Soldering and Plating for Tin-Lead and Lead-Free Connection Reliability

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Abstract

Aerospace Defense High Performance (ADHP) electronics products primarily use tin-lead solders, but electrical and electronic component finishes (i.e., platings) increasingly are designed for lead-free solders. The knowledge-gap on tin-lead integrity with new component finishes is growing over time. Also, the reworking of components to make them tin-lead compatible presents a component reliability risk. Therefore, it is important to understand and overcome the interfacial reliability risk for every combination of solder alloy and component finish used in ADHP products. The intermetallic compounds, which nucleate and grow during the soldering and use environments of electronics hardware, are of two general types. These are, 1) Precipitation Compounds and 2) Diffusion Compounds. The precipitation compounds occur during the soldering process. The diffusion compounds can begin during the soldering process, and can grow during the environmental exposure of the solder connection to the product application (time at temperature, temperature cycling). We report numerous material combinations of soldering alloys and plating metals, where a common finding is that the growth of the diffusion compounds, at the solder-to-plating interface, is a precursor indicator of solder connection interfacial failure. The precursor is associated with vacancy accumulation and observation of Kirkendall voiding. Diffusion between the plating and the precipitation compounds leads to connection separation because the vacancy content of the plating can be up to twenty percent, and that vacancy content accumulates into area voids as the diffusion compounds grow. The diffusion compounds occur concurrent with, or subsequent to, the precipitation compounds. So the precipitation compounds are called first compounds. The diffusion compounds are called second compounds. The second (diffusion) compounds are stoichiometrically richer in the plating metal than are the first (precipitation) compounds. Technical examples show cross-sectional microstructures, and compound chemistry identifications, from the following solder-to-plating systems: tin-lead-to-gold, tin-lead-to-copper, indium-lead-to-gold, gold-germanium-to-nickel, tin-lead-to-iron-nickel and tin-lead-to-palladium. The influence of the first compounds on the mechanical properties of the solder connection can be characterized with predictability equations. However, the second compounds need to be avoided or minimized, by means of material selection (solder alloy, volume), plating design (metal, thickness, area) and processing parameters (plating, soldering). Lead-free solder connections to copper and iron-nickel finishes indicate qualification testing is needed, for lead-free solder alloys, showing their failure precursor compounds and voids are minimized.

Introduction

There are two ways that solder connections (aka solder joints) fail. The solder can fail in the bulk of the solder. Reliability can be modelled and predicted for bulk solder failure. However, solder also can fail at the interface of the solder and the plating. At the interface, a general metallurgical approach is needed. That is the focus of the paper: A general metallurgical approach to understand and model solder connection reliability at the plating interface.

Metallurgical observations were accumulated over several decades, with a large variety of solders and platings. The analyses, run on polished cross-sections of solder joints, included the stoichiometric identification of specific intermetallic compounds (IMCs). In turn, the IMCs were matched to industry-accepted equilibrium phase diagrams, leading to IMC identification confidence. As a result of rigor in the microstructural analyses, we have discovered a failure mechanism which is common to every combination of solder alloy and plated metal.

During the soldering process, IMCs form by dissolution of plated metal, which is soluble in molten solder. When plated metal has a high melting point, it does not melt, but it does dissolve. The dissolved metal then reacts with a metallic element such as tin or indium in the solder, and forms IMCs (aka compounds). The compounds precipitate as particles in the bulk of the solder, and often also as precipitated layers at the solder connection's plated interfaces. During soldering and after solidification, thermally-driven, solid-state diffusion enables more and different reactions, and can form new compounds, having more plating rich stoichiometry. The new compounds signal reliability degradation, because they are associated with observation of Kirkendall voiding at the solder-to-plating interface.

Aerospace Defense High Performance (ADHP) electronics products primarily use tin-lead solders, but electrical and electronic component finishes (i.e., platings) increasingly are designed for lead-free solders. The knowledge-gap on tin-lead integrity with new component finishes is growing over time. Also, the reworking of components to make them tin-lead compatible presents a component reliability risk.

An interface reliability enhancement approach, based on known degradation mechanisms, has as its goal the speedy implementation of known, lead-free solder connection reliability for ADHP products. It seeks to remove the risks incurred from two sources. The reliability risk sources are, 1) Use of components with finishes not designed for tin-lead solder, and 2) Addition of component rework process steps, which increase system reliability risk, compared with as-manufactured components.

Review of case studies shows the same dissolution-reaction-precipitation-diffusion-reaction-voiding phenomenon for lead-free solders, as with tin-lead solders. The solid state diffusion step is the one that risks solder-to-plating interface failures.

Metallurgical Principle of Soldering and Plating for Connection Reliability.
We propose consideration of a principle, which is supported by each of the metallurgical combinations of solder alloys and platings, described in the case studies that follow. The solder alloys include lead-free and lead-bearing solders, as well as soft and hard solders. The solder-plating combinations include a variety of platings and basis metals, such as copper, palladium, nickel, iron-nickel and gold. The proposed principle is: Detection of a solder-to-plating intermetallic compound other than the most solder element-rich one is evidence of connection reliability degradation.

For example when soldering a tin (Sn)-based solder to gold (Au) over nickel component finish, the most solder element-rich compound is $AuSn_4$. Therefore, detection of $AuSn_2$ is evidence of connection reliability degradation.

Case Studies of Plating and Solder Connections
The purpose of the case studies is to demonstrate how to predict and detect the unwanted IMC or compound, which is harmful to reliability, for every combination of solder alloy and plated metal. A plated metal is used as a surface finish for each component and circuit board, which is joined by a solder connection.

Below is a list of the plating-solder systems.

1. Electroless Nickel Electroless Palladium Immersion Gold (ENEPIG) Plating and Tin-Lead Solder[1]
2. Iron-Nickel Alloy and Tin-Lead, or Tin-Silver-Bismuth Lead-Free Solder[2]
3. Nickel-Gold Plating and Gold-Germanium Lead-Free Solder[3]
4. Copper Plating and Tin-Lead, or Pure Tin Lead-Free Solder[4]
5. Gold Plating and Tin-Lead or Indium-Lead Solder[5]

Images shown in the case studies are polished cross-sections of solder joints, magnified and analyzed.

Soldering to ENEPIG Case Study
Sn63Pb37 tin-lead soldering of Electroless Nickel Electroless Palladium Immersion Gold (ENEPIG) circuit board finish has different results, depending on the palladium thickness.

Figure 1 shows a solder connection with a stable interface where the embrittling palladium metal is fully dissolved in soldering[1]; meaning there is not a solid state diffusion reliability concern. During tin-lead soldering assembly to ENEPIG with 0.5 microns of palladium, the palladium is fully dissolved and it reacts with the tin in the solder to form the most tin-rich compound, $PdSn_4$. The microstructural morphology of the compound at the nickel interface appears columnar, so while it would influence mechanical properties at the interface, a Kirkendall voiding issue is not evident.

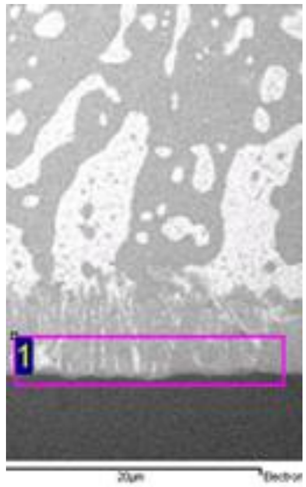


Figure 1 – 0.5 Micron Palladium on ENEPIG is Fully Dissolved below Tin-Lead Solder[1](shown after 100 temperature cycles, -55C to 125C, with 20 micron scale bar at bottom).

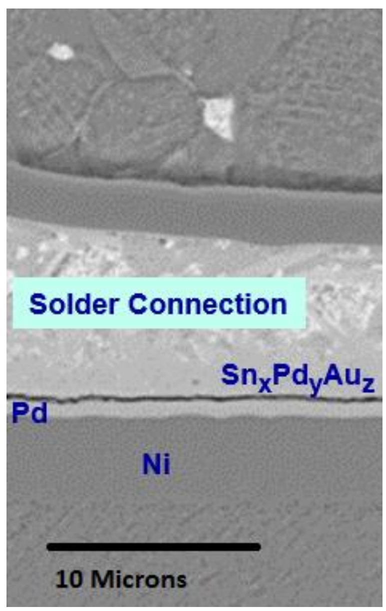


Figure 2 – Experimental Thick Palladium in ENEPIG Finish Separates from Diffusion-Formed Compound.

Figure 2 demonstrates what can happen when an ENEPIG finish with much thicker palladium (unspecified) is not fully dissolved in soldering. After soldering, an environmental exposure (unspecified) results in separation of a diffusion-formed compound from the undissolved palladium.

Soldering to Iron-Nickel Alloy Case Study

Sn63Pb37 soldering directly to iron-nickel alloy, such as Alloy 42 (Fe58Ni42), with no plating, results in a weak interface and interface failure, between the solder and the basis metal, as shown in Figure 3.

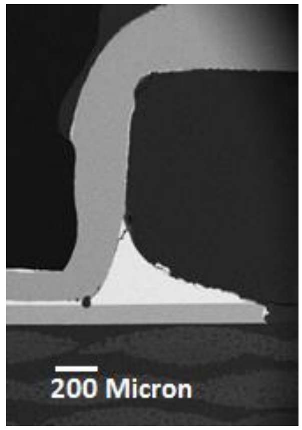


Figure 3 –Sn63Pb37 Tin-Lead Soldering to Iron-Nickel Alloy with Interface Crack

In a different study (not Figure 3), Hwang et al[2] soldered to Alloy 42 with tin-silver and tin-silver-bismuth, lead-free solders. They reported on solder connections made by soldering at 300C for one hour. $FeSn_2$ compound precipitates, prior to solidification. FeSn compound grows at the interface between the Alloy 42 basis metal and $FeSn_2$. A line of pores, indicative of Kirkendall porosity, grows between the two compounds, due to uncompensated diffusion across the interface, and vacancy coalescence.

According to the metallurgical principle of soldering and plating for connection reliability, when soldering to iron-nickel, the presence or amount of the more plating-rich compound, FeSn, is evidence of solder connection reliability degradation at the interface of the solder and the soldered metal.

Soldering of Gold-Germanium to Nickel-Gold Case Study

Gold-germanium soldering uses Au88Ge12 which melts at 361C. When soldering to gold over nickel plating, the nickel bonds to the germanium. During the soldering process, a duplex compound layer forms[3]; i.e., two layers of compound grow. Based on the metallurgical principle of soldering and plating, it is clear that first the scallop shaped compound layer precipitates onto the plating. Then the relatively nickel-rich compound layer grows, resulting in voiding at its interface with the nickel. Please see Figure 4.

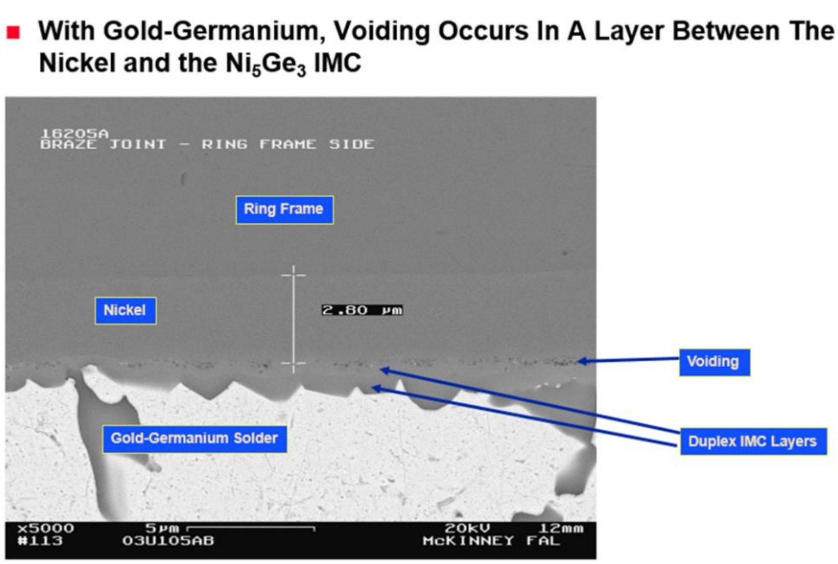
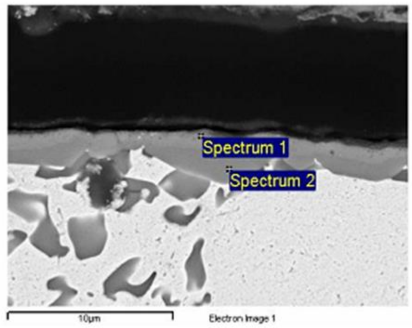


Figure 4 – In Gold-Germanium (Au-Ge) Soldering, Ge Reacts with Nickel (Ni). Vacancy-Induced Voids Result[3].

- **Identification Of The IMC, Ni_5Ge_3 , Associated With Failure of Gold-Germanium (361C Melting Point) Solder Joints**

Non-FIB Area - AuGe



Spectrum 1, Ni_5Ge_3

Element	Weight%	Atomic%
Ni K	57.92	62.99
Ge K	42.08	37.01
Totals	100.00	

Spectrum 2, NiGe

Element	Weight%	Atomic%
Ni K	44.09	49.37
Ge K	55.91	50.63
Totals	100.00	

Figure 5 – Stoichiometry Analysis Identifies the Compounds. Spectrum 1 is Ni_5Ge_3. Spectrum 2 is NiGe.

Figure 5 (obtained in the same study as Figure 4) shows a scanning electron microscope's compositional capability to identify intermetallic compounds in terms of their quantified stoichiometry. For example, Ni_5Ge_3 has 62.5 At. % nickel, which is very close to the 62.99 number in the figure.

There is a separation between the nickel and the nickel-rich compound, because solid state diffusion kinetics cause vacancy accumulation, void formation and failure.

Plated layers can have up to 20% vacancies (Bhadeshia[6]). Therefore, during solid state diffusion the vacancies accumulate in a weakened/voided layer.

The more vacancies that are present in the metal lattice of a plating, the faster the diffusion can occur. In a face centered cubic metal, there is supposed to be an atom at each corner of the cube, and in the middle of each face. Those places where metal atoms are missing are called vacancies. In diffusion, as compounds grow coherently, meaning free of vacancies, the plated vacancies are expelled, accumulating at an interface, resulting in voids.

Soldering to Copper Plating Case Study

Tin-lead on copper is very common for military aerospace (Mil-Aero) products. Figure 6 shows Sn60Pb40 tin-lead plating on top of a copper plating. (There is a nickel layer between the copper and the brass.) The connector's housing was selectively plated, and then subjected to a thermal exposure during manufacture. The thermal exposure causes the tin-lead plating and the copper to diffuse and react. Kirkendall voids occur, as shown in the green oval. Normally, tin-lead and copper do not have an interface reliability problem. However, the supplier's plating bake thermal exposure created the voids, prior to solder assembly.

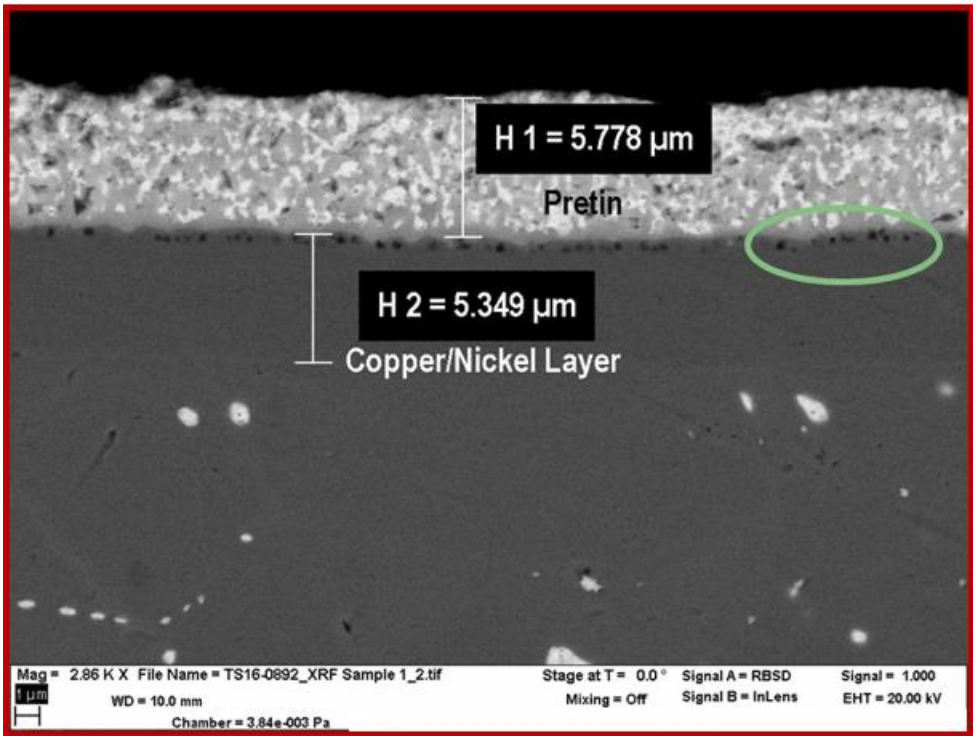


Figure 6 - Diffusion of Copper and Cu_6Sn_5 Causes Cu_3Sn and a Line of Voids in the As-Received Connector.

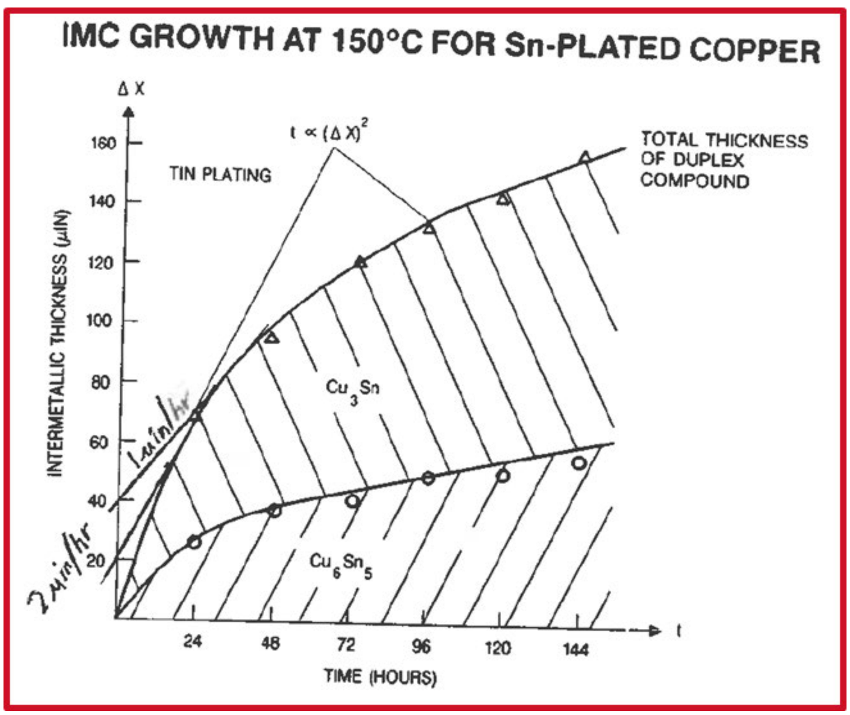


Figure 7 – Plated Tin Grows Two Compounds between the Copper and the Tin[7].

Only the Cu_6Sn_5 compound forms during soldering of tin-lead to copper. However, when tin-lead plating on copper is subjected to a time and temperature excursion, both Cu_3Sn and Cu_6Sn_5compounds grow at the copper interface. In Figure 7, for the case of tin plated copper aged at 150C, again both compounds grow[7]. The parabola shows that the growth is by Fickian diffusion, where it takes quadruple the time, to double the compound thickness.

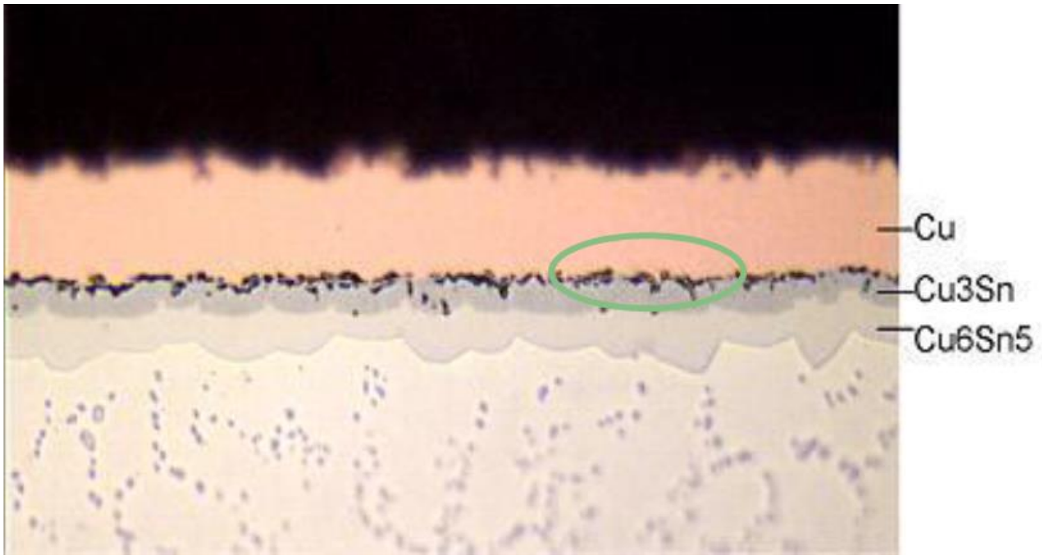


Figure 8 – A Relatively Plating-Rich Compound, Cu_3Sn, Can Indicate Voids, for Copper Soldered with Tin[4].

Figure 8 shows a reflowed pure tin solder connection[4]. A relatively copper-rich compound, Cu_3Sn, forms between the copper and the Cu_6Sn_5 compound. The latter had precipitated at the interface during soldering. The separation failure was between the copper and the copper-rich compound. It shows the pure tin lead-free solder follows the same metallurgical principle of reliability degradation at the interface as does the tin-lead solder.

The solder connection reliability degradation at the interface also depends on the copper plating process[4]. Organic plating additives and tin thickness are causal factors for reliability assurance. A higher potential than the potential of zero charge (PZC) also is helpful in the plating process, to reduce the likelihood of Kirkendall voiding.

Solving Embrittlement in Every Case

Figure 9 summarizes several of the case studies. Solving solder embrittlement in several cases reveals a common root cause, to aid solving embrittlement in every case. We have shown items 2 and 3, including a lead-free equivalent. We conclude with items 4 and 1, in that order.

	Solder Alloy	Plating	Duplex or Triplex Compound	Failure Mechanism
1	Indium-Lead	Gold	$AuIn_2 + AuIn + Au_9In_4$	Au_9In_4 and Au Separation Kirkendall Voiding
2	Gold-Germanium	Nickel	$NiGe + Ni_5Ge_3$	Ni_5Ge_3 and Ni Separation Kirkendall Voiding
3	Tin-Lead	Copper	$Cu_6Sn_5 + Cu_3Sn$	Cu_3Sn and Copper Kirkendall Voiding
4	Tin-Lead	Gold	$AuSn_4 + AuSn_2$	$AuSn_2$ and Au Separation Kirkendall Voiding

Figure 9 – The Failure Mechanism is Between the Plating and the Relatively Plating-Rich Compound.

Soldering to Gold Plating with Tin-Lead Solder Case Study

While each of the case studies describes hard, embrittling compounds, the combination of gold plating and tin-lead solder is the solder connection design most frequently associated with solder connection embrittlement.

The $AuSn_4$ compound is the most solder-rich one, and the relatively plating rich compound, $AuSn_2$, separates from the gold due to solid state diffusion and Kirkendall voiding[5]. See Figure 10.

In Figure 10, the gold plating (a vertical white line) on the pin is incompletely dissolved during soldering. The $AuSn_2$grows only by diffusion, as part of a duplex (i.e., double compound) interface layer, adjacent to the $AuSn_4$layer. Additional $AuSn_4$ is distributed throughout the soldered fillet, proving all the $AuSn_4$precipitates prior to diffusion.

The Sn63Pb37 tin-lead solder fillet separates from the undissolved gold on the pin, because the duplex layer breaks from the gold as a result of solid state diffusion.

$AuSn_4$is the first compound to form, and the relatively gold-rich, $AuSn_2$ forms afterward. Fast diffusion[8] between the undissolved gold and the $AuSn_4$ layer weakens the gold-to-$AuSn_2$ interface due to vacancy accumulation. The fillet contraction produces a peeling stress and cracks the weakened interface.

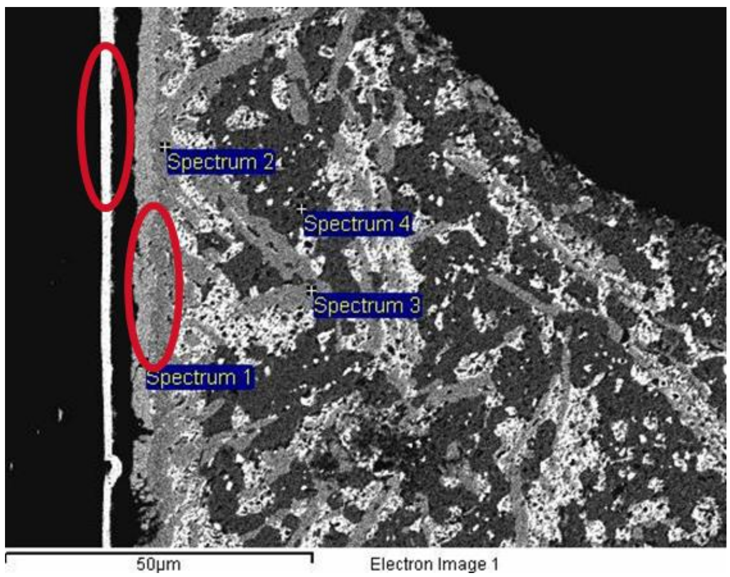


Figure 10 –Upper Oval Shows Undissolved Gold. Other Oval Shows $AuSn_2$(Spectrum 1)and $AuSn_4$(Spectrum 2)[5].

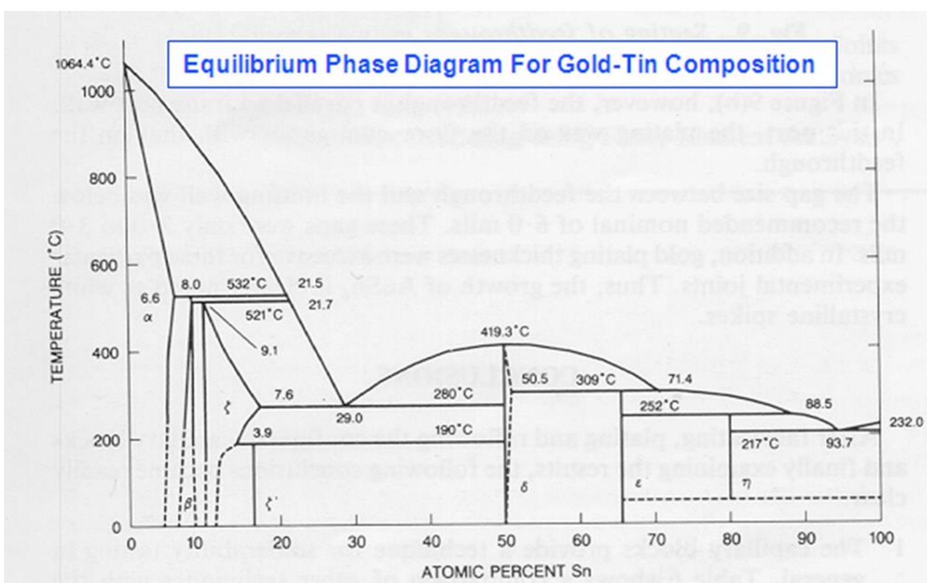


Figure 11 – Equilibrium Phase Diagrams Aid Solder-Plating Connection Analyses[9].

The metallurgical engineer looks at the applicable, equilibrium phase diagram for every case study. Figure 11, for example, shows the gold-tin diagram[9], where 100% tin is on the right. At 80 At% tin, the eta compound is the most tin-rich one, $AuSn_4$, per the vertical line at 80. The more gold-rich compound at 67 At% tin, $AuSn_2$, is the reliability degradation indicator. So while $AuSn_4$ in sufficient quantity is a reliability risk when there is more than 4.0 Wt% gold in the bulk solder connection[10], a different reliability risk occurs at the solder-to-plating interface, once the $AuSn_2$ is detected.

Soldering to Gold Plating with Indium-Lead Solder Case Study

In the indium-lead (In50Pb50) to gold system, Au_9In_4 compound is the microstructural precursor of connection reliability loss. $AuIn_2$compound precipitates first during soldering. Interestingly, it is not the AuIn, but the even more gold-rich, Au_9In_4compound, which separates from the gold (Au), noted after 1000 temperature cycles. See the pink arrows in Figure 12.

A thermally aged connection of the same indium-lead (In50Pb50 solder alloy), joined to gold plating[11] is shown in Figure 13.

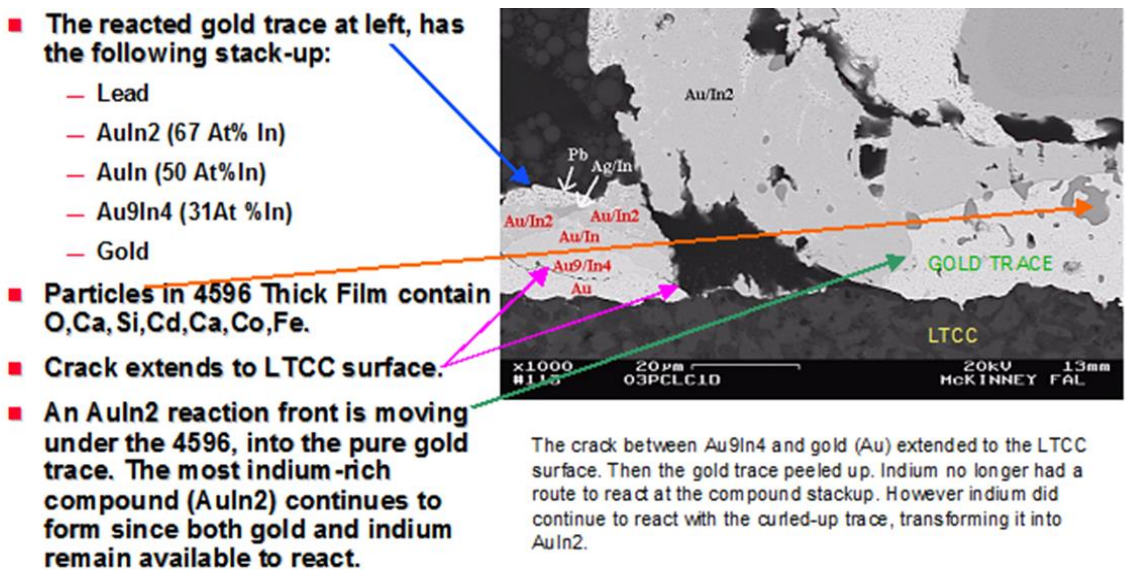


Figure 12 – Gold Trace Failure Mechanism at the Au_9In_4 Compound to Gold Interface.

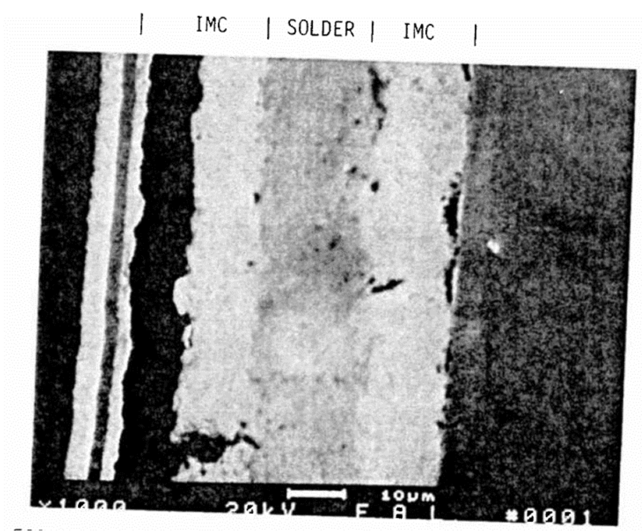


Figure 13 – Indium-Lead to Gold Plating, Vacancy Accumulation and Voiding/Separation, Aged 50 Hours at 125C[11].

Conclusions

The following metallurgical principle of soldering and plating was deduced from the case studies. Detection of a solder-to-plating intermetallic compound other than the most solder element-rich one reveals evidence of connection reliability degradation, for both tin-lead and lead-free soldering. (The degradation is at the interface of the solder and the plating, and is caused by a diffusion mechanism.)

Metallurgical observations of solder joint embrittlement, for all analyzed plating-solder systems (below), reveal that solder connections tend to fail from a separation of the solder from the plating, associated with a relatively plating-rich compound, as a function of the soldering process and the connection thermal history.

1. Electroless Nickel Electroless Palladium Immersion Gold (ENEPIG) Plating and Tin-Lead Solder[1]
2. Iron-Nickel Alloy and Tin-Lead, or Tin-Silver-Bismuth Lead-Free Solder[2]
3. Nickel-Gold Plating and Gold-Germanium Lead-Free Solder[3]
4. Copper Plating and Tin-Lead, or Pure Tin Lead-Free Solder[4]
5. Gold Plating and Tin-Lead or Indium-Lead Solder[5]

The precipitated, relatively solder-rich compound, formed during soldering, does not usually separate at the plating interface. Nevertheless, the hard-intermetallic compounds (IMCs), dissolved from platings, do precipitate and change the bulk solder properties.

The reliability of the connection, made of both solder and dissolved plating, is expected to be influenced by the bulk joint, away from the plating interface. In addition, IMCs present in many lead-free solder alloys, prior to any plating dissolution, are expected to influence bulk joint reliability.

However, our data with tin-lead and lead-free solders, and published data with lead-free solders, show a different failure phenomenon. It is a separation phenomenon at the plating interface. It occurs similarly for both tin-lead and lead-free solder alloys.

The interface reliability degradation by diffusion, and the bulk solder joint reliability degradation by plating dissolution/contamination are two, superposed reliability issues. Both seek reliability modelling and prediction solutions, for lead-free solders to be used in high reliability electronics hardware applications.

The discovered, common, interface failure mechanism is easily detected with cross-sectional analysis, and confirmed with equilibrium phase diagram analysis[9,12]. Detection of a solder-to-plating intermetallic compound other than the most solder element-rich one reveals evidence of connection reliability degradation.

Kirkendall voiding causes plating-rich compound separation from plating. The vacancy level in the plating is causal to vacancy-induced voiding.

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Soldering and Plating for Tin-Lead and Lead-Free Connection Reliability

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Agenda:

Predict and Detect, for Every Solder Alloy/Plating Combination, the Unwanted Intermetallic Compound (IMC), Which Indicates an Interfacial Reliability Risk

- Metallurgical Observations of Solder Joint Embrittlement
- Case Studies of Plating and Solder Connections
- Categories of Compound Contribution to Embrittlement
- Discovered Common Failure Mechanism, Detection Method

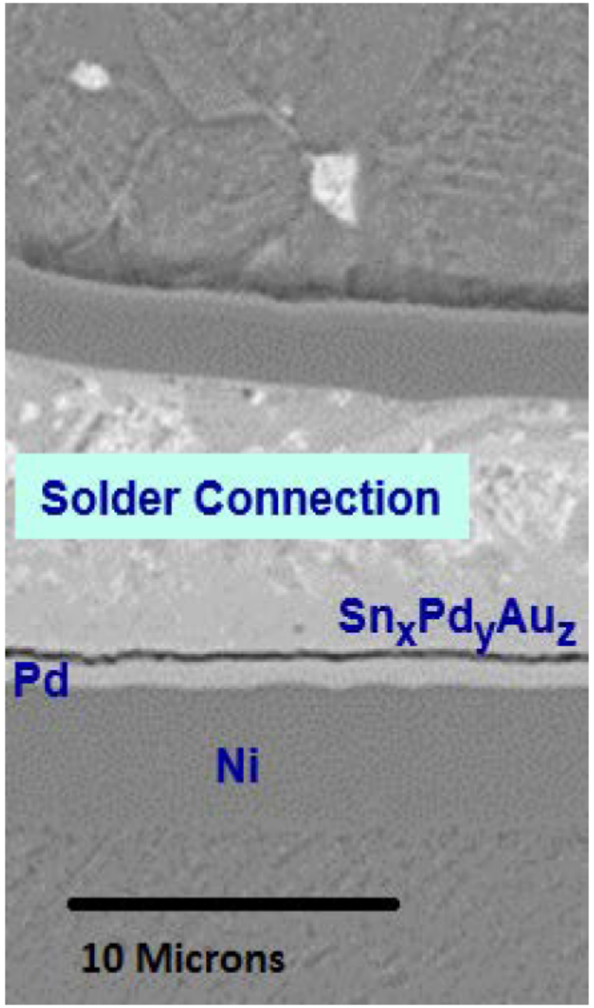
Goal of Presentation

- Address assembly reliability for every solder alloy used in solder connections to any embrittling metal plating.
- Observe a common method of determining reliability degradation for any solder/plating combination.
  - ***Failures are between a relatively plating rich compound and the plating.***

	Solder Alloy	Plating	Duplex or Triplex Compound	Failure Mechanism
1	Indium-Lead	Gold	$AuIn_2$ + $AuIn$ + Au_9In_4	Au_9In_4 and Au Separation Kirkendall Voiding
2	Gold-Germanium	Nickel	$NiGe$ + Ni_5Ge_3	Ni_5Ge_3 and Ni Separation Kirkendall Voiding
3	Tin-Lead	Copper	Cu_6Sn_5 + Cu_3Sn	Cu_3Sn and Copper Kirkendall Voiding
4	Tin-Lead	Gold	$AuSn_4$ + $AuSn_2$	$AuSn_2$ and Au Separation Kirkendall Voiding

Cross-Sections Help to Detect Imminent Failures

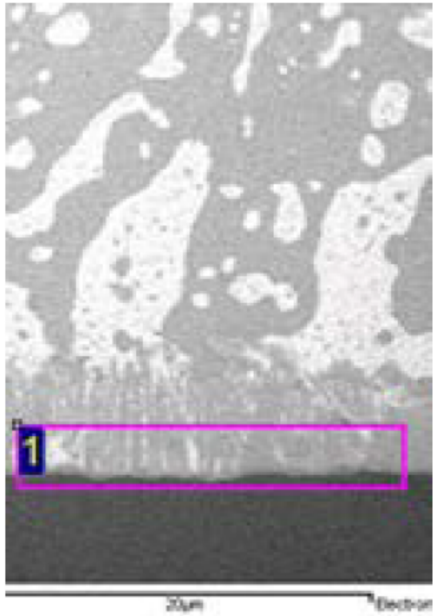
- Address assembly reliability for every solder alloy used in solder connections to any embrittling metal plating.
- Observe a common method of determining reliability degradation for any solder/plating combination:
  - ***Detection of an intermetallic compound other than the most solder element-rich one reveals evidence of connection reliability degradation.***
- A Sn63Pb37 tin-lead solder connection separated between Electroless Nickel Electroless Palladium Immersion Gold (ENEPIG) and an IMC, due to extra thick palladium (Pd).



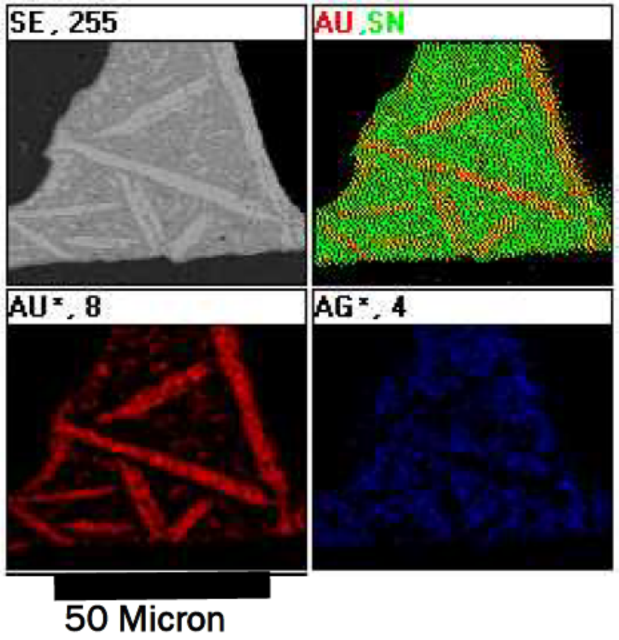
Intermetallic Compound (IMC) Mechanisms:

Cracked Interface (Left), Stable Interface (Middle) and Embrittled Bulk (Right)

- On Left is Interface Crack between Iron-Nickel Fe42Ni Alloy and Tin-Lead Solder
  - FeSn and Kirkendall Porosity Occur for Tin-Silver Solder SnAg3 Baked [2]
- In Middle is Dissolved Palladium (Pd) and Stable $PdSn_4$ IMC from ENEPIG



[1]



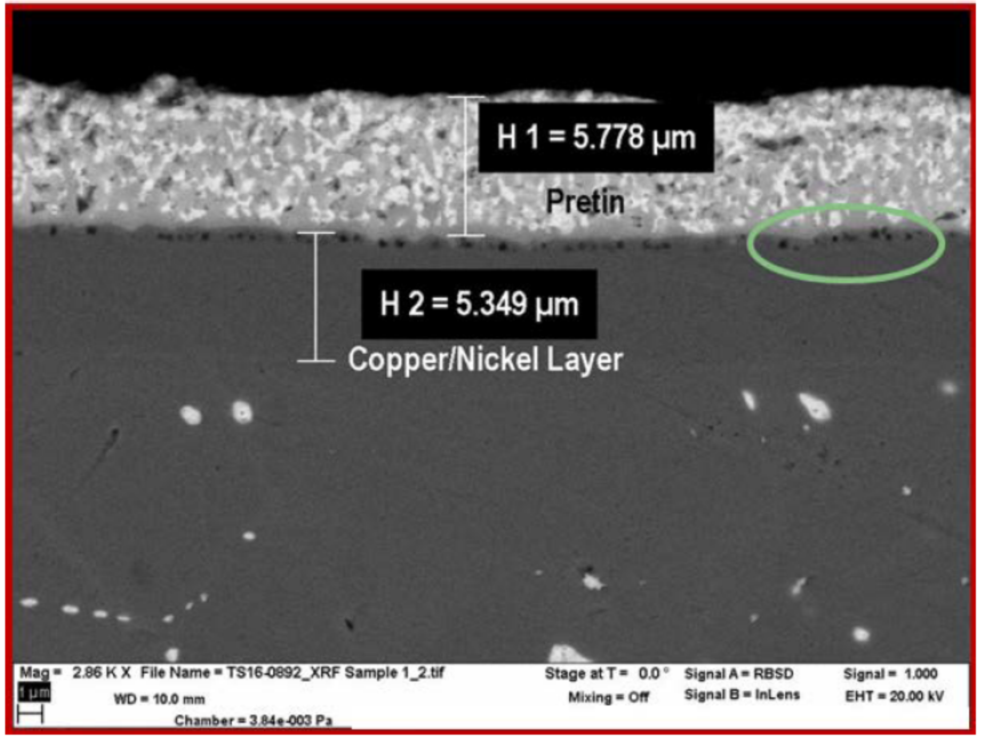
[5]

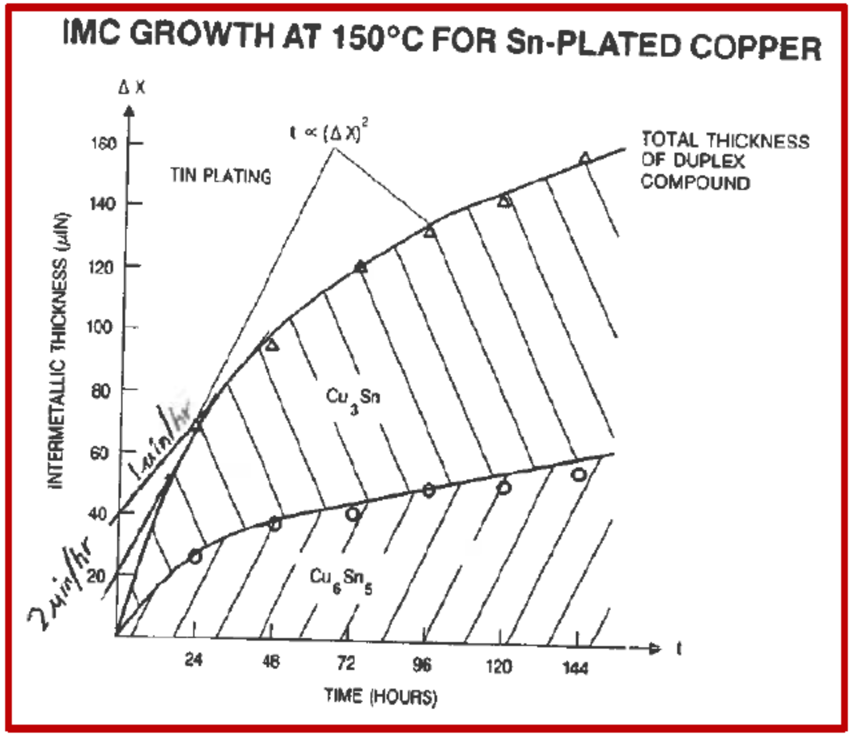
On Right: Lead-Free SnAg3.7 has Excessive Gold (Au) [10], $AuSn_4$

Metallurgical Analysis Can Solve the Interface Crack Problem.

Copper Plating and Tin-Lead (Sn-Pb) Solder

- Time and Temp. Exposure of Sn60Pb40 Tin-Lead Plating on Copper (Cu) Plating
  - Kirkendall Voids Result (find)
  - Plating Bake Time and Temp. Cause Voids Between Cu and Cu_3Sn IMC.
  - Diffusion of Copper and Cu_6Sn_5 Causes Cu_3Sn and a Line of Voids

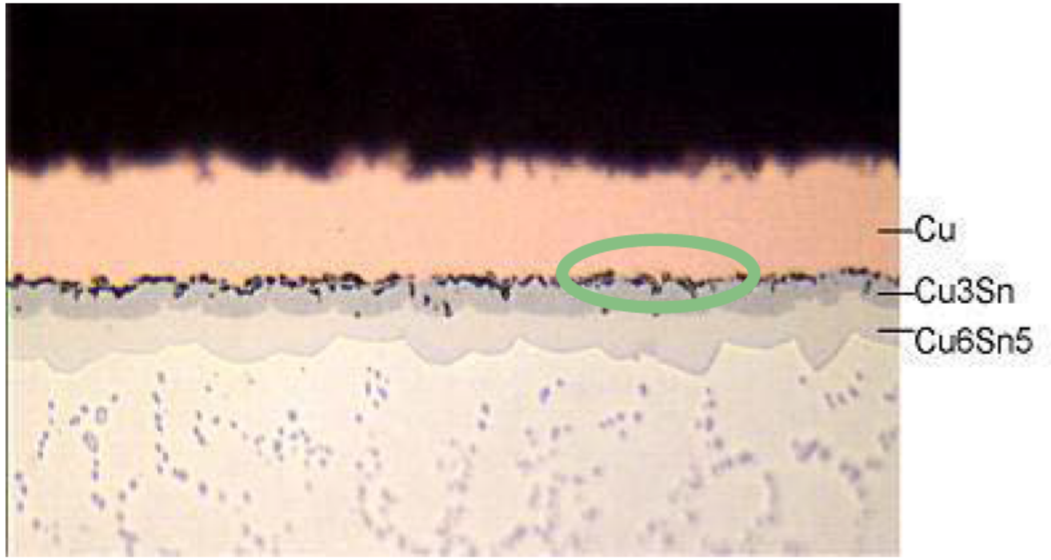




[7]

Copper Plating and Pb-Free Solder

- Time and Temp. Exposure of Sn (Tin) on Cu Plating
  - Kirkendall Voids Result (find)
  - Both Tin-Lead and Pb-Free Solder Cause Voids Between Cu and Cu_3Sn IMC
  - Organic Plating Additives and Tin Thickness are Causal Factors
  - In Plating Process, Use Higher Potential than Potential of Zero Charge (PZC) In Order to Reduce Organic Coverage (and Voids).

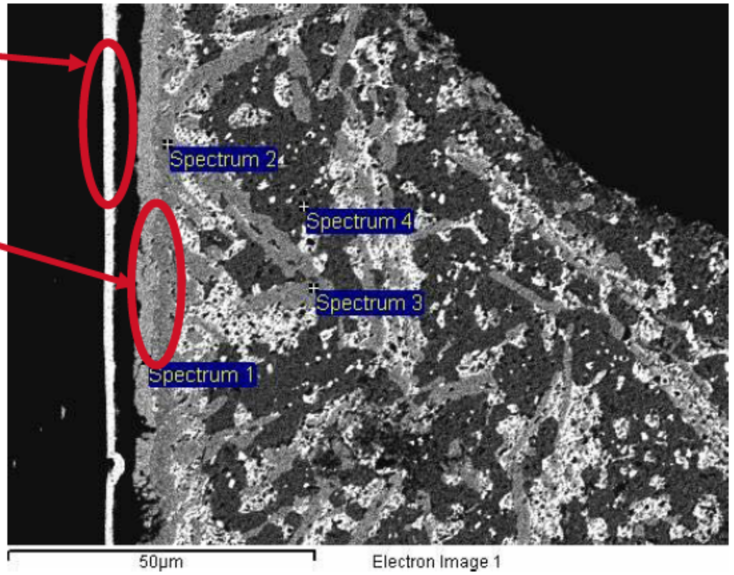


[4]

Gold Plating and Tin-Lead Solder

Solder Connection Embrittlement Mechanism: Gold Plating (Vertical White Line) on Pin is Incompletely Dissolved During Soldering. The $AuSn_2$ Occurs in a Duplex Interface Layer, Created by Solid State Diffusion.

- Sn63Pb37 Tin-Lead Solder Fillet Separates
  - From Undissolved Gold on Pin
  - Because Compound Layers Break From Gold by Solid State Diffusion.
    - $AuSn_2$ Layer Separates from Gold Layer
    - $AuSn_2$ Layer is Contiguous with $AuSn_4$ Layer.
    - Additional $AuSn_4$ Compound is Distributed Throughout Fillet.
    - Therefore, $AuSn_4$ forms during soldering and is present after solidification.
    - In contrast, $AuSn_2$ forms by solid state diffusion.



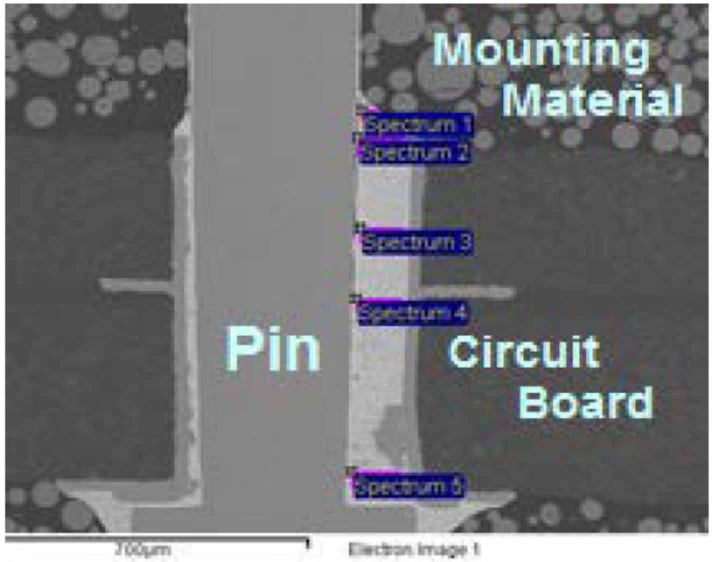
[5]

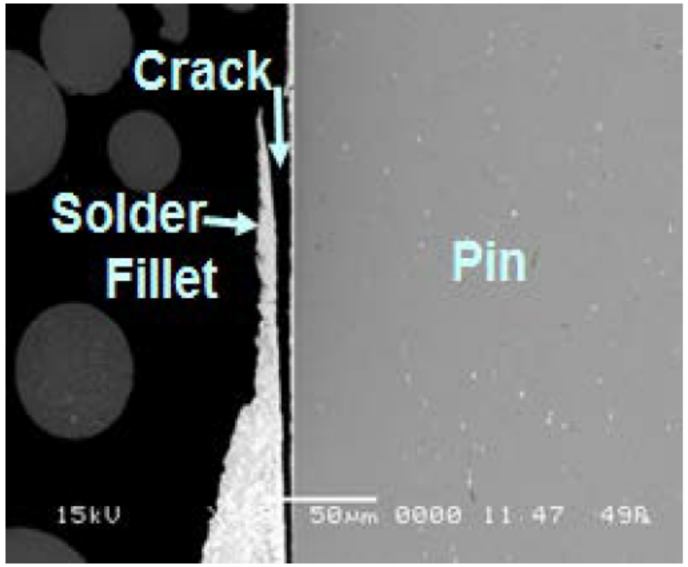
The Most Tin-Rich Compound Forms by Precipitation.

A Less Tin-Rich Compound Forms By Solid State Diffusion and Fails.

Weakness/Voids Are From Vacancy Accumulation

- Gold Plating and Tin-Lead Solder: Why Does Fillet Separate?
  - Gold Dissolution and Reaction with Tin Form $AuSn_4$ While the Solder is Molten.
  - In Contrast, Higher Melting Point $AuSn_2$ Forms by Solid State Diffusion.
  - Fast Diffusion (Warburton and Turnbull) [8] Between Undissolved Gold and the $AuSn_4$ Occurs During Cooling of the Solidified Joint, and Forms the Adjacent $AuSn_2$ Layer.
  - The Diffusion Weakens the Gold-to-$AuSn_2$ Interface due to Vacancy Accumulation.
  - The Fillet Contraction Produces a Peeling Stress and Cracks the Weakened Interface.



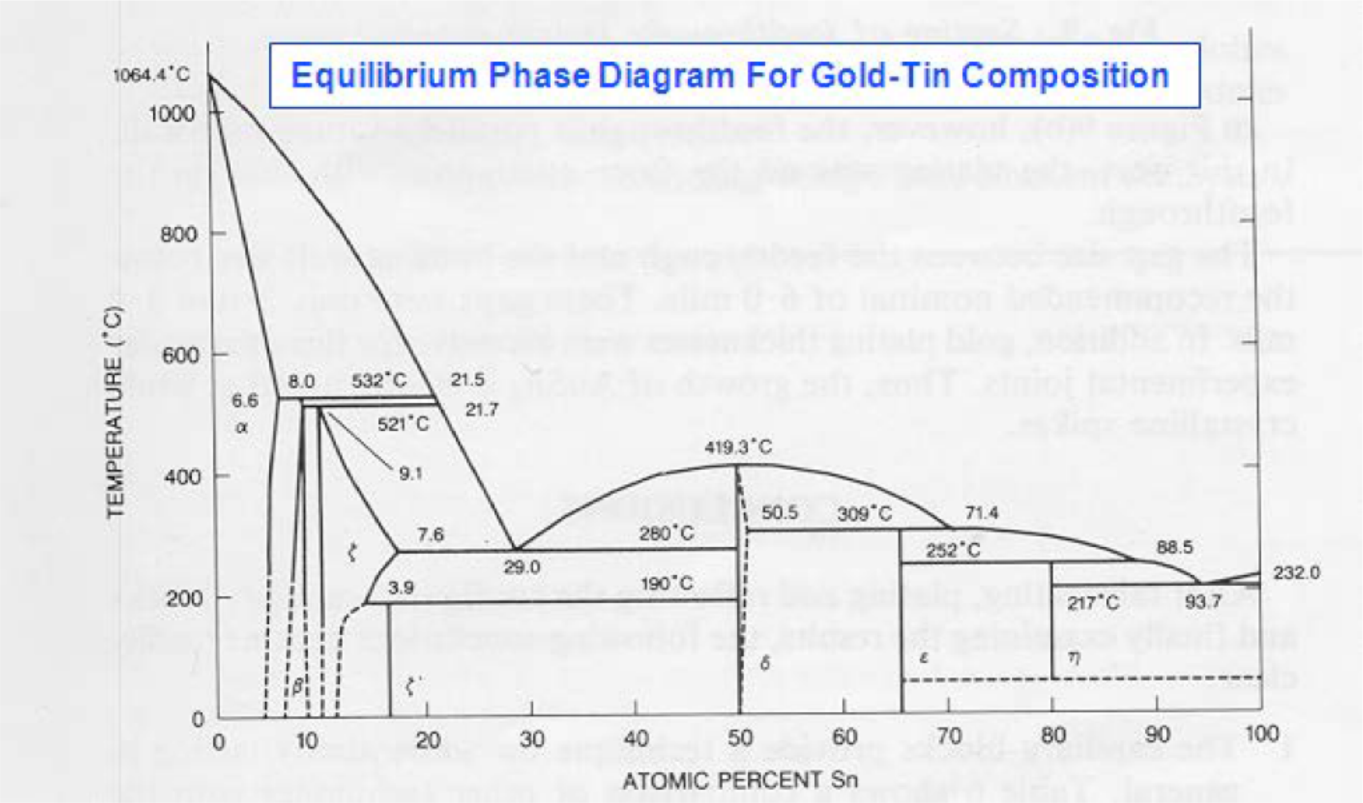


[5]

Plated Layers with Up to 20% Vacancies (Bhadeshia) [6] Enable Solid State Diffusion and Accumulation of Vacancies in a Weakened/Voided Layer.

Embrittling Compounds

- The Gold Embrittlement Culprit, $AuSn_4$ (Eta) Gold-Tin Intermetallic Compound (IMC), In Sufficient Quantity, Can Embrittle Soft Solder. It Is The Hardest Of The Gold-Tin IMCs.



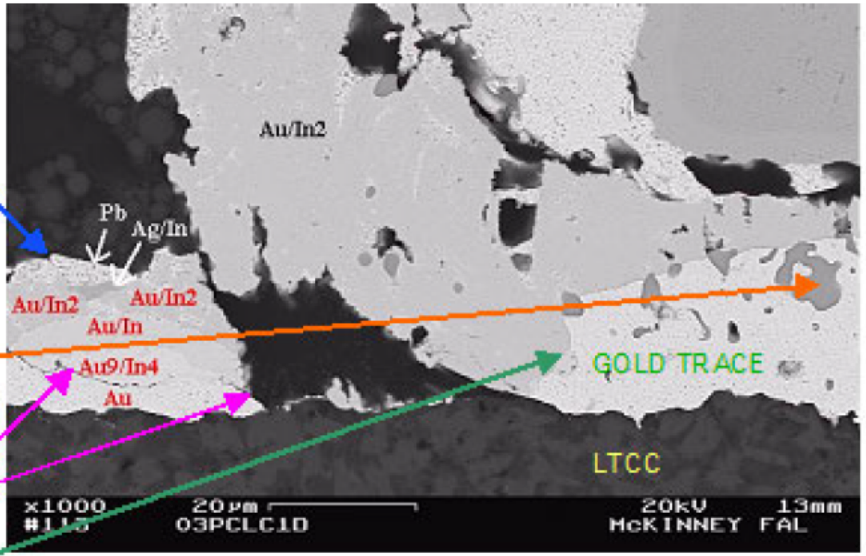
[9, 12]

Equilibrium Phase Diagrams Aid Solder-Plating Connection Analyses

Gold Plating and Indium-Lead Solder

- The Gold Trace Fails Due to Compound (IMC) Growth.
  - *Au_9In_4 Compound is the Microstructural Precursor of Connection Reliability Loss.*

- The reacted gold trace at left, has the following stack-up:
  - Lead
  - AuIn2 (67 At% In)
  - AuIn (50 At%In)
  - Au9In4 (31At %In)
  - Gold
- Particles in Thick Film contain O,Ca,Si,Cd,Ca,Co,Fe.
- Crack extends to LTCC surface.
- An AuIn2 reaction front is moving under the film into the pure gold trace. The most indium-rich compound (AuIn2) continues to form since both gold and indium remain available to react.



The crack between Au9In4 and gold (Au) extended to the LTCC surface. Then the gold trace peeled up. Indium no longer had a route to react at the compound stackup. However indium did continue to react with the curled-up trace, transforming it into AuIn2.

Thermal Exposure from 1000 Temperature Cycles Caused Diffusion of Gold and Gold-Indium IMC, Causing Failure between the Gold-Rich IMC and the Gold

Gold Plating and Indium-Lead Solder

- A Thermally Aged Connection of the Same Indium-Lead (In50Pb50) Solder Alloy, Joined to Gold Plating, Also Failed.

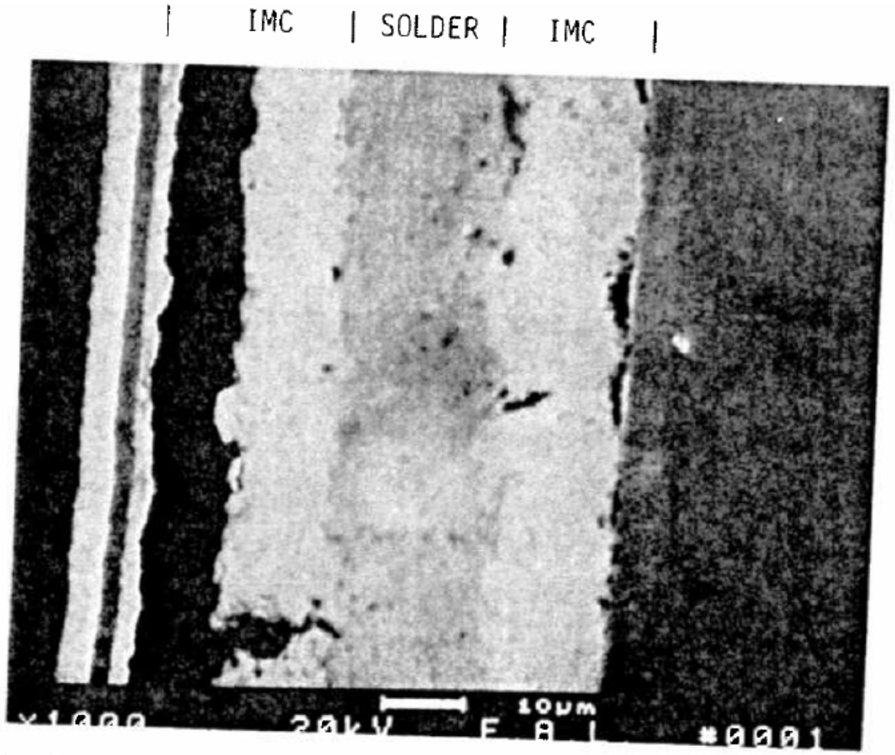


FIGURE 13B. Indium-Lead Solder Bond After Aging 50 Hours at 125C.

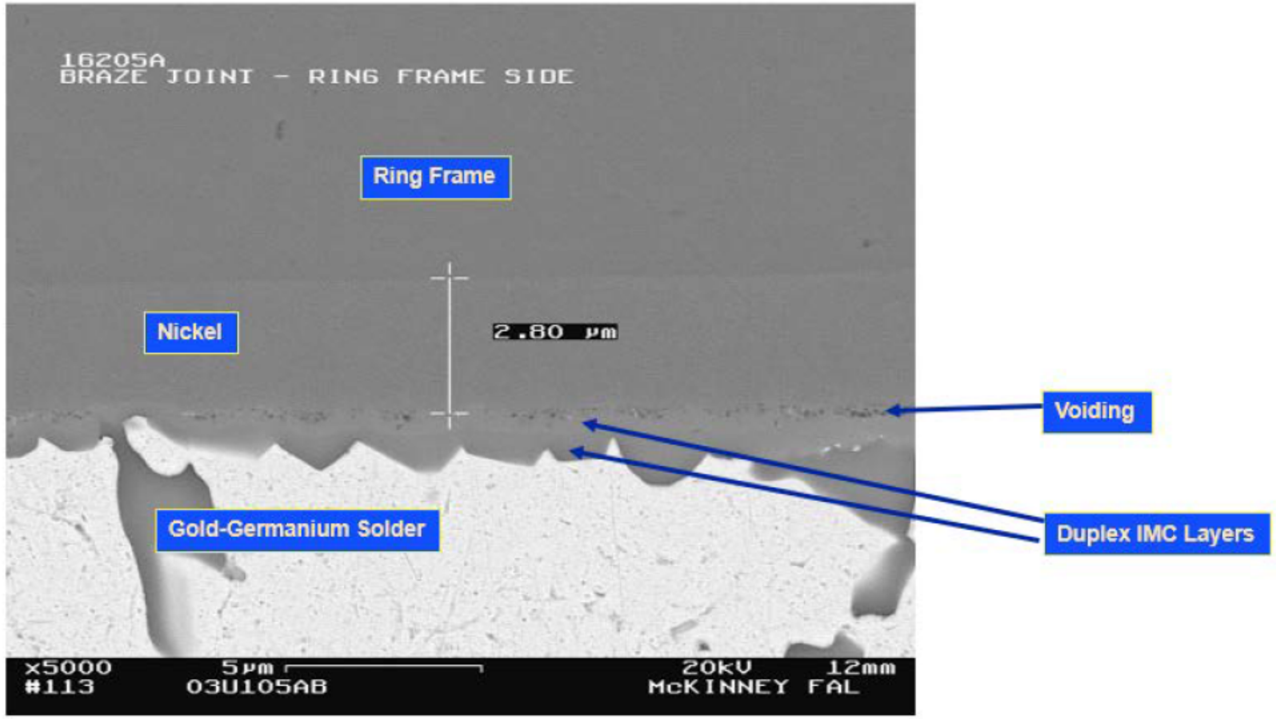
[11]

Gold Plating Vacancy Accumulation and Voiding/Separation from IMC

Nickel-Gold Plating and Gold-Germanium (Au-Ge) Solder

- Au-Ge Soldering Requires Ge Reaction with Nickel (Ni).

  - **With Gold-Germanium, Voiding Occurs In A Layer Between The Nickel and the Ni_5Ge_3 IMC**



[3]

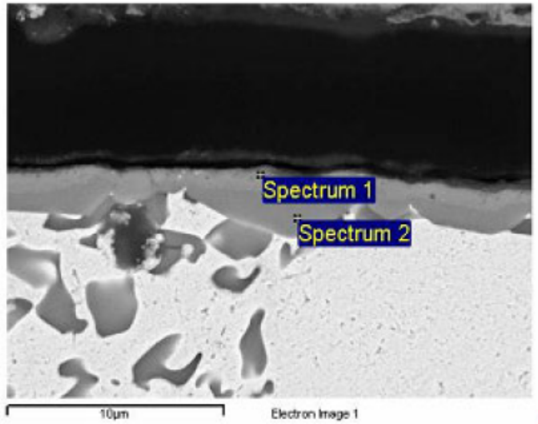
The NiGe IMC Precipitates are Scallop-Shaped at the Plating Interface.

Ni_5Ge_3 Grows Between NiGe and Ni. Vacancy-Induced Voids Result.

Nickel-Gold Plating and Gold-Germanium (Au-Ge) Solder

- During Au-Ge Soldering, Solder Melts, Compounds Form.
  - *Then Solid State Diffusion Kinetics Cause Vacancy Accumulation, Void Formation and Failure.*
    - **Identification Of The IMC, Ni_5Ge_3 , Associated With Failure of Gold-Germanium (361C Melting Point) Solder Joints**

Non-FIB Area - AuGe



Spectrum 1, Ni_5Ge_3

Element	Weight%	Atomic%
Ni K	57.92	62.99
Ge K	42.08	37.01
Totals	100.00	

Spectrum 2, NiGe

Element	Weight%	Atomic%
Ni K	44.09	49.37
Ge K	55.91	50.63
Totals	100.00	

Scanning Electron Microscopy Compositional Spectrums Identify the Ni-Rich Ni_5Ge_3 IMC, Which Separates from the Nickel Plating.

Conclusions

- Metallurgical Observations of Solder Joint Embrittlement Have Broad Application
  - Interfacial reliability risk previously was shown for tin-lead on gold finish [5].
  - Eight combinations of solder alloys and platings, including three lead-free examples, were shown here to have embrittlement and a specific IMC indicator compound.
  - All combinations exhibited interfacial failures due to separation of the plating and a relatively plating-rich compound, as a function of solder alloy and thermal exposure.
  - In contrast, a relatively solder-rich compound precipitates during soldering, and does not usually separate at the plating interface.
  - Tin-lead and lead-free solders both have a diffusion-driven, separation mechanism.
- There is a Common Failure Mechanism and Detection Method
  - Kirkendall voiding, indicated by a relatively plating-rich compound, leads to visible voiding and separation from plating.
  - Intermetallic compound identifications and phase diagram analyses enable detection
- **Aerospace Defense High Performance electronics products seek embrittlement reliability validations for each lead-free solder and plating combination**

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Thank You!

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