Test and Measurement Equipment Coalition

RoHS Scope Review of Category 9 Products

Lead in Solder, Component Finishes, and Ball Grid Array (BGA) Components Dossier

Abstract:

Due to its toxic effects upon humans, the use of lead in products of any type has become a target for elimination. In the bloodstream, lead is a toxin resulting in damage to vital organs and the central nervous system. The most common delivery route to the human body is by ingestion. Delivery by inhalation and topical exposure can also occur. Electronic products, with their use of lead in solder connections, have been targeted, along with other lead-containing products, for the complete eradication of lead.

Standard solder contains 63% tin and 37% lead and has a melting point of 183 C. Removing the lead and substituting other elements changes the melting point substantially. At this time, there is no drop-in replacement for Sn/Pb solder. Globally, there is no single replacement lead free solder alloy identified. Various alloys are proposed for electronics - the majority some combination of Sn/Ag/Cu (SAC). One frequently recommended alloy is 96.5% tin, 3% silver and 0.5% copper (SAC305). Although this alloy has one of the lowest melting points for lead free solders at 218 C, it still begins to melt at temperatures 35 degrees higher than standard solder. These higher melting points result in higher processing temperatures. This causes problems with:

- Components that are not compatible with the increased heat required; the increased process temperatures require changes in materials of construction and increase moisture sensitivity.
- PCB laminates that are not capable of surviving the increased process heat; this results in warping, delamination, softening and changes in electrical characteristics.
- Higher rework and touchup temperatures have a potential to cause localized delamination and barrel and via cracking of the PCB.

In addition to the temperature related problems, other issues exist with the change in solder formulation:

- The use of pure tin content in the finishes results in tin whiskers
- Solder joint reliability and intermetallic bond formation can be compromised.
- The wetting and flow characteristics are reduced resulting in higher defects.

1. <u>Use of Lead in solder, component finishes, and in BGAs in Test and Measurement equipment</u>

1.1 General

Lead has been used as a significant constituent in solder attachment of electronic components for more than 60 years. It has taken the Test and Measurement industry that time to achieve the level of understanding we now have for tin-lead solder assembly. Lead-free processes require significant changes and still require considerable testing and real-world experience to fully characterize and understand.

1.2 Lead in Solders

- Eutectic tin/lead solder is the industry standard alloy
- It is inexpensive, readily available, and widely recycled
- There is more than 60 years of industry generated real-world reliability data
- Lead is the most effective, known mitigant to the growth of tin whiskers

  http://nepp.nasa.gov/whisker/reference/reference.html ("A History of Tin Whisker Theory: 1946 to 2004",)

- Lead is currently subject to the following RoHS exemptions:
    - Lead in high-melting-temperature-type solders (e.g., tin/lead solder alloys containing more than 85% lead).
    - Lead in solders for servers, storage, and storage-array systems.
    - Lead in solders for network infrastructure equipment for switching, signaling, transmission, and network management for telecommunications.
    - Lead in electronic ceramic parts (e.g., piezoelectronic devices).
- Lead is currently exempted in other applications such as lead-acid batteries, which are controlled by the European Directive on end-of-life vehicles (European Directive 2000/53/EC).
- Lead is commonly used in the component finish of electronic components.
- Lead usage is highly regulated and subject to strict laws on personal safety, use, disposal, and recycling. The effect on and permissible exposure limits to humans is well understood and documented.

1.3 Technical Characteristics

- Where products are used in high reliability environments, lead in solder has a long, documented history of safe, reliable performance.
- Lead has a proven history of mitigating tin whiskers. In the past, the emphasis has been on alloying tin coatings with a minimum of 5% lead by weight for this purpose. Whisker formation has an unpredictable rate of growth, ranging from instantaneous to years. No current accelerated testing exists that can be correlated to years of product usage. At this time, testing to validate whisker formation or lack of it would require real-time monitoring equivalent to years of product life ranging from 5 to 10+ years. Future data may support some form of accelerated testing; current testing has resulted in conflicting opinions. Supporting information can be found at:

  http://thor.inemi.org/webdownload/newsroom/TW_biblio-July03.pdf

1.4 Trends

Since the introduction of WEEE and RoHS legislation, many suppliers to the Test and Measurement industry are eliminating the use of lead in component and Printed Circuit Board (PCB) finishes because the majority of their business is with manufacturers making products that have to meet RoHS compliance by mid-2006. This poses serious dilemmas for Test and Measurement equipment manufacturers currently working under RoHS exemptions. The following observation is from the 3rd quarter, 2005 IPC Quarterly Supply Train Tracker: “The shift to lead-free affects the entire supply chain, including the end markets. If the trend continues, industries currently exempt from lead-free requirements may find a dwindling number of suppliers offering lead-based components. These industries may face problems due to a lack of a dual supply chain.”

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2005 Quarterly Supply Train Tracker

- Newly designed components are available only with lead-free finishes. The most critical issue here is that RoHS-compliant BGAs cannot be reliably processed using eutectic tin/lead soldering processes. Unlike most components Ball Grid Arrays (BGAs) cannot be reliably assembled on printed circuit boards using eutectic tin/lead soldering processes. Unlike most components, BGAs are NOT backwards compatible. In order to take advantage of new technology in our designs we are forced to have the BGAs re-balled with tin/lead balls. This adds cost, cycle time, and defects to the process. Furthermore, accidental processing of lead-free BGAs in a tin/lead environment results in marginal solder joints: the lower tin/lead processing temperatures are not sufficient to melt lead-free balls. For more information:

  ACI - The Impact of Reflowing A Pb-free Solder Alloy Using A Tin/Lead Solder Alloy Reflow Profile On Solder Joint Integrity

- Our Test and Measurement equipment customers are requiring that we do not supply them with products containing “prohibited materials.” These prohibited materials are NOT necessarily materials regulated by the RoHS legislation. They are simply materials our customers are asking us not to use in products we sell them. In their words, “As you are aware, use of prohibited materials in our applications can have negative and potentially catastrophic effects. The prohibited materials, coatings, and finishes are as follows:

    - Pure tin and tin alloy coatings and finishes greater than 97% weight tin….."
    - Pure tin is the most widely used lead-free component finish…
    - We are trapped between the competing demands of RoHS and our high reliability customers.

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  Raytheon Request Letter to National Instruments

- Changing existing components to lead-free versions forces high reliability manufacturers to:
    - Spend additional time, money, and resources re-qualifying every part to ensure package integrity and reliability;
    - Rework components to safer equivalents (re-balling BGAs, re-plating component leads).

Empfasis - Tin Whiskers and the Impending RoHS Conversion to Lead-free

- Older, low volume, and custom-designed parts are being discontinued rather than transitioned to lead-free replacements, forcing high reliability manufacturers to:
    - Perform costly, speculative lifetime buys which increases the potential scrap of lead bearing components;
    - Discontinue maintenance and support of products with years of service left because replacement parts are not available. This also increases the scrap of lead containing equipment.

2. Alternatives for Lead

2.1 Alternatives for lead in solder include:

- Tin-Silver-Copper (SAC) alloys
- Tin-Bismuth alloys
- Tin-Nickel alloy

The primary problems with lead solder alternatives are:

- Alternative alloys have little data to support long term success in high reliability applications especially across the commonly required temperatures (-40C to +70C) and environments Test and Measurement products experience. Additional information can be found at:

  CALCE Long-Term Pb-Free Study

- The high tin content alloys can cause catastrophic failure due to tin whiskers:

  http://thor.inemi.org/webdownload/projects/ese/tin_whiskers/User_Group_mitigation_May05.pdf

  http://www.inemi.org/projects/ese/tin_whisker_activities.html

  NASA Goddard Tin Whisker Homepage

- Tin-Bismuth alloys are extremely sensitive to lead contamination levels rendering them unsafe for use in a transitional environment. Even small amounts of lead in a tin-bismuth solder joint can lead to the formation of a ternary alloy of tin, lead and bismuth that melts at 96ºC. This ternary alloy can collect in the solder joint and cause decreased reliability in applications that approach or exceed the melting temperature.

- The temperature increase required for lead free processing induces additional strain on the laminates and the components used on them.

2.2 Alternatives for lead in component finishes include:

- Pure Tin plating
- Nickel Palladium (NiPd)
- Nickel Palladium Gold (NiPdAu)
- Nickel Gold
- SAC alloys
- Pure Silver plating

The primary problems with alternatives for lead in component finishes are:

- Pure tin plating can cause catastrophic failures due to tin whiskers.
- Availability of components in finishes other than pure tin is limited at this time.
- Increased cost and cycle time. Additional information:

  Green SupplyLine | Get the lead out
  http://www.npl.co.uk/ei/documents/matworld.pdf

2.3 Alternatives for lead in PCB finishes include:

- Immersion Silver
- Immersion Tin
- Electroless Nickel/Immersion Gold (ENIG)
- Organic Solderability Preservative) (OSP)
- Lead-free Hot Air Level (HAL)
- Electroplated Nickel Gold

The primary problems with lead alternatives in PCB finishes are:

- Silver is currently restricted by regulation. Limited data shows that silver leaches more readily into water than does lead. For more information:

  http://www.leadfree.org/files/RoHS_16.pdf

  http://eerc.ra.utk.edu/ccpct/lfsp-docs/Solder_Leachate_Report1.doc

- Pure tin plating is prone to tin whiskers. Further information can be found at the same links above.

  http://thor.inemi.org/webdownload/projects/ese/tin_whiskers/User_Group_mitigation_May05.pdf

  http://www.inemi.org/projects/ese/tin_whisker_activities.html

  http://www.empf.org/empfasis/july05/whiskers705.htm

  NASA Goddard Tin Whisker Homepage

- NiPd and NiPdAu finishes are more expensive and not widely available (less than 10% of commercial components use these finishes). Additional information can be found at:

  http://www.hdpug.org/public/4-papers/2005/finishes/ppf-final-report-ver2.pdf

- OSP has poor solderability performance on repeated thermal cycles.
- Lead-free HAL suffers from the same issues as tin plating; it is prone to the formation of tin whiskers.
- Electroplated Nickel Gold is more expensive and not widely available.

3. Selection and Testing of substitutes

Today, the solder alloy most frequently used in Test and Measurement equipment is the Sn (63%)/Pb (37%) eutectic alloy with a melting point of 183^{o}C. Not long ago there were more than 100 lead-free solder alloys under consideration. Today, after extensive testing and many immediate failures, the leading lead-free solder alloy in the electronics industry is: Sn (96-97%), Ag (3-4%), and Cu (0.5-0.7%) (or simply SAC alloy). The melting point is approximately 217^{o}C – which is 34^{o}C higher than that of traditional SnPb solder alloys!

There are a number of undesirable impacts due to the use of SAC solders. During PCB assembly with SAC solders, sensitive electronic components and PCB substrates are subjected to much higher soldering temperatures; additional defect cost, long-term performance, and reliability are of great concern. Since the use of SAC solder alloys is in its infancy in the Test and Measurement equipment industry, long term solder joint reliability is unknown. The addition of silver into solder is also a concern. In the US, silver is regulated as a toxic substance and has been shown to leach into ground water. Finally, energy consumption using SAC solders increases by nearly 20% due to the significant increase in processing temperatures required. In summary: by using SAC solder, products may not be reliable enough for Test and Measurement applications, and use of SAC solder can have adverse effects upon the environment.

4. Impact of Substitution on Reliability

Reliability of the solder joint of a particular package in electronics products is defined as the ***probability*** that the solder joint will perform its intended function for a specified period of time, under a given operating condition, without failure. Most reliability tests are accelerated tests with increased intensity of exposure to aggressive environmental conditions using realistic sample sizes and test times. Thus, acceleration models are needed to transfer the failure probability, reliability function, failure rate, and mean time to failure from a test condition to real-world operating conditions. In establishing the acceleration models of lead-free solder joints their surrounding materials, (e.g., solder, molding plastic, ceramic, copper, fiber reinforced glass epoxy, and silicon), loadings (e.g., stress, strain, temperature, humidity, current density, and voltage), and failure mechanisms and modes (e.g., overload, fatigue, corrosion, and electromigration) must be considered. At least a dozen models have been established since 2003 for SAC solder reliability assessment under thermal cycle conditions. But, the industry has not yet adopted, accepted, or validated any of these models for lead-free soldering.

http://www.jpclech.com/CLECH_SMTAI2005_PAPER.pdf

http://www.jpclech.com/CLECH_SMTAI2005_PRESENTATION.pdf

4.1 As discussed earlier the most commonly used substitute for standard tin/lead solder is an SAC (Tin-Silver-Copper) solder. SAC alloys require solder processing temperatures of at least 34°C degrees higher than those commonly used for traditional tin/lead solders. Higher processing temperatures have driven changes in PCB laminates, components, and assembly processes. All of these changes have negatively impacted reliability.

4.2 PCB Changes

4.2.1 Laminate: The laminate resin changes from bisphenol, an epoxy, to a high thermal decomposition phenolic resin. Changes in polymer structure will result in changes to the electrical characteristics of the material such as dielectric constant, dissipation factor, and controlled impedances. In addition, the changes made to laminates to make them withstand higher processing temperatures have increased failures caused by several unique modes.

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Assessment of the Suitability of Current PCB Laminates to Withstand Lead-free Reflow Profiles

4.2.2 Reparability: The exposure to higher soldering temperatures and SAC alloys reduces the ability to repair and rework PCB assemblies. New, lower limits have been imposed on the number of times a repair can be attempted in a lead-free processing environment. Repairs to soldered components using SAC alloys have been shown to cause the following failures.

4.2.2.1 Plated Through Hole (PTH) Via Cracks due to Z axis expansion. Since PCB laminates see much higher temperatures in lead free processes, the PCB expands more in the Z direction. This creates an increased potential for cracks in vias and PTH barrels.

http://www.dfrsolutions.com/Information/Printed%20Circuit%20Boards%20and%20Pb-Free.pdf

4.2.2.2 Cracks in the Laminate: Cracks created due to high temperatures required for repair. This photo shows a crack next to a repaired lead-free PTH joint:

4.2.2.3 Copper Dissolution: Partial or complete dissolving of the PCB copper plating into the SAC alloy.

4.2.2.4 Fillet Lifting: Separation of the external land from the PCB. See photos attached in section 4.5.2

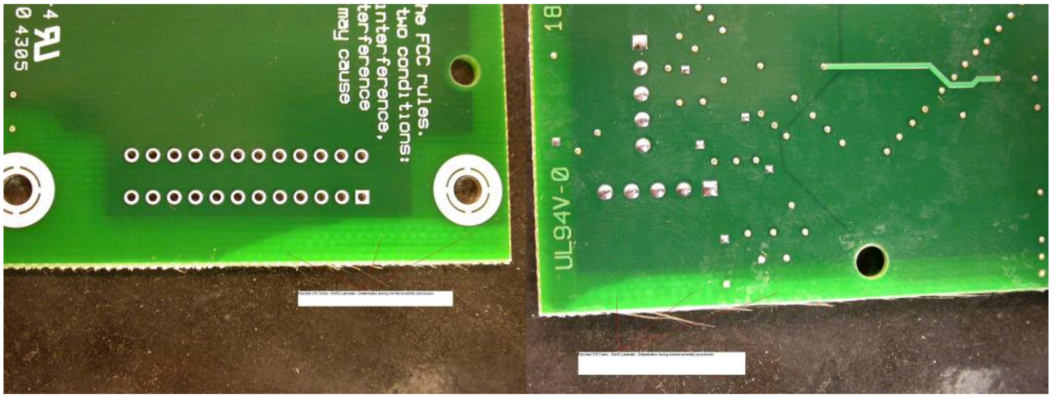
4.2.3 Conductive Anodic Filament (CAF): CAF is a PCB failure mode that occurs mostly in humid environments and has caused catastrophic field damage. A conductive filament forms along the epoxy/glass interface from anode to cathode. Higher process temperatures increase the likelihood of the failure significantly. PCB suppliers have put additional tests in place to catch and prevent this failure mode. However, long term reliability has not been established. Additional data can be found at:

http://www.smta.org/files/SMTAI00-Turbini.PDF

4.2.4 Pad Cratering: Since both the RoHS laminates and lead-free solder joints are more rigid, more stress is transmitted into the laminate during the manufacturing process. This strain results in fractures under BGA components. To reduce this failure mode, we have had to implement reduced strain limits for lead-free assembly processes and institute a revised testing protocol. The defect is only identifiable through destructive testing and is capable of escaping to the field. Additional data can be found at:

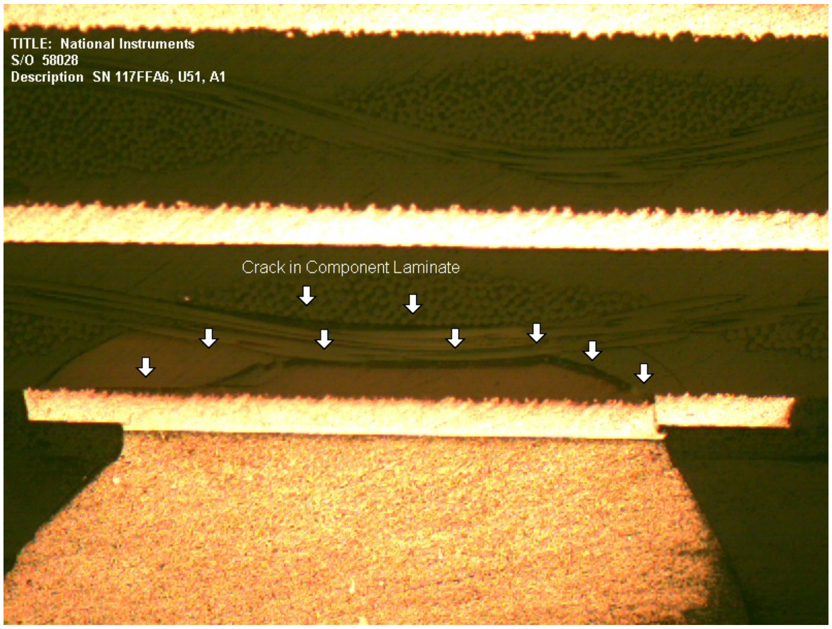
http://www.dft.co.uk/BTW2005/Presentations/6-Joyce-Board%20Test%20Workshop%202005.pdf

4.2.5 Delamination: Again, the RoHS laminates are more rigid (brittle) than the laminates commonly in use today so they are prone to delamination caused by the assembly depanelization processes. (Small PCBs are commonly built with multiple cards on a given panel. This allows for greater efficiency in assembly processes. After processing, the multiple PCBs are separated using various types of depanelization or singulation processes. These separation processes include routing, scoring, and use of clipper tabs or mouse bites.)

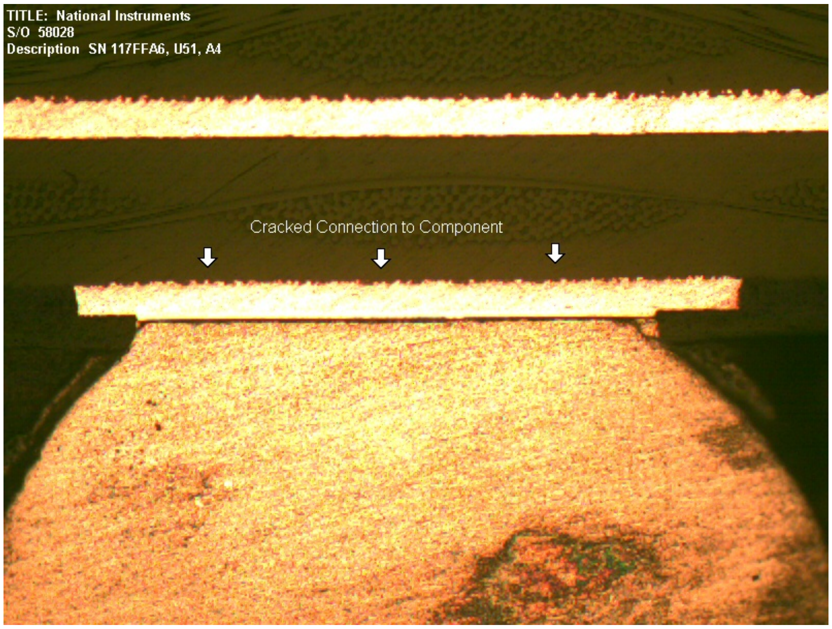


4.3 BGA Specific Failures: We have experienced failures with the combined use of lead-free BGA components, RoHS-compliant laminates, and lead-free soldering processes.

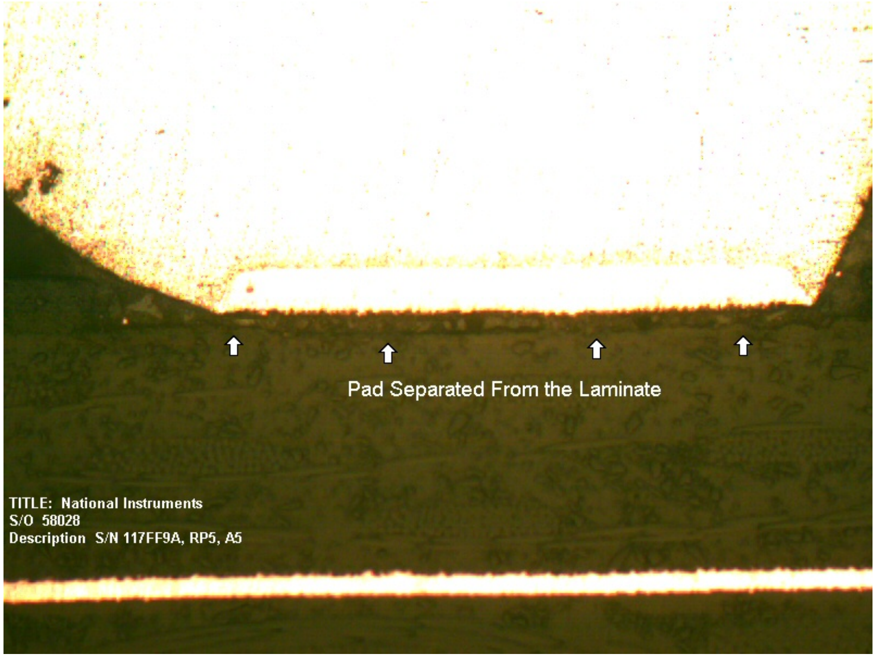
4.3.1 Cracks in BGA laminate.



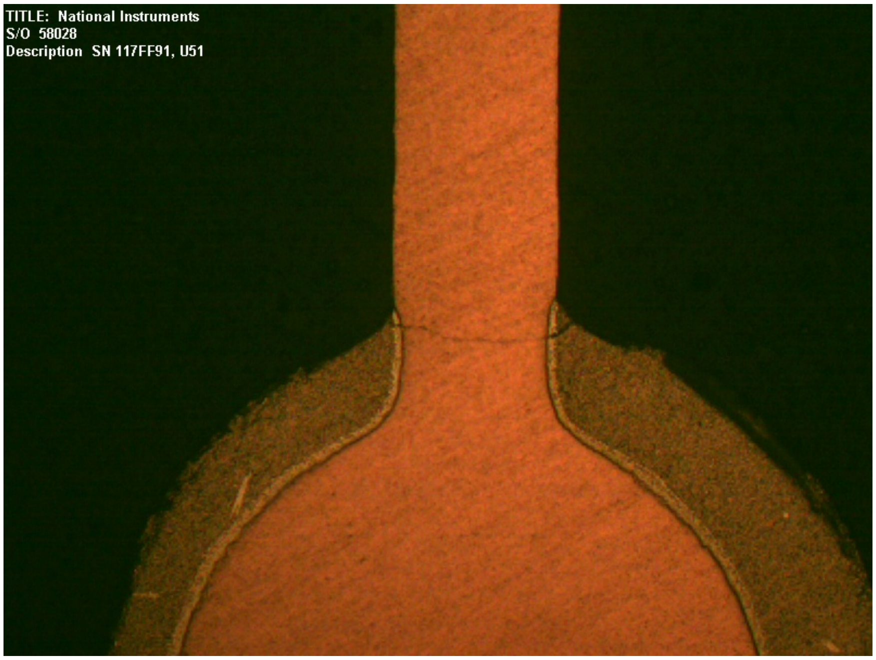
4.3.2 Cracks at ball to BGA interface.



4.3.3 Cracks at BGA pad to PCB interface.



4.3.4 Cracks in traces from outer rows of BGA balls.



4.4 Component Changes: Changes to components to allow higher temperature processing have left them vulnerable to increased failure as well.

4.4.1 Moisture Sensitivity Levels (MSL) Failures: Higher processing temperatures increase vulnerability to “popcorn” failures caused by moisture absorbed into plastic body components.

This moisture is volatilized at processing temperatures and causes the components to crack or explode. Because of the greater than 34°C degree soldering temperature increase required by SAC alloys, more components fall into higher MSL categories which require greater control and restriction with an increased likelihood of failure. Link to further information:

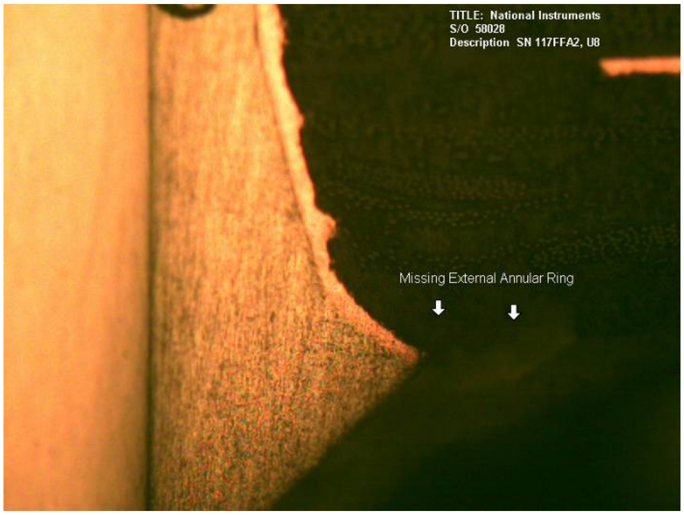
http://www.dfrsolutions.com/Information/Popcorning.pdf

4.4.2 Component Finish Failures: The component finishes have converted primarily to pure tin finishes prone to tin whiskers. (Discussed earlier.)

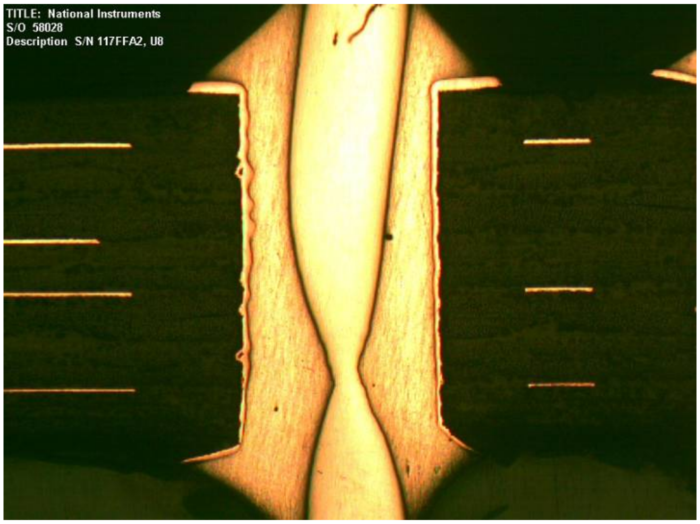
4.4.3 Plastic/Plasiticizer Failures: The plastics for many component bodies require modifications to withstand higher processing temperatures. These changes alter electrical performance for some types of components. This then drives design changes to legacy products. In some cases the components are indeed RoHS compliant but not RoHS process compatible meaning that they contain no restricted substances but they are NOT capable of withstanding peak SAC solder process temperatures.

4.5 Solder Joint Long Term Reliability: The changes made to bulk solder, component finishes, and soldering processes have drastically altered the mechanics of the solder joint. Lead-free solder joints have proven more prone to the following defects:

4.5.1 Copper Dissolution: In this photo the annular ring has been dissolved away from contact by a lead-free solder fountain.

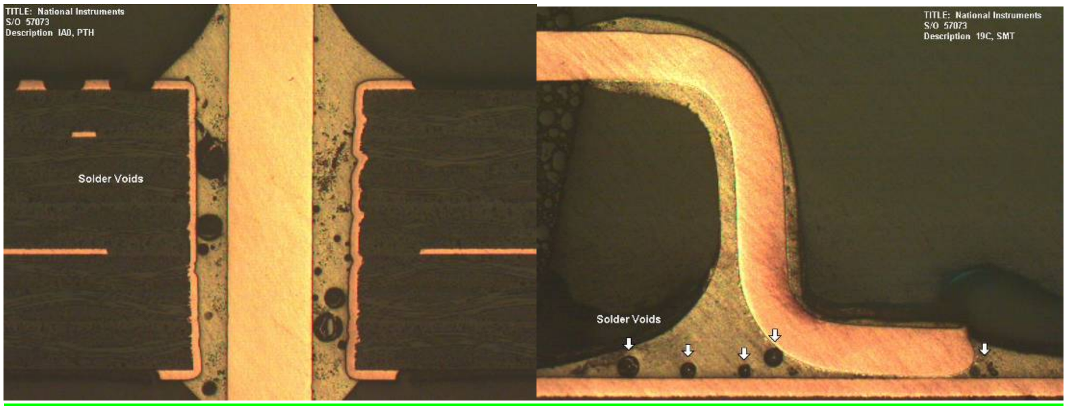


4.5.2 Fillet Lifting: This photo shows lifting at the bottom of the solder joint – note the flared angles at the base:



4.5.3 Repaired PTH Hole Fill: Note almost complete lack of solder in the hole. This area was difficult to heat and fill with solder without adversely affecting adjacent components.

4.5.4 Voids: Voids are more prevalent in lead-free solder joints. The long-term impact on reliability is currently unknown.



Clearly there will be impacts on producers in order to carry out due-diligence surveys on suppliers of all potentially affected parts with a view to obtaining compliance declarations. The cost will be amortized to the extent that each part declaration will include compliance data information (absence, etc.) for all RoHS substances in each part.

5. Environmental

- There is an energy impact. Lead-free solder processes require higher temperatures for both soldering and cleaning along with increased HVAC.

- Non-compliant materials containing lead will be disposed of as waste.

- Products experiencing shorter life cycles and failed repair will result in a larger amount of disposed waste product. Shorter life cycles would also result in higher usage of materials to build new/replacement products.

6. Safety

- Malfunctioning Test and Measurement equipment used in high voltage or amperage industrial or maintenance applications can result in serious injury or death to the operator.

- Erroneous readings from malfunctioning Test and Measurement equipment can yield incorrect data and/or information resulting in equipment that is miss-adjusted, misinterpreted, or miss-calibrated causing failure in mission critical or life critical applications.

7. Financial

- New process equipment must be purchased including pre-heating ovens, reflow ovens, wave solder machines, rework stations, fixtures, etc. This new equipment is needed to address the higher processing temperatures, materials compatibility, and to provide tighter process control necessary for SAC soldering. Significant process analysis and tuning will be needed to improve yields and reduce defects over time.

- There are higher material costs:
    - PCB board laminate
    - PCB final finishes
    - Component final finishes
    - Higher temperature resistant component packaging
    - Solder alloys
    - Loss of non-compliant inventory
    - Increased field failure and repair

- There will be higher production and product costs:
    - Material qualification
    - Process development
    - Process qualification
    - Increased defects and related repair
    - Documentation control
    - Higher equipment maintenance
    - Higher energy consumption
    - Training

8. Re-Design/Qualification

- There is a possibility for re-design. However the ramifications are huge. High reliability/long life cycle products, particularly in the Test and Measurement industry, have a lot more technology involved than those required by mainstream electronic manufacturers.

- Unlike consumer and general commercial products, Test and Measurement equipment is expected to function at a much higher level of reliability and performance/accuracy over the product's life. These are tools used by other electronic designers and manufactures to measure, adjust, and calibrate their end products and processes.

- Material changes to meet higher processing temperatures require functional qualifications as well as reliability qualifications. Certain critical circuits are sensitive to parametric changes (impedance, capacitance, voltage creep, dielectric constant, etc.) in materials. Also note that our industry sector is characterized by low-volume high-mix products; the qualification costs for such products will be large.

- When developing Test and Measurement products, the various materials and processes used in their assembly are incorporated into their performance design. This includes not only the circuit design and components but also the circuit board laminate, solder mask, and assembly processes. Changes to laminate, assembly processes, different components and materials of construction can all influence the final electrical performance of the finished product. Such physical parameters as dielectric constant, dissipation factor, and impedance can all be affected. This is of particular concern in high frequency

Test and Measurement equipment. Changes in dielectric constants and laminate construction can dramatically alter high frequency response. The re-design qualification is highly involved and very complex. Because of the multiple factors and interactions involved it is not unusual for qualification processes to take 1 to 2 years for each product affected.

http://www.smta.org/files/SMTAI02-Brist.pdf

http://grouper.ieee.org/groups/802/3/10G_study/public/jan00/morgan_1_0100.pdf

9. Requests/recommendations

Tin-Lead (Sn-Pb) solder is a key element in Test & Measurement sector applications as it is used to make electrical connections between components mounted on assemblies in virtually all our products. Lead in solder has been crucial to the development of highly reliability over generations of products providing a successful inhibitor to control growth of tin whiskers. Reliable joint connections are also heavily dependent on material finish layers of component lead-frame and ball joins.

Our members have spent considerable time testing potential Tin-Silver-Copper (SAC) solder using conventional Sn-Pb as a baseline to assess the reliability of SAC solders and component finishes in our product operational environments.

Reliability data means the probability and confidence levels required to prove that Pb-free solder joints under specific operating conditions and periods of time will perform equally as well as lead solder. The operating conditions of Test and Measurement products have wider extremes than other sectors already in scope of the RoHS Directive. We must ascertain the failure mechanisms, failure modes, acceleration models and acceleration factors of Pb-free solder joints under these extremes including temperature, shock, vibration, mechanical shear, pull, twist and bend, electromigration, corrosion and humidity.

Extensive investigations and test results of our pilot developments to date reveal:

- Insufficient long-term reliability data on tin whisker mitigation using Pb-free solders and material finishes. Currently some clients are refusing to buy products assembled with lead-free solder for this reason and they will not change their position until this issue is resolved.
- Insufficient long-term reliability data on Pb-free solder joint reliability and indications of degraded reliability in the short-term below 0ºC – we have products operating as low as -40ºC.
- Board de-lamination and pad lifting in assembly or repair situations giving rise to scraped board assemblies
- Unknown effects of higher processing temperatures on component lifetime and product stability
- Unknown consequences of dependencies on board material and lead-free conductors – these include transmission line effects at high frequencies in Test and Measurement products (frequencies which must exceed the frequencies on boards being tested by our customers.)

Only when these factors are understood will we be in a position to confirm if lead-free solders, compatible components, component finishes and balls on ball Grid Array packages can be realized successfully and reliably in all product families. **We request an exemption for lead solder and component finishes including ball grid arrays in monitoring and control products since there is no scientifically practical alternative which is proven to meet reliability requirements over the range of operating conditions of products in our sector.** This exemption will require periodic review of evidence to determine when it may be withdrawn and lead-free substitutes phased-in.

Phase in period

As shown in our sector description (page 26) annex, lead solder is widely used in most Test & Measurement product applications. After reliability of lead-free solder technology is proven to be acceptable in our applications, our sector will need five years as a minimum to implement practical alternatives in all products. We have extensive numbers of custom (ASIC) chips which will incur time and cost to convert and test in addition to the large numbers of products constructed with off the shelf components; consequently the impacts of converting all existing designs with current resources even in five years will in all probability cause overloading of our capacity to introduce new products during the phase-in period.