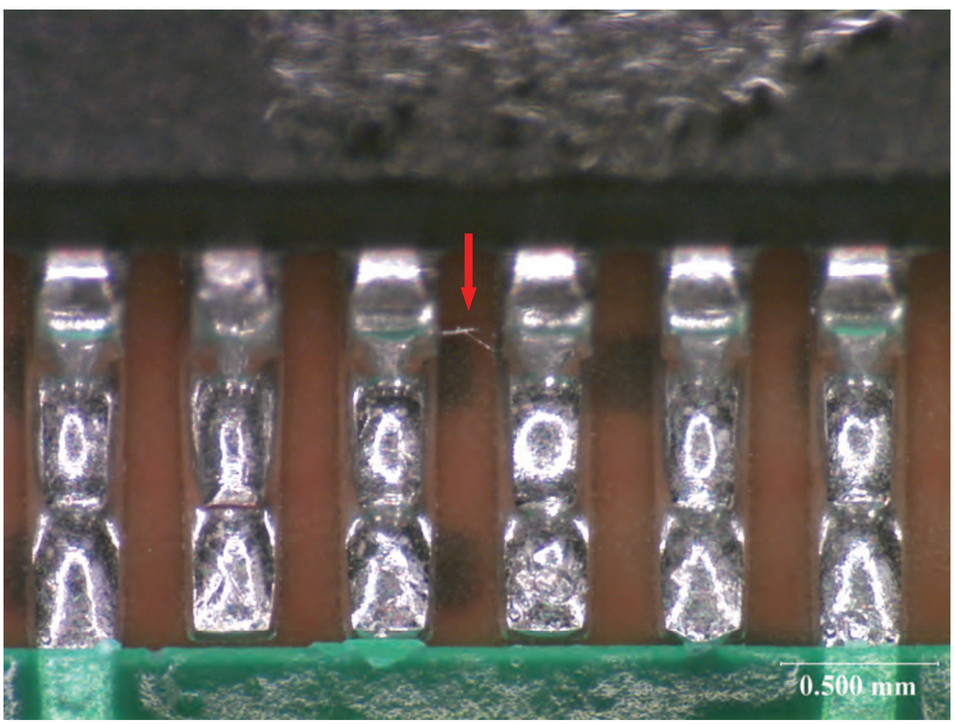


Figure 11: Production microbridge (red arrow) consisting of multiple needle like segments found in the 0.15 mm gap between 0.5 mm pitch gull wing leads on an Sn62/Pb36/Ag2 paste assembly. The above solder joints were hand reworked.

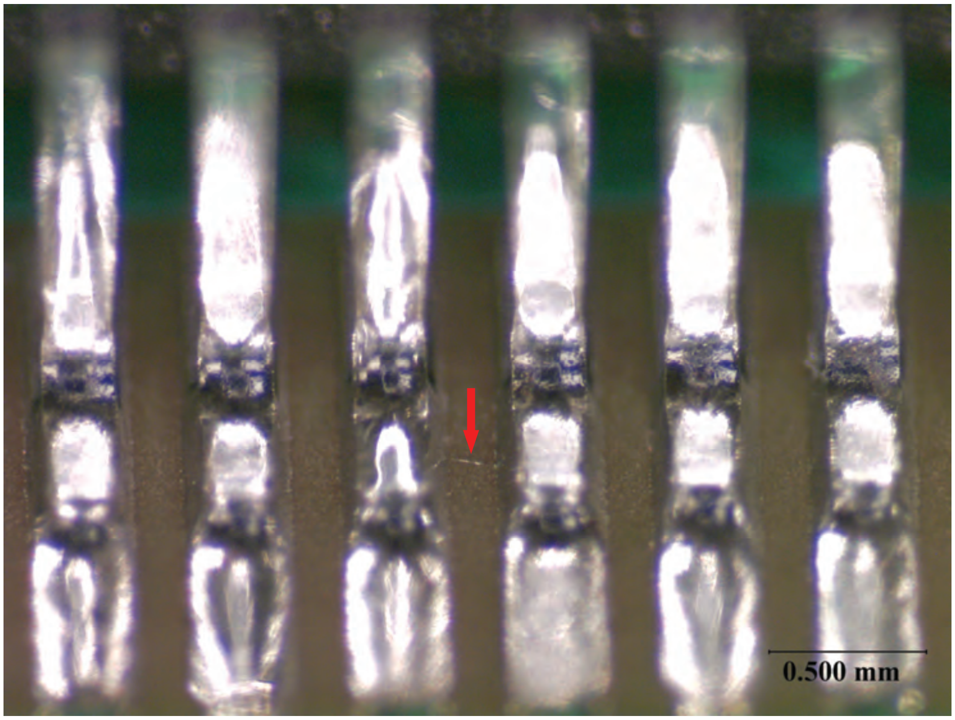


Figure 12: Production microbridge (red arrow) consisting of a single needle like segment found in the 0.15 mm gap between 0.5 mm pitch gull wing leads on an Sn63/Pb37 paste assembly. The above solder joints were hand reworked.

The continued appearance of microbridges and their requisite Cu_6Sn_5 intermetallic crystals on production assemblies indicated that a different mechanism of formation, involving alternate sources of copper, must be at work. A review of the materials and processes associated with the formation and ultimate rework of a typical solder bridge from a paste reflow operation identified only two other probable sources for the copper in the microbridge Cu_6Sn_5 crystals: the component leads and printed wiring board lands that had been joined by the original solder paste reflow bridge.

Most discussions of surface mount solder joints and copper/tin intermetallic compounds typically focus on the solid state development of intermetallics along the interface between printed wiring board lands and component leads, their brittle characteristics, and ultimately the deleterious effect that their appearance along these interfaces has on the thermal cycle fatigue life of affected solder joints. Less consideration is given to their presence within the bulk solder of those same joints as a consequence of the reflow process. Furthermore, the copper saturation problems associated with wave solder joints, as described earlier in this paper, are generally not a concern with surface mount joints. The solder pastes printed on most surface mount assemblies, excluding of course the many lead free varieties, contain virtually no copper. Because it is applied fresh to each assembly, the solder paste found in the reservoir of a typical stencil printing operation does not have the same opportunity to absorb copper over a period of time, as does the solder in a wave solder pot. That being said, processing conditions associated with the typical solder paste reflow process by necessity promotes the dissolution of copper, and the formation of Cu_6Sn_5 crystals within, the bulk mass of a typical fine pitch solder joint as outlined below.

The volume of solder paste initially deposited on a fine pitch PWB land is fixed in comparison to the volume of solder that forms a through hole solder joint. The solder in a wave operation is circulated by a pump, and is in constant motion. Thus the solder that forms a typical wave solder joint is the last volume of molten solder that remains in contact with the through hole and its lead as the assembly leaves the pot. Any copper that enters the joint from the surfaces of the through hole and its component lead is constantly being diluted by the comparatively vast volume of molten solder in the wave soldering machine's reservoir (typically hundreds of pounds). For this reason, through hole solder joints do not exhibit signs of excessive Cu_6Sn_5 crystal formation until the entire volume of molten solder in the wave solder machine does as well. By comparison, the volume of solder in a typical fine pitch gull wing solder joint is fixed by the volume of paste that is printed on the PWB's solder land. Thus, any copper that enters the printed solder paste during the reflow process remains in that volume of solder. There is no opportunity for dilution.

Contact area and time of exposure to the molten solder also favors the formation of Cu_6Sn_5 crystals in fine pitch solder joints. The contact area of the printed soldering land and the component lead is relatively large in comparison to the small fixed volume of solder present in the typical stencil paste deposit. Additionally, the hot air reflow environment also comparatively favors the dissolution of copper in fine pitch surface mount solder joints. The contact time between a through hole, its lead, and the molten solder in a wave machine typically runs from three to eight seconds. In a paste reflow operation, the contact time between the molten solder, the PWB land, and its component lead, can be as long as two hundred seconds.

Ultimately, it was this review of the process characteristics associated with the typical solder paste reflow process that identified the shortcomings of the first lab experiment. The simulated solder bridges had been made with solder from fresh solder wire. It had been applied in just the few seconds it took to melt the wire with the tip of a soldering iron. As such, the solder in these simulated bridges did not have the opportunity to absorb a significant amount of copper from their bridged PWB lands and component leads. If the PWB lands and component leads were either the source of, or significant contributors to, the copper responsible for the Cu_6Sn_5 crystals in the microbridges, then clearly the simulated solder bridges made with fresh solder wire had not fully duplicated the internal conditions associated with a solder bridge from a paste reflow process.

On the basis of this insight, a second round of experiments was performed. This time, when preparing the simulated solder bridges, the tip of the soldering iron was kept in contact with the bridged PWB lands and component leads for up to ninety seconds. This kept the molten solder bridge in contact with the copper in the component leads and PWB lands for a time interval similar to that experienced during a typical paste reflow process. When these "improved" simulated bridges were reworked with the same desoldering braid, flux, and solder tip used in the earlier experiment, several microbridges formed (see example Figure 13).

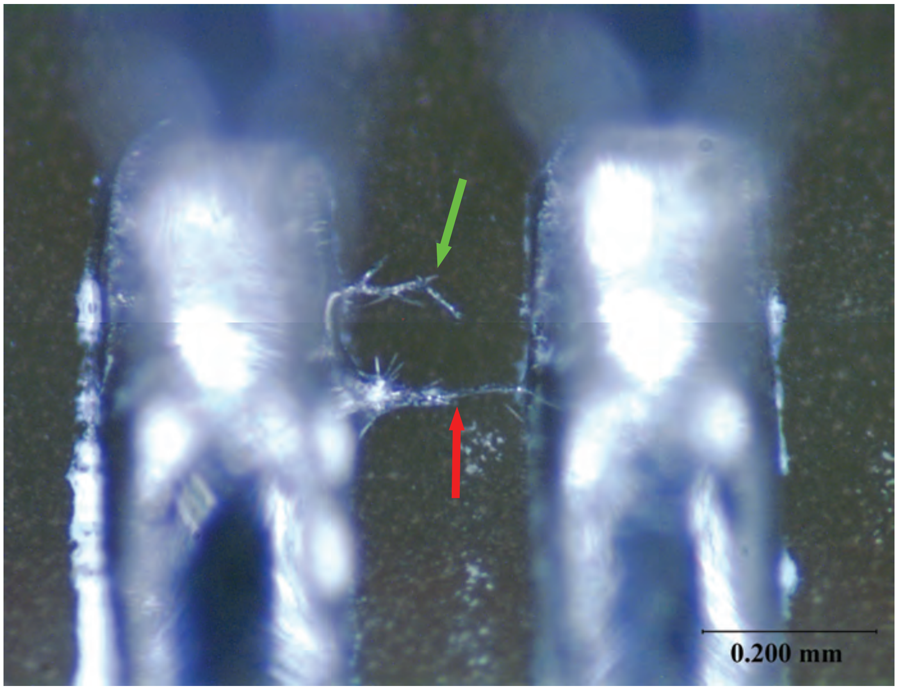


Figure 13: This lab created microbridge (red arrow) consisted of a single large Cu_6Sn_5 crystal embedded in a large conical base along with many smaller Cu_6Sn_5 crystal protrusions. A partial microbridge (green arrow), consisting of several linked Cu_6Sn_5 crystals, can be seen in the background. Both microbridge structures formed when the excess solder from a simulated solder bridge was extracted with a soldering iron and copper desoldering braid. The simulated solder bridge was made by filling the 0.2 mm gap between 0.5 mm pitch gull wing leads with molten solder from a rosin cored Sn63/Pb37 solder wire. The molten solder, which was heated with a soldering iron tip, was kept in contact with the PWB lands and their component leads for 60 seconds. The prolonged heating simulated the contact time between copper PWB lands, component leads, and molten solder in a typical paste reflow process.

Together, the first two experiments confirmed that PWB lands and component leads were the primary source of the copper in the Cu_6Sn_5 crystals that formed the basis of the observed microbridges. The original microbridge formation hypothesis was then restated as follows. The typical solder bridge from a tin/lead paste reflow process is already saturated with copper, and contains some Cu_6Sn_5 crystals (see Figure 14A). During the rework process, as the bridge and its linked solder joints are again returned to the liquid state, additional copper from the PWB lands, component leads, and desoldering braid continues to enter solution and form Cu_6Sn_5 crystals (see Figures 14B and 14C). As solder wicks away from the bridge and onto the desoldering braid, Cu_6Sn_5 crystals, which do not melt during the rework process, become entangled, and eventually lodge between the affected solder joints, forming a microbridge (see Figures 14D and 14E).

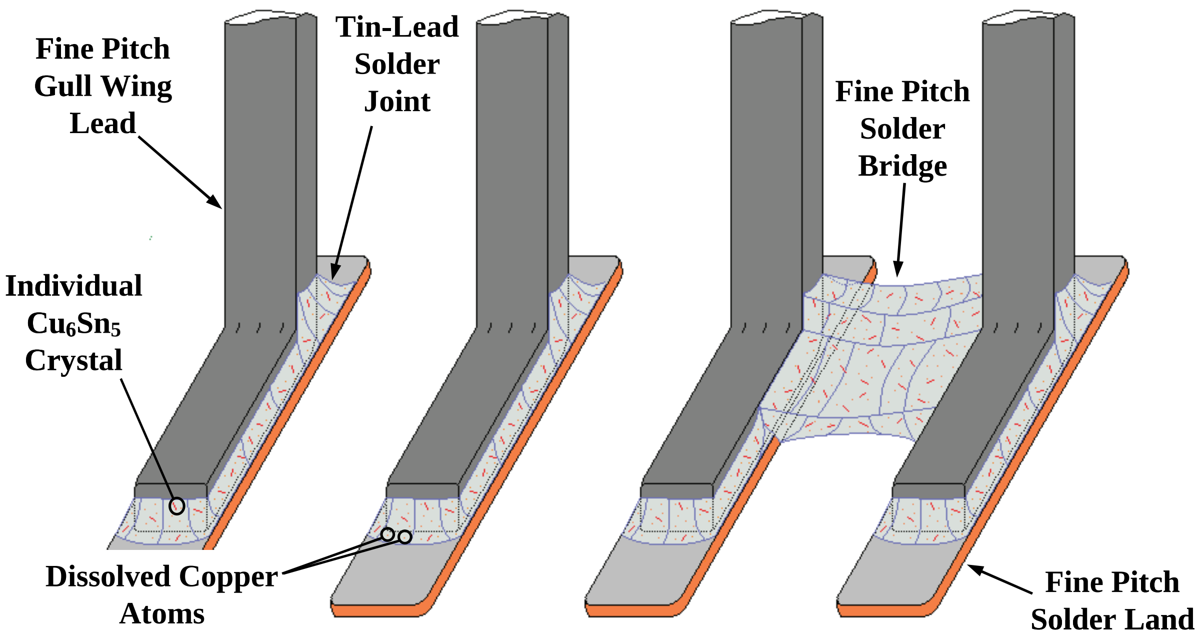


Figure 14A: The reflowed condition of a solder paste bridge between fine pitch gull wing leads. The solder in the joints and the bridge is already saturated with copper and some Cu_6Sn_5 crystals.

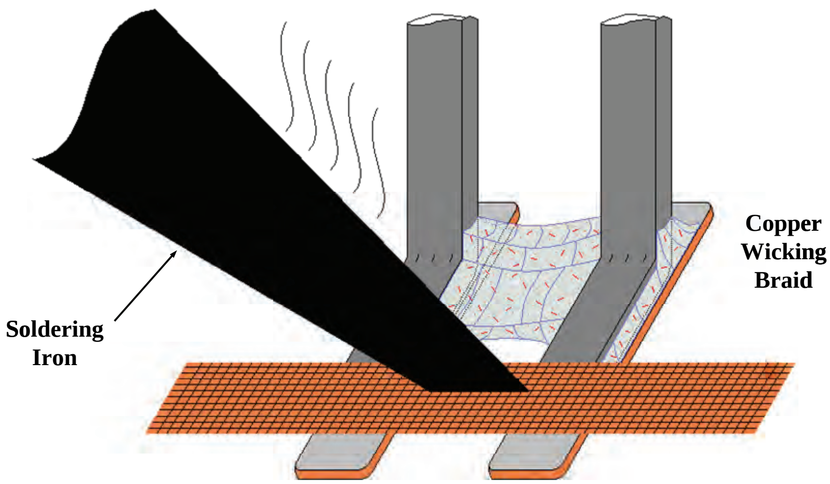


Figure 14B: During the initial stage of the rework process, the solder in the bridged joints returns to the molten state.

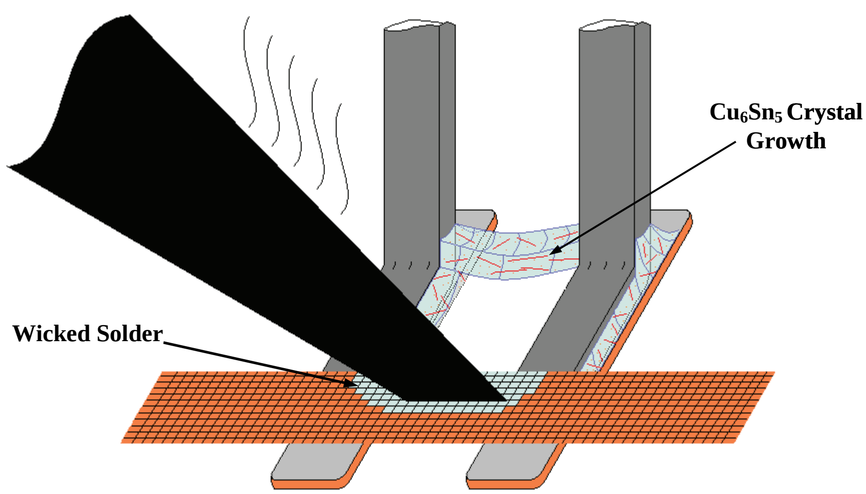


Figure 14C: As the rework process progresses, the braid soaks up excess solder, while Cu_6Sn_5 crystals continue to grow and concentrate within the remaining bridge material.

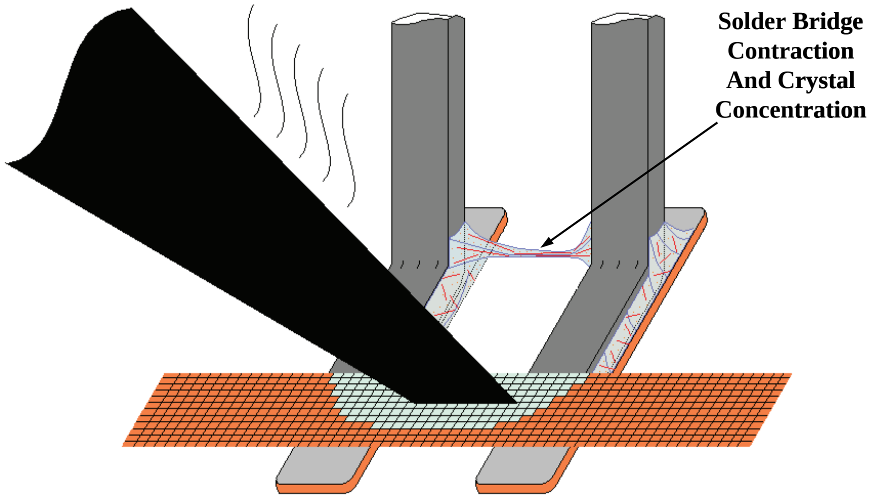


Figure 14D: As the last of the solder drains from the bridge, large Cu_6Sn_5 crystals become entangled.

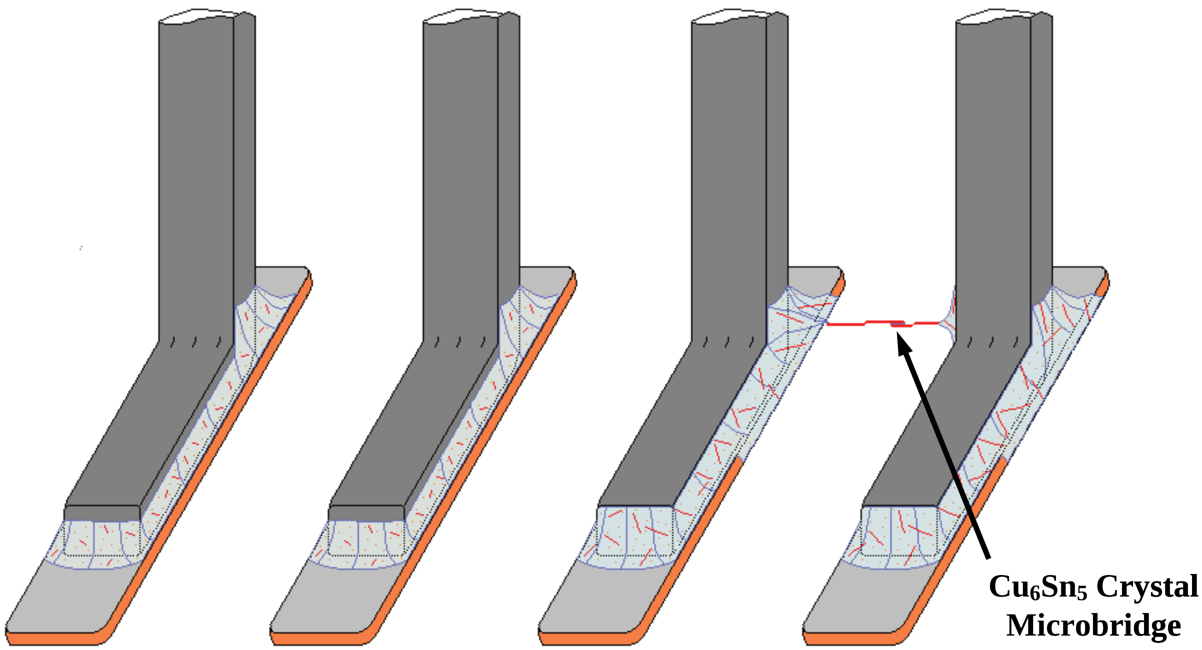


Figure 14E: A single large Cu_6Sn_5 crystal, or several smaller linked Cu_6Sn_5 crystals, form a microbridge at the site of the original solder paste bridge.

A final experiment, using actual solder paste, was conducted to confirm the refined hypothesis. It was performed on a scrap Sn63/Pb36/Ag2 solder paste assembly. Excess solder paste was applied to the fine pitch gull wing leads of several components prior to the paste reflow operation. After the reflow operation these paste reflow bridge structures were carefully examined for any signs of Cu_6Sn_5 crystal growth or protrusion. None were found (see Figure 15). Several of these locations were then reworked using the same soldering iron, flux, and desoldering braid previously described in this paper. This time, microbridges formed between several of the reworked fine pitch gull wing leads (see Figures 16 and 17). A hand held multimeter confirmed resistance readings of less than one ohm across these structures.

The reworked assembly and its microbridge structures were subsequently processed through a Microjet Inline Cleaner featuring 20 psi to 40 psi pressure aqueous wash and rinse jets, which replicated and completed the normal production rework process. The lab created microbridges, despite their delicate appearance and brittle constituent structures, survived this washing process intact. The component with the two microbridges shown in Figure 17 was then selected for further analysis. With the aid of an end mill the subject component was cut from the scrap assembly, along with its solder joints and underlying PWB material. Afterwards the excised component was mounted on an aluminum viewing stub with double sided carbon tape, and its surfaces were sputtered with palladium. Various features associated with this mounted specimen were then examined via scanning electron microscopy and energy dispersive spectroscopy (see Figures 18 through 25).

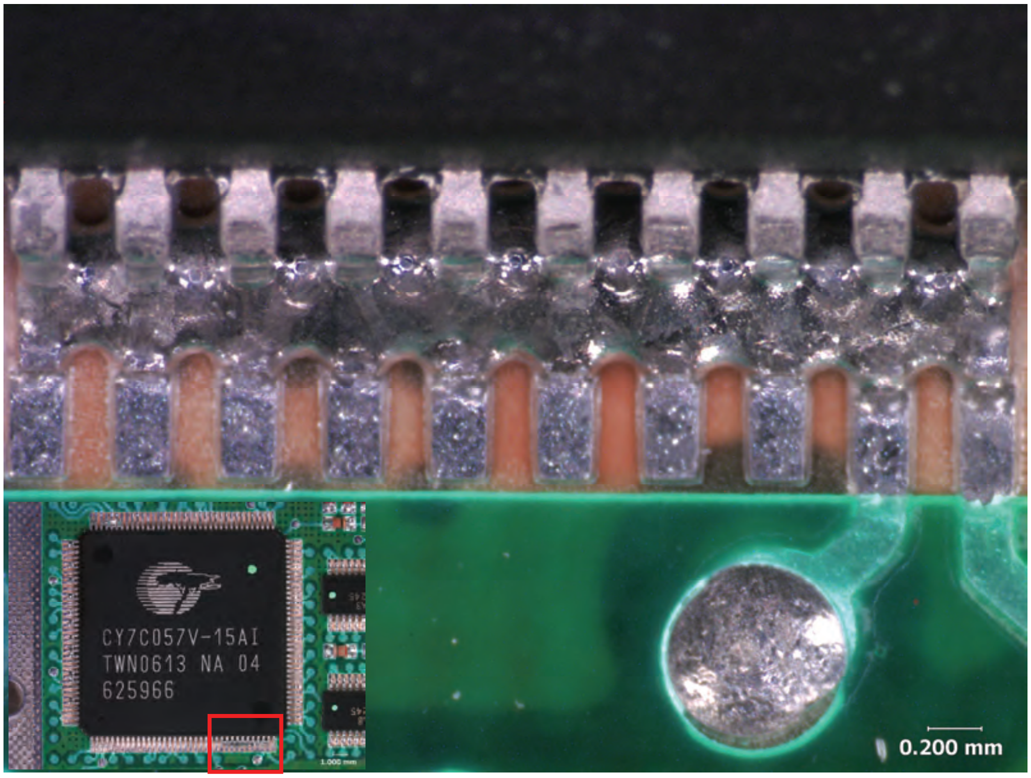


Figure 15: Solder bridges made by applying excess Sn62/Pb36/Ag2 solder paste to the 0.2mm gaps between the 0.5 mm pitch gull wing leads of the inset component. The paste was subjected to a normal reflow profile in a hot air belt oven. The bridges were located in the area outlined in red.

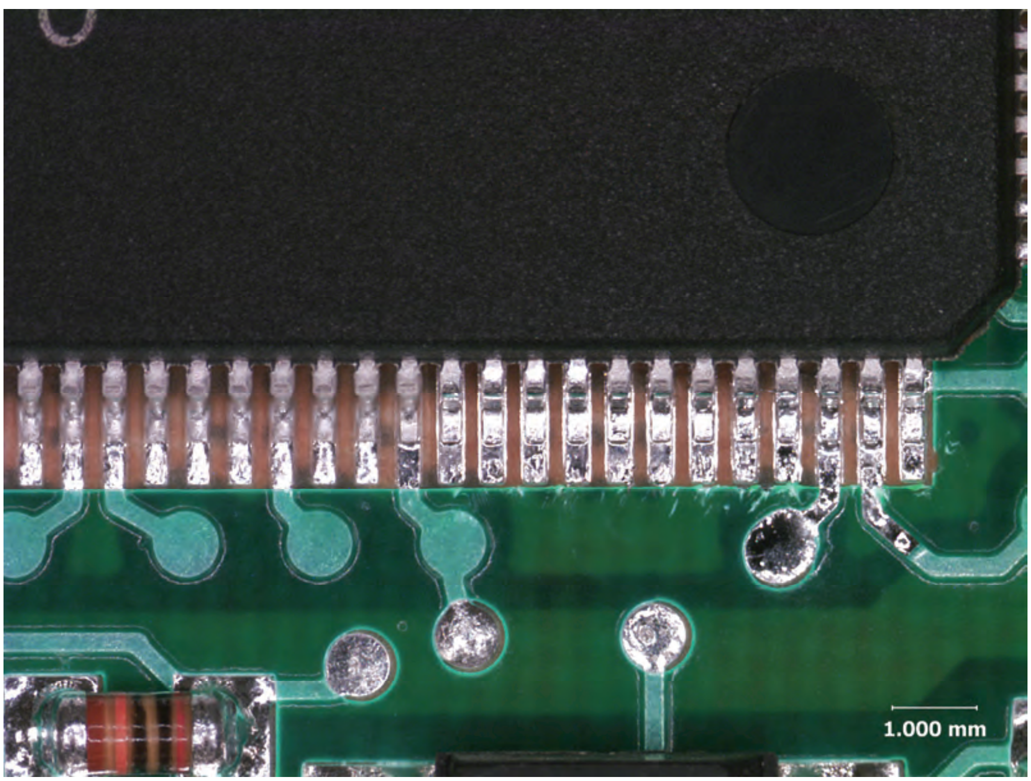


Figure 16: This overall view of the bridge site shown in Figure 15 was taken after the bridged joints had been reworked with desoldering braid and a soldering iron. Note that the reworked solder joints on the right are bright and shiny, while the as reflowed joints on the left are somewhat duller.

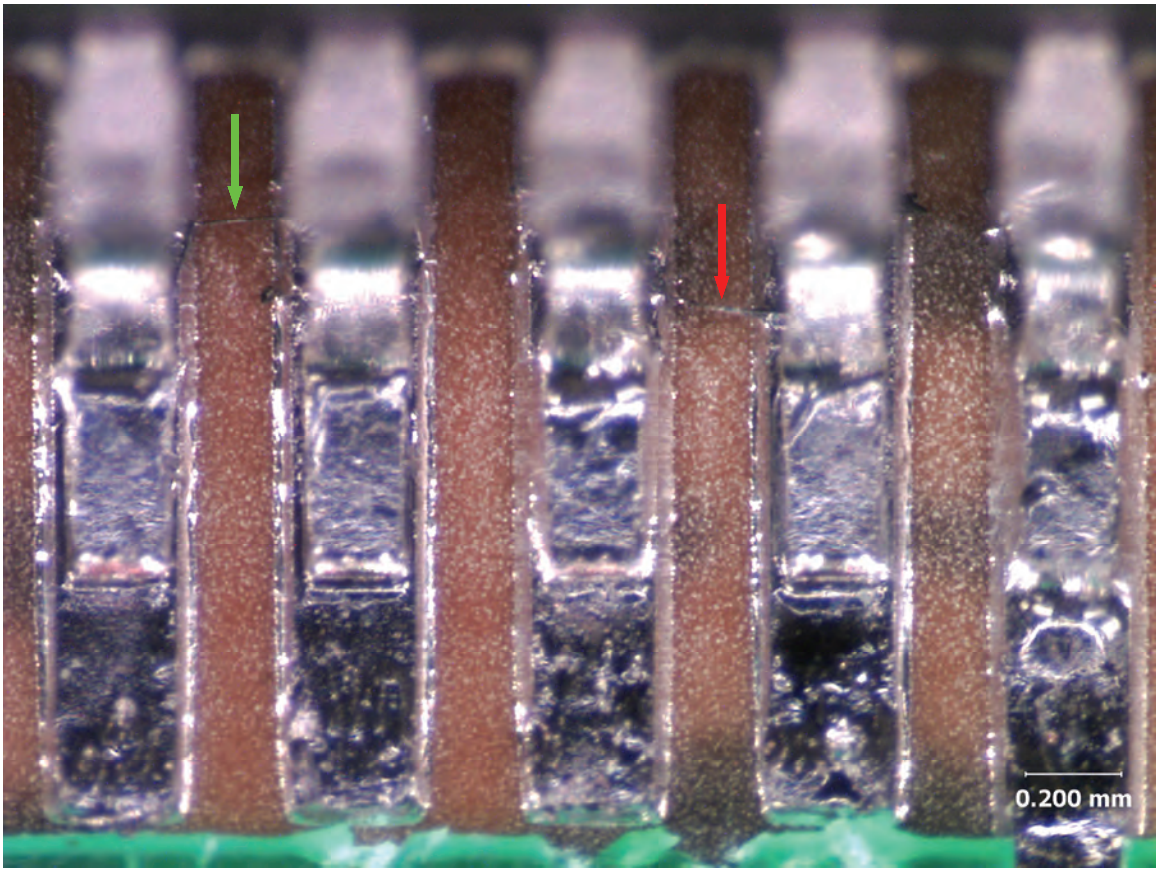


Figure 17: Two microbridges (red and green arrows) that formed while reworking the Sn62/Pb36/Ag2 solder paste bridges shown in Figure 15.

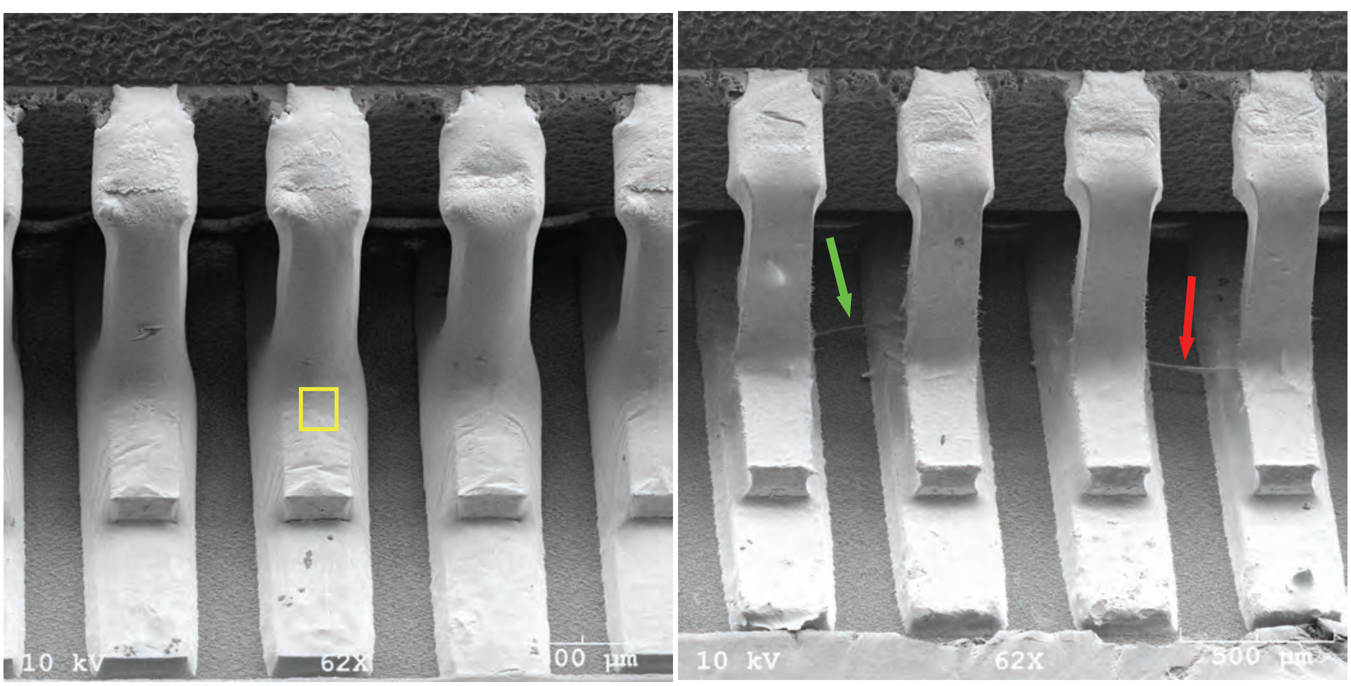
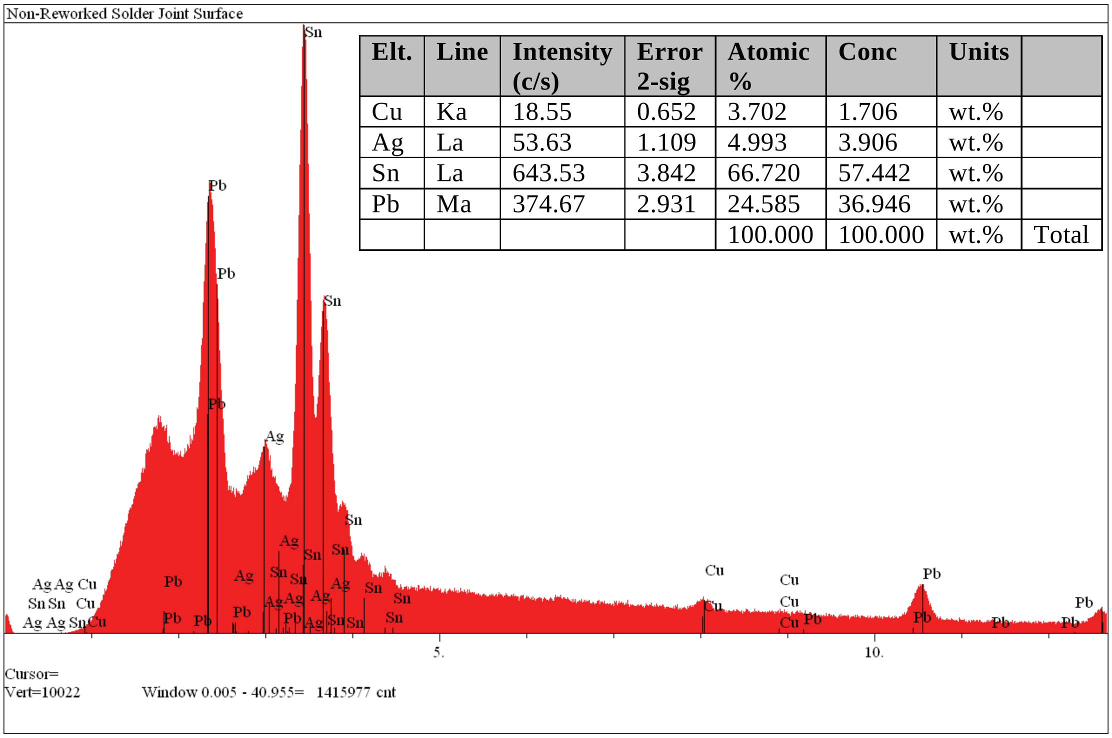


Figure 18: Scanning electron micrographs of as reflowed solder joints (left) and reworked solder joints (right) from the row of solder joints shown in Figure 16. The red and green arrows highlight the same two microbridges first shown in Figure 17. The yellow box on the left shows the location from which the EDS spectrum in Figure 19 was obtained.



Elt.	Line	Intensity (c/s)	Error 2-sig	Atomic %	Conc	Units	
Cu	Ka	18.55	0.652	3.702	1.706	wt.%	
Ag	La	53.63	1.109	4.993	3.906	wt.%	
Sn	La	643.53	3.842	66.720	57.442	wt.%	
Pb	Ma	374.67	2.931	24.585	36.946	wt.%	
				100.000	100.000	wt.%	Total

Figure 19: EDS spectrum obtained from the as reflowed solder joint surface outlined by the yellow box in Figure 18. The Sn62/Pb36/Ag2 solder paste that formed this joint absorbed approximately 1.7% copper (Cu) by weight.

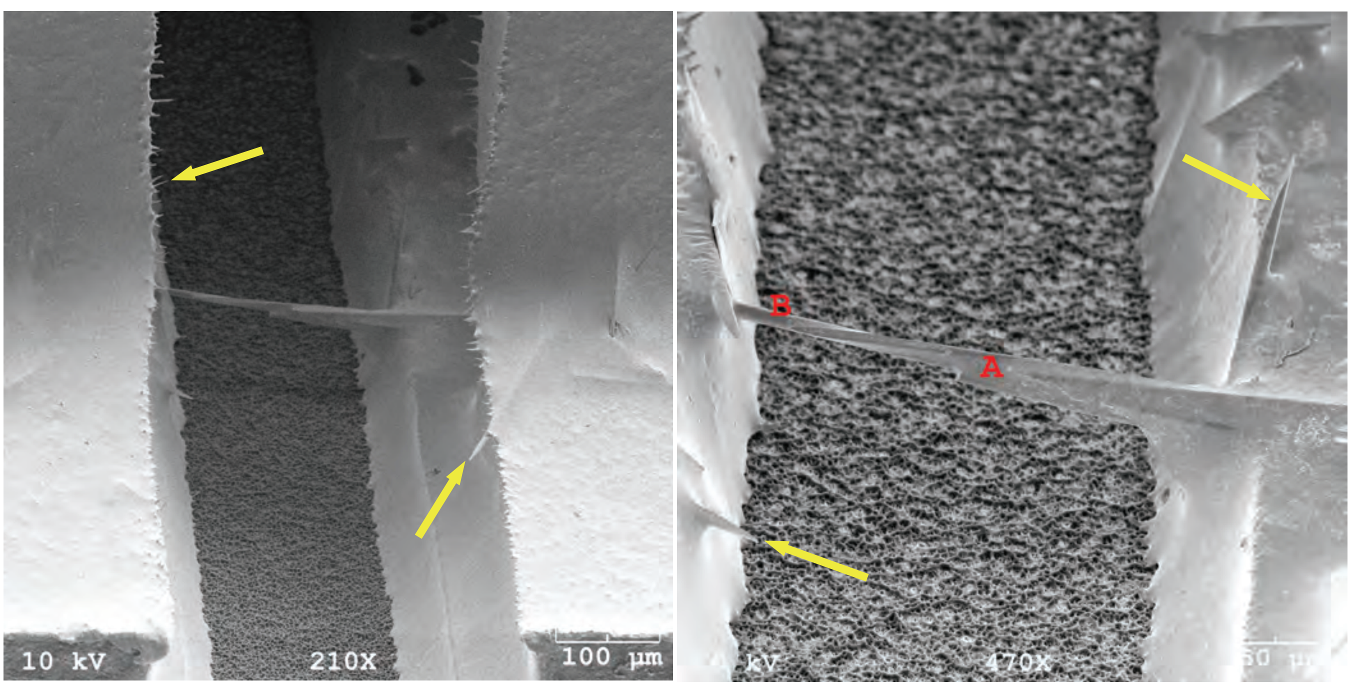
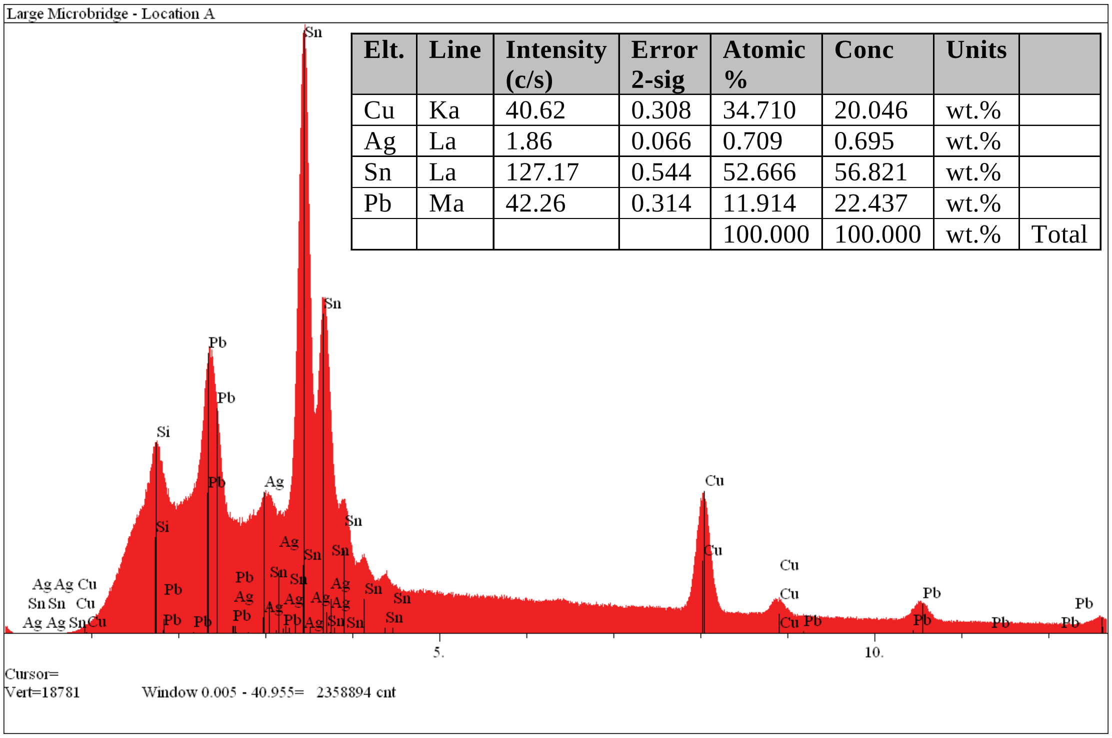
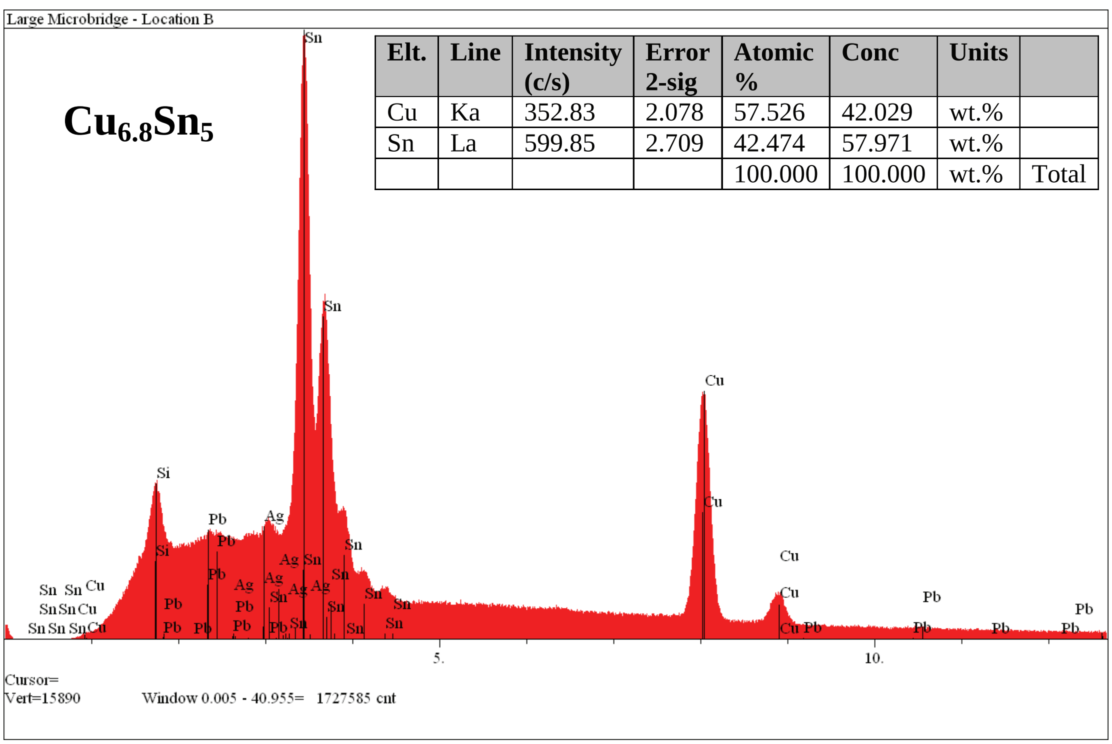


Figure 20: Detail scanning electron micrographs of the microbridge highlighted by the red arrow in Figures 17 and 18. This microbridge consisted of several mutually aligned Cu_6Sn_5 crystals, held together within a narrow cone of solder (Location A) that merged with the solder joint on the right. The longest of these crystals (Location B) extended out of this cone, and merged with the solder joint on the left. Additional Cu_6Sn_5 crystals can be seen embedded within the thin layer of solder along the edges of the gull wing leads. Several of these are highlighted here with yellow arrows. EDS spectra obtained from Locations A and B are shown in Figures 21 and 22 respectively.



Elt.	Line	Intensity (c/s)	Error 2-sig	Atomic %	Conc	Units	
Cu	Ka	40.62	0.308	34.710	20.046	wt.%	
Ag	La	1.86	0.066	0.709	0.695	wt.%	
Sn	La	127.17	0.544	52.666	56.821	wt.%	
Pb	Ma	42.26	0.314	11.914	22.437	wt.%	
				100.000	100.000	wt.%	Total

Figure 21: EDS spectrum obtained from Location A in Figure 20. The combination of elements present at this location confirmed the initial visual assessment that this site consisted of a subsurface bundle of Cu_6Sn_5 crystals covered by a thin film of Sn62/Pb36/Ag2 solder.



Elt.	Line	Intensity (c/s)	Error 2-sig	Atomic %	Conc	Units	
Cu	Ka	352.83	2.078	57.526	42.029	wt.%	
Sn	La	599.85	2.709	42.474	57.971	wt.%	
				100.000	100.000	wt.%	Total

Figure 22: EDS spectrum obtained from Location B in Figure 20. This single crystal surface exhibited virtually no silver (Ag) or lead (Pb). The copper/tin stoichiometric ratio at this location was 6.8 to 5 respectively, a close match for Cu_6Sn_5. The silicon peak was attributed to the PWB surface (i.e. glass fibers) in the background.

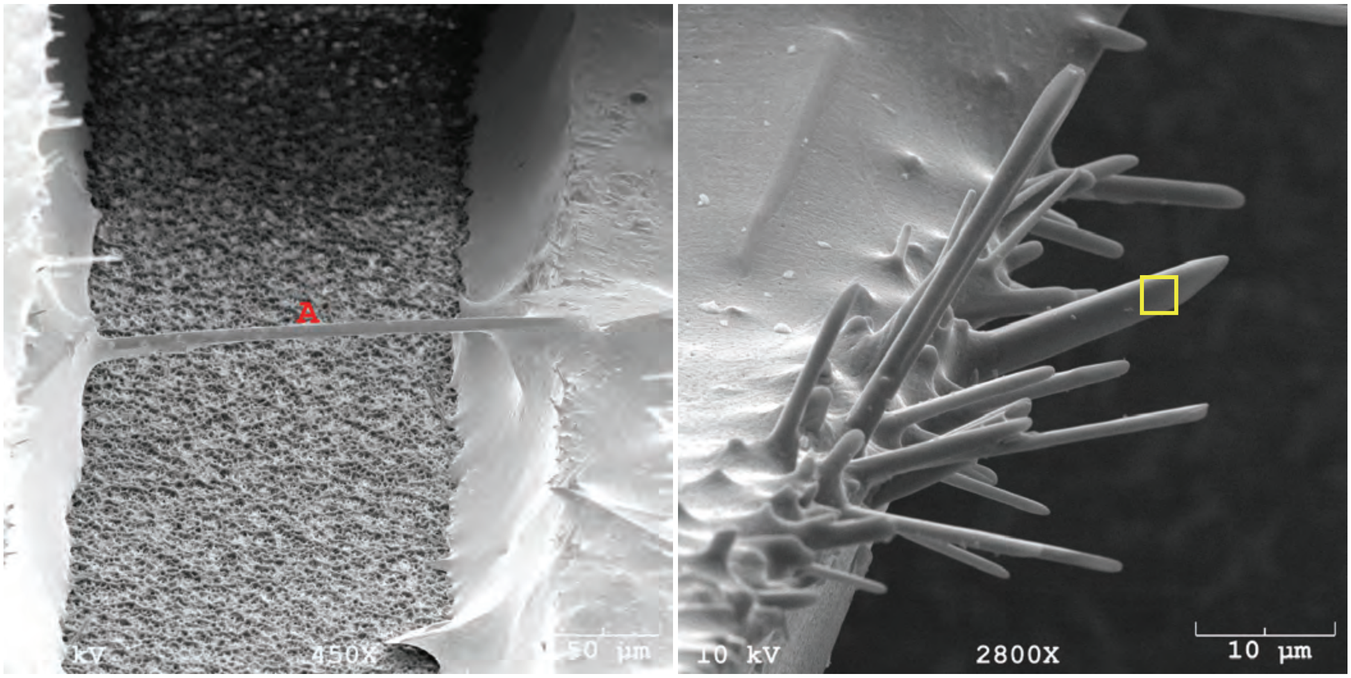
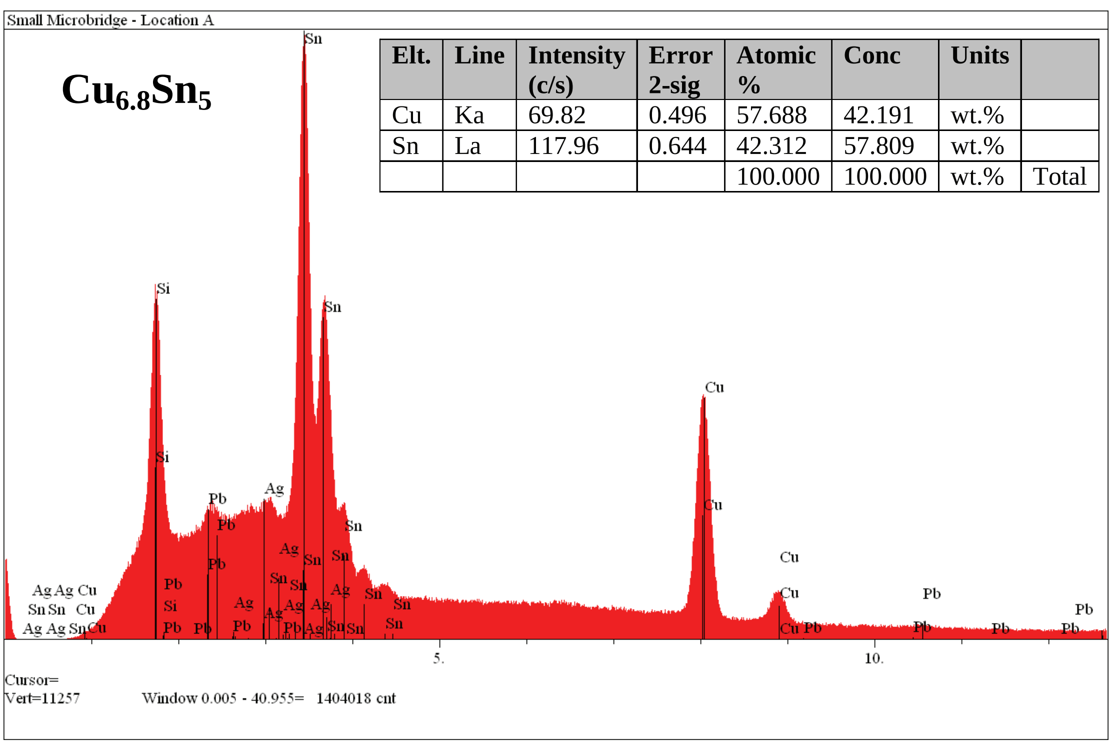
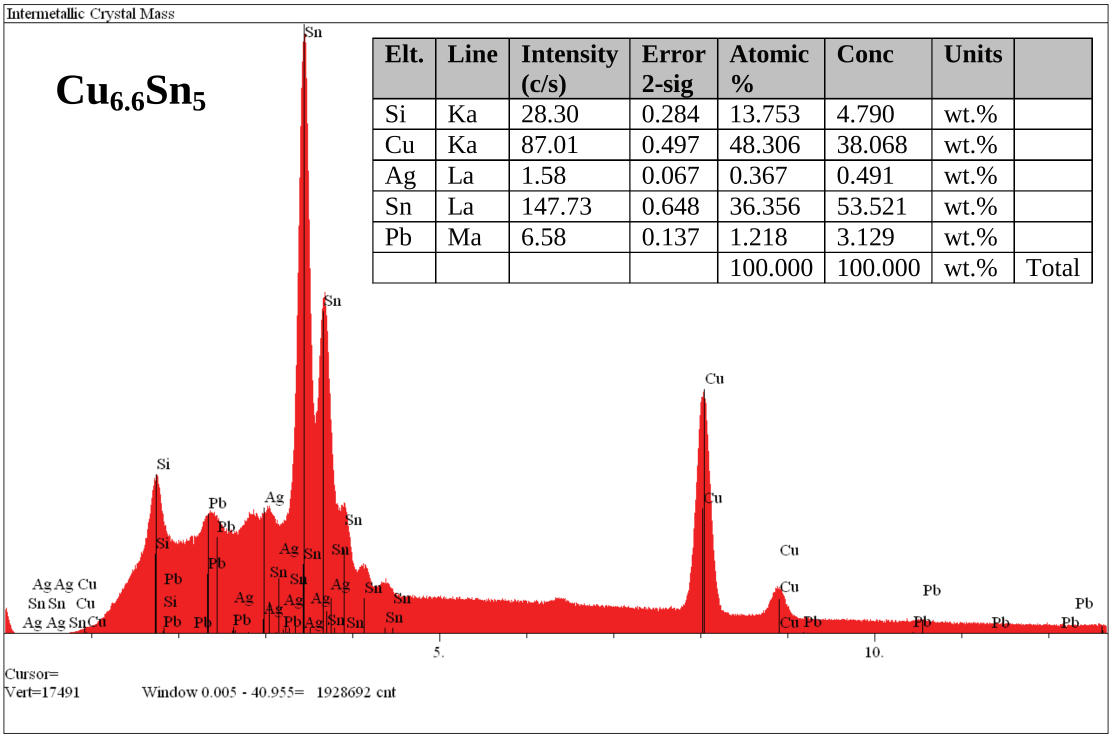


Figure 23: On the left is a detail scanning electron micrograph of the microbridge highlighted by the green arrows in Figures 17 and 18. This microbridge consisted of a single Cu_6Sn_5 crystal that merged into narrow cones of solder on the surfaces of two gull wing solder joints. An EDS spectrum obtained from Location A is shown in Figure 24. The micrograph on the right shows a dense cluster of smaller intermetallic crystals found along the edge of one of the reworked gull wing leads. An EDS spectrum obtained from the area outlined in yellow is shown in Figure 25.



Elt.	Line	Intensity (c/s)	Error 2-sig	Atomic %	Conc	Units	
Cu	Ka	69.82	0.496	57.688	42.191	wt.%	
Sn	La	117.96	0.644	42.312	57.809	wt.%	
				100.000	100.000	wt.%	Total

Figure 24: EDS spectrum obtained from Location A in Figure 23. This single crystal surface exhibited virtually no silver (Ag) or lead (Pb). The copper/tin stoichiometric ratio at this location was 6.8 to 5 respectively, again a close match for Cu_6Sn_5. The silicon peak was attributed to the PWB surface in the background.



Elt.	Line	Intensity (c/s)	Error 2-sig	Atomic %	Conc	Units	
Si	Ka	28.30	0.284	13.753	4.790	wt.%	
Cu	Ka	87.01	0.497	48.306	38.068	wt.%	
Ag	La	1.58	0.067	0.367	0.491	wt.%	
Sn	La	147.73	0.648	36.356	53.521	wt.%	
Pb	Ma	6.58	0.137	1.218	3.129	wt.%	
				100.000	100.000	wt.%	Total

Figure 25: EDS spectrum obtained from the site outlined by the yellow box on the cluster of intermetallic crystals shown in Figure 23. The metallic crystal that generated this spectrum was composed primarily of copper and tin, and relatively little silver (Ag) or lead (Pb). The copper/tin stoichiometric ratio at this location was 6.6 to 5 respectively, again a close match for Cu_6Sn_5. The silicon peak was attributed to the PWB surface in the background.

The first structures to be examined in detail were the as reflowed solder joints. As expected, their surfaces were smooth and unbroken by any protruding intermetallic crystals (see Figure 18). However, an EDS spectrum obtained from the solder that formed one of these joints contained 1.7% copper by weight (see Figure 19). This confirmed the hypothesis that the solder paste which had been deposited to form these joints was indeed absorbing significant amounts of dissolved copper from the component leads and PWB lands during the reflow process.

The next structure to be examined was the larger of the two microbridges (see Figures 18 and 20). It consisted of several aligned intermetallic crystals that were bound together on one end by a narrow cone of solder attached to the lateral fillet surface of one of the component's gull wing leads. The longest of these aligned and bound crystals extended out of the cone, and was buried on its other end in the lateral fillet surface of the adjacent gull wing lead. EDS spectra were obtained from two locations on this microbridge. The first location was at the point where several of the crystals were covered by a thin layer of solder near the tip of the cone. The thin layer of solder at this location registered measureable quantities of tin, lead and silver. Even so, this site still registered 20% copper by weight (see Figure 21). The nearby location on the surface of the single protruding intermetallic crystal, where there was no visible layer of solder, exhibited negligible lead and silver peaks. It was composed primarily of copper and tin in a stoichiometric ratio of 6.8 to 5 respectively (see Figure 22), a close match for known intermetallic compound Cu_6Sn_5.

The third structure examined was the smaller of the two microbridges (see Figures 18 and 23). It consisted of a single intermetallic crystal that spanned the lateral fillet surfaces of two adjacent fine pitch gull wing solder joints. An EDS spectrum obtained from the center span of this crystal was composed primarily of copper and tin, in a stoichiometric ratio of 6.8 to 5 respectively (see Figure 24), again a close match for known intermetallic compound Cu_6Sn_5.

During the SEM examination of the reworked solder joints it was noted that many of the gull wing leads had fine needle like protrusions along their lateral edges. These were typically grouped in clusters, and were considerably smaller than the microbridge structures (see again Figure 23). An EDS spectrum was obtained from a single protrusion in one of these clusters. It too was composed primarily of copper and tin (see Figure 25) in a stoichiometric ratio of 6.6 to 5 respectively. These structures were essentially outcroppings of Cu_6Sn_5 crystals. In a parallel study conducted on production hardware with real solder paste bridges, a production operator working on an Sn63/Pb37 paste assembly produced more intermetallic crystal clusters along the edges of reworked fine pitch leads than actual microbridges (see examples Figure 26).

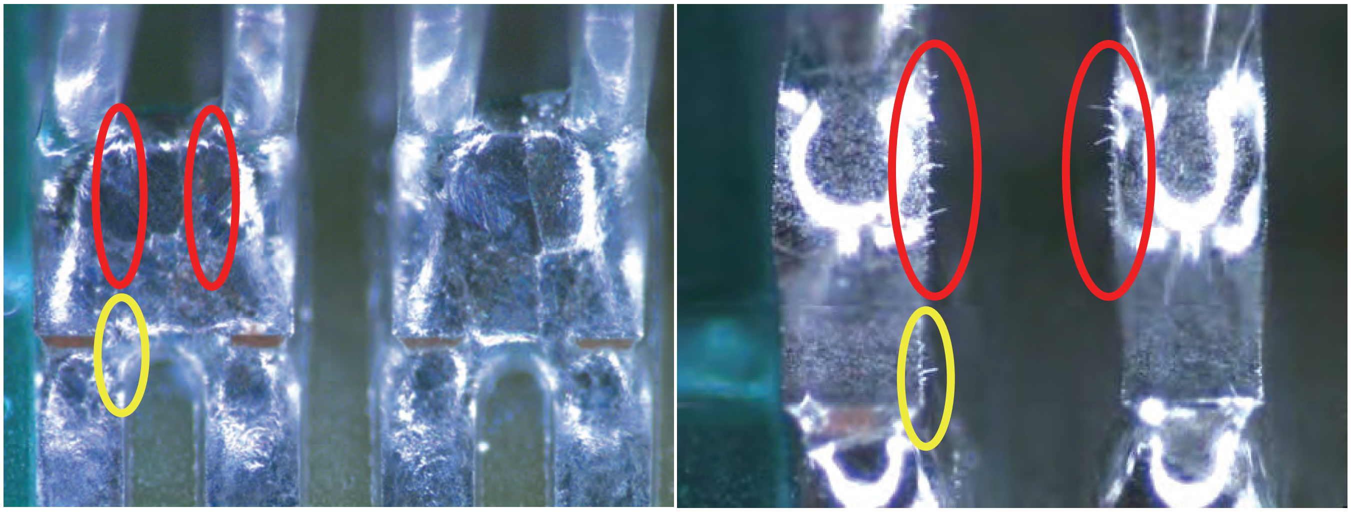


Figure 26: Actual production Sn63/Pb37 solder paste bridges located in the 0.2 mm gap between adjacent 0.5 mm pitch gull wing leads (left). The same locations outlined on the left are shown again on the right after being hand reworked by a production operator with a soldering iron and desoldering braid. Clusters of Cu_6Sn_5 crystals can be seen along the edges of both component leads.

The experimental results detailed in Figures 15 through 26 confirmed the mechanism outlined in Figure 14. Fine pitch solder joints and bridges absorb copper from component leads and PWB lands during the paste reflow process. When the amount of absorbed copper exceeds the solubility limit of the solder in these structures, it precipitates out as Cu_6Sn_5 crystals, particularly as the solder cools and solidifies. When the bridge is subsequently reworked with a soldering iron and copper desoldering braid, its constituent Cu_6Sn_5 crystals continue to grow and concentrate as molten solder is drawn from the bridge site. A single large crystal, or several smaller entangled crystals, can then lodge between the two fine pitch leads as the last of the molten bridge solder wets onto the desoldering braid. It is these lodged crystals that form a microbridge.

Attempts to reflow sample microbridges with a soldering iron and flux alone proved futile. A literature search soon revealed why. The melting point of Cu_6Sn_5 intermetallic compound is 415°C, far above allowable rework soldering temperatures[4]. Clearly, a different approach to reworking fine pitch solder bridges was needed.

The need for a more suitable rework method was driven home by a customer return. A microbridge on an assembly from this return unit caused a short circuit condition between two fine pitch component leads. This condition had gone undetected because the in house test process did not simultaneously activate the signals associated with the two affected component leads. The customer application, however, did enable both signals simultaneously, and the ensuing signal interference resulted in a failure. While the individual test condition for that particular lead pair was quickly identified and corrected, it soon became apparent that identifying a similar test condition for every adjacent fine pitch lead pair on every assembly would not be feasible. The more practical approach was to prevent the formation of microbridges in the first place.

Recommended Rework Method

Taking into account the mechanism outlined in this paper, the obvious way to prevent microbridges is to prevent the formation of their precursor structures: solder paste reflow bridges. This is certainly the leanest approach, and one that is the main thrust of ongoing process improvements at BAE Systems' Fort Wayne facility. However, those specific efforts lie outside the scope of this paper. Within the context of this discussion, a reliable rework method is needed for solder paste reflow bridges. In a low volume, high mix, high value assembly operation, reflowed solder paste bridges are a process problem that occasionally must be dealt with. Without a reliable rework method for paste reflow bridges, the formation of microbridges is a definite risk. Once formed, a microbridge can slow the progress of an expensive electronic subassembly through in house test and unit build processes. Ultimately, as already demonstrated, a microbridge can delay hardware shipments and cause field returns.

The rework method developed out of this investigation takes advantage of the peculiar mechanism that results in the formation of Cu_6Sn_5 crystals in the first place: the solubility limit of copper in tin/lead and tin/lead/silver solders. Clearly, if the amount of dissolved copper in the reflowed solder paste can be kept low, Cu_6Sn_5 crystals will not form, and therefore cannot be left behind to form a microbridge during the rework process. As will be outlined later, one way to limit the dissolution of copper is to utilize components and PWBs with solderable base metal surfaces of some material other than copper. That being said, if a fine pitch component and its PWB lands both have pure copper finishes, then the solder bridge that joins them will almost certainly be saturated, if not already supersaturated, with copper and Cu_6Sn_5 crystals after a typical paste reflow process. Thus, the key to reworking a copper saturated fine pitch solder bridge comes down to dissolving its Cu_6Sn_5 crystals, and diluting its dissolved copper. While the method that has been derived from this premise is somewhat unconventional, it has produced satisfactory results.

As outlined in Figures 27A and 27B, the first step is to add several drops of liquid flux to the site, after which **a soldering iron is applied to the PWB lands of the affected fine pitch solder fillets, while rosin cored solder wire of the appropriate alloy is used to add even more solder to the bridge site**. On first glance, this step may seem counterintuitive. However, it serves a key purpose. Adding fresh solder to the bridge site dilutes the copper in the bridge material, and allows any Cu_6Sn_5 crystals to enter back into solution. The affected fillets and bridge solder should be kept molten just long enough to roughly double the volume of solder in the solder bridge (Figure 27C). Once this has been accomplished, desoldering braid should be pressed against the bridge site with the tip of the soldering iron (27D). After the excess solder has been melted and drawn off, fresh solder can be added back to the individual fine pitch solder joints as needed, again using the soldering iron and solder wire of the appropriate alloy. If executed properly, this rework method should eliminate the paste bridge without creating a microbridge (Figure 28)

The rework method for an actual microbridge, should one form, follows the same regimen. Fresh solder is first added to the site of the microbridge. The added solder should be kept molten for a few seconds to allow time for the Cu_6Sn_5 crystals in the microbridge to again dissolve and enter back into solution. Only then should the excess solder be drawn off with desoldering braid as described above.

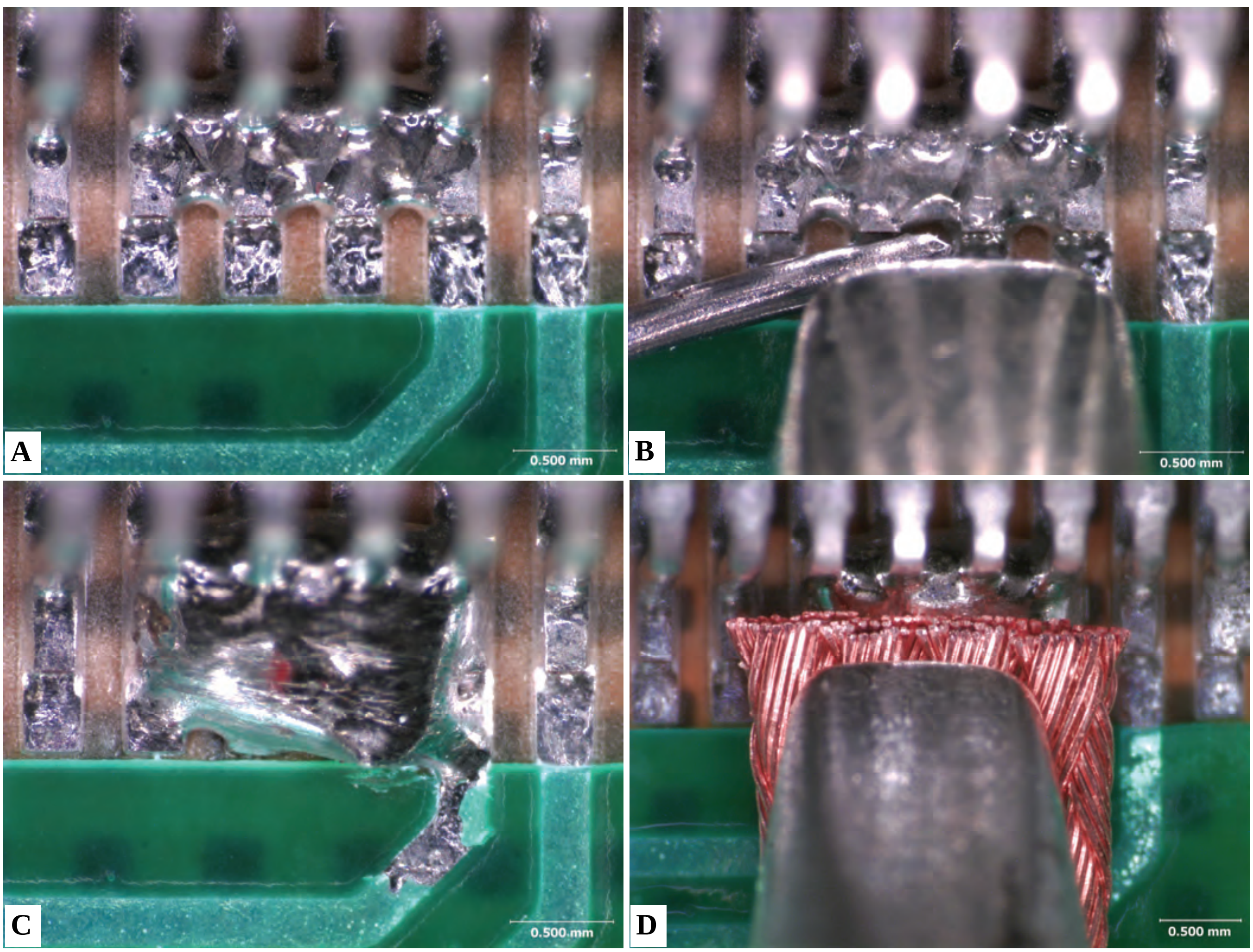


Figure 27: To rework a fine pitch solder bridge (A), use a soldering iron to melt the bridge and add in fresh solder from solder wire of the appropriate alloy (B). Keep the fresh solder and the bridge solder molten for several seconds to allow time for both to mix. The fresh solder will dissolve any Cu_6Sn_5 crystals in the bridge solder. The added solder should roughly double the size of the bridge (C). Afterwards, apply desoldering braid directly to the bridge site with the tip of the soldering iron.

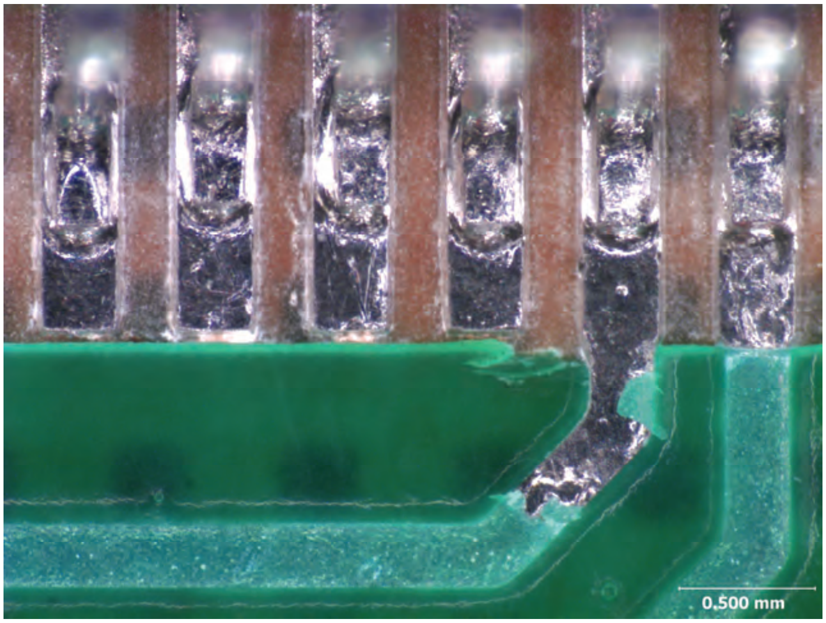


Figure 28: The reworked fine pitch solder bridge site from Figure 27. No microbridges formed during the rework process.

It is also possible, as already mentioned in this paper, to mechanically remove an existing microbridge structure with the tip of a fine test probe or dental pick. Cu_6Sn_5 crystals are brittle and easily broken. However, this particular rework method concedes the formation of the microbridge in the first place, and assumes that the microbridge will either be visually identified at the point of rework, or detected during a subsequent electrical test. Because of their extremely small size, and the difficulties associated with evaluating every adjacent fine pitch lead pair on an electronic assembly, neither method of detection is guaranteed. Furthermore, electrical detection is frequently accompanied by long production delays, as the affected subassembly must be pulled from a test stand, or worse yet a finished unit, and rerouted back to a repair station. Additionally, it is one thing to know that a short circuit condition exists on an assembly, quite another to physically isolate it to a nearly invisible microbridge on the basis of a single fault code in a subassembly or unit test report. Mechanical removal methods also entail certain risks. Fine pitch gull wing leads are mechanically delicate and easily damaged. Inserting any type of tool between them can cause lead damage, and broken microbridges produce even smaller conductive particles that need to be removed from the reworked assembly. For these reasons, production operators were instructed to rework solder paste reflow bridges in a manner that minimized the risk of microbridge formation. They were also advised to rework actual microbridges using the soldering iron method described in the preceding paragraph.

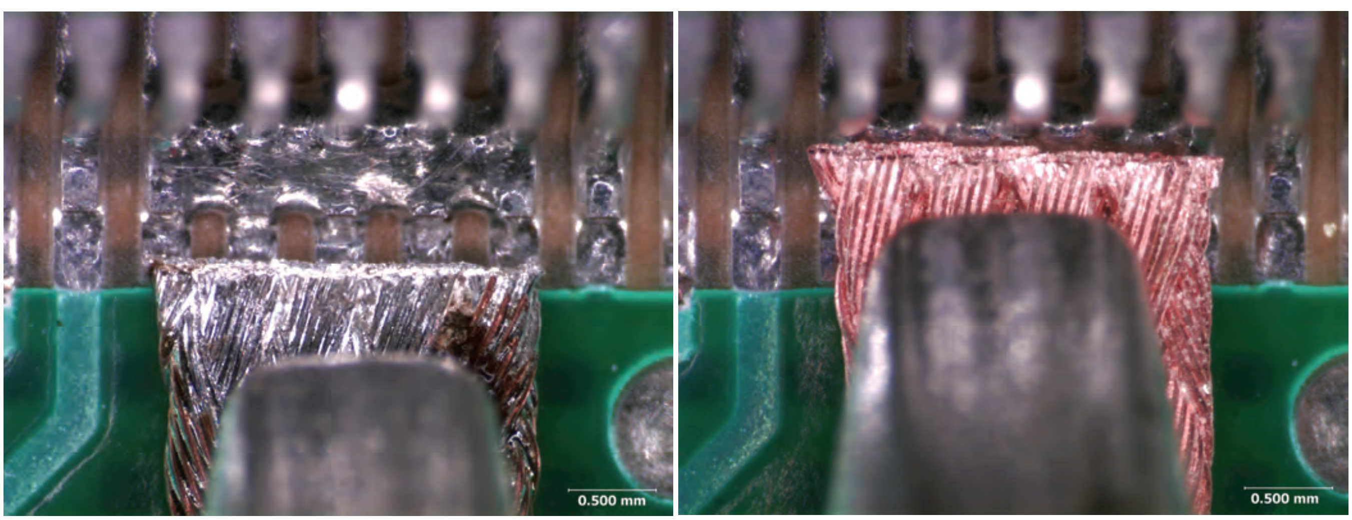


Figure 29: Lab experimentation indicated that microbridges were more likely to form when the desoldering braid was applied along the extreme outside edge of the printed wiring board lands, and when the desoldering braid was already partially soaked with solder (left). No microbridges formed when fresh desoldering braid was applied directly to the bridge site, in conjunction with the rework method outlined in Figure 28.

Additional Observations

While developing the basic soldering iron rework methods outlined in the preceding section, the following related phenomena were noted:

- Microbridges are more likely to form if the intent of the rework operator is to draw off just enough solder to break the solder paste bridge. A better technique is to draw off all of the available solder from the bridged joints, and then add back fresh solder as needed with a soldering iron and solder wire.

- The placement of the desoldering braid at the rework site impacts the likelihood of microbridge formation. If the braid is placed near the outside ends of the PWB lands, rather than in direct contact with the solder bridge, microbridges are more likely to form (see Figure 29). Placing the braid and the soldering iron near the end of the PWB land results in the slower draw of molten solder from the paste bridge, which must wick along the surfaces of the fine pitch joints and the PWB lands. This method of limited solder withdrawal takes longer, and as such promotes additional copper dissolution and Cu_6Sn_5 crystal growth. Large Cu_6Sn_5 crystals are not easily transported within the thin stream of solder that flows along the surfaces of fine pitch solder joints. This contributes to the eventual concentration and entanglement of the larger crystals between the fine pitch leads linked by the ever shrinking bridge site. Applying the desoldering braid directly to the bridge allows the excess solder to be drawn off rapidly, leaving less time for Cu_6Sn_5 crystal growth, and little opportunity for large crystals to lodge between the fine pitch leads.

- Fresh desoldering braid is less prone to produce a microbridge than braid that has already absorbed some solder (see again Figure 29).

- Rework is best performed at magnifications of 30X or higher. Microbridges are difficult to see at lower magnifications.

Mitigating Factors

Lead Finish: Copper fine pitch gull wing leads shed copper atoms into the molten solder that surrounds them during the paste reflow process. Nickel barriers, like those found on component leads with palladium/nickel and palladium/nickel/gold surface finishes, will prevent copper dissolution during the reflow process. As such, component leads with a nickel barrier layer are expected to be less prone to the formation of microbridges during a rework operation.

PWB Finish: As with component leads, printed wiring boards made with a nickel barrier will not contribute copper to their solder fillets during the paste reflow process, and will be less prone to form microbridges during a rework operation.

Multiple Reflows: Electronic assemblies made with double sided surface mount printed wiring boards, and processed through two solder paste print and reflow operations, pose a special risk. Fine pitch components and PWB lands located on the first print and reflow side of the assembly will be subjected to an additional exposure to molten solder when the alternate side of the assembly is put through its solder paste reflow operation. This second reflow process essentially doubles the contact time between fine pitch copper leads and printed wiring board lands and their molten solder joints, which in turn promotes additional copper dissolution, and even more Cu_6Sn_5 crystal growth. Fine pitch solder bridges located on this side of the assembly, if not reworked between reflow operations, will be especially prone to microbridge formation.

Conclusion

A mechanism has been identified that details the steps by which nearly invisible short circuit paths form between adjacent fine pitch gull wing leads on Sn63/Pb37 and Sn62/Pb36/Ag2 solder paste reflow assemblies. These short circuit paths, which have been named microbridges, are comprised mainly of orthorhombic Cu_6Sn_5 intermetallic crystals. The crystals initially form during the original solder paste reflow operation, and upon solidification, can be found within the solder joints of fine pitch leads, as well as any reflowed solder paste bridges that might join them. Cu_6Sn_5 crystals continue to grow and concentrate when exposed to the conditions associated with a common hand rework process meant to remove solder bridges. Under the right rework conditions, a single large Cu_6Sn_5 crystal, or multiple small Cu_6Sn_5 crystals linked by a thin film of solder, can lodge between adjacent fine pitch gull wing leads, forming a microbridge that short circuits the affected component terminations.

The hand rework method used to remove fine pitch solder paste bridges was reviewed and modified. The revised method minimizes the chance that a microbridge will form when hand reworking a solder bridge between adjacent fine pitch gull wing leads on a solder paste reflow assembly. An additional hand rework method was developed that allows for the effective elimination of an actual microbridge should one form while reworking a fine pitch solder bridge.

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