IEC/TS 62647-22

Edition 1.0 2013-09

TECHNICAL SPECIFICATION

Process management for avionics – Aerospace and defence electronic systems containing lead-free solder –
Part 22: Technical guidelines

IEC/TS 62647-22:2013(E)

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

Useful links:

IEC publications search - www.iec.ch/searchpub

The advanced search enables you to find IEC publications by a variety of criteria (reference number, text, technical committee,…).
It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished

Stay up to date on all new IEC publications. Just Published details all new publications released. Available on-line and also once a month by email.

Electropedia - www.electropedia.org

The world's leading online dictionary of electronic and electrical terms containing more than 30 000 terms and definitions in English and French, with equivalent terms in additional languages. Also known as the International Electrotechnical Vocabulary (IEV) on-line.

Customer Service Centre - webstore.iec.ch/csc

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: csc@iec.ch.

IEC®

IEC/TS 62647-22

Edition 1.0 2013-09

TECHNICAL SPECIFICATION

Process management for avionics – Aerospace and defence electronic systems containing lead-free solder –
Part 22: Technical guidelines

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE XB

ICS 03.100.50; 31.020; 49.060

ISBN 978-2-8322-1112-0

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

____

PROCESS MANAGEMENT FOR AVIONICS – AEROSPACE AND DEFENCE ELECTRONIC SYSTEMS CONTAINING LEAD-FREE SOLDER –

Part 22: Technical guidelines

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

The main task of IEC technical committees is to prepare International Standards. In exceptional circumstances, a technical committee may propose the publication of a technical specification when

- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC/TS 62647-22, which is a technical specification, has been prepared by IEC technical committee 107: Process management for avionics.

The text of this technical specification is based on the following document: IEC/PAS 62647-22[1].

This technical specification cancels and replaces IEC/PAS 62647-22, published in 2011. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) Coherence with IEC/TS 62647-1 and IEC/TS 62647-2 definitions.

b) Reference to IEC 62647 documents when already published.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
107/205/DTS	107/218/RVC

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62647 series, published under the general title *Process management for avionics – Aerospace and defence electronic systems containing lead-free solder*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

1 IEC/PAS 62647-22, which served as a basis for the present document, has been derived from GEIA-HB-0005-2.

INTRODUCTION

0.1 General

The global transition to lead-free (Pb-free) electronics impacts the aerospace, defence, and high performance (ADHP) industry and other industries having high reliability applications in various ways.

0.2 Transition to Pb-free

In addition to the perceived need to replace the tin-lead solders used as an interconnect medium in electronic and electrical systems, the following variations to established practice will need to be considered:

- components and printed circuit boards (PCBs)/printed wiring boards (PWBs) will need to be able to withstand higher manufacturing process temperatures;
- printed circuit boards (PCBs)/printed wiring boards (PWBs) will need to have robust solderable lead-free (Pb-free) surface finishes;
- manufacturing and inspection techniques are needed that yield repeatable reliability characteristics;
- at least initially, Pb-free alloys used within the equipment should be restricted to those that are compatible with tin-lead soldering systems;
- a maintenance strategy should be developed that will facilitate the support repair of new and existing equipment throughout a long life time which can be higher than 20 years.

This document will establish guidelines for the use of Pb-free solder and mixed tin-lead/lead-free alloy systems while maintaining the high reliability standards required for aerospace electronic and electrical systems. Currently the largest volume of lead (Pb) in many of these electronic systems is in the tin-lead eutectic (Sn-37Pb) and near eutectic alloys (Sn-36Pb-2Ag, Sn-40Pb) used in printed circuit board/printed wiring board assemblies, wiring harnesses and electrical systems. High-lead solder alloys are not specifically addressed in this document; however, many of the methodologies outlined herein are applicable for their evaluation.

A good deal of the information desired for inclusion in this technical guidelines document does not exist. A large number of lead-free (Pb-free) investigative studies for aerospace and high reliability electronic and electrical systems are either in progress or in the initiation stage. The long durations associated with reliability testing necessitates a phased release of information. The information contained herein reflects the best information available at the time of document issuance. It is not the goal of this document to provide technical guidance without an understanding of why that guidance has technical validity or without concurrence of the technical community in cases where sufficient data is lacking or conflicting. The document will be updated as new data becomes available.

Further complicating matters is the fact that no single alloy across the supply base will be replacing the heritage tin-lead eutectic alloy and that it is not likely that qualification of one alloy covers qualification for all other alloys. Given the usual requirement for long, high performance electronic service lives, any lead-free (Pb-free) alloy will need to have predictable performance when mixed with heritage tin-lead alloys. Lead-free (Pb-free) alloys containing elements such as bismuth (Bi) or indium (In) that can form alloys having melting points within the equipment's operating temperature range will need to be considered very carefully before use. Although lead-free (Pb-free) solder alloys are still undergoing some adjustments, it appears that the Sn-Ag-Cu family of alloys will be used for surface mount assembly and either Sn-Ag-Cu, Sn-Cu or Sn-Cu-Ni (Sn-Cu stabilized with nickel) alloys will be dominant in wave solder applications. In addition, some applications are using the Sn-Ag alloy family [1] [2] [3].[2]

The majority of the lead-free (Pb-free) solder alloys being considered have higher melting temperatures than tin-lead eutectic solder. In order to make use of the lead-free (Pb-free) solders, changes to the molding compound, die attach and printed circuit board (PCB)/printed wiring board (PWB) insulation systems are being introduced to accommodate the 30 °C to 40 °C higher (54 °F to 72 °F higher) processing temperature. Thus, not only is the lead-free (Pb-free) transition changing the solder alloy, but a significant portion of the electronic packaging materials are changing as well. The higher melting point, greater creep resistance and higher strength of the lead-free (Pb-free) alloys have driven a significant amount of study into the thermal cycling and mechanical vibration/shock assessments of these new alloys.

The consumer electronics industry has invested considerable resources to ensure that lead-free (Pb-free) solder will perform adequately for their products. Creep resistance of lead-free (Pb-free) alloys can vary considerably from heritage tin-lead solders. The creep/stress relaxation performance of the solder depends on the stress level, temperature and time for a specific solder material and joint composition. Therefore, one needs to establish what the acceleration factor is between a particular test condition and application. The interpretation of the results of a head-to-head testing needs to be assessed in terms of the anticipated service conditions with respect to these acceleration factors. Thermal preconditioning prior to thermal cycling should be considered in the lead-free (Pb-free) solder assessment plan particularly as it relates to changes in solder microstructure. Modeling/analysis is needed to properly compare the tin-lead and lead-free (Pb-free) alloy performance and correct for the stress relaxation differences obtained for the various piece parts and thermal cycling conditions.

While there is much data on near eutectic SAC (e.g., SAC305 and SAC405) Pb-free thermal cycling, there is less information regarding lead-free (Pb-free) vibration and shock performance. Fortunately, the vibration and shock performance data can be obtained relatively quickly. During vibration/shock testing, the near eutectic SAC Pb-free solder behaves more rigidly than the Sn-Pb solder transferring greater loads to the interfaces between the solder alloy and the substrate interfaces. The increased amount of tin in Pb-free alloys increases the intermetallic thickness when copper substrates are used. In addition, when nickel or electroless nickel (nickel – phosphorous) substrates are used, the increased copper in the SAC alloy can result in the formation of intermetallics on the nickel interface, which are less robust than Sn-Cu or Sn-Ni intermetallics that are typical of tin-lead solder joints. Mechanical test results to-date suggest that a robust assessment of lead-free (Pb-free) alloy assembly in vibration and shock environments will need to include thermal aging for interface and microstructural stabilization prior to any dynamic mechanical testing. Alloys other than SAC should be assessed to determine their vibration and shock performance characteristics.

---

2 Numbers in square brackets refer to the Bibliography.

PROCESS MANAGEMENT FOR AVIONICS – AEROSPACE AND DEFENCE ELECTRONIC SYSTEMS CONTAINING LEAD-FREE SOLDER –

Part 22: Technical guidelines

1 Scope

This part of IEC 62647 is intended for use as technical guidance by aerospace, defence, and high performance (ADHP) electronic applications and systems suppliers, e.g., original equipment manufacturers (OEMs) and system maintenance facilities, in developing and implementing designs and processes to ensure the continued performance, quality, reliability, safety, airworthiness, configuration control, affordability, maintainability, and supportability of high performance aerospace systems (subsequently referred to as ADHP) both during and after the transition to Pb-free electronics.

The guidelines may be used by the OEMs and maintenance facilities to implement the methodologies they use to ensure the performance, reliability, airworthiness, safety, and certifiability of their products, in accordance with IEC/TS 62647-1:2012.

This document also contains lessons learned from previous experience with Pb-free aerospace electronic systems. The lessons learned give specific references to solder alloys and other materials, and their expected applicability to various operating environmental conditions. The lessons learned are intended for guidance only; they are not guarantees of success in any given application.

This document may be used by other high-performance and high-reliability industries, at their discretion.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC/TS 62647-1:2012, *Process management for avionics – Aerospace and defence electronic systems containing lead-free solder – Part 1: Preparation for a lead-free control plan*

IEC/TS 62647-2, *Process management for avionics – Aerospace and defence electronic systems containing lead-free solder – Part 2: Mitigation of deleterious effects of tin*

IEC/TS 62647-3:–, *Process management for avionics – Aerospace and defence electronic systems containing lead-free solder – Part 3: Performance testing for systems containing lead-free solder and finishes*[3]

GEIA-HB-0005-4, *Guidelines for Performing Reliability Assessment for Lead Free Assemblies used in Aerospace and High-Performance Electronic Applications*

IPC/JEDEC JP002, *Current Tin Whiskers Theory and Mitigation Practices Guideline*

3 Under consideration.

IPC-1066, *Marking, Symbols and Labels for Identification of Lead-Free and Other Reportable Materials in Lead-Free Assemblies, Components and Devices*

IPC-9701, *Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments*

3 Terms, definitions and abbreviations

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1.1
alloy composition
whole ingredients of an alloy whose weight is defined in percent

Note 1 to entry: For instance 63Sn-37Pb corresponds to a mixture of 63 % by weight of tin (Sn) and 37 % by weight of lead (Pb).

3.1.2
alloy 42
nickel-iron controlled-expansion alloy containing 42 % nickel that is often used as a lead-frame material in electronic packages

3.1.3
assemblies
electronic items that require electrical attachments, including soldering of wires or component terminations

EXAMPLE Circuit cards and wire harnesses.

[SOURCE: IEC/TS 62647-1:2012, 3.1]

3.1.4
CAF
conductive anodic filament
copper conductive filament form between two adjacent conductors or plated vias in a printed circuit board (PCB)/printed wiring board (PWB)

Note 1 to entry: See IPC-TM-650, method 2.6.25.

3.1.5
critical
state of an item or function, which if defective, will result in the system’s inability to retain operational capability, meet primary objective, or affect safety

[SOURCE: IEC/TS 62647-1:2012, 3.2]

3.1.6
creep
time-dependent strain occurring under stress

3.1.7
CSAM
C-mode scanning acoustic microscopy
method for evaluating electronic packages for internal delamination using high frequency sound waves

3.1.8
CTE
coefficient of thermal expansion
degree of expansion of a material divided by the change in temperature

Note 1 to entry: PCB/PWB CTE (x-y axis) is measured in the direction in the plane of the piece part mounting surface and is used to quantify the stresses in the solder joint arising from the differences in CTE between the piece parts and the PCB/PWB during thermal cycling. CTE (z axis) is measured in the "thickness" direction and is typically used to quantify plated through hole stress.

3.1.9
customer
entity or organization that (a) integrates a piece part, soldered assembly, unit, or system into a higher control level system, (b) operates the higher control level system, or (c) certifies the system for use

EXAMPLE This may include end item users, integrators, regulatory agencies, operators, original equipment manufacturers (OEMs), and subcontractors.

[SOURCE: IEC/TS 62647-1:2012, 3.5]

3.1.10
dicy cure
use of dicyandiamide (dicy), as a curing agent for epoxy resins

3.1.11
EM
electromigration of the PCB/PWB metallization

Note 1 to entry: Resistance to electromigration testing is typically performed between electrically biased conductors at elevated humidity and temperature.

3.1.12
eutectic
mixture of two or more metals at a composition that has the lowest melting point, and where the phases simultaneously crystallize from molten solution at this temperature

Note 1 to entry: A non-eutectic mixture will exhibit a pasty range during cooling where both liquid and solid phases are present prior to reaching the mixture's solidus temperature.

3.1.13
FR4
flame retardant laminate made from woven glass fiber material impregnated with epoxy resin

3.1.14
Fick's law
classic diffusive mass transport model where the mass diffusion is proportional to the concentration gradient in the material

3.1.15
fillet lifting
separation that occurs between a solder fillet and a PCB/PWB pad where the solder fillet has the appearance that it has lifted off the PCB/PWB pad

Note 1 to entry: The fillet lifting is caused by the formation of a low melting point phase (often a ternary alloy) or liquid phase in an alloy having a large pasty range. The thin layer of liquid present adjacent to the PCB/PWB pad results in a layer that allows the solidified solder above it to pull off the PCB/PWB pad [38] [73].

3.1.16
high performance
continued performance or performance on demand where an application (product, equipment, electronics, system, program) down time cannot be tolerated in an end-use environment which can be uncommonly harsh, and the application must function when required

EXAMPLE: Examples of high performance applications are life support or other critical systems.

[SOURCE: IEC/TS 62647-1:2012, 3.7]

3.1.17
incubation period
<tin pest formation> time required at cold temperature to initially form the brittle gray (α) tin phase from the ductile white (β) tin phase

3.1.18
inoculation
<tin pest formation> practice of facilitating the white (β) tin to gray (α) tin phase transformation by using seed particles of the gray tin phase on the white tin to reduce the nucleation barrier energy associated with the transformation

3.1.19
ICP-MS
inductively coupled plasma mass spectrometry
type of mass spectrometry used for analysis and capable of detecting metals and non-metals

3.1.20
Kirkendall void formation
void induced in a diffusion couple between two metals that have different interdiffusion coefficients

3.1.21
lead-free
Pb-free
less than 0,1 % by weight of lead (Pb) in accordance with reduction of hazardous substances (RoHS) guidelines

[SOURCE: IEC/TS 62647-1:2012, 3.8]

3.1.22
MSL
moisture sensitivity level
moisture sensitivity level rating of a plastic encapsulated electronic device as it relates to soldering

3.1.23
PCB
printed circuit board
PWB
printed wiring board
substrate using conductive pathways, tracks or signal traces etched from copper sheets laminated, and allowing to connect electrically a set of electronic components to realize a circuit card

[SOURCE: IEC/TS 62647-21:2013, 3.1.10]

3.1.24
peritectic
in a peritectic reaction, solid phase and liquid phase react on cooling to produce a new solid phase

3.1.25
piece part
electronic component that is not normally disassembled without destruction and is normally attached to a printed wiring board to perform an electrical function

[SOURCE: IEC/TS 62647-1:2012, 3.14]

3.1.26
PTH
plated through hole
plated through hole used on printed circuit boards (PCBs)/printed wiring boards (PWBs) for interconnecting between layers and for component attachment

Note 1 to entry: Plating of metal the wall of the hole allows electrical connection between internal and/or external conductive patterns on different layers.

3.1.27
repair
act of restoring the functional capability of a defective article in a manner that precludes compliance of the article with applicable drawings or specifications

[SOURCE: IEC/TS 62647-1:2012, 3.17]

3.1.28
rework
action taken to return a unit (SRU/LRU/system) to a state meeting all requirements of the engineering drawing, including both functionality and physical configuration by making repairs

Note 1 to entry: Also used to define the act of reprocessing non-complying articles, through the use of original or equivalent processing in a manner that assures full compliance of the article with applicable drawings or specifications.

[SOURCE: IEC/TS 62647-1:2012, 3.16]

3.1.29
SAC
family of Pb-free alloys containing tin, silver and copper used in surface mount technology or sometimes in wave solder processes

Note 1 to entry: The alloys typically have a composition near the eutectic (95,6Sn-3,5Ag-0,9Cu).

3.1.30
SAC-L
low silver content SAC alloys that are not eutectic compositions

Note 1 to entry: These alloys have increasingly been used for BGA package interconnects.

3.1.31
SIR
surface insulation resistance
method of electrical resistance measurement used to quantify the deleterious effects of fabrication, process or handling residues and performed on PCB/PWB

Note 1 to entry: These electrical resistance measurements are often performed after periods of humidity exposure.

3.1.32
Sn-Cu
solder or alloy refering to Pb-free alloys that are comprised of tin-copper (Sn-0,7Cu)

3.1.33
Sn-Cu-Ni
solder or alloy refering to tin-copper with nickel trace (Sn-0,7Cu-0,05Ni)

Note 1 to entry: Some formulations also include other minor additions such as germanium (Ge).

3.1.34
Sn-Pb
solder generally refering to the family of tin-lead alloys at or near the eutectic composition with or without silver added (Sn-37Pb, Sn-40Pb, or Sn-36Pb-2Ag)

3.1.35
solder ball technology
technology for a family of components employing solder balls or bumps to make mechanical and electrical connections between components and a printed circuit board (PCB)/printed wiring board (PWB)

Note 1 to entry: Examples are ball grid arrays (BGA), flip chip, and chip scale interconnections.

3.1.36
soldered assembly
assembly of two or more basic parts interconnected by a solder alloy

Note 1 to entry: A lead (Pb)-based soldered assembly is one in which the solder alloys are solely lead (Pb)-based. A lead-free soldered assembly is one in which the solder alloys are solely lead-free.

3.1.37
supplier
entity or organization that designs, manufactures, repairs, or maintains a piece part, unit, or system

Note 1 to entry: This includes original equipment manufacturers (OEMs), repair facilities, subcontractors, and piece part manufacturers.

[SOURCE: IEC/TS 62647-1:2012, 3.23]

3.1.38
system
one or more units that perform electrical function(s)

[SOURCE: IEC/TS 62647-1:2012, 3.24]

3.1.39
T_d
decomposition temperature of a PCB/PWB laminate

3.1.40
T_g
glass transition temperature of a PCB/PWB laminate

3.1.41
tin whisker
spontaneous crystal growth that emanates from a tin (Sn) surface and which may be cylindrical, kinked, or twisted

Note 1 to entry: Typically tin whiskers have an aspect ratio (length/width) greater than two, with shorter growths referred to as nodules or odd-shaped eruptions (OSEs).

[SOURCE: IEC/TS 62647-1:2012, 3.26]

3.1.42
µm
unit of length measure defined to be a micro-meter or one millionth of a meter, commonly referred to as a micron

3.1.43
unit
one or more assemblies within a chassis or higher level system to perform electrical function(s)

[SOURCE: IEC/TS 62647-1:2012, 3.27]

3.1.44
XY
paraxylylene resin conformal coating

Note 1 to entry: This is also known by the trade name Parylene. This information is given for the convenience of users of this document and does not constitute and endorsement by IEC of this product.

3.2 Abbreviations

ADHP	Aerospace, defence, and high performance
Ag	Silver
AR	Acrylic resin (related to conformal coating)
Au	Gold
Bi	Bismuth
BGA	Ball grid array (related to electronic component package)
CALCE	University of Maryland Center for Advanced Life Cycle Engineering (CALCE) consortium
CLCC	Ceramic leadless chip carrier (related to electronic component package)
CSP	Chip scale package (related to electronic component package)
Cu	Copper
EMR	Electrochemical migration resistance
ENIG	Electroless nickel immersion gold (related to PCB/PWB surface finish)
ER	Epoxy resin (related to conformal coating)
Ge	Germanium
HALT	Highly accelerated life test
HASL	Hot air solder level (related to PCB/PWB surface finish)
HAST	Highly accelerated stress test
Imm Ag	Immersion silver (related to PCB/PWB surface finish)
In	Indium
JCAA	Joint Council on Aging Aircraft (organization within the US Department of Defense that has performed extensive PB-free solder reliability testing)
JG-PP	Joint Group on Pollution Prevention (NASA group that began the Pb-free solder testing)[4]
LGA	Land grid array (related to electronic component package)

4 JG-PP Pb-free solder testing was completed with the support of JCAA.

LRU	Line replaceable unit
Ni	Nickel
OEM	Original equiment manufacturer
OSP	Organic solderability preservative (related to PCB/PWB surface finish)
Pb	Lead
PEM	Plastic encapsulated microcircuit
RMA	Rosin, mildly activated (related to solder flux type)
Sb	Antimony
SMT	Surface mount technology (related to circuit card assembly technology)
SMTA	Surface Mount Technology Association (headquarters in Edina, MN)
Sn	Tin
TSOP	Thin small-outline package (related to electronic component package)
UR	Urethane resin (related to conformal coating)

4 Approach

4.1 General

The guidelines given here are intended to be used in conjunction with IEC/TS 62647-3:– and GEIA-HB-0005-4 to demonstrate that the solder materials and processes used in a given application will be reliable. They include:

- identifying potential failure modes and mechanisms related to the solder materials, piece part types, and processes;
- ascertaining the program environmental and operating requirements;
- reviewing the details of the assembly solder process, solder stress, metallurgy, temperature capability, and solder pad/terminal attachment strength;
- selecting data sources or designing tests to evaluate the reliability of the selected materials and processes, with respect to the potential failure mechanisms, in the application;
- analyzing data or test results, and comparing them with program criteria.

The guidelines described here address the majority of concerns regarding the use of Pb-free solder in aerospace systems. The list is not exhaustive however, and other guidelines may be required for specific applications, service environments, and materials. The guidelines described here are not, by themselves, sufficient to assure the performance, reliability, airworthiness, safety, or certifiability of any given system in any given application. To provide such assurance, the program, including any unique functional, performance, and life tests, should be run per the program contractual requirements. The methods to convert data from one set of environmental conditions to another are described in IEC/TS 62647-3:– in conjunction with the guidelines given in the subsequent clauses/subclauses.

4.2 Assumption

For the purposes of this document, if the element “lead” is implied, it will be stated either as Pb, as lead (Pb), or as tin-lead.

If a piece part terminal or termination “lead” is referred to, such as in a flat pack or a dual-inline package, the nomenclature lead/terminal or lead-terminal will be used.

5 General Pb-free solder alloy behavior

5.1 General

The three main Pb-free solders are based on the tin rich Sn-Cu, Sn-Ag or the Sn-Ag-Cu (SAC) families of alloys. Sometimes small alloy additions of Bi, Ni, Ge, In, and Sb, are made to these basic alloys in an effort to alter dissolution, solidification, mechanical properties or wetting characteristics. The melting point of pure Sn is 231,9 °C (449,4 °F) and the addition of 37 % Pb to the Sn reduces the melting temperature to the eutectic point of 183 °C (361 °F). Similarly, the addition of Ag and Cu to Sn reduces the melting temperature but not to the same extent as Pb. The 95,6Sn-3,5Ag0,9Cu ternary eutectic SAC alloy melting temperature is 217,2 °C ± 0,2 °C (423 °F ± 0,36 °F) [4], the Sn-0,7Cu eutectic alloy melts at a temperature of 227 °C (441 °F) [5], and the 96,5Sn-3,5Ag eutectic alloy melts at 221 °C [5]. These Pb-free solder melting temperatures are considerably higher than Sn-Pb eutectic. The higher melting temperature of Pb-free alloys, results in a 30 °C to 40 °C increase (54 °F to 72 °F increase) in processing temperature as compared to the temperatures used to process heritage Sn-Pb alloys. Higher melting temperatures result in increased amounts of base metal dissolution (see 10.3) and increased shrinkage stresses on components during cooling. An additional consideration is that the SAC alloys have generally been found to be stronger and more creep resistant than the heritage Sn-Pb solders at typical electronic use temperatures [2] [3].

The Pb-free alloy microstructure differs substantially from the lamellar/colony structure of eutectic Sn-Pb. The microstructure of Sn-Ag alloy and Sn-Ag-Cu alloy is comprised of relatively large β phase Sn dendrites. In between the dendrites, there are arrays of β-Sn, Ag_3Sn and Cu_6Sn_5 phases [6]. In some studies large Ag_3Sn platelets have been observed. The solidification behavior strongly influences the solid microstructure. The Sn-Pb eutectic solder joint requires only 2 °C of undercooling to begin solidification [6]. In contrast, the eutectic Sn-Ag-Cu system begins solidification with the formation of the Ag_3Sn intermetallic. Unfortunately, the presence of Ag_3Sn intermetallic does not facilitate the nucleation of the β-Sn and significant undercooling can occur. An undercooling of 18 °C (32 °F) was reported for β-Sn [7]. The formation of large Ag_3Sn intermetallic plates in liquid Sn was observed during slower solidification rates for SAC alloys having 3,5 wt % and 3,8 wt % Ag and not with the 3,0 wt % Ag alloy [8] [9]. These plates are expected to change the mechanical response of the system. The Ag_3Sn intermetallic plate may stop or re-direct a crack propagating through the solder joint during environmental testing (such as thermal cycling). If the plate is in the same direction of the shear load, life can be reduced [10], but it is more common to see randomly oriented plates throughout the solderball in larger joints. The presence of Ag_3Sn plates is of greater concern for flip chip and wafer scale chip pack solder joints [11]. The volume fraction of β-Sn dendrites in the solidified solder is dependent upon cooling rate and alloy composition [12]. The grain size of the β-Sn is relatively large with respect to the solder joint size. A BGA solder joint can be comprised of as few as 10 β-Sn to 30 β-Sn grains and even fewer for wafer level chip scale package and flip chip joints [13]. Since dispersed intermetallics in a SAC alloy tend to increase the hardness and stiffness of the solder, a greater volume fraction of Sn dendrites generally results in a solder joint with decreased stiffness. Reduced solder stiffness can be beneficial in some high stress shock applications because the solder does not impart as much stress on the pad intermetallic or the pad laminate interfaces. Presently, some investigators are evaluating SAC alloys with reduced Ag and Cu content (SAC-L) from the eutectic such as 98,5Sn-1,0Ag-0,5Cu alloy in an effort to obtain improved drop shock performance of BGA assemblies. Unfortunately, the melting temperatures of SAC-L alloys are greater than the traditional SAC alloys and their thermal cycling characteristics require evaluation.

5.2 Elevated temperature

At elevated temperatures, accelerated intermetallic growth, grain growth and redistribution of constituents within the solder joint occur via solid-state diffusion mechanisms. The majority of Pb-free solder alloys being considered have substantially higher tin content than the Sn-Pb eutectic solder, resulting in a greater availability of tin to form intermetallics. The intermetallic layer development generates property discontinuities that may influence the load carrying capabilities of the solder joints during dynamic testing. Intermetallic growth on unassembled

PCB/PWB, or product that has already been fielded, can adversely affect the solderability of the PCB/PWB for initial assembly, or the entire module for repair or modification.

5.3 Low temperatures

At low temperatures, the principle concerns are the ductile-brittle transition temperature and tin pest (e.g., tin plague). The Sn-Ag, SAC, and Sn-Cu bulk Pb-free alloys exhibit ductile-brittle transition behavior that differs substantially from Sn-Pb alloys on bulk solder samples [14]. While the fracture toughness for the bulk Pb-free alloys tested by Ratchev were higher than tin-lead eutectic, the Pb-free alloys exhibit a larger, more pronounced, change in fracture toughness with temperature as compared to tin-lead eutectic alloy. It is unclear if the fracture toughness characteristics observed on the bulk samples tested by Ratchev would also be evident with solder joint size geometries. Thermal cycling tests to –55 °C 15] have not revealed a brittle SAC solder fracture surface morphology. At the present time, a systematic test of Pb-free alloy vibration and shock performance at cold temperatures is not available.

Electronic equipment that is utilized in applications having prolonged low temperature exposure may be susceptible to tin pest. The allotropic transformation of white (β) tin (which has a body-centered tetragonal structure) to gray (α) tin (which has a cubic crystal) is known as tin pest or tin plague. This transformation occurs below 13,2 °C. Above this temperature, white (β) tin is the stable form. Tin pest is potentially a menace to Pb-free solder joints because the crystalline transformation results in a 26 % increase in volume, crack generation, and brittle characteristics. The increase in volume and accompanying cracking usually causes the metallic tin to develop fractured and powdery regions on the surface. The presence of the gray (α) tin serves to promote further transformation of the white (β) tin which can eventually cause a significant amount of the metallic tin to convert to the brittle gray tin. Since solder joints are inherently small in volume, reliability may be compromised with the initiation of tin pest. Solder with 40 % Pb is seldom affected by tin pest provided that inoculation with previously transformed gray tin is avoided [16].

During the operating life of electronic piece parts, tin-rich joints will be subjected to temperature excursions (typically between –55 °C to 125 °C) with the colder temperatures being conducive to the allotropic transformation of the Pb-free solder joints. It is likely that the incubation time is reset each time the tin is exposed to temperatures above the transformation temperature. However, once powdery tin pest has formed, oxidation and phase transformation kinetics prevent the reformation of a continuous white (β) tin metal again.

An early reported instance of tin pest was described by Fritzsche [17] where the disintegration of some blocks of Banka pig tin was observed after exposure to the Russian winter of 1867-1868, when the temperature during January fell as low as –38 °C (–36,4 °F). The blocks of tin had disintegrated into granular crystalline pieces and coarse powder.

NOTE 1 The typical composition of Banka tin is 99,950 Sn, 0,007 Sb, nil As, trace Pb, nil Bi, 0,018 Cu, 0,045 Fe, nil Ag and nil sulfur [18].

The growth phase of tin pest is typically much shorter than the incubation period. The transformation may occur after a long incubation period at temperatures below 13 °C (54 °F), the rate of transformation being highest at –30 °C (–22 °F) [16]. Subjecting the tin material to a mechanical load that results in a residual tensile stress considerably accelerates the process. Some possible sources of tensile stress in Pb-free assemblies include bending of leads and thermomechanical stresses encountered during thermal excursions. Mechanical treatment decreases the nucleation time due to an increase in the number of reaction sites. Becker [19] noted that annealing and oxidation tend to increase the nucleation time. Becker usually made his tin pest observations at 0 °C (32 °F) presumably to minimize the effect that temperatures above 13 °C (54 °F) would have on the transformation nucleation and rate data. Tin pest nucleation is encouraged through inoculation with α tin [20] and elements or compounds having a diamond cubic crystal structure similar to α tin such as InSb, CdTe, and Ge [19]. The transformation is dependent upon the impurities and alloying elements of the tin. The incubation time of tin pest is highly variable.

Tin pest is not a new problem with lead-free solder. Bornemann [21] found that Pb, in the amount generally found in solder, will not prevent tin pest from eventually occurring given enough time and cold enough temperatures. The work by Bornemann highlights some of the variability associated with the transformation. Bornemann stored four un-inoculated pure tin specimens in clean sealed vials at –73 °C (–99,4 °F). One transformed in six months and the other three showed no visible traces of transformation after four years. Bornemann also found that Pb, in the amount generally found in solder, will not prevent tin pest from eventually occurring.

NOTE 2 Bornemann went through extensive effort in his second set of experiments to ensure that the tin surfaces were oxide free.

The addition of as little as 0,1 percent by weight of Sb or 0,05 percent by weight of Bi to Sn-Pb alloys inhibited the transformation. There is presently one commercially available patented Pb-free alloy containing Sb, which has a composition of 96,2Sn-2,5Ag-0,8Cu-0,5Sb. There is a possibility that the results of the Bornemann's investigation lead to a change in the ASTM B32 solder specification. The role of antimony in the prevention of tin pest in Sn-Pb alloys is discussed in IPC J-STD-006B:2009, 6.1.1.1, which concludes by stating that the minimum requirement for antimony in tin-based alloys is not necessary, presumably because no tin pest has been observed in tin-lead alloys over the last decade.

Although tin pest has been found in various laboratory tests [19] to [25], the nucleation kinetics are still poorly understood and it is unclear what the incubation time is for normally processed solder joints. Tin pest has been found under laboratory conditions in Sn-0,5Cu alloy bulk test samples [22]. Tin pest transformation was also observed on 0,010-inch-thick inoculated solder joints stored at –40 °C (–40 °F) [23]. Williams [23] found that the transformation occurs more readily in joints soldered with pure tin than in joints soldered with Sn-Pb alloy. The pure tin joints soldered at high temperature (204 °C (367 °F) above the liquidus), dissolved more Cu and tended to transform more readily than joints formed at lower temperature (4 °C (7 °F) above the liquidus). Recent experiments by Sweatman evaluated the role of impurities in commercial purity Pb-free solder alloys (Sn-3Ag-0,5Cu, Sn-4Ag-1Cu, Sn-0,7Cu-0,05Ni, and others) on the nucleation and growth of tin pest and found that Pb and to a lesser extent Bi and Ag impurities appeared to suppress the transformation of β-tin to α-tin [24]. In the first phase of the evaluation by Sweatman [24], Pb-free alloys were formulated from 99,9 % "three nines" pure tin, placed in contact with an α-Tin nucleant and exposed to a temperature of –45 °C for 180 days with no signs of tin pest, while 99,99 % "four nines" pure tin was observed to readily transform within hours. The impurity analysis of the 99,9 % pure tin revealed that the largest impurity was Pb at a level of 0,031 % followed by Sb at 0,006 % and As and Bi at 0,004 %. The second phase of the Sweatman evaluation [24] assessed the addition of 0,01 % Pb, Bi, Ag, Zn, In, P, Au, Al, Cu, Ge, Ni, Sb, Ga, and Fe alloying materials to 99,99 % pure tin in contact with α-tin for up to 30 hours and found that Pb at the 0,01 % level appeared to suppress the transformation while 0,01 % Fe significantly promotes the transformation. Sweatman suggests that since Pb occurs naturally in primary tin at around the 0,03 % to 0,01 % level, which is still well below the 0,1 % limit of the RoHS directive, there can be some confidence that tin pest will not occur in a Pb-free alloy made with standard 99,9 % "three nines" pure tin. The effect of alloying additions to tin on the promotion or inhibition of tin pest is provided in Clause 8, Table 3. With long exposure at low temperature of electroplated pure tin coatings on copper, it is possible to encounter transformation, but not with hot dip coating [25]. Bornemann [21] evaluated the transformation of electrodeposited tin and tin alloys on steel panels. The pure electrodeposited tin coatings 0,0002-inch thick (5 μm), whether inoculated or un-inoculated began to show evidence of transformation after about four days at –73 °C (–99,4 °F). Becker [19] found that reflowed electrodeposited coatings exhibited different tin pest formation characteristics. During exposure to –73 °C (–99,4 °F), the inoculated specimens exhibited transformation in 4 days while the un-inoculated specimen took 14 months. The tin-zinc electroplated samples (79,3Sn-20,7Zn, 0,0005-inch (12,7 μm) thick) did not exhibit transformation after two years at –73 °C (–99,4 °F) for either the inoculated or un-inoculated samples. Later, Becker [19] attempted to directly deposit thin gray tin films onto substrates using electro deposition or evaporation, but he was unsuccessful. Becker was however able to obtain tin pest on inoculated thin films of tin.

While tin pest has been reported under laboratory conditions on test samples, real solder joints have not exhibited tin pest. Tin-silver (Sn-3,5Ag) solder has a long history of use in high reliability applications and tin pest has not been an issue. Recent testing of Sn-0,7Cu-0,05Ni or the Sn-3,8Ag-0,7Cu solder joints evaluated in the JCAA/JG-PP –55 °C to +125 °C (–67 °F to 257 °F) thermal cycling testing did not exhibit tin pest after over 4 000 thermal cycles 15]. The thermal cycling data suggests that the incubation time clock may be "reset" each time the solder is exposed to temperatures above the gray to white transition temperature. The tin pest resistance of real solder joints has been evaluated over a 12-month period and no tin pest was observed [26]. Similar evaluations have been performed by the CALCE group and they have not observed tin pest transformation in either inoculated or un-inoculated real solder joints [27].

In summary, tin pest in solder joints may be a field concern in some applications subjected to extremely cold temperatures (e.g. –40 °C) continuously for long durations (e.g., on the order of a year). These applications may require further evaluation. In practice, refining costs of lead-free solders are likely to result in Pb concentrations just under 0,1 % and will have some tin pest resistance 15] [24] [26]. The majority of high performance applications are not expected to have an issue. Long term testing of real solder joints is continuing.

5.4 Temperature cycling

5.4.1 General

Creep-fatigue models for the various Pb-free alloys being considered are at various levels of completeness. An assessment of thermal fatigue reliability to the service environments, in many cases, presents the greatest challenge due to the long test durations. Invariably, some acceleration factor, either increased temperature difference or reduced dwell time, is required to complete the temperature testing in a reasonable amount of time. The thermal cycling performance of a Pb-free alloy is determined by its ability to survive upper and lower temperature limits, the ramp time required to transition between the temperature limits, and the dwell time at the temperature extremes.

High performance applications have historically relied on –55 °C to +125 °C thermal cycling testing to provide confidence that equipment will function reliably once it is in service. It has already been established that Pb-free eutectic SAC solder does not perform as well as tin-lead under high stress thermal cycling conditions (large temperature difference and/or large thermal expansion coefficient mis-match driven solder joints) [28]. Implicit in any thermal cycling discussion is that the printed circuit board used to connect the Pb-free technology piece parts is reliable. The PCB/PWB plated through holes and traces should be able to withstand the higher temperature Pb-free solder reflow and rework stresses and go on to perform reliably in test and service.

There has been, and will continue to be, considerable debate on why solders perform differently under different thermal cycling conditions. There are many factors influencing solder life that interact in complicated ways that are not completely understood. While the understanding of the Sn-Pb system has improved greatly over the years, the study of this system has revealed that several other factors may also be important contributors to solder fatigue. In addition to the obvious need to define thermal cycling temperature extremes, dwell time (at hot and cold) and ramp rate, the following should also be considered during an assessment of solder fatigue:

- solder joint oxidation
- stress distribution in the solder joint
- manufacturing process history
- conformal coat type
- non-linear package and PCB/PWB properties over temperature
- PCB/PWB surface finish, etc.

All these factors combined influence the long-term solder life in service and may or may not be accounted for in accelerated testing and modeling of heritage Sn-Pb solder [29] [30] [31] [32]. At the present time, there is no indication that any of the aforementioned solder life factors will be eliminated with the introduction of Pb-free technology. To the contrary, a few more factors have been added, such as Sn crystallographic orientation [13], CuSnNi ternary intermetallics [33], and ENIG interfacial concerns [34]. In addition, some phenomena that may have always been present but were not a concern with tin-lead, such as voiding at the Cu/Cu_3Sn interface [35] [36] [37] [38], will need to be understood in greater detail when Pb-free solders are used.

Generally, the thermal cycling test results indicate that for high strains, tin-lead performs better in thermal cycling than SAC alloys and that under small strain conditions (e.g., a small temperature cycle) the SAC alloy performs better than tin-lead [28] [39]. However, closer examination of the Bartelo data [28] reveals that dwell time is a significant factor in the aforementioned statement. In the case of Bartelo's 0 to 100 °C temperature range thermal cycling, SAC outperformed tin-lead for the 7- and 22-minute dwell times but at a dwell time of 112 minutes, SAC reliability was comparable to tin-lead. Generally though, long dwell time thermal cycling data is lacking and few investigators have performed testing with dwell times greater than 60 minutes, a few exceptions are Bartelo, Pan and Osterman [40]. Although modeling has been proposed to extrapolate to long dwell times [28] [39] [41] [42] [43] [44], these models continue to be updated as more package types and longer dwell time tests results become available. The nature of the mixed results observed to date suggests that a careful review of the service environments is also needed in order to avoid costs associated with unnecessarily conservative design limits.

For temperature cycling test data to be interpreted properly, documentation of test conditions and results in accordance with IEC/TS 62647-3:–, which utilizes guidance from IPC-9701, is required.

5.4.2 Solder thermal cycling failure mode

Typically intergranular fracture of the solder occurs during thermal cycling. In cases where high stresses are present, failure can occur at the intermetallic interfaces when weak intermetallic layers are present [6], but this does not usually occur in a properly designed and manufactured joint.

5.4.3 Stress relaxation considerations

One impact of using a less ductile lead-free SAC solder is that it can have 10 times to 100 times longer stress relaxation times than heritage Sn-Pb solder depending on applied stress, temperature, and the alloy type. The result of any stress testing needs to be evaluated in the context of the acceleration factor between the test and the intended use environment. Acceleration factors of Pb-free solders vary from conventional tin-lead with changes in temperature extremes, ramp rates, or dwell times. These factors should be considered in order to ensure that a representative amount of damage occurs during the cycling. The other impact is that the different piece parts on the same assembly will undergo varying degrees of stress relaxation due to the dependence of relaxation time on the applied stress. Validated model(s) will be required to translate thermal cycling results to service environmental conditions.

5.4.4 Ramp rate

IPC-9701 recommends that the ramp time be less than 20 °C per minute. It may be beneficial to accurately control the ramp rate between comparative tests because significant stress relaxation can occur during the ramp. In addition, thermal cycles having longer ramp times may be able to use shorter dwell times.

5.4.5 Dwell time at elevated temperature

Continued testing is in process to validate model performance at longer dwell times.

5.4.6 Dwell time at low temperature

Dwell time sensitivity at low temperature has not been experimentally evaluated by many researchers. Modeling suggests that the majority of damage at cold occurs because of yielding due to the slow creep rates present at low temperatures. The influence of low mean temperature on reliability is being investigated by CALCE [46]. A modeling assessment of stress relaxation time for chip components was presented by Grossman [47]. The strain remaining in a 2 220-chip capacitor solder joint after 10 minutes at –40 °C (–40 °F) was 4,2 % and after 8 hours was still 1,8 %. Note that the maximum possible strain was reported to be 5,6 %.

5.5 Rapid mechanical loading (vibration/shock)

With regards to dynamic mechanical loading such as vibration and shock, little has been done in the commercial industry, mostly because these are not environments of interest for the mainstream electronic products being driven to Pb-free. The stiffer Pb-free SAC solders are expected to transmit higher loads to the piece part terminals and the PCB/PWB pads, potentially causing increased incidence of failure in intermetallic layers, interfaces, and non-solder (copper and PCB/PWB laminate) interconnect structures. In addition, there will be an increased sensitivity to the presence of voids in the solder or at the interfaces. Another aspect of using a stiffer solder is that the reliability will be more sensitive to voids located in the solder or the interfaces. Typically, vibration solder fatigue failure is not an issue on piece parts with relatively flexible leaded terminations (as in J-leaded parts or quad flat packs). Under rapid loading conditions, solder is quite strong and stiff and the load is transferred to the leads, which typically have a smaller cross-section than the solder, so that the leads will experience fatigue failure before the solder. Thus the majority of the concern with vibration and shock loading is with area array (e.g., BGAs, CSPs) piece parts, piece parts with stiff leads, leadless devices (e.g., LCCCs), and large surface mount chip parts. Mechanical shock test performance of Pb-free solders has been found to be less than Sn-Pb solders particularly when nickel substrates are used [33] or where there is a tendency to form copper voids at the pad interface [36].

From the final results from the JCAA/JG-PP vibration testing on BGAs, the combination of eutectic Sn-Pb solder/Sn-Pb balls always outperformed the combination of Pb-free solder with Sn-3,9Ag-0,6Cu balls [48]. For other component types, the results were mixed. It is the working group's opinion that, given the propensity for Pb-free alloy to form intermetallic compounds and/or voids that could result in brittle interfaces, it seems appropriate that high performance electronics include assembly thermal preconditioning prior to dynamic mechanical testing. Unfortunately, systematic studies of thermal preconditioning times/temperatures prior to dynamic mechanical testing are still needed for a variety of device types.

6 System level service environment

6.1 General

Given that Pb-free solder alloy performance in a particular assembly is not guaranteed to be better than tin-lead solder alloy, the best way to provide an accurate assessment of the Pb-free alloy reliability is to begin with a comprehensive understanding of the electronic service environments. The results from high performance testing such as JCAA/JG-PP [49] have yielded mixed results for some piece part types. It is unlikely that a heritage assembly can be converted to Pb-free solder without a re-design activity. In low stress solder joints, SAC alloy performs better than tin-lead eutectic. As the solder stress is increased, tin-lead outperforms SAC. It is clear that each application needs to be individually evaluated when Pb-free solder alloys are being considered. It is likely that some design adjustments to reduce solder strain will be needed on some applications to implement Pb-free solder.

6.2 Service environment

The system level requirements imposed by the aerospace vehicle manufacturer on an OEM electronics system supplier are intended to ensure reliable operation of the equipment in service for its expected lifetime. To demonstrate that the system environmental requirements are met, a series of tests and analyses are performed. The tests performed often stress the equipment to greater levels than would be encountered in service to ensure design margin or to accelerate testing (reduce test time). The strategies employed to establish margin or to accelerate testing should exercise the failure mechanisms expected in service without introducing non-relevant failure mechanisms.

The solder joint reliability is determined by its ability to survive accelerated life time service environments. To perform the reliability analysis, the solder joint environment is obtained from the assembly level analysis whose boundary conditions are obtained from the box level and the vehicle level environments. Extensive discussion on the thermal cycling assessment of surface mount assemblies is given in IPC-9701. Many of the principles outlined in IPC-9701 are applicable to the evaluation of Pb-free alloys. The underlying physics-of-failure concepts are also applicable; however, Pb-free alloys have different creep behavior, stress relaxation times, and creep-fatigue models than the heritage Sn-Pb alloys as described in IEC/TS 62647-3:– and modeling should be used to compare Pb-free and Sn-Pb fatigue test results.

In 6.3 to 6.7, the special considerations required for the assessment of Pb-free solders alloys in aerospace environments will be outlined. Depending upon the individual application, there may be additional testing and analysis required to substantiate the Pb-free alloy soldered assembly.

6.3 Electronics/electrical equipment thermal environments

6.3.1 General

Steady state and cyclic thermal environments of the equipment utilizing the Pb-free alloy provide the basis for the reliability determination. The steady temperatures are used for intermetallic growth and Kirkendall void formation, while the cyclic environments will be used to determine the thermomechanical fatigue life of the electronic/electrical system. The LRU level thermal environments, in combination with the power dissipation and the cooling design, should be used together to determine the PCB/PWB assembly temperatures driving the solder thermomechanical fatigue.

6.3.2 Electronics/electrical equipment steady temperatures

A range of operating temperatures that includes the fraction of time the equipment will be at the various temperatures and the state of power dissipation within the box should be provided as is described in Annex A.

6.3.3 Electronics/electrical equipment temperature cycling

The thermal cycling performance of a Pb-free alloy is determined by its ability to survive upper and lower temperature limits, the ramp time required to transition between the temperature limits, and the dwell time at the temperature extremes. A series of thermal cycling environments that captures the spectrum of cycles that equipment will be exposed to throughout its life should be provided. The thermal cycling environment should be specified for both “operating” and “un-powered storage” conditions as described in Annex A.

6.4 Vibration and shock

Vibration and shock performance of Pb-free solders for some piece part types is less than Sn-Pb. Accurate representation for the service conditions would prevent unnecessary costs during the Pb-free implementation. Thermal preconditioning may be required as part of this service life assessment to simulate intermetallic growth.

6.5 Humidity

No special considerations beyond the normally specified humidity testing are required. Care should be used when using zinc or indium-bearing solder alloys due their corrosive tendencies. In these alloys, the zinc and the indium are the species that corrode.

6.6 Other environments: salt spray, fungus, cooling air quality, and fluid compatibility

No special considerations beyond the normally specified testing are required. Silver finishes are not prone to whisker growth in most environments. However, rapid growth of silver dendrites or, in some cases, silver whiskers may form in the presence of H_2S (found in some cases where the environmental air pollution contains SO_2) [50]. Pb-free solder and finish performance evaluations in sulfur-bearing atmospheres (such as salt fog testing in accordance with ASTM G85:2011, Annex A4) have not been extensively evaluated.

6.7 Other special requirements

No data is available for acoustic vibration or pyroshock performance of Pb-free alloys.

7 High performance electronics testing

The Joint Group on Pollution Prevention (JG-PP) and the Joint Council on Aging Aircraft (JCAA) conducted a multiyear evaluation of Pb-free solder [49]. The test utilizes the best practices for printed circuit board thickness and plane layer content, assembly design, assembly and piece part characterization, monitoring, and failure analysis as outlined in IPC-9701. The test plan includes an assessment of the standard high performance environments: thermal shock from –55 °C to +125 °C, thermal cycling (–20 °C to +80 °C and –55 °C to +125 °C), vibration, mechanical shock, humidity, salt fog, surface insulation resistance (SIR), electrochemical migration resistance, and combined thermal/vibration environments. The thermal cycling tests are utilizing 30-minute hot and 10-minute cold dwell times (after assembly temperature stabilization). Although preliminary results are available, the principal investigators are cautious about drawing conclusions from the data until the failure analysis and modeling activities have been completed. As has been observed in previous studies, the results are mixed. Sometimes Pb-free exhibits better performance than Sn-Pb and sometimes the opposite was found to be the case. Modeling will be needed to properly compare the Sn-Pb and Pb-free alloy performance and correct for the stress relaxation differences observed on the various piece parts and thermal cycling conditions. A summary of JCAA/JG-PP testing associated with Sn-Pb and Pb-free finish/solder alloy mixing is given in 8.6, after the mixing of alloys discussion.

In 2006, the results of a thermal cycling test performed by CALCE were presented in a SAC modeling paper [51]. The test design of experiment (DOE) matrix included temperature differences, mean temperatures, and dwell times. The study evaluated the performance of ceramic leaded chip carriers on glass epoxy PCB/PWB with three solder alloys, 95,5Sn-3,8Ag-0,7Cu, 96,5Sn-3,5Ag3,5, and 63Sn-37Pb. Dwell times of 15 minutes and 75 minutes were evaluated for various temperature cycling ranges and mean test temperatures (e.g,. cycles of 0 °C to 100 °C (32 °F to 212 °F), –25 °C to 75 °C (–13 °F to 167 °F), 25 °C to 125 °C (77 °F to 257 °F), etc.). Sn-Pb outperformed Pb-free solder at the highest tested cyclic mean temperatures, which had a peak temperature of 125 °C (257 °F). However, Pb-free solder was more reliable than Sn-Pb solder at peak temperatures under 100 °C (212 °F) regardless of dwell time. Finally, the reliability of Pb-free solders showed much stronger dependence than the Sn-Pb solder on the cyclic median temperature.

The thermal cycling performance of SAC305 and SAC405 for –55 °C to +125 °C (–67 °F to 257 °F) thermal cycling exposure was assessed on ENIG finished PCB/PWB for a variety of component types [45]. The thermal cycling performance of SAC405 was better than the SAC305. The land grid arrays package (LGA 64) exhibited some degree of interfacial fracture at the ENIG board interface with the ENIG exhibiting signs of a moderate level of black pad corrosion.

8 Solder joint reliability considerations

8.1 General

8.1.1 Overview

The reliability of a solder joint is dependent upon the integrity of the solder in the joint and the metallurgical interfaces to the leads and pads. Particularly for SMT assemblies, due to the limited solder volume present, the solder joint reliability is strongly influenced by the final solder alloy composition and microstructure, the shape of the solder surface and the terminal-to-solder interfacial strength. Mixing of Pb-free and Sn-Pb finishes are a significant consideration with assemblies with a 20-year maintenance plan. Some issues associated with finish compatibility and mixing are introduced in Clause 8 and are then discussed further and summarized in Clauses 9, 10, and 11.

8.1.2 Final solder joint composition

The initial composition of the solder used to form the joint is typically modified to some extent during the soldering process as the pad metallization and the finish of the pads are dissolved into the solder joint. The amount of dissolved piece part and pad metal typically does not significantly alter the final alloy composition but may affect the final solder joint mechanical properties. There are some pad constituents (e.g., Au in solder or Pb in SAC solder) that have a tendency to segregate to either the pad interfaces and/or grain boundaries causing a change in mechanical properties of the joint and the interfaces. In addition, contact pad metallization and finish solubility can create unanticipated intermetallic compounds near the joint interfaces. It is important to embody these effects in the test assembly ultimately used to validate the assembly performance/reliability. The effect of the pad dissolution is one of the factors considered in Clause 5 of IEC/TS 62647-3:–.

While the final solder joint composition is not significantly influenced by the component metallization on most electronic devices, BGAs and CSPs need to be considered differently. With BGA and CSP devices the final solder joint composition is strongly influenced by the ball composition because the ball volume is large compared to the solder provided by the printed solder paste used during the assembly process. There are also reliability concerns when mixing Sn-Pb and Pb-free alloys during manufacture and/or repair.

In addition, some Pb-free alloy formulations contain other constituents. It is commonly recognized that zinc and indium bearing Pb-free alloys tend to corrode readily in moist environments and should be evaluated carefully before use [52]. Solder alloy composition may need to be defined more accurately if ternary or quaternary alloy systems are used. As the industry transitions from Sn-Pb to Pb-free, additional measures may be critical in assuring that the proper materials are utilized. X-ray fluorescence (XRF) spectroscopy measurement techniques are presently being used as a means of verifying alloy and finish compositions. While the Pb-free alloy’s structural properties influence the reliability of the assembly, the wetting characteristics of Pb-free alloys also need to be considered.

8.1.3 Solder wetting and final joint shape

The solder stress-strain distribution within the joint is often determined by the final solder joint shape, which is defined by the solder wetting and the resulting solder-free surface shape. The wetting angles for Pb-free alloys are greater than Sn-Pb alloys [53][54]. Greater wetting angles are indicative of poorer spreading and less metallurgically bonded area resulting in potentially weaker joints. The addition of Ag to Sn and Sn-Cu alloys significantly decreases wetting in solder drop spreading experiments [55]. Although Pb-free solders do not wet as well as the heritage Sn-Pb solders, not all solder configurations are impacted by this issue. Solder geometries, such as ball grid arrays, are usually not dependent upon wetting angle as long as the entire pad is metallurgically wet. In contrast, piece parts with leads, particularly those with stiff leads, which depend upon the heel fillet geometry for strength, are expected to be more sensitive to wetting variations. Quad flat packs soldered with SAC alloy exhibited premature failures during thermal cycling from –55 °C to +125 °C (–67 °F to 257 °F) that was attributed to solder process variability (e.g., insufficient solder volume, insufficient heel fillet, solder voids, etc.) [15] [56]. Chip piece parts and leadless ceramic chip carrier solder joints may be less prone to wetting variation because any solder that does not wet up onto the vertical surfaces will tend to increase the solder thickness under the device. The final consideration in assembly performance is the reliability of the interfaces. Lead-free process variability should be minimized before beginning extensive reliability testing. Some quick process quality checks include: lead terminal pull testing, cross-sectioning, HALT/HAST testing, and vibration/shock.

8.1.4 Strength of the PCB/PWB and component interfaces

The piece part and pad interface strength is typically dependent upon the intermetallic strength. The stress imparted upon the interface is dependent upon the solder alloy and the load application rate. Under slow loading conditions, such as thermal cycling, the solder tends to creep and the resulting interfacial stress is lower than during rapid loading. In the case of rapid loading such as vibration or shock, the solder does not have time to creep and greater loads will be observed on the interfaces. Nickel-tin intermetallics are generally weaker than copper-tin intermetallics [57]. Another source of reduced interfacial strength is the presence of voids near the interfaces. Voids result in reduced strength by decreasing the metallurgically bonded areas. Some investigators have found voiding in the copper substrate adjacent to the Cu_3Sn intermetallic [35] [36] [37] [38].

The laminate integrity under the solder pads is also impacted by these interfacial stresses and will be discussed in Clauses 9 to 11. This topic is under considerable study in the industry at the present time. Mechanical design modifications may be needed to reduce vibration and shock loads of Pb-free solder joints to prevent damage to the underlying laminate material (e.g., PCB/PWB BGA pad cratering [58]).

8.2 Mixing of solder alloys and finishes

As the Pb-free transition is occurring, metallurgy mixing is one of the biggest assembly concerns to the ADHP electronics equipment suppliers and users. Sn-Pb BGA ball metallurgy and Sn-Pb finished piece parts are being quickly replaced by Pb-free alternatives. A special consideration for ADHP applications is that Pb-free solders may be either intentionally or unintentionally mixed with Sn-Pb solder or Pb-bearing finishes throughout their service life and during repair depot activity.

Some common issues with Pb-free surface finishes are given in Table 1 and in the remaining paragraphs of Clause 8. The assessment of piece part and PCB/PWB finishes is extended in greater detail in Clauses 9, 10, and 11. A finish process compatibility matrix and a relative process reliability summary are given in Table 6 and Table 7.

Piece parts and PCB/PWB finishes used in high performance applications often require an assessment of tin whisker propensity and tin pest risk. The impact on tin whisker and tin pest formation due to elemental additions into pure tin are given in Table 2 and Table 3. A detailed discussion of the tin whisker and tin pest propensity for the various piece part and PCB/PWB finishes is given in Table 4 and Table 5.

8.3 Pb-free terminations in tin-lead joints

8.3.1 General

One result of the WEEE/RoHS directives and the responding piece part fabricator initiative is the introduction of piece parts with Pb-free surface finish terminations into existing traditional tin-lead soldering processes. The variety and compositions of the Pb-free surface finishes being delivered into the electronics industry is extensive. Many of these piece part materials will find their way into the inventory of aerospace and defense assembly processes under government acquisition reform initiatives. Additionally, the banning of tin-lead surface finishes could reduce the supplier base and adversely affect the readiness of some critical missions. Electronics assembly design teams should be knowledgeable on the potential impact of the Pb-free surface finish piece part and pad interface on solder joint integrity.

Recent test results indicate that Sn-Pb finished PCB/PWB with SAC alloy solder BGAs exhibits poor thermal cycling performance (Figures 38 and 39 of [15]) when the Pb concentrations are low (e.g., flux only rework of a SAC BGA on an Sn-Pb finished PCB/PWB pad). Earlier testing on CLCCs suggests that the fatigue life of SAC solder is improved with the addition of some Pb [74]. The addition of Pb in SAC changes the solder composition and affects the fatigue performance. The presence of Pb in SAC expands the considerations of property changes on the reliability of the solder alloy. The impact is not universal – solder joint integrity degradation can range from slight-to-severe depending upon the use environment.

The amount of Pb versus solder joint volume, the amount of stress the solder joint experiences and the overall reflow thermal profile have direct impact on the final solder joint integrity. These process interactions are not fully understood and a mixed metallurgy situation should be carefully characterized to assure that product integrity is not compromised.

8.3.2 Ball grid array Pb-free terminations in tin-lead joints

Industry has two opposing camps on the BGA mixed metallurgy issue and whether specific factors such as PCB/PWB thickness, reflow temperature profile, and testing parameters result in a level of performance variability. A general statement on the mixing issue is not possible at this time and each application will need to determine if mixing will impact product integrity. If mixed (Pb-free/Sn-Pb) ball metallurgy is being considered, the fatigue exponents need to be developed that will allow extrapolation from accelerated tests conditions to service conditions for the range of solder joint compositions that the process will yield.

It was found during the JCAA/JG-PP testing that the mixed alloy (Sn-Pb/Pb-free) systems were not "as good or better" than either of the pure material sets for highly stressed assemblies. Both SAC BGAs soldered with Sn-Pb paste and Sn-Pb BGAs soldered with SAC paste combinations were tested in the JCAA/JG-PP test and both mixed combinations failed very early in –55 °C to +125 °C (–67 °F to 257 °F) thermal shock (starting at a few hundred cycles) as can be seen in (Figure 14 and Table 6 of [59]). In comparison, non-mixed solder BGAs (i.e., pure SAC or pure Sn-Pb) had no failures after 1 000 thermal shock cycles. Early failures for these mixed metallurgy BGA combinations were also seen in the –55 °C to +125 °C (–67 °F to 257 °F) thermal cycle test (see Figures 6 and 7 of [15]). In addition, early failures were observed for Sn-Pb BGAs soldered with SAC (Figure 8 of [60]) in the –20 °C to +80 °C (–4 °F to 176 °F) thermal cycle test.

NOTE SAC BGAs soldered with Sn-Pb were not tested.

In highly stressed chip scale package (CSP) thermal cycling testing, the mixed metallurgy combinations did not perform as well as the non-mixed soldered CSPs [61]. In addition to compositional complications associated with the addition of more elements into the solder joint, mixed metallurgy performance is also affected by processing time and temperature process controls, as discussed later in 8.3.2.

Under rework conditions, the JCAA/JG-PP testing revealed some poor thermal cycling performance at the lower limit of Pb contamination in SAC BGAs. Testing of SAC BGAs soldered with flux only to Sn-Pb HASL (hot air solder level) finished PCB/PWB exhibited poor thermal cycling reliability. The solder failed with a fracture near the pad interface where Pb had accumulated along Sn grain boundaries near the interface (see Figures 38 and 39 of [15]).

Those tests that have evaluated the mixed metallurgy configuration have found that it is much better if the Pb-free alloy and the Sn-Pb are well mixed. The solder process temperature and time above Sn-Pb liquidus are important considerations when assembling BGAs with SAC balls to PCB/PWB using Sn-Pb solder paste. It has been found that, in order to have a well mixed final SAC/Sn-Pb metallurgy, solder time/temperature process parameters may need to be tailored beyond the standard Sn-Pb solder profiles. It can be very difficult to practically implement the tight process temperature windows on large complex assemblies. If mixed (Sn-Pb/Pb-free) ball metallurgy is being considered, the fatigue exponents need to be developed that will allow extrapolation from accelerated tests conditions to service conditions for the range of solder joint compositions that the process will yield.

The melting points of SAC alloys are generally toward the upper limit of the Sn-Pb solder processing temperatures. The Pb-free BGA ball composition variations influence the melting temperature. In cases where improved drop shock performance is desired, SAC with reduced Ag content (e.g., SAC with 1 % Ag, melting point = 226 °C (439 °F)) is used instead of the near eutectic SAC composition (e.g., SAC with 3 % Ag, melting point = 220 °C (428 °F)). SAC balls attached to a PCB/PWB with Sn-Pb solder can have various microstructures, depending upon the maximum soldering temperature of the solder joint, the time above liquidus, and the ratio of deposited Sn-Pb paste to the SAC BGA volume. These factors will determine the degree of SAC ball and Sn-Pb paste solder alloy mixing. It is generally desirable to have a SAC ball that is completely molten such that it will form a well mixed alloy upon solidification. As discussed below, the thermal cycling performance of the SAC ball and Sn-Pb paste is generally lower than either the SAC ball/SAC paste or the Sn-Pb ball/Sn-Pb paste combinations. However, thermal cycling fatigue life may be acceptable for assemblies having lower solder stresses.

When full mixing is not attained, the SAC ball is partially dissolved into the Sn-Pb alloy. In some cases, the Pb migrates along the Sn grain boundaries [62]. Some of the drawbacks associated with a partially mixed joint are:

- Poor self alignment of piece parts during reflow increasing the risk of an open circuit condition.
- Insufficient collapse of the balls during reflow making them susceptible to package coplanarity variations and abnormally formed solder joints that are difficult to inspect.
- Variation in joint microstructure homogeneity that could lead to poor fatigue characteristics.

Chung [62] and Maire [63] evaluated the thermal cycling performance of SAC BGAs that were soldered with near eutectic Sn-Pb solder where the finally solidified BGA ball was not mixed. Chung utilized Sn-Pb solder and reported no electrical failures after 1 000 thermal cycles from –40 °C to +85 °C (–40 °F to 185 °F). Maire used Sn-36Pb-2Ag solder and observed some amount of cracking after 1 000 thermal cycles from –40 °C to +100 °C (-40 °F to 212 °F), however, the observations were similar to the cracks observed on pure Sn-Pb joints. Both investigators agreed, however, that a well mixed solder ball was desirable for the reasons previously mentioned.

Non-uniformly mixed SAC BGAs attached to ENIG PCB/PWB pads were evaluated for thermal cycling life by Hillman [34]. Hillman found that this configuration exhibited poor thermal cycle reliability. Cracks rapidly formed between the solder and the ENIG pads. The JCAA/JG-PP testing also showed some poor thermal cycling performance at the lower limit Pb concentration in Sn-Pb/SAC BGAs mixed metallurgy rework assemblies with Sn-Pb PCB/PWB pads during the –55 °C to +125 °C thermal cycling tests. See 8.4.

In some cases, the Sn-Pb solder temperature profile can be increased slightly to ensure good mixing. However, there are cases where the temperature limitations of heritage Sn-Pb piece parts may not allow solder process temperature increases. There is another way to achieve the desired results. Mixing can be achieved through a combination of increasing the amount of Sn-Pb solder paste printed onto the PCB/PWB and increasing the time above Sn-Pb liquidus during soldering. Snugnovski found that Sn-Pb solder will dissolve solid SAC BGA balls with solder temperatures below 220 °C (428 °F) as long as the proper ratio between Sn-Pb paste and SAC ball mass is obtained [64].

Uniformly mixed SAC BGA balls attached to PCB/PWB using Sn-Pb solder were evaluated in thermal cycling [65] [56]. These assemblies successfully completed 2 000 thermal cycles from –55 °C to +125 °C (–67 °F to 257 °F).

8.3.3 Flat pack and chip device Pb-free terminations in tin-lead joints

8.3.3.1 General

The majority of Pb-free finishes (see Table 1 and Table 8) are compatible with tin-lead alloys and will not impact solder joint reliability. The most common finishes are pure tin, high tin content alloys with silver and/or copper, and nickel/palladium/gold over copper alloys or low coefficient expansion leads/terminations. Detailed solder joint reliability considerations associated with several finishes are discussed next.

8.3.3.2 Pure tin (matte tin and bright tin)

A very common Pb-free finish is pure tin [3]. There are many different matte tin and bright tin plating finishes in use in the various electronic components (microcircuits, connectors, resistors, capacitors, axial leaded devices, relays, switches, etc.). Tin plating characteristics can vary greatly from supplier to supplier. Process chemistry and control of these plating processes is critical in determining solderability and tin whiskering characteristics (see IEC/TS 62647-2 and IPC/JEDEC JP002). Pure Sn finishes are fully metallurgically compatible with Sn-Pb assembly solder alloys. The Sn finishes applied to the devices are thin enough that they will dissolve completely into the bulk solder during reflow even if the melting point of Sn is not attained. Since Sn-Pb eutectic solder already contains Sn, the principal effect of soldering to pure Sn terminations is a slight Sn enrichment in the final solder joint composition. The properties of Sn-Pb solders change little with a variation of a few percent in composition [66]. In bright tin or thicker matte tin coatings, co-deposited organics can yield solder voids during reflow in some solder joint geometries.

One should note that tin finished piece parts may exhibit poorer wetting than Sn-Pb finishes if they are stocked for extended times. When a “last time buy” is made of a pure tin finished part, careful stock control should be in place to ensure solderability at the time of assembly. Bright tin surface finishes can exhibit solderability difficulty due to the presence of co-deposited organics in the plating that can volatilize and can also exhibit degradation of the base metal solderability after extended storage.

8.3.3.3 Sn-Bi

Bismuth is typically added to tin finishes in amounts of 2 percent to 4 percent by weight. Mixing Sn-Bi finishes with Sn-Pb solder is discussed in 8.5.

8.3.3.4 Sn-Cu and SAC

Sn-Cu and SAC finishes are metallurgically compatible with Sn-Pb solder. Similarly to matte tin, the use of these alloys will result in minor enrichment of Sn and some added copper and silver to the final solder joint. There are some indications that Sn-Ag-Pb solders are more durable than Sn-Pb solders [67]. The electrodeposited Sn-Cu finish should be avoided because this finish has a very high propensity for whisker growth [68] [69].

8.3.3.5 Ni-Pd-Au

The maintenance of Au concentration in the final solder joint is still required to ensure that gold embrittled joints do not form. There may be some instances with Pd bearing finishes, where Pd can diffuse into the solder joint resulting in the formation of brittle Pd-Sn intermetallics. Palladium has been used since 1989 as a termination finish on microcircuit leads and many Pd finished components have been fielded [70]. In some cases, the formation of a Pd-Au-Ni-Sn intermetallic near the interface can reduce durability [45]. $PdSn_4$ has the same brittle characteristics as $AuSn_4$ intermetallic. [71]. For applications in high moisture or corrosive environment, if the Ni-Pd-Au is cracked during lead-forming, stress corrosion can result [3]. In a typical solder joint, this amount of gold contributed to the solder joint is negligible and the conventional 3 % gold concentration limit will not be exceeded.

8.4 Tin-lead terminations in Pb-free joints

8.4.1 General

The introduction of tin-lead terminated components in a Pb-free solder system is likely during the early stages of Pb-free assembly processing while the piece part supply stream still contains Sn-Pb terminated components. In addition, fine pitch leaded piece parts have been granted an EU exemption and will be permitted to use Sn-Pb finish [72].

8.4.2 Ball grid array tin-lead terminations in lead-free joints

First it should be noted that heritage Sn-Pb BGAs were not designed to be capable of withstanding the higher Pb-free solder process temperatures and that maximum temperature capabilities of the Sn-Pb BGAs should be assessed prior to soldering at Pb-free solder temperatures. As was mentioned in 8.3.2, industry has two opposing camps on the mixed metallurgy issue and specific factors such as PCB/PWB thickness, reflow temperature profile, testing parameters result in a level of performance variability such that a general statement of the mixing issue is not possible at this time and the user needs to investigate their design more fully to determine how mixing will impact their product integrity. In contrast to JCAA/JG-PP findings discussed in 8.3.2, Wickham's [56] evaluation of Sn-Pb BGAs soldered to PCBs/PWBs with SAC solder showed comparable reliability to Sn-Pb BGAs soldered with Sn-Pb-Ag solder.

NOTE Failures for both of these configurations were observed in the BGA die region between 1 000 and 2 000 thermal cycles from –55 °C to +125 °C (-67 °F to 257 °F).

8.4.3 Flat pack and chip device tin-lead terminations in lead-free joints

Surface mount solder fillet lifting is possible during secondary soldering processes [73], resulting in low strength solder joints. Generally however, Pb contamination of SAC solder joints did not adversely impact solder joint reliability in –55 °C to +125 °C (–67 °F to 257 °F) thermal cycling and vibration for the majority of components tested [56] [65]. Thermal cycling testing from –40 °C to +125 °C (–40 °F to 257 °F) on leadless ceramic chip carriers showed that the addition of small amounts of Pb (~0,2 wt % to 0,9 wt % depending upon the assembly tested) improved the thermal cycling performance of 95,5Sn-3,8Ag-0,7Cu and 96,5Sn-3,5Ag but decreases the reliability of Sn-0,7Cu [74].

8.5 Bismuth effects

The addition of bismuth to SAC has been shown to yield a solder joint which has improved reliability [74] [75]. The principle concern is that when Bi is mixed into Sn-Pb solder, a low melting point Sn-Bi-Pb ternary alloy can form, particularly at the grain boundaries. The melting point of the ternary alloy is 96 °C and the solder can lose strength during hot mission environments. Trace amounts of Pb were found to have a detrimental effect on solder life of bismuth containing solders (91,8Sn-3,4Ag-4,8Bi and 92,3Sn-3,4Ag-1,0Cu-3,3Bi) and resulted in catastrophic failure of Sn-58Bi solder joints where the joints essentially turned into a powder after 835 thermal cycles from –40 °C to +125 °C (–40 °F to 257 °F) [74]. Since ADHP products have a 20-year service life and a repair depot infrastructure that will have both Sn-Pb and Pb-free alloy configurations for a significant amount of time, bismuth bearing solder alloys are noted as a concern in IEC/TS 62647-1:2012. However, there are some piece parts that are only available with an Sn-Bi lead termination finish; preliminary testing suggests that trace amounts of Bi in Sn-Pb joints are not detrimental to solder life in this case. The present IPC J-STD-006B:2009 solder alloy specification allows 0,1 % Bi in Sn-Pb solder.

The various combinations that may be encountered are:

- Sn-Pb-Bi-X solder joint where there is sufficient amounts of Pb and Bi and the Sn-Bi-Pb ternary alloy can form. The risk that Sn-Pb-Bi ternary alloy can form is greatly reduced if Bi bearing alloys having significant Bi concentrations are not used.
- Bismuth based Pb-free solder alloys with “Pb contamination”. The presence of trace amount of Pb in a bismuth based Pb-free solder alloy (SACB) solder joint was found to cause a measurable reduction in solder joint integrity that is most likely due to the deformation of the soft Pb phase that segregates along the tin grains [76]. (Kayria [75] showed the phase and the segregation. The user needs to determine the level of risk.)
- Tin-lead based solder alloys with “Bi contamination”. Some piece parts are being provided with tin-bismuth plating finish. The bismuth concentration in the plating is typically 2 wt % to 5 wt % and only ~3 μm (120 microinches) thick. There has been some indication that Sn-Bi finishes used on Alloy 42 lead-frames that are soldered with Sn-Pb will exhibit some reduction in solder joint thermal cycling fatigue life compared to an Sn-Pb finished lead termination soldered with Sn-Pb solder [77] [78]. Sn-Bi finished copper lead-frames soldered with Sn-Pb solder, have exhibited comparable thermal cycling reliability to Sn-Pb finished copper lead-frames soldered with Sn-Pb solder [78]. Other testing has shown good thermal cycling performance with SOIC14/16 (small outline integrated circuit) packages (note that the type of lead material was not reported) [65]. Further testing is in process [76].

Provided that uniform solder reflow processing is followed to ensure that Bi segregation does not occur, it is expected that there is little risk of forming the Sn-Bi-Pb ternary eutectic (96 °C (205 °F) melting point) with small (1 % to 5 % by weight) additions of Bi to Sn finishes when soldered with Sn-37Pb [79] [80] [81].

NOTE: Segregation of low melting point phases can occur under some soldering conditions. Segregation of a 178 °C (352 °F) melting point Sn-Ag-Pb alloy has been observed during reheating of Pb bearing components attached with SAC solder alloys [73].

There is a ternary Sn-Pb-Bi peritectic that is thermodynamically stable for Bi above 6 % by weight in the component finish, and this peritectic has a melting point of 135 °C (275 °F). As long as the Bi concentration on the lead termination is less than 6 %, the peritectic should not be an issue [79] [80] [81]. With eutectic Sn-Pb solder, it is necessary to control the bismuth content of the finish between 2 % and 4 % so as to have enough bismuth to help retard whisker formation without getting into the compositional range of the ternary eutectic. In addition, keeping the Bi content low is required to retain solderability of formed leads [80]. The reader is also referred to the JCAA/JG-PP testing of mixed alloys discussed in 8.6. Applications should evaluate Sn-Bi lead termination finish for acceptability in the given use environment.

8.6 JCAA/JG-PP testing of mixed alloy combinations

8.6.1 General

Various combinations of solder alloy and solder finish were evaluated in the JCAA/JG-PP Pb-free evaluation for military and high performance environments. The study evaluated Sn-37Pb, Sn-3,9Ag-0,6Cu (SAC) and Sn-3,4Ag-1,0Cu-3,3Bi (SACB) solder alloys. Subclauses 8.6.2 to 8.6.4 discuss the vibration, thermal shock, and combined (thermal cycling and vibration) results for the mixed alloy scenarios evaluated.

8.6.2 Vibration

The JCAA/JG-PP Pb-free solder study investigated the effect that Sn-Pb component finish had on solder joints manufactured with lead-free solder alloys (SAC and SACB). Results from vibration testing indicated that BGA-225 components with Sn-Pb balls assembled with Sn-Pb paste outperformed Sn-Pb balls assembled with either lead-free paste (with the SAC paste showing the worst performance) [48]. With regards to the CLCC-20 components, in those cases where the CLCC finish was Sn-Pb combined with either Sn-Pb paste, SAC paste or SACB paste, the combination of SACB paste/Sn-Pb finish performed the best. Bismuth alloys combined with trace amounts of lead (Pb) have been shown to fail prematurely in thermal cycling due to the formation of a low melting ternary 16Sn-32Pb-52Bi alloy (melting point

96 °C (205 °F) [74]). Either the ternary alloy is not vibration sensitive or the formation of the ternary alloy was suppressed somehow by the large amount of lead (Pb) in the final joints (approximately 17 % by ICP-MS (inductively coupled plasma mass spectrometry) analysis). The large amount of lead (Pb) in the solder joints is due to the large amount of Sn-Pb solder held by the castellations on each CLCC [48].

8.6.3 Thermal shock testing

The results from thermal shock testing, TSOP-50 component with an Sn-Pb component finish, indicated that the only TSOPs to have significant failures were those with an Sn-Pb finish and soldered with SACB. The early failure of the TSOPs soldered with SACB is presumably due to the formation of a low melting ternary 16Sn-32Pb-52Bi alloy (melting point 96 °C (205 °F)). The amount of Pb in these solder joints was approximately 3 % as determined by ICP analysis. This result is in contrast to the CLCC data, where large amounts of lead (Pb) contamination had only a slightly negative effect on the reliability of SACB [59]. In those cases where the CLCCs were finished with Sn-Pb and were combined with either SAC paste or SACB paste, the lead (Pb) contamination in the final solder joints had only a slightly negative effect on the survival times of the solder joints (see Figure 31 of JCAA/JG-PP thermal shock test report [59]). This was unexpected because bismuth alloys combined with trace amounts of lead (Pb) have been shown to fail prematurely in thermal cycling due to the formation of a low melting ternary 16Sn-32Pb-52Bi alloy (melting point 96 °C (205 °F)). In addition, trace amounts of lead (Pb) (0,5 %) have been shown to have a positive effect on the survival times of CLCC SAC solder joints subjected to –40 °C to +125 °C thermal cycling [74]. The large amount of lead (Pb) in the CLCC solder joints in this study (approximately 17 % by ICP analysis) appears to have a very different effect on solder reliability than do trace amounts of lead. The large amount of lead (Pb) in the solder joints is due to the large amount of Sn-Pb solder held by the castellations on each CLCC [59]. For BGA-225 components, Sn-Pb balls assembled with SAC paste failed on six out of a total of 25 BGAs. No Weibull analysis was done since the number of failures was less than 25 % of the population. These failures suggest that using Sn-Pb BGAs in combination with SAC solder is to be avoided. In comparison, only one failure was seen when SACB paste was used with Sn-Pb balls [59].

8.6.4 Combined environments

For combined environments testing, BGA-225 components with Sn-Pb balls soldered with lead-free solder alloys (SAC and SACB), it was shown that tin-lead degrades the early life performance of tin-silver-copper while the number of cycles where 63 % of the samples failed (N63 values) is similar. The data results showed no effect in the reliability performance of tin-silver-copper-bismuth when used to solder tin-silver-copper or tin-lead BGA-225 components [82]. For the CLCC-20 components, the presence of tin-lead appears to improve the reliability of the tin-silver-copper solder joint. However, the presence of tin-lead appears to degrade the reliability of the tin-silver-copper-bismuth solder joint [82]. For the TSOP-50 components, the presence of tin-lead appears to slightly improve the reliability of the tin-silver-copper solder joint. However, the presence of tin-lead appears to severely degrade the reliability of the tin-silver-copper-bismuth solder joint [82].

8.7 Pb-free solder and mixed metallurgy modeling

The solder joint metallurgy is the principal factor affecting the attachment reliability of mixed Sn-Pb/Pb-free assemblies. The record for SAC balls/Sn-Pb paste assemblies under accelerated thermal cycling conditions varies. No life prediction model or acceleration factors are reported for such mixed assemblies [83]. To arrive at a validated model for mixed assemblies, we need to develop proven models for Pb-free solder joints first. Using the JCAA/JG-PP data Osterman has developed a Coffin-Manson type equation that accurately predicts the reliability of Pb-free solder joints for plastic BGAs and leadless SMT devices [84]. The Norris-Landsberg acceleration model with constants similar to those of Sn-Pb solder are also shown to fit the JCAA/JG-PP data [85]. Additional testing and analysis are needed before a validated model is developed for Pb-free assemblies, and later for mixed Sn-Pb/Pb-free assemblies.

Table 1 – Review of piece part surface finish and potential concerns

Surface finish	Potential impact concern(s)
Palladium (Pd)	A number of piece part fabricators utilize surface finishes that contain Pd. Pd has been shown to be flux sensitive and has a relatively slow diffusion rate into tin-lead solder alloys in comparison to other metals. A slight increase in solder process temperatures (e.g., 5 °C to 10 °C (9 °F to 18 °F)) and extension of the solder process dwell time have been used to compensate when using Pd surface finishes in tin-lead soldering processes. Pd thicknesses in the 0,51 μm to 0,76 μm (20 μinch to 30 μinch) range has been shown to cause solder joint embrittlement due to the formation of $PdSn_4$ microstructure phase.
Gold (Au)	Gold has a long tradition of being utilized as a piece part surface finish for some piece part styles. Au has a propensity to embrittle solder joints due to the formation of the $AuSn_4$ microstructure phase when the Au content exceeds 3 % of the solder joint [86]. Some investigators suggest that the Au limit lies from 2 wt % to 7 wt % [6]. Thin Au platings used on BGAs, CSPs, and flip chip packages result in Au concentrations typically less than 1 % in the solder joints. Gold plating thicknesses in the 0,025 μm to 0,51 μm (1 μinch to 20 μinch) range can be prone to solderability problems for some piece part types. In lead-free solder systems, the intermetallic compound formation is more complex than in the Sn-Pb system. In smaller volume SAC joints (300 μm diameter balls with 300 μm diameter Au/Ni pads), re-deposition of $(Au,Ni)Sn_4$ intermetallic was closely associated with the migration of Cu from the bulk solder to the surface [87].
Tin-silver-copper (SAC)	The introduction of SAC solder alloys as the primary solder attachment material has also led to the introduction of SAC solder alloys as piece part surface finishes. These SAC surface finishes are typically applied through a "hot dipping" process. The interaction of a SAC surface finish and tin-lead solder is not fully understood although initial solder joint reliability studies have not revealed any major solder joint integrity problems.
Bright acid tin (Sn)	Bright acid tin contains co-deposited organic materials to produce the "bright" appearance. These co-deposited organic materials have a detrimental impact on solderability and have been shown to be more prone to produce tin whisker phenomena.
Matte tin (Sn)	Industry studies have shown that matte tin can produce tin whisker phenomena under some conditions. Matte tin also has a greater potential of having solderability problems due to the formation of tin oxides in comparison to tin-lead surface finishes.
Palladium-silver (Pd-Ag) or palladium-platinum-silver (Pd-Pt-Ag)	Pd-Ag and Pd-Pt-Ag surface finishes are commonly used as surface finishes on ceramic bodied piece parts such as surface mount chip capacitors or piece parts utilizing castellations. These finishes can be "dissolved (e.g., leached) off" the piece parts due to dissolution of the surface finish into the solder joint during the tin-lead solder process resulting in degradation of the piece part termination/solder joint interface. Pd-Ag and Pd-Pt-Ag surface finishes exhibit reduced solderability as compared to tin-lead finishes.
Bismuth (Bi)	Tin, lead and bismuth can form low melting microstructure phases that would have a detrimental impact on solder joint reliability. The industry is currently conducting solder joint integrity investigations to determine the severity and consequences of the interaction of Bi and Sn-Pb solder in high performance electronics use conditions. Testing suggests that a small amount of Bi introduced into Sn-Pb solder joints from an Sn-Bi electroplated lead termination finish (2 % to 4 % with a thickness of ~3 μm (120 μinches)) does not present a reliability issue. Increasing the Bi content in an Sn-Pb solder joint can result in solder joint integrity degradation. There have been concerns expressed that solidification profiles need to be validated to ensure that low melting point tin-lead-bismuth composition alloys would not segregate into interfacial sites.

Table 2 – Elements promoting and supressing tin whiskers

Added element	Solubility limit (weight %)	Sn whisker (plating)		Experiment duration
		Promoter	Suppressor [b]	
Ag [a] 2 % to 5 % [144] 2 % to 4 % [137]	0,04 [139],[140]	—	—	> Significantly worse than Sn-10Pb after 3 months of aging at 52 °C (126 °F) [144] > Reduces whisker growth [137]
Cu	0,0063 [139],[140]	1,0 % [141], 1,5 % [147], 1,4 % to 3,7 % [69]) and 3,0 % to 36,5 % [68]	—	9 days [147] 2 hours to 15 days [69]
Bi [a] 2 % to 4 % [136], [137] 5 % to 10 % [144] Not specified [145]	21,00	—	—	> 3 months to 4 months nucleation delay at RT [136] > Partially effective after 3 months of aging at 50 °C (122 °F) [137] > Similar to Sn-Pb10 after 3 months of aging at 52 °C (126 °F) [144] > No whisker growth after 4 months of aging at 51 °C (124 °F) [145]
Pb	2,50	—	> 3,0 % [135], ≥ 1,0 % [142]	1 year to 12 years [142]
Ni	nil	—	12 % to 35 % [136],[138]	> Sn-35Ni, no whisker nucleation after 48 months at RT [136]
Sb [a] 2 % to 3 % [136]	10,50	—	—	> 3 months to 4 months nucleation delay at RT [136]
Al	nil	?		
Zn	0,33	9 % [146]	—	> 21 days to nucleate whiskers at 50 °C (122 °F) [146]
Mg	nil	?		
Te	nil		?	
Co	nil		?	
Mn	nil	18 % to 23 % [143]	—	> 17 hours to nucleate whiskers at RT [143]
Au	0,30		?	
Cd	~1,00		?	
Fe	nil	?		

[a] Element addition tends to delay the whisker growth, but not suppress it.

[b] A minimum of 1 year of testing is needed for inclusion into the suppressor column.

Table 3 – Elements promoting and supressing tin pest

Added element	Solubility limit (Weight %)	Sn pest (bulk)		Experiment duration
		Promoter	Suppressor [a]	
Ag	0,04 [139],[140]	—	0,01 % [24]	> Slows down transformation during 5 months at –45 °C (–49 °F) [24]
Cu	0,0063 [139],[140]	0,01 % [24]	—	Cu added to 99.99 % pure tin placed in contact with gray tin for 2 hours at –45 °C (–49 °F) [24]
Bi	21,00	—	0,1 %[133],[23], 0,05 % [21]	> No visible transformation in 14 months at –73 °C (–99 °F) [21]
Pb	2,50	—	≥ 5,0 %[133], 0,01 % [24], 0,02 % [21]	> No visible transformation in 14 months at –73 °C (–99 °F) [21]
Ni	nil	0,01 % [24]	—	
Sb	10,50	—	> 0,5 % [133],[23],[18], 0,27 % [21], 0,2 % (tinned Cu wire) [25]	> No visible transformation in 14 months at –73 °C (–99 °F) [21]
Al	nil	0,01 % [19],[24]	—	
Zn	0,33	9,0 % [24]	0,01 % [24] 20,7 % (7,6 μm and 12,7 μm thick plating) [21]	> No visible transformation in 24 months at –73 °C (–99 °F) [21]
Mg	nil	small quantity [19] 0,01 % [20]	—	
Te	nil	small quantity [19]	—	
Co	nil	small quantity [19]	—	
Mn	nil	small quantity [19]	—	
Au	0,30	0,01 % [24]	small quantity [19]	
Cd	~1,00	—	small quantity [19]	
Fe	nil	0,01 % [24]	—	

[a] A minimum of 1 year of testing is needed for inclusion into the suppressor column.

9 Piece parts

9.1 Materials

The IPC/JEDEC J-STD-609A specification defines an e-code system that should be used to communicate the piece part terminal finish. Although the e-code definitions do not capture all the attributes needed to perform a tin whisker assessment, they will allow designers to quickly identify piece parts with pure Tin finishes. Other systems may be necessary to capture attributes such as matte tin or bright tin, nickel under plating, and base lead/terminal material.

NOTE IPC/JEDEC J-STD-609A is merging JESD97 and IPC-1066 standards.

9.2 Temperature rating

The higher soldering process temperature requirements of Pb-free solder alloys have driven an increase in part soldering temperature capability of surface mount devices (typically from 230 °C to 260 °C). It is not appropriate to assume that the presence of a Pb-free piece part and pad interface finish is always accompanied by a 260 °C maximum temperature capability. The maximum temperature capability should be verified for devices typically susceptible to solder stress damage, such as those having large silicon die, thin parts, and BGAs. Piece part solder temperature capabilities should be communicated to the repair facility if they are below the normally expected value for a particular assembly type (e.g., a 260 °C maximum temperature device on a Pb-free assembly).

Piece parts not typically used in commercial Pb-free assemblies such as hybrid circuits, optical device, larger multilayer ceramic capacitors, special oscillators, optocouplers, mechanical relays, special RF devices, etc., should be reviewed for their solder temperature capability.

9.3 Special considerations

As the elimination of Pb in piece parts proceeds, tin and zinc finishes may be used instead of Sn-Pb plating. The substrate, the plating type, and the thicknesses involved all drive whisker formation. Tin and zinc electroplated finishes (not hot dipped galvanized) have both demonstrated the ability to form pronounced metal whiskers particularly when the base material is steel, brass or copper. Zinc whiskers were a problem in raised floor data centers where air conditioning was distributed via sub-floor passages and the floor tiles were made of galvanized steel. The flowing air carried zinc whiskers to sensitive locations causing electrical shorts [88]. Piece parts comprised of metal parts, frames or shells, should be reviewed to ensure that tin or zinc plating be avoided internally or externally where a metal whisker reliability risk exists.

9.4 Plastic encapsulated microcircuit (PEM) moisture sensitivity level (MSL)

Moisture sensitivity level of the plastic encapsulated microcircuits and other plastic encapsulated piece parts such as capacitors and resistor networks are often re-assessed for Pb-free soldering temperatures. In some cases, piece part suppliers may be raising MSL for Pb-free soldering and may not maintain the MSL rating for the lower Sn-Pb soldering temperature. If the assembly manufacturer is using Sn-Pb eutectic solder, they may face increased MSL maintenance cost associated with the Pb-free MSL level. Some of the parts standards related to moisture sensitivity and handling are: IPC/JEDEC J-STD-020 and IPC/JEDEC J-STD-033.

9.5 Terminal finish

Devices with a pure tin terminal finish should be stored in a humidity controlled or desiccated packaging to preserve solderability. (See IPC/ECA J-STD-002) The metallurgical stability of lead-free lead/terminal finishes as compared to tin-lead finish is presented in Table 1.

Table 4 – Piece part lead/terminal and BGA ball metallization tin whisker and tin pest propensity

Piece part terminal metallization [a]	Whisker propensity [b,c,d]	Tin-pest propensity [d] (for applications with a duration greater than a year at cold temperatures)
Sn-(3 wt % to 5 wt %)Pb	Low [e]	Low [e]
Sn-(37 wt % to 40 wt %)Pb	Low [e]	None
Sn reflowed	Medium-high [f]	Low [g]
Sn bright electrodeposit	High [h]	High [g]
Sn matte electrodeposit	Medium-high [f,i]	High [g]
Sn matte electrodeposit with nickel underplating	Low	No data
Sn-Bi (2 % to 4 % Bi content in terminal plating) [j]	Medium-high [f]	None Bi > 0,1
Antimony earing [k]	No data	None Sb > 0,5
SAC dipped	Medium [f]	Low short term [l]
Sn-Cu plated finish	High [h]	High [l]
Sn-Cu dipped finish	High [h]	High [l]
Ni-Pd-Au electrodeposit	None	None
CBGA/BGA/C4 ball		
Sn-37Pb ball alloy (includes Sn-36Pb-2Ag)	None	None
10Sn-90Pb ball alloy	None	None
Sn-Cu ball alloy	Low [m]	High [l]
SAC ball alloy	Low [m]	Low [l]
Cu wire column [n]	No data	No data

[a] Alloy percentages given as weight percent

[b] IEC/TS 62647-2 provides guidance on finishes and risk mitigation methods. There is presently significant effort being directed toward understanding the tin whisker growth mechanism. Generally, the substrate material, plating parameters, the presence of nickel underplating, annealing and reflowing the finish also influence the whisker growth but long term testing is still underway. For the purposes of Table 4, the base lead termination material is taken to be copper. Base materials such as brass (copper and zinc alloy) have a high propensity for tin whisker formation and have actually been used to create tin whiskers in very short times. Nickel under plating is recommended if brass lead termination material is used.

[c] See [80].

[d] See Table 2 and Table 3.

[e] The risk is considered low for the heritage Sn-Pb finishes. Small Pb whiskers have been observed on the JCAA/JG-PP –55 °C to +125 °C thermal cycling testing.

[f] Medium-high risk corresponds to those finishes that iNEMI recommends be tested in accordance with JEDEC JESD201:2006 to verify that the finish has a relatively low tendency for whisker growth. In some cases, other mitigations such as nickel underplating may be necessary to reduce whiskering to a low risk level.

[g] Spergel [25] evaluated tin coated copper wire for up to 5 years at –40 °C (–40 °F) to –55 °C (–67 °F). Spergel found that fused tin finished copper wire had a low propensity for tin pest formation while the electrodeposited tin finish had a high propensity for pest formation. (See 5.3)

[h] iNEMI [80] suggests that dipped Sn-Cu finish may or may not be effective reducing tin whiskers. In electrodeposited layers Cu in Sn promotes rapid whisker formation (see Table 2).

[i] iNEMI recommends a matte tin plating thickness greater than 8 μm for whisker mitigation however, thick matte platings may be susceptible to voiding during soldering.

[j] Bi finishes may need to be restricted on low volume Sn-Pb solder joints in cases where the total Bi content of the joint becomes 0,2 wt % to 0,5 wt % in typical SMT solder joints. Bi also can accumulate to undesirable levels in wave solder pots.

[k] Antimony greater than 1 000 ppm needs to be reported in accordance with HAZMAT as referenced in IPC-1752.

[l] Alloy additions to high purity 99,99 % tin were evaluated by Sweatman [24]. Note that both Cu and Ni demonstrated a propensity for tin pest formation. Long term tin pest test data has not been published on many of the elemental additions evaluated by Sweatman.

[m] Tin whiskers have not been identified to be an issue on bulk Pb-free alloys like BGA balls or solder joints.

[n] The copper wire column typically uses a wire that is 254 μm in diameter, 1 524 μm long and having a finish of 0,05 μm Sn. [148]

9.6 Assembly stresses

Increased processing temperatures can result in increased stresses on the piece parts during manufacturing processing and upon cooling. These stresses can result in excessive warpage or internal damage. Devices having large silicon die or large linear dimensions such as area arrays, connectors etc., should be evaluated.

9.7 Hot solder dipping

If the piece part has an unacceptable Pb-free finish configuration, it may be possible to utilize hot solder dipping to refinish the leads/terminals with Sn-Pb solder. Solder dipping can result in damage to the piece part particularly if the die is large or pre-existing delamination is present [89].

NOTE C-mode scanning acoustic microscopy (CSAM) is typically used to determine internal package delamination between the molding compound and various internal features, e.g., the die, die paddle, and the lead-frame.

It was unclear if the devices that exhibited increased delamination would have had similar delamination tendencies after surface mount soldering. There exists a potential risk in exposure of the base-metal of the lead frame at corners, especially for etched lead frames owing to their concave geometrical shape [89]. The document GEIA-STD-0006 is being written to provide requirements for solder dipping piece parts. A solder dipping project is nearly completed [90]. The control of preheat and cool down of piece parts reduces the thermally induced stresses associated with the solder dipping process [91]. It is worth noting that an increasing number of components with leads are being provided with a dipped SAC finish by the suppliers.

10 Printed circuit boards

10.1 General

Circuit cards provide the means necessary to interconnect the piece parts mounted on them. With the industry moving to Pb-free solder, a number of bare printed wire board issues (laminate material, trace width, plated through hole size, external finish, external copper thickness, etc.) should be addressed when designing for Pb-free assembly. Higher processing temperatures are required for Pb-free soldering. The guidance outlined by iNEMI [92] states that while laminate materials used for assembly with Sn-Pb have been used successfully in lower complexity assemblies at Pb-free (i.e., SAC) processing temperatures, there are issues in using these materials for complex, thermally challenging products at Pb-free process temperatures. Moving to higher temperatures increases materials sensitivities and a number of parameters (e.g., thermal decomposition (T_d), glass transition temperature (T_g), time to delamination (see IPC-TM-650, method 2.4.24.1) and coefficients of thermal expansion in-plane (CTE(x-y axis)) and out-of-plane (CTE (z axis)) should be reexamined. More testing and evaluation is required before a new laminate material can claim to be compatible for assembly with Pb-free materials intended for high reliability systems. After initial material selection, the manufacturer will need to validate acceptable performance of the PCB/PWB materials under the service conditions. iNEMI provides potential test methods for validation of performance, which include conductive anodic filament (CAF), rework simulation, and thermal/temperature cycling. iNEMI recognizes that the validation methods presented are not all encompassing; as Pb-free technologies mature and more field data is gathered, there will be a greater understanding of the Pb-free PCB/PWB design constraints. In addition, the point application of heat and dwell time associated with hand soldering can result in printed circuit board damage such as pad, laminate and plated through hole damage. Further discussion regarding the use of supplemental PCB/PWB solder process assessment coupons is presented in 11.2.

10.2 Plated through holes

Some of the factors driving plated through holes (PTH) reliability are laminate material, overall PCB/PWB thickness and PTH diameter, soldering temperature, number of rework events and the subsequent field stresses. Thermo-mechanical stresses mainly due to mismatch in out-of-plane (z axis-direction) CTE between the PTH metal and the laminated material can result in the failure of the PTHs. Failure of a PTH constitutes an electrical discontinuity that may be caused by fracture of the plating material at the barrel, fracture at the land-barrel junction, or delamination of the plating from the PWB.

Printed circuit board materials require changes from today's typical "dicy cured" FR4 materials in order to support Pb-free assembly. The High Density Packaging User Group has completed a study of via reliability through air to air thermal cycling after various Sn-Pb and Pb-free reflow profiles [93]. Six different materials, with different numbers of reflow profiles were studied in this test through 6 000 accelerated thermal cycles. The boards in this test were subjected to 0, 3, and 5 reflows. (Note that a repair heat cycle may require up to 3 reflow temperature excursions; one for part removal, one for site dressing, and one for part replacement). The boards were 0,125 inches thick, did not contain internal nonfunctional pads, and contained several PTHs sizes and laminate materials. After reflow, the boards were subjected to continuity monitoring for 6 000 thermal cycles over a 95 °C (203 °F) temperature range from 5 °C to 100 °C (41 °F to 212 °F). Data from this testing showed that all PCB/PWB laminate materials that claimed to be Pb-free compatible exhibited considerable variation in reliability. The authors suggest that given the differences in material performance related to plated through hole reliability and the difficulty in relating material properties directly to the resulting plated through hole reliability, it is highly recommended that high reliability and/or long life applications include some quantifiable fatigue life evaluation of materials prior to specifying them on this type of product. Drill hole wall roughness and plating quality continued to be key parameters controlling plated through hole reliability. Additionally, for higher aspect ratio plated through holes, the tensile strength and elongation properties of the PTH copper appeared to be significant variables affecting long term reliability. The number of reflow cycles used in the reference [93] assessment may not be adequate for aerospace and high performance applications. Some applications may need to consider increasing the number of reflows used in the PCB/PWB assessment in order to account for additional repair events that may occur through the life cycle of the product.

10.3 Copper dissolution

Many of the Pb-free solder alloys cause greater copper dissolution than the heritage Sn-Pb alloys during soldering [94]. The phenomenon that is taking place during the dissolution is a solvent/solute interaction. Given enough time, the liquid solder solvent will dissolve the copper solute until it reaches saturation. Although the Pb-free SAC was formulated to contain copper in an effort to reduce copper pad dissolution, at a given processing temperature it has the ability to "dissolve" copper until the solubility limit is reached. The dissolution process is basically a concentration-driven diffusion/convection process. Solid metal substrate dissolution by liquid Sn is a very complex phenomenon that is dependent upon the solid and liquid materials, temperature, contact time, and liquid velocity. It is not clear what role intermetallic plays in the dissolution process since the liquid solid boundary cannot be observed directly due to the opacity of the liquid metal. In some cases, transient solid phases can form and re-liquefy [95].

During surface mount soldering, the volume of liquid solder solvent is limited by the volume of the deposited solder paste and, in the case of BGAs, the BGA solder ball volume. Early in the Pb-free transition, copper was added to Sn-Ag eutectic alloy to reduce copper pad dissolution during surface mount soldering [96] [97]. Recently, de Sousa et al. [98] recommended increasing the Cu concentration in SAC BGAs to 1 % Cu, which the investigators felt was a level where pad dissolution was minimized but there was still enough dissolution occurring to obtain good wetting. Dissolution is not unique to Pb-free solder; some older Sn-Pb immersion dissolution studies of copper wire [99] [100] and flat foil coupons [101] suggest that significant dissolution is also possible when liquid Sn-Pb solder exposure is prolonged.

Wave and fountain soldering are more likely to dissolve PCB/PWB pad metallization because of the larger volume of solder available for dissolution. The solder in the wave/fountain acts continuously as a solvent that will completely dissolve the copper pad (e.g., the solute) given enough time. While the PCB/PWB is in contact with the solder, fresh solder at low copper concentrations continuously impinges on the PCB/PWB copper pad carrying away the pad material, eroding the pad. For Pb-free SAC, it was determined that the knee of the PTH solder joint is the most susceptible Cu dissolution location [102]. The knee not only has a thinner initial Cu thickness layer compared to the pad, but the rate of Cu dissolution is greater at this (convex) surface as compared to the pad and/or the inner barrel wall. Also, it was determined that it is possible for a good solder fillet to form even when 100 % Cu dissolution occurs at the knee location. Solder bridging over the dissolved knee can in some cases result in latent failures. There are, however, many cases where there will be no impact to functionality because either (a) the solder completes the connection satisfactorily for the intended life or (b) there are no surface connections made to the periphery of the pad. PCB/PWB intended for soldering in wave, and fountain applications should have surface land and plated through hole metallization thickness, particularly over the hole knee, evaluated for adequacy. If the item is intended to be repaired during the service life using these processes, then there should be enough metal remaining to allow for reliable depot/field repair. Different copper plating processes from different suppliers could potentially produce different copper plating densities, which should be considered during testing, since they are likely to play an important role in copper dissolution. Nickel metallization (ENIG or electrodeposited Ni) significantly improves the dissolution resistance and in combination with gold plating can promote improved wetting characteristics. However, the ENIG finishes have historically been susceptible to a phenomenon called “black pad”.

NOTE The “black pad” phenomenon on ENIG finishes is thought to be a function of the phosphorous content in the nickel plating, the immersion gold plating process, and the chemical attack of the nickel plating.

In addition, Ni-Sn intermetallics have lower strength than Cu-Sn intermetallics. In some designs, a mixture of PCB/PWB finishes on the same panel may be useful. Some suppliers are evaluating the use of copper pads for the SMT devices and ENIG for the plated through hole regions requiring high dissolution resistance. Testing of a Sn-0,7Cu-0,05Ni alloy in fountain soldering on a thermally massive PCB/PWB showed slightly greater dissolution rates as compared to Sn-Pb [103]. In some cases, improving pre-heat prior to soldering can reduce liquid solder contact time, significantly reducing dissolution.

10.4 PCB/PWB laminate materials

10.4.1 General

Material selection will need to be carefully considered when designing for Pb-free assemblies [93]. Lead (Pb) containing assemblies have been around for more than 50 years, are well understood, and are very forgiving during the soldering and assembly process. Pb-free solders require higher processing temperatures and materials should be selected to assure low stress, compatibility of piece parts to substrate material, mechanical characteristics, board finish and tin whisker mitigation. The higher temperatures required for Pb-free processing requires materials to be selected and matched to the thermal expansions of the assembly components. Good material selection and thermal expansion matching directly affect the integrity of the finished product. Both the glass transition temperature and the decomposition temperature should be considered when evaluating a PCB/PWB laminate material. Fiber debonding and conductive anodic filament (CAF) formation should be assessed for PCB/PWB laminates subjected to increased Pb-free soldering and rework temperatures. There has also been an issue with laminate strength under BGAs. In some cases, PCB/PWB pads exhibit laminate cracking under the BGA solder pads after soldering and/or after rapid mechanical loading [58] [104]. The cracks are typically located in the resin rich layer between the copper pad and the glass fiber bundles. In this failure mode, the copper trace connecting the BGA solder pad to the adjacent PTH eventually fractures and creates an open circuit condition. Resin fractures where the pad has been weakened but where there is still electrical continuity are difficult to detect without cross-sectioning.

10.4.2 Coefficient of thermal expansion

Configurations requiring controlled thermal expansion PCB/PWB construction in order to match the thermal expansion of low CTE piece parts may exhibit greater warpage and plated through hole stresses during Pb-free soldering and rework.

10.5 Surface finish

The PCB/PWB finish should be communicated to the repair facility using the e-code system defined in IPC-1066. Various Pb-free finishes have emerged. The key assembly attributes for various board surface finishes such as shelf life, multiple assembly reflow cycles, SMT land surface topology, test probe characteristics, etc, are summarized in Table 5-2 of IPC-7095B:2008. A summary of the tin whisker and tin pest propensity tendencies of various Pb-free PCB/PWB finishes is given in Table 5.

Electroless nickel immersion gold (see IPC-4552) or electrolytic nickel can form Sn-Ni-Cu ternary intermetallics when used with Cu bearing solder or Cu pads in close proximity. This interaction is also possible in Sn-Pb solders when a Cu pad is opposite a Ni pad (ball size = 125 μm) [105]. The diffusive transport of Cu through Sn is somewhat unusual and may not necessarily be governed by traditional concentration gradient based descriptions based on Fick's law. One investigator found that Cu from a Cu plate was transported through solid Sn to an adjacent Ni plate to form a Cu-Ni-Sn intermetallic. It was noted that no Cu was found in the Sn separating the plates [106]. Some of these Sn-Cu-Ni intermetallics have lower strength than Sn-Cu or Sn-Ni binary intermetallics and maybe less durable than Sn-Pb soldered joints during mechanical shock testing. There has been some work suggesting that the thermal cycling performance of reduced silver content SAC alloy (SAC-L) chip scale package solder joints is improved when a nickel surface finish is used instead of copper [107]. The nickel surface finishes, however, typically have lower vibration and shock performance than copper [108].

Immersion Ag (seeIPC-4553) is a metallurgically compatible finish to Cu, Sn, Pb, and Ag bearing solder alloys. The wettability of Pb-free alloys in surface mount applications is such that the deposited solder alloy does not generally wet out to the extents of the pads, leaving non-solder coated immersion Ag coating at the edges. Caution should be exercised when using silver in assemblies exposed to sulfur bearing atmospheres. Immersion Ag is considerably thinner than typical plated silver finishes that have exhibited silver migration tendencies in the past under voltage-biased humidity conditions. Silver thickness should be monitored and controlled. Immersion Ag surface finish performs adequately in SIR and EM tests and is not readily prone to dendritic growth in presence of high humidity. However, ENIG and OSP are superior in the water droplet conditions simulating condensation and are less likely to electromigrate under those circumstances [109]. Conformal coating should prevent liquid moisture contact with immersion silver finishes in most cases.

NOTE All polymer coatings are permeable to molecular moisture. Good conformal coat adhesion is needed. If separation between the assembly and the coating occurs, liquid moisture will eventually accumulate in the gap if sufficient moisture is present in the surrounding atmosphere.

Immersion tin (Sn) (see IPC-4554) is a metallurgically compatible finish to Cu, Sn, Pb and Ag bearing solder alloys. The immersion tin (Sn) thickness should be at least 1 μm thick to ensure adequate solderability (see IPC-4554). Immersion tin (Sn) differs from electrolytic tin (Sn) used on tin (Sn) plated piece parts. Immersion tin (Sn) has not been shown to produce whiskers when exposed to the classic acceleration methods used for electrolytic tin (Sn). However, whiskers have been grown on immersion tin (Sn) coated features after some time at ambient conditions and not as a result of exposure to heat, vacuum, pressure, humidity or bias voltage (see IPC-4554). IPC/JEDEC JP002 suggests that the primary source for whisker growth is film stresses associated with the growth of Cu_6Sn_5. Whisker length has been reported to be significant in vias, with lengths measured to be 150 μm. Whiskers of much smaller lengths have been recorded growing off the edge of surface mount (SMT) component pads, as well [110] (IPC/JEDEC JP002, IPC-4554). Immersion tin (Sn) plating suppliers have implemented specific tin whisker mitigation protocols as part of their chemistry (e.g., alloy elements, additives, organic content control, etc.) that are expected to reduce tin whisker risk. The industry continues to work on a test method designed to quickly indicate the susceptibility of a deposit to whisker growth. Whiskers forming on the immersion tin (Sn) will not be an issue in cases where tin-lead solder completely wets to the edge of PCB/PWB pads. While complete pad solder wetting is not an issue with Sn-Pb solders, most of the lead-free solders do not wet much beyond the location of the printed solder paste. PCB/PWB pad and/or solder stencil print adjustments may be needed to completely cover PCB/PWB pads with solder.

As long term storage and rework/repair capability improves, OSPs may become increasingly used in the future. Although the solder joint reliability is good, this finish often leaves areas of exposed copper [111], which may be susceptible to corrosion and present long term reworkability issues. OSPs are fully compatible with all solder alloys.

Table 5 – PCB/PWB metallization tin whisker and tin pest propensity

PCB/PWB metallization	Tin whisker propensity [a,b]	Tin-pest risk (cold applications)
Sn-(3 wt % to 5 wt %)Pb	Low	Low
Sn-(37 wt % to 40 wt %)Pb electroplated and fused	None	Low
Sn-(37 wt % to 40 wt %)Pb hot air solder level	None	Low
Sn-Cu HASL	High [c]	No data [d]
Imm Ag (PCB/PWB) [e]	None (no Sn on surface)	None (no Sn on surface)
Imm Sn (PCB/PWB)	Low-medium [f]	No data [g]
Au/Ni electroplate or ENIG (electroless Ni-P/immersion Au)	None	None
Organic solderability preservative	None	None

[a] See IEC/TS 62647-2.

[b] See [80].

[c] iNEMI [80] suggests that dipped Sn-Cu finish may or may not be effective reducing tin whiskers. In electrodeposited layers, Cu in Sn promotes rapid whisker formation (see Table 2). See [141].

[d] Cu in high purity 99,99 % Sn promotes tin pest (see K. Sweatman et al [24]). Williams [23] found some tin pest transformation on 99,98 % Sn after it was soldered to copper at 204 °C (400 °F) above the liquidus and attributed this to the increased Cu content in the Sn. Spergel [25] did not observe tin pest transformation in dipped wire.

[e] Silver is susceptible to the formation of silver sulfide dendrites.

[f] See 10.5. The tin whisker risk for immersion tin (Sn) differs from electrolytic Sn used on Sn plated piece parts.

[g] See 5.3. If the Sn coating is hot dipped on copper, Spergel tin indicates that the tin pest risk is low but not with electrodeposited Sn. For thin Sn film configurations, tin pest has been observed by Bornemann [21] and Becker [19] under laboratory conditions. No long term tin pest testing is available for immersion tin (Sn) finish (fused or not) over copper.

10.6 Pb-free PCB/PWB qualification

PCB/PWB laminate and construction integrity qualification requirements are evolving. PCB/PWB being considered for Pb-free solder processing should be tested for plated through hole and inner layer integrity at the reflow temperatures expected in the proposed process and also be subjected to solder float testing with all solder alloy(s) that will be used. The supplier should qualify the Pb-free laminate materials and the plating process to the thermal exposure levels that are expected during soldering and rework processes. Both decomposition (T_d) and glass transition temperatures (T_g) as well as time to delamination need to be considered when choosing a laminate. PCB/PWB board solder float temperature requirements for Pb-free PCB/PWB are likely to increase from 260 °C to 288 °C (500 °F to 550 °F). It is expected that these requirements will eventually flow into IPC-6011 and IPC-6012. Cross-section and warpage assessments of PCB/PWB after multiple Pb-free solder reflow exposures have shown that different Pb-free laminates have varying levels of performance [104].

10.7 PCB/PWB artwork and design considerations for Pb-free solder applications

There are a number of issues to consider when designing piece part land patterns for Pb-free solder. A thorough understanding of the Pb-free solder properties and the soldering process becomes important. At the present time, the surface mount land patterns based on Sn-Pb solder have not changed significantly for Pb-free solder. Designers should address material compliance restrictions (such as RoHS restrictions) early in the design cycle and need to be aware of the Pb-free manufacturing process considerations. Design review discussions should include moisture sensitivity levels (MSLs), piece part plating options, maximum reflow temperatures for parts, thermal balance, and required printed circuit board (PCB/PWB) finishes. Early involvement of manufacturing engineering will be needed to help ensure success. There are some cosmetic aspects of the present IPC land pattern design that may change to account for the reduced spreading characteristics associated with Pb-free alloys. In some instances, pads may require design changes to support higher temperature processing and rework. It is expected that the land pattern designs will continue to evolve.

11 Printed circuit board (PCB)/printed wiring board (PWB) assembly

11.1 General

The assembly manufacturing requirements are given in IPC J-STD-001 with the printed circuit board (PCB)/printed wiring board (PWB) design guidance being provided in IPC-2221 and IPC-7095B:2008. Many of the IPC standards have changed or are in the process of changing to provide Pb-free design guidance [112]. The introduction of Pb-free finishes and alloys has significantly increased the number of possible finish/alloy combinations. Each combination requires some level of cross-compatibility assessment. Various Pb-free finishes can be used in different solder processes and solder alloys. A high level summary of the various component and PCB/PWB process compatibility and reliability considerations is given in Tables 6, 7, 8, and 9.

11.2 PCB/PWB process indicator coupons

A dissolution assessment coupon for PTH technology PCB/PWB is a useful way to ensure that adequate dissolution resistance is verified for each lot of PCB/PWB. The dissolution assessment coupon is one means of determining if a particular PCB/PWB can be subjected to solder fountain repair(s) after the initial assembly wave soldering process has been done. It may also be beneficial to incorporate a surface mount wettability coupon (e.g., as defined in IPC-6012) that would be manufactured at the same time as the production PCB/PWB. The coupon would be stored along with or remain attached to the main PCB/PWB to assess solder wettability for applications requiring long term storage. Patterns should be representative of the piece part technology used on the board (e.g. a decreasing pitch pattern).

11.3 Solder inspection criterion

IPC-A-610 provides visual guidance for Pb-free acceptance criterion. Not all combinations of solder, lead/terminal finish, and processes are captured for the various joint configurations. Individual programs may need to establish/define requirements regarding the suitability of the various joint configurations and appearances. Presently, fillet lifting for PTH solder joints (not SMT) is allowed because it does not significantly reduce the solder joint strength. In some instances, the thin gap of the lifted fillet may be undesirable because it could tend to accumulate or trap contamination or be difficult to conformal coat.

11.4 Fluxes, residues, cleaning and SIR issues

Pb-free solder fluxes and higher processing temperatures may result in residues that are less soluble and more difficult to remove. Surface insulation resistance (see IPC-9201) should be used to assess cleaning effectiveness. Flux residues may also present conformal coat adhesion issues if not removed.

Table 6 – Piece part terminal and BGA ball metallization solder process compatibility risk

Terminal or PCB/PWB metallization [a]	Sn-Pb solder	SAC solder (SMT and wave)	Sn-Cu or Sn-Cu-Ni wave solder	Sn-Ag solder
Sn-(3 wt % to 5 wt %)Pb	None	Low [b,c]	Low [c]	Low [b,c]
Sn-(37 wt % to 40 wt %)Pb	None	Medium [b,c]	Medium [c]	Medium [b,c]
Sn, reflowed/fused/dipped [d]	None	None	None	None
Sn, bright electrodeposit – avoid [e]	Shelf life [f,g] Solder voids [h]	Shelf life [f, g] Solder voids [h]	Shelf life [f,g] Solder voids [h]	Shelf life [f,g] Solder voids [h]
Sn, matte electrodeposit [d]	Short shelf [f,g] Solder voids [h]	Short shelf [f,g] Solder voids [h]	Short shelf [f,g] Solder voids [h]	Short shelf [f, g] Solder voids [h]
Sn-Bi (2 wt % to 5 wt % Bi content in terminal plating, which results in ~0,2 wt % to 0,5 wt % in most final SMT solder joints) Bi finishes are not recommended for wave solder [j]	SMT low-medium [i]	None SMT	None SMT	None SMT
Antimony bearing	No data	No data	No data	No data
SAC dipped [k]	None	None	None	None
Sn-Cu electrodeposit, avoid [m]	None	None	None	None
Sn-(0,5 wt % to 0,9 wt %)Cu-0,05Ni plated or dipped, avoid [l]	None	None	None	None
Ni-Pd-Au electrodeposit	Low [m]	Medium	Medium	Medium
CBGA/CCGA/BGA/C4 ball				
Sn-37Pb (includes Sn-36Pb-2Ag)	None	Unlikely combination	Unlikely combination	Unlikely combination
10Sn-90Pb	None	High [n]	Unlikely combination	High [n]
Sn-Cu	No data	None	None	None
SAC	Medium [o]	None	None	None
Cu wire column [p]	Low	Low	Low	Low

NOTE Low risk represents good processability and high risk represents poor processability. Several finishes have insufficient tin whisker or tin pest data; however, based on the metallurgy, they have been ascribed a risk level based on the best information available.

[a] All alloy percentages are given in weight percent.

[b] Some investigators have found that a Sn-Ag-Pb alloy can form having a melting point of 178 °C, which may impact processing. [73], [149]

[c] Pb from the finish can contaminate the wave solder bath.

[d] Organic co-deposited compounds are typically removed from the tin coating during the reflow/fusing process.

[e] Bright tin finish is not recommended due to tin whisker propensity of bright tin plating. Bright tin is defined as having 0,2 % to 1,0 % carbon content with 0,5 µm to 0,8 µm grain size. Matte tin is a film with lower internal stresses and larger grain sizes than bright tin. Matte tin plating is defined as having 0,005 % to 0,050 % carbon with 1 µm to 5 µm grain size. [80]

[f] Co-deposited organics can limit shelf life and/or solderability.

[g] Insufficient coating thickness can result in reduced shelf life. Recommended thickness is 10 µm nominal (8 µm minimum) when no nickel underplating is used. The minimum thickness should be 2 µm when a nickel underplate is used to ensure shelf life. [80]

The lower rate of nickel diffusivity retards nickel/tin intermetallic formation thus limiting the stresses which would drive tin whisker growth.

[h] In bright tin or thicker matte tin coatings, co-deposited organics can yield solder voids during solder reflow for some solder joint geometries.

[i] Environmental reliability should be substantiated on the programs considering small amounts of total Bi in the final solder joint.

[j] Not recommended for pin through hole, Bi may accumulate in wave solder pot.

[k] There may be tin whisker risk with SAC alloy dipped finishes where they become thin around corners and edges. Note that thicker coating tends to isolate the intermetallic layers and dissipates whisker formation inducing stresses.

[l] Avoid Sn-Cu due to the tin whiskering propensity of this plating. Sn-Cu provides all of the raw materials for generating the intermetallics that drive tin whisker formation. Tin whiskering propensity is high. Hot solder dipped Sn-Cu is being used in some applications.[80]

[m] Electrodeposited plating should be analyzed to ensure that the final solder joints will not be susceptible to strength reduction associated with gold embrittlement.

[n] See [152].

[o] Mixed alloy (SAC ball/Sn-Pb paste or Sn-Pb ball/SAC paste) combinations are not as reliable as the unmixed (SAC ball/SAC paste or Sn-Pb ball/Sn-Pb paste) combination. See 8.2 related to the mixing of solder alloys. Fatigue models do not exist for Sn-Pb and SAC alloy mixtures at this time. See 8.2 related to the mixing of solder alloys.

[p] The copper wire column typically uses a wire that is 254 µm in diameter, 1 524 µm long having a finish of 0,05 µm Sn. [148]

Table 7 – PCB/PWB finish solder process compatibility risk

PCB/PWB metallization [a]	Sn-Pb solder	SAC solder	Sn-Cu or Sn-Cu-Ni wave solder	Sn-Ag solder
Sn-(37 wt % to 40 wt %)Pb electroplated and fused	None	Medium [b,c]	Medium [c]	Medium [b,c]
Sn-(37 wt % to 40 wt %)Pb hot air solder level (HASL)	None	Medium [b,c]	Medium [c]	Medium [b,c]
Sn-Cu HASL	None	None	None	None
Immersion Ag [d]	Low	Low	Low	Low
Immersion Sn [e]	Low	Low	Low	Low
Au/Ni electroplate [f]	Low	Low	Low	Low
ENIG (electroless Ni-P/immersion Au) [g]	Low	Low	Low	Low
OSP (organic solderability preservative) [h]	None	None	None	None

NOTE Low risk represents good processability and high risk represents poor processability. Several finishes have insufficient tin whisker or tin pest data; however, based on the metallurgy, they have been ascribed a risk level based on the best information available.

[a] All alloy percentages are given in weight percent.

[b] Some investigators have found that a Sn-Ag-Pb alloy can form having a melting point of 178 °C which may impact processing. [73], [149]

[c] Pb from the finish can contaminate the wave solder bath.

[d] When using immersion Ag, thickness uniformity and porosity should be monitored. The thickness can vary with feature size [61]. The immersion Ag surface finish is susceptible to degradation by finger oils during handling. Storage precautions should be considered to ensure sufficient shelf life.

[e] The shelf life for immersion Sn is typically lower than Sn-Pb finishes. Storage precautions should be considered to ensure sufficient shelf life.

[f] Gold embrittlement may be a concern in some applications if the gold concentration in the final solder joint exceeds 3 % to 4 %.

[g] The “black pad” pheonomenon associated with ENIG is an industry concern.

[h] The shelf life for OSP is lower than Sn-Pb finishes and there is an increased incidence of exposed copper regions on the PCB/PWB pads where the solder does not wet to the pad extents. Storage precautions should be considered to ensure sufficient shelf life.

Table 8 – Piece part terminal and BGA ball metallization reliability risk

Terminal or PCB/PWB metallization [a]	Sn-Pb solder	SAC solder [b]	Sn-Cu or Sn-Cu-Ni wave solder	Sn-Ag solder
Sn-(3 wt % to 5 wt %)Pb	Low	Low [c]	Low [c]	Low [b]
Sn-(37 wt % to 40 wt %)Pb	Low	Medium [c,d]	Medium [c]	Medium [c,d]
Sn (bright or matte tin)	Low (5)	Low-medium [e,f]	Low [e,f]	Low [e]
Sn-Bi (2 % to 5 % Bi content in terminal plating typically results in ~0,2 to 0,5 % in most SMT final solder joints)	Low	Low	Low	Low
Sn-Cu, Sn-(0,5 wt % to 0,9 wt %)Cu-0,05Ni, or SAC dipped finish	Low	Low [f]	Low [f]	Low [f]
Ni-Pd-Au [g]	Low-medium	Low-medium [f]	Low [f]	Low
CBGA/column grid/BGA/C4 ball				
Sn-37Pb (includes Sn-36Pb-2Ag)	Low	No data	No data	No data
10Sn-90Pb	Low	High [h]	No data	No data
SAC	Medium [i]	Low-medium	No data	No data
Cu wire	-	Low-medium	No data	No data

NOTE Low risk represents good reliability and high risk represents poor reliability.

[a] All alloy percentages are given in weight percent.

[b] SAC does not perform as well as Sn-Pb in vibration or shock loading [49]. Thermal cycling performance of SAC is generally better than if the maximum temperature is below 100 °C (212 °F) [46].

[c] Pb from the finish can contaminate the wave solder bath.

[d] Some investigators have found that an Sn Ag–Pb alloy can form, having a melting point of 178 °C, which may impact processing [73]. If delamination is present, then solder reliability will be impacted.

[e] In bright tin or thicker matte tin coatings, co-deposited organics can yield solder voids during reflow in some solder joint geometries.

[f] There is a possibility of forming lower strength Sn-Ni-Cu intermetallics after aging. [150], [151], [33]

[g] In some cases, the formation of a Pd-Au-Ni-Sn intermetallic near interface can reduce reliability, [45]. $PdSn_4$ has the same brittle characteristics as $AuSn_4$ intermetallic, [71]. For applications in high moisture or corrosive environment, if the Ni/Pd/Au is cracked during lead-forming, stress corrosion can result, [2].

[h] Column grid array columns, particularly for heavy parts, can become tipped after SAC reflow if the column attach alloy melting temperature is below the Pb-free soldering temperature. [151]

[i] Mixed alloy (SAC ball/Sn-Pb paste or Sn-Pb ball/SAC paste) combinations are not as reliable as the unmixed (SAC ball/SAC paste or Sn-Pb ball/Sn-Pb paste) combination. See 8.2 related to mixing of solder alloys. Fatigue models do not exist for Sn-Pb and SAC alloy mixtures at this time. (See 8.2 related to mixing of solder alloys).

Table 9 – PCB/PWB metallization reliability risk

Terminal or PCB/PWB metallization [a]	Sn-Pb solder	SAC solder [b]	Sn-Cu or Sn-Cu-Ni wave solder	Sn-Ag solder
Sn-Pb	Low	Medium [c, d]	Medium [c]	Medium [c,d]
Immersion Ag	Low	Low	Low	Low
Immersion Sn	Low	Low	Low	Low
Electrolytic nickel/gold	Low [f]	Low-medium [e]	Low-medium [e]	No data
Electroless nickel/immersion gold ENIG [f]	Low	Low-medium [e]	Low-medium [e]	No data
SAC HASL	Low	Low	Low	Low
Sn-Cu-Ni HASL	Low	Low	Low	Low

NOTE Low risk represents good reliability and high risk represents poor reliability. Several finishes have insufficient tin whisker or tin pest data; however, based on the metallurgy, they have been ascribed a risk level based on the best information available.

[a] All alloy percentages are given in weight percent.

[b] SAC does not perform as well as Sn-Pb in vibration or shock loading [49]. Thermal cycling performance of SAC is generally better than Sn-Pb eutectic when the maximum temperature is 100 °C (212 °F) or lower. [46].

[c] Pb from the finish can contaminate the wave solder bath.

[d] Some investigators have found that an Sn-Ag-Pb alloy can form, having a melting point of 178 °C, which may impact processing, [73]. If delamination is present, then solder reliability will be impacted.

[e] Solder joint strength can be reduced after extended baking due to the diffusion of dispersed Au from the bulk to the Ni interface to form Au-Sn_4 in the grain boundaries near the interface or Au0,5Ni0,5Sn4 over the NiSn interface intermetallic (discussed in [6]). There is also the possibility of forming lower strength Sn-Ni-Cu intermetallics after aging, [150], [151], [33].

[f] ENIG is susceptible to a low strength solder joint condition called “black pad” which is due to corrosion of the Ni-P by the immersion Au process (discussed in [6]).

12 Module assembly considerations

12.1 Connectors and sockets

Little work has been published regarding Pb-free soldering of connectors. Warpage conditions of PCB/PWB edge and long SMT connectors may be exacerbated due to the higher processing temperatures.

The connector contacts and bodies should be reviewed for the presence of pure tin and zinc plating and assessed for metal whisker risk, both internal and external to the connector body. Contacting surfaces are usually not conformally coated and can be susceptible to shorting if whiskers grow between adjacent contacts. Tin plated contacting surfaces not surrounded by insulating materials should be avoided. Of particular concern are un-mated test connectors on printed circuit assemblies that may form tin whisker shorts. Tin plated brass without a nickel barrier is undesirable. Tin over brass has been frequently used to grow whiskers in very short times for experimental purposes. For an extended discussion regarding tin whiskers, the reader is referred to IEC/TS 62647-2 and IPC/JEDEC JP002.

Press fit connectors should be reviewed for tin whisker risk because there is no solder present to mitigate tin whiskers. In addition, compressive stresses are imparted on the tin plating by the compliant pins pressed into the holes. It has been shown that whisker growth is stress dependent. Compliant pins act as a stress source. In these instances, the residual stresses supplied by the compliant pin energize and promote the growth of tin whiskers. In particular, compliant pin connectors pressed into immersion tin finished PCBs/PWBs should be avoided unless suitable tin whisker risk mitigation is used. Press fit connectors and PCBs/PWBs having noble metal finishes have been shown to be successful with increased consideration for the mechanical press fit system (e.g., material compatibility, lubricity, insertion force, hole integrity, tolerances).

12.2 Heatsinks/modules

The addition of heatsinks can substantially alter the solder stresses. Heatsinks can significantly stiffen the assembly and alter the piece part mounting surface coefficient of thermal expansion. If the heatsink-PCB/PWB assembly is asymmetric, bending can occur during thermal cycling, which will tend to increase the stress on the piece part solder joints. Thick stiff assemblies often have greater solder strain during thermal cycling, but usually have lower strain during vibration and shock as compared to thin flexible boards and/or piece parts. In addition, the constraining effects of a thermal interface material used on top of an area array component can impact the thermal cycle reliability of the part. Therefore, thermal cycle qualification testing of a part that is to be used with a heat sink should be performed with the heat sink attached [113].

12.3 Conformal coating

Conformal coating (IPC-CC-830, MIL-I-46058) application over pure tin finished conductors is one of the tin whisker mitigation options given in IEC/TS 62647-2. Although conformal coating should be used in conjunction with other mitigation techniques, it is frequently employed in high reliability assemblies. Conformal coating can influence the solder fatigue behavior of an assembly. Conformal coatings are available in a wide range of hardnesses and tin whisker mitigation effectiveness [114] [115]. Conformal coatings generally have a much higher coefficient of thermal expansion than solder. Conformal coating can increase solder stress during thermal cycling [30] [116] [117], particularly if the coating is rigid, the piece part has a stiff lead termination geometry and the coating bridges the gap between the piece part and the PCB/PWB. The relative rigidity of common conformal coating materials is shown in Table 10. Compliant conformal coating usually results in reduced solder stress as compared to the rigid conformal coating. Assemblies used for thermal cycling testing and environmental stress testing should be conformally coated if the conformal coat is expected to effect the thermal cycling reliability of the assembly.

Table 10 – Relative rigidity of IPC-CC-830 conformal coating categories

Coating type	Rigidity/stiffness
XY (paraxylylene)	High
UR (urethane)	Low to high
ER (epoxy)	Medium to high
AR (acrylic)	Low to medium
SI (silicone)	Low

The conformal coating should be evaluated for coverage, particularly on the vertical surfaces of leads/terminals and other features if intended for use in tin whisker mitigation. Conformal coating viscosity and spray configuration are key factors in controlling coverage. Shadowing should also be evaluated. Conformal coating has been shown to extinguish whisker initiated arcing as the coating decomposes (e.g., burns) [118], but it may be possible that the decomposition by-products could support the arcing event under some conditions.

13 Manufacturing resources

Considerable information on the application and reliability of Pb-free soldering is available in many handbooks. A partial list follows as:

- Lead-Free Electronics, edited by S. Ganesan, M. Pecht, Wiley-IEEE, NY Press, 2006 [3]
- Implementing Lead-Free Electronics, J. S. Hwang, McGraw-Hill Professional Engineering, NY, NY, 2004. [119]
- Handbook of Pb-Free Solder Technology for Microelectronic Assemblies, K. Puttlitz and K. Stalter, Marcel-Dekker, NY, NY 2004.[120]
- Electronics Manufacturing: with Lead-Free, Halogen-Free, and Conductive-Adhesive Materials, John H. Lau, C.P. Wong, Ning-Cheng Lee, Ricky S.W. Lee, McGraw-Hill, NY, NY, 2003. [121]
- Lead-free Solder Interconnect Reliability, D. Shangguan, ASM International, Materials Park, OH, USA 2005. [32]

14 Aerospace wiring/cabling considerations

14.1 Insulation temperature rating

Pb-free may not be a critical issue with cable/harness soldering. Parrish [122] suggests that because of the type of heat sources commonly used in cable and harness applications, and the intimate operator control of hand soldering operations, cable harness Pb-free soldering is not nearly as significant an issue as Pb-free PCB/PWB machine reflow soldering where temperature sensitive piece parts and internal elements can be degraded with increased temperatures.

14.2 Cable connectors

Cable connectors should be assessed using the same criterion that is mentioned in 12.1. The connector contacts and bodies should be reviewed for the presence of pure tin and zinc plating and assessed for metal whisker risk, both internal and external to the connector body. As with the electronic module connectors and sockets, tin plated contacting surfaces not surrounded by insulating materials should be avoided. Of particular concern are un-mated test connectors that may form tin whisker shorts. Tin plated brass without a nickel barrier in undesirable. Tin over brass has been frequently used to grow whiskers in very short times for experimental purposes.

14.3 Wire terminals

It is possible to form thin solder regions over corners of terminals and wires. If the thickness of Pb-free solder in these areas approaches the thickness obtained from fused Pb-free solder on component leads, tin whiskers may form. In almost all cases, the large spacing between conductors associated with these configurations effectively eliminates the tin whisker shorting risk.

14.4 Splices

During the transition, communication with the splice supplier will be needed to ensure that the solder alloy and surface finish are known. There are no anticipated technical compatibility issues between Pb-free wire and splices.

14.5 Sleeving

Temperature rating of sleeving should be adequate for the Pb-free processing temperatures required for soldering.

15 Rework/repair

15.1 General

Considerable effort has centered on rework/repair, which is paramount to aerospace maintenance. During the creation of the present document, it was decided that the rework topic required a separate document. At the present time IEC/TS 62647-23 has been written to address the topic of rework and repair. Much of the text below is being considered for the rework and repair document. Upon its completion, Clause 15 will be revised. Due to higher unit costs and fewer, more complex parts, aerospace organizations rework or repair products instead of discarding them. As a result, consortia have been studying the rework/repair issues, such as the JCAA/JG-PP Pb-free solder study [49] which investigated the impact of rework/repair of Pb-free assemblies in contrast to Sn-Pb assemblies, and the iNEMI consortia on lead (Pb) contamination.

Also to be noted is the Airlines Electronic Engineering Committee of the Avionics Maintenance Conference issuance of ARINC Project Paper 671, which states that “mixing Pb-free and Pb-based solder processes within a single soldered assembly is undesirable and should be avoided.” This is of significance to rework and repair over a 20-year service life because of the strong possibility of mixing Pb-free and lead (Pb)-based solders.

The need for a metallurgically stable solder joint under harsh environmental conditions, high stress and shear loading, and long term storage presents a set of requirements that are significantly different from most commercial applications. It is well documented that processing conditions during soldering can significantly affect the microstructure and reliability of the joint. While methods for repairing assemblies using Sn-Pb solders are well established, limited data is available for re-work and repair of Pb-free solder processing, especially when the resulting joint is a combination of Sn-Pb and Pb-free solders [123], [124], [125].

The JCAA/JG-PP study [49] looked at various configurations of reworked assemblies with the following tests:

- thermal cycling –20 °C to 80 °C and –55 °C to 125 °C
- combined environments
- vibration
- mechanical shock
- thermal shock

- salt fog
- humidity
- SIR
- EMR

With regards to reworked solder joints, the following was concluded by the JCAA/JG-PP study:

- Rework operations have the potential to reduce the reliability of both Pb-free and Sn-Pb solders.
- Results from individual tests (combined environments, thermal cycling, and vibration testing) should not be used alone to make definitive decisions on Pb-free reliability. Results from this study should be taken as a whole.
- The impact of Sn-Pb contamination on the Pb-free solder alloy reliability is mixed. For SAC, Sn-Pb contamination can either increase or decrease reliability depending upon the amount of Pb contamination. For SACB, Sn-Pb contamination has a detrimental effect on reliability. The topic of mixing is discussed in further detail in 8.2. Under high-stress conditions, Sn-Pb generally outperforms Pb-free. For low stress conditions, Pb-free outperforms Sn-Pb.

iNEMI companies have also done considerable work in the rework arena. Results from the 2005 study [126], determined that elevated Pb-free SMT and rework processing temperatures can cause significant quality and reliability concerns when using existing PCB/PWB laminate systems (originally designed for conventional Sn-Pb processes). The study also concluded the following:

- The high temperature exposures necessary for lead-free or tin-lead rework on high thermal-mass PCB/PWB can induce partial reflow of adjacent piece part solder joints.
- Degradation was measured on non-reworked adjacent piece parts after accelerated thermal cycling. This likely reflects the influence of unintended joint reflow.
- High temperature exposures during the lead-free assembly and rework thermal excursions on Ni-Au PCB/PWB had a detrimental impact on the mechanical deflection sensitivity in the board resin material.
- High temperature exposures during lead-free rework had a detrimental effect on PCB/PWB solder mask and vias.

McCall [127] acknowledged that liquid tin is an efficient solvent that readily dissolves copper and other metals (see 10.3). McCall warns against the tendency to just increase the temperature during rework. The issue is not temperature, but the ability of the reworking iron and tip configuration to transfer heat to the work efficiently and the heater’s ability to keep up with heat loss during the work. Without standardization of a single alloy, the use of various alloys creates potential compatibility issues between alloys. It will be impossible for a rework technician to visually identify which alloy has been used on a given PCB/PWB. Solder alloys used in initial manufacturing and on the bench-top should be compatible with one another to avoid creating an uncontrolled alloy. Adjusting an alloy piece part by 0,5 % can change joint wetting and strength characteristics, as well as melting points.

The use of nitrogen-assisted soldering equipment mitigates some problems associated with using lead-free solders. First, it creates an inert environment around the solder tip, reducing the potential for tip oxidation, which would reduce its ability to transfer heat and hold solder. Second, it assists with the soldering process at the PCB/PWB level by purging oxygen from the immediate area, reducing or eliminating oxidation on the worksite. This not only reduces the amount of flux required, but also helps improve wetting and spreading, and leaves a shinier, less-grainy finish. In the process, care should be taken to prevent the nitrogen flow from cooling or disturbing the solder joint. Excessive flow during solidification may cause a "cold solder joint," eliminating the beneficial aspects of the non-oxidizing shroud.

15.2 Piece part rework

15.2.1 Area array rework

Ball grid array devices, which are Pb-free should be soldered at sufficient temperature to reflow the Pb-free alloy even if soldered using tin-lead solder (see 8.3.2).

According to the iNEMI study [126], BGA rework has the following concerns:

- The adjacent and bottom side temperatures need to be minimized to avoid collateral damage. Failure to do this may result in multiple reflows of adjacent solder joints which will weaken the mechanical solder joint integrity.
- Better thermal controls of the rework equipment are needed.
- Bottom-side heat and thermal uniformity are critical to raise the PCB/PWB to proper lead-free rework temperatures. However, increased bottom heating may impact the reliability of the PCB/PWB laminate material.
- Use of a retrofit heat shroud over the reworked board could have the benefit of reducing the amount of bottom preheat required, especially for thicker PCB/PWB.
- Rework equipment suppliers need further development of their equipment to accommodate higher temperature lead-free soldering with an emphasis on optimized rework profiles and machine tool sets.

In a recent BGA rework study [128], no major issues were found after reworking a significant number of Pb-free BGA packages and sockets on PCB/PWB with multiple surface finishes and board thicknesses.

15.2.2 Surface mount capacitor/resistor rework

In the Colfax et al. study [123], results indicated that the shear strength of surface mount capacitors was, in general, highest for the Sn-Pb solders and lowest for the SAC solders. Mixed Sn-Pb and Pb-free alloys had a shear strength value that was in-between the individual alloys. As has been previously reported, shear strength decreased with an increase in the number of temperature cycles. Examination of the solders before and after temperature cycling indicated that the eutectic microstructure before temperature cycling was eliminated during thermal excursions. The higher shear strength of the mixed Sn-Pb/SAC alloy compared with pure Sn-Pb after repair was attributed in-part to preserving the original Cu/Sn intermetallic layer along the solder/copper interface. Unfortunately, it is difficult to correlate shear or pull strength to thermomechanical fatigue performance, which is the reason extended fatigue testing is still necessary. Examination of the solders before and after temperature cycling indicated that the eutectic microstructure before temperature cycling was eliminated during thermal excursions. The findings by Colfax et al. are consistent with the JCAA/JG-PP and the Hunt test results discussed in 8.4.3. The JCAA/JG-PP and Hunt test determined that, Pb contamination of SAC solder joints did not adversely impact solder joint reliability in –55 °C to +125 °C (–67 °F to 257 °F) thermal cycling and vibration for the majority of components tested [56] [65].

15.2.3 Through hole piece part rework

A concern for through hole piece part rework is encountered when Pb-free solders containing high percentages of tin are mixed with iron (the hard protective layer on soldering tips). The high tin concentration wears away the tip iron more quickly than when a typical Sn-Pb solder alloy is used. This causes two problems. One is shorter tip life as the protective iron coating is dissolved in the tin. The second is that oxidation forms more quickly. Once oxides begin to form, the tip loses its ability to wet with solder. If it is not cleaned immediately, the oxide becomes nearly impossible to remove, and the tip should be replaced [127]. Pb-free solder alloys in fountain soldering rework processes can result in undesirable PCB/PWB pad dissolution [102]. The liquid solder can rapidly dissolve the PCB/PWB pads (see 10.3). The rework process development should include the characterization of the PCB/PWB pad dissolution.

15.3 Depot level repair

Most aerospace programs contractually rework and repair the avionics systems or LRUs at the airframe maintenance depot level. However, newer programs are starting to impose warranties on the products so that depot repair and rework is performed at the OEM. Depot rework/repair guidelines need to be provided by the avionics OEM, particularly if the avionics include Pb-free PCB/PWB finishes or soldered assemblies (see IEC/TS 62647-23). Detailed mapping and documentation of the assembly to be reworked or repaired is needed from the OEM to determine what solder alloy to use. If no detailed assembly information is available, at a minimum, the maintainer should check whatever documentation that is available to determine which solder alloy was used, and then use the closest alloy that is available. Additional training is needed for depot rework/repair technicians to determine solder alloys, respond to the difference in alloy percentages, know what the reliability concerns are of mixing alloys, and what to do if the alloy is unknown.

The rework/repair problem of mixing alloys can create a myriad of solder alloy compositions (see Table 11). Note, that impurities may become present in the solder joint due to the effect of the high processing temperatures on the composite system. Impurities may include iron (from the soldering iron), copper (from the base PCB/PWB laminate), silver (i.e., Imm Ag PCB/PWB finishes), or gold and nickel from ENIG PCB/PWB that dissolve into the joint during reflow (see Clauses 8 through 11).

15.4 Mixed solder rework temperature profiles

Development of a rework profile reflow temperature should include an assessment of the PCB/PWB, piece part and solder joint temperature, if known by the operator. This would require knowledge of the original solder alloy used, the PCB/PWB finish, and the piece part finish. It would also require an analysis of the relative percentages of each of the alloys. This kind of information would be difficult to ascertain and possibly outside the ability of the typical rework/repair operator.

Table 11 shows the processing temperatures of typical mixed alloys. Note, that all but one of the reflow temperatures of the typical Pb-free mixed alloys exceeds that of Sn-Pb (183 °C).

15.5 Solder fluxes

A significant number of high performance electronics assemblies are soldered with RMA flux. However, lead-free may need to use more active flux to enhance the wetting characteristics of the soldered surfaces. Conformal coating and humidity exposure often necessitate insuring complete removal of the flux residues. Thermal stability of fluxes will likely continue to improve with time.

Table 11 – Process temperatures of mixed alloys

Alloy composition							Process temperatures (°C)		
Sn	Ag	Cu	Sb	Bi	In	Zn	Liquidus	Reflow	Melt range
98,0	2,0								221 to 226
96,5	3,5						221	240 to 250	
99,3		0,7					227	245 to 255	
96,5	3,0	0,5					220	238 to 248	
96,3	3,2	0,5					218	238 to 248	217 to 218
95,8	3,5	0,8					218	238 to 248	
95,5	3,8	0,7					220	238 to 248	217 to 220
95,5	4,0	0,5					219		217 to 219
95,0	4,0	1,0					220	238 to 248	217 to 220
93,6	4,7	1,7					244	237 to 247	
95,0			5,0						232 to 240
96,2	2,5	0,8	0,5				225	233 to 243	
90,5	2,0			7,5			216	220 to 230	
94,0	3,0			3,0			218	233 to 243	
92,0	3,0			5,0			216	230 to 240	
91,8	3,4			4,8			215	225 to 235	200 to 216
93,5	3,5			3,0			217	230 to 240	
42,0				58,0					138
92,7	3,2	1,1		3,0			240	230 to 240	
96,5	3,5				3,0		215	230 to 240	
89,0				3,0		8,0			189 to 199
NOTE See [153].									

15.6 Rework/repair cleaning process

Since higher temperatures and possibly more active fluxes are used for lead-free soldering, the flux residues will be harder to clean from the assembly. This implies that the cleaning process needs to be longer and better controlled. Refer to IPC J-STD-001 for process qualification testing.

15.7 Inspection requirements

IPC-A-610 provides guidance on inspection criterion. The visual finish of the joint may be different from what operators are accustomed to seeing on Sn-Pb solder joints. Operators and inspectors will need to be retrained and acclimated to work with lead-free solder.

16 Generic life testing

16.1 Thermal cycling, vibration, and shock testing

The test protocol used to substantiate thermal cycling, vibration and shock life for Pb-free solder and mixtures of repair solder alloys can be found in IEC/TS 62647-3:–.

16.2 Other environments

16.2.1 Salt fog

The JCAA/JG-PP Pb-free solder salt fog study has been completed [129]. The JCAA/JG-PP testing compared the corrosion of Pb-free assemblies to Sn-Pb assemblies. Based on the salt atmosphere and humidity exposure tests performed, tin-silver-copper (Sn-Ag-Cu) lead-free solder joints reliability was equivalent to tin lead (Sn-Pb) solder joints. No open circuit conditions attributable to the salt fog environment were observed at the conclusion of 48 hours of salt spray atmosphere in accordance with ASTM B117-3.

16.2.2 Cooling air quality

Special considerations may be required if the Pb-free alloys are subjected to direct air cooling.

16.2.3 Fluid compatibility

There have been no recently reported fluid compatibility concerns with tin or gold finishes. Silver, gold, and rhodium finishes in energized 28 V connectors and wiring that can come in contact with glycol/water mixtures should be reviewed. These metals cause the decomposition of glycol/water mixtures (such as ethelyne glycol) that can result in the production of a flame [130] [131]. Most modern applications are sealed such that glycol mixtures are prevented from making contact with electrically biased metal circuit elements or the glycol mixtures contain chemicals that inhibit the flame producing reaction. The majority of the reported occurrences of silver fire occurred in the late 1960s to mid 1970s time frame on silver plated wiring and silver, gold, and rhodium elements in connectors. Electrical circuit reactivity with glycol/water solutions does not occur with pure copper, nickel covered copper, or tin plated copper elements [130]. At that time, investigations were undertaken to identify the mechanism of the involved hazards and to find methods of counteracting the hazards, including additions to the glycol mixtures that inhibited these reactions. The authors are not aware of any recent reported issues with silver wire interacting with glycol mixtures used for cooling or de-icing. It is unlikely that these fluids would be allowed to come into direct contact with typical electronic assemblies since their functionality would be significantly degraded due to the electrically conductive nature of these fluids.

16.2.4 Generic humidity

The JCAA/JG-PP Pb-free solder study evaluated humidity testing of Pb-free assemblies and found no significant difference in solder joint continuity as compared to Sn-Pb [129]. The interaction between SAC alloys on copper and silver finished pads on polyimide laminate materials subjected to thousands of hours of testing is presently being evaluated by CALCE.

17 Similarity analysis

During the Pb-free transition, metallurgical changes can be encountered in the assembly attached solder alloy, the PCB/PWB finish, or the part finish. Often, the assembly configuration used for the Pb-free reliability testing is not exactly the same as all the manufactured products. However, if thoughtfully designed, it can be similar enough to the manufactured products to allow a similarity analysis to be performed.

IEC/TS 62647-21:2013 recommends that the program and the customer agree upon the level of qualification required on a particular item. Qualification by similarity is most appropriate for piece parts and configurations having similarly stressed solder joints and similar metallurgy (e.g., fused Sn-Pb vs. HASL Sn-Pb). Care should be taken to ensure that the material properties used in the similarity analysis are representative of the actual material behavior in a particular assembly. Sometimes, significant differences exist between material datasheets and actual material behavior [132].

The following items can be considered for qualification by similarity and/or analytical extrapolation:

- Piece part similarity: piece part type, solder geometry, and size.
- Conformal coating changes.
- Changes in lead-free PCB/PWB laminate materials in an assembly. It is preferred to perform the similarity analysis using measured properties. In some instances, the data sheet properties can differ significantly from the actual measured properties in a given application. The general PCB/PWB construction should be evaluated for the aspects outlined in Clause 10 prior to use on a specific assembly.

Testing is recommended for the following items:

- Board finish variations changing the solder joint metallurgy. (e.g., Imm Ag cannot be used to substantiate ENIG).
- Solder alloy stress response and intermetallic formation characteristics which differ.
- Mixed alloy composition resulting from rework/repair combinations.
- Vibration and shock environments.

Annex A
(informative)

Equipment service environmental definition

A.1 Steady temperature service environments

a) Service type: such as storage or operation.

b) Exposure time (years, days, hours, minutes, etc.).

c) Equipment power state: off, on, stand-by.

d) Equipment power dissipation: the amount of power dissipated by the equipment (watts).

e) Definition of cooling conditions and other heat-transfer considerations that would influence the temperature of the solder joints being evaluated.

f) Temperature of unit translated to circuit card assembly.

A.2 Service cyclic temperature environments

a) Service type: Storage, operation (cruise, take-off, landing, cold day, hot day, etc.):
   1) flight/mission mix
      – very cold day, cold day, standard day, hot day, very hot day, after-burner operation,
   2) storage
      – very cold day, cold day, standard day, hot day, very hot day,
   3) special space considerations
      – take-off, orbit, etc.

b) Number of cycles (or hours).

c) Equipment power state: off, on, stand-by.

d) Equipment power dissipation: the amount of power dissipated by the equipment (watts).

e) Definition of cooling conditions and other heat-transfer considerations that would influence the temperature of the solder joints being evaluated.

f) Temperature extremes: the temperatures of the unit should be translated to the circuit card assembly for the various service conditions and power dissipation levels.

g) Ramp rates: the temperature transitions of the unit should be correlated to the circuit card assembly and power dissipation levels.

Bibliography

[1] Vianco, P.T., “Solder Trends and Pb-free Soldering Issues”, SMTA International Conference Proceedings (2005)

[2] Ganesan, S., Pecht, M., *Lead-Free Electronics,* CALCE SPSC Press, University of Maryland, College Park, Maryland (2004)

[3] Ganesan, S., Pecht, M., *Lead-Free Electronics*, Wiley-IEEE, NY Press, 2006

[4] Moon, K.-W., Boettinger, W. J., Kattner, U. R., Biancaniello, F. S., and Handwerker, C. A. “Experimental and Thermodynamic Assessment of Sn-Ag-Cu Solder Alloys”, J. Electron. Mater. 29 (2000) pp. 1122-1236

[5] Solberg, V., "No-Lead Solder for CSP: The Impact of Higher Temperature SMT Assembly Processing," Proc. NEPCON West 2000 Conf. (Feb. 28 – Mar. 2, 2000) Anaheim, CA (Source: Indium Corp.) from NIST, "Database for Solder Properties with Emphasis on New Lead-free Solders". http://www.boulder.nist.gov/div853/lead%20free/part2.html

[6] Mei, Z., “Microstructural Evolution and Interfacial Interactions in Lead-Free Solder Interconnects”, in *Lead-Free Solder Interconnect Reliability*, Shanguan, D., Ed., ASM International, Materials Park, OH, (2005)

[7] Snugovsky, L., et.al, “Some aspects of nucleation and growth in Pb-free Sn-Ag-Cu solder”, Material Science and Technology, Vol. 21 No. 1 (2005) pp. 53-60

[8] Lehman, L.P. and Athanvale, S.N., et. al, “Growth of Sn and Intermetallic Compounds in Sn-Ag-Cu Solder,” J. Electronic Materials, Vol. 33, No. 12 (2004) pp 1429-1439

[9] Kim, K.S., Huh, S.H. and Suganuma, K. “Effects of cooling speed on microstructure and tensile properties of Sn–Ag–Cu alloys”, Materials Science and Engineering A (2001)

[10] Kang, S.K., Choi, W.K., Shih, D.-Y., Henderson, D.W., Gosslin, T., Sarkhel, A., Goldsmith, C., Puttlitz, K.J., “Formation of Ag_3Sn Plates in Sn-Ag-Cu Alloys and Optimization of their Alloy Composition”, Electronic Component and Technology Conference Proc. IEEE/CPMT (2003) pp. 64-70

[11] Kang, S.K., Lauro, P.A., Shih, D.-Y., Henderson, D.W., Puttlitz, K.J., “Microstructure and mechanical properties of Lead-free solders and solder joints used in microelectronic applications”, IBM Journal of Research and Development Vol. 49, No. 4/5 (2005)

[12] Snugovsky, L. et.al., “Effect of cooling rate on microstructure Ag-Cu-Sn solder alloys”, Material Science and Technology, Vol. 21 No. 1 (2005) pp. 61-68

[13] Lehman, L.P., Kinyanjui, R.K., Wang, J., Xing, Y., Zavalij, L., Borgesen, P., Cotts, E. J., “Microstructure and Damage Evolution in Sn-Ag-Cu Solder Joints”, IEEE Electronic Components and Technology Conference (2005)pp. 674-681

[14] Ratchev, P., Loccufier, T., Vandevelde, B., Verlinden, B., Teliszewski, S., Werkhoven, D., Allaert, B., “A study of Brittle to Ductile Fracture Transition Temperatures in Bulk Pb-Free Solders”, EMPC June 12-15 Brugge, Belgium, 2005

[15] Hillman, D., “JCAA/JG-PP No-Lead Solder Project: -55 to 125C Thermal Cycling Testing Final Report” The Proceedings of SMTA International Conference Proceedings, Rosemont, IL, September 24-28, 2006. The report can also be found on the NASA web site at http://acqp2.nasa.gov/JTR.htm

[16] Klein-Wassink, R.J., *Soldering in Electronics*, Electrochemical Publications, Isle of Man, British Isles, (1989) Section 4.2.3

[17] Fritzsche, Mem. Acad. St. Petersburg (1), 7:15 (1870)(Source Mantell [18])

[18] Mantell, C.L, *Tin – Its Mining, Production, Technology and Applications,* The Chemical Catalog Company, Inc. New York, NY, 1929

[19] Becker, J.H., "On the Quality of Gray Tin Crystals and Their Rate of Growth", Journal of Applied Physics, Vol. 29, No. 7 (1958) pp. 1110-1121

[20] Plenderleith, H.J., and Organ, R.M., "The Decay and Conservation of Museum Objects of Tin", Studies in Conservation, International Institute for Conservation of Historic and Artistic Works, Vol. 1 No. 2 London, 1952, pp. 63-72

[21] Bornemann, A., "Tin Disease" in Solder Type Alloys", ASTM Spec. Techn. Publ. 189, 129-148 (1956)

[22] Kariya, Y., Williams, N., Gagg, C., and Plumbridge, W., "Tin Pest in Sn-0.5 wt% Cu Lead-Free Solder," *JOM,* June 2001, pp.39-41

[23] Williams, W.L., "Gray Tin Formation in Soldered Joints Stored at Low Temperatures", ASTM Spec. Techn. Publ. 189, 149-159 (1956)

[24] Sweatman, K., Suenaga, S., Nishimura, T., "Suppression of Tin Pest in Lead-Free Solder," JEDEX Conference, San Jose, 2005

[25] Spergel, J., "Tin Transformation of Tinned Copper Wire", ASTM Spec. Techn. Publ. 319, 83-92 (1962)

[26] Hillman, D., Schmidt, M., and Christian, B., "Tin Pest Phenomena: A Real World Test Scenario", SMTA International Conference Proceedings (2006)

[27] Osterman, M. Private Communication September 2006

[28] Bartelo, J., Cain, S. R., Caletka, D., Darbha, K., Gosselin, T., Henderson, D. W., King, D., Knadle, K., Sarkhel, A., Thiel, G., Woychik, C., "Thermomechanical fatigue behavior of selected Lead-free solders", Proceedings IPC SMEA Council APEX 2001, CA, Paper LF2-2

[29] Solomon, H.D., "Life Predictions and Accelerated Testing" in *The Mechanics of Solder Alloy Interconnects*, edited by D.R. Frear, S.N. Burchett, H.S. Morgan, and J.H. Lau, Chapman and Hall, New York, NY (1994)

[30] Dunn, B.D., "Evaluation of conformal coatings for future space craft applications", Technical Report ESA SP-1173, European Space Agency, Paris France August (1994)

[31] Englemaier, W., "Surface Mount Solder Joint Long-term Reliability: Design, Testing, Prediction", Soldering and Surface Mount Technology, February 1989, pp. 14-22

[32] Shanggaun, D., *Lead-Free Solder Interconnect Reliability*, ASM International, Materials Park, OH, USA (2005)

[33] Gregorich, T., Holmes. P., Lee, J., and Lee, C., "SnNi and SnNiCu Intermetallic Compounds Found When Using SnAgCu Solders", IPC/Soldertec Global 2nd Int. Conf. on Lead Free Electronics, June (2004)

[34] Hillman, D., Wells, M., Cho, K., "The Impact of Reflowing A Pb-free Solder Alloy Using A Tin/Lead Solder Alloy Reflow Profile On Solder Joint Integrity," CMAP (Centre for Microelectronics Assembly and Packaging in Canada) International Conference on Lead-free Soldering, University of Toronto, Toronto, ON Canada, May 2005

[35] Anderson, I.E., and Harringa, J.L., "Elevated Temperature aging of solderjoints based on Sn-Ag-Cu: Effect on Joint Structure and Shear Strength," J. Electronic Materials, Vol. 33. No. 12 (2004) pp. 1485-1496

[36] Chiu, C., Zeng, K., Stierman, R. Edwards, D., and Ano, K., "Effect of Thermal Aging on Board Level Drop Reliability for Pb-free BGA Packages", 54th ECTC Conf., (2004)

[37] Yin, L., "Degradation of Cu Pad Solder Joints", IMAPS Garden State Chapter Spring 2006 Symposium, May 2, 2006

[38] Handwerker, C.A., Moon, K.-W., Kattner, U., Boettinger, W., and Williams, M., "Manufacturing and Reliability of Manufacturing and Reliability of SnAgCu: Issues of "Backward" and Issues of "Backward" and "Forward" Compatibility "Forward" Compatibility", TMS Annual Meeting, March 2006

[39] Pan, N., Henshall, G.A., Billaut, F., Dai, S., Strum, M.J., Benedetto, E., and Rayner, J., "An Acceleration Model for Sn-Ag-Cu Solder Joint Reliability Under Various Thermal Cycle Conditions", SMTA International Conference Proceedings, September 2005

[40] Osterman, M., Choubey, A., Dasgupta, A., Han, B., "Effect of Temperature Cycle on the Durability of Lead Free Interconnects (Sn-Ag-Cu and Sn-Ag)", Project C05-06, University of Maryland CALCE (Computer Aided Life Cycle Engineering) Center, College Park, Maryland (2005)

[41] Clech, J.P., "Acceleration Factors and Thermal Cycling Test Efficiency for Lead-Free Sn-Ag-Cu Assemblies," SMTA International Conference Proceedings, Chicago, IL, Sept. 25-29, (2005)

[42] Osterman, M., Dasgupta, A., and Han, B., "A Strain Range-Based Model for Life Assessment of Pb-Free SAC Solder Interconnects", Proceedings of the 56th Electronic Component and Techology Conference, IEEE, May 30 – June 2, 2006

[43] Blattau, N., and Hillman, C., "1st Order Failure Model for Leadless Ceramic Chip Devices with Pb-Free Solder", SMTA International Conference Proceedings, 2006

[44] Hillman, C., Blattau, N., Dodd, E., and Arnold, J., "Epidemiological Study on Sn-Ag-Cu Solder: Benchmarking Results from Accelerated Life Testing", 2006 SMTA International Conference Proceedings, Rosemont, IL, Sept. 24-28, 2006, pp. 946-953

[45] Snugovsky, P., Bagheri, Z., McCormick, H., Bagheri, S., Hamilton, C., and Romansky, M., "Failure Mechanism of SAC 305 and SAC 405 in Harsh Environments and Influence of Board Defects Including Black Pad", SMTA International Conference Proceedings, Chicago IL (2006)

[46] Osterman, M., "CALCE Lead-free Project Progress Report", University of Maryland CALCE (Computer Aided Life Cycle Engineering) Center, College Park, Maryland, October 2006

[47] Grossman, G., "Accelerated Testing Methodology for Lead-Free Solder Interconnects", in *Lead-Free Interconnect Reliability*, edited by D. Shangguan, ASM International, Material Park, OH (2005)

[48] Woodrow, T., "JCAA/JG-PP Lead-Free Solder Project: Vibration Test", Contract No: BM3419-01, Prepared for ITB, Inc. January 9, 2006. http://acqp2.nasa.gov/JTR.htm Also published in The Proceedings of SMTA International Conference, Rosemont, IL, September 24-28, 2006

[49] Kessel, K., Joint DoD/NASA/Industry Lead Free Solder Project, Joint Test Report, Joint Council on Aging Aircraft/NASA Joint Group on Pollution Prevention, NASA Acquisition Pollution Prevention (AP2) Program 2006. http://acqp2.nasa.gov/JTR.htm

[50] Chudnovsky, B. H., "Degradation of power Contacts in Industrial Atmosphere: Silver Corrosion and Whiskers", Proceedings of the 48th IEEE Holm Conference on Electrical Contacts, 2002

[51] Osterman, M., Dasgupta, A., and Han, B., "A Strain Range Based Model for Life Assessment of Pb-free SAC Interconnects", IEEE Electronic Components and Technology Conference (2006)

[52] Vianco, P.T., *Soldering Handbook*, 3rd edition, American Welding Society Pub., New York, New York (1999)

[53] Lopez, E.P., Vianco, P.T., and Regent, J.A., "Solderablity Testing of Sn-Ag-XCu Pb-Free Solders on Copper and Au-Ni-Plated Kovar Substrates", J. Electronic Materials, Vol. 34, No. 3 (2005) pp. 299-310

[54] Grusd, A. and Miric, A.Z., "Lead-Free Alloys", Soldering & Surface Mount Technology, Vol. 10, No. 1, pp. 19-25, February 1998

[55] Singler, T.J., Yin, L., Chauhan, A., "Effect of Ag Content on Wetting Performance of Sn-Ag-Cu Alloys on Ni/Au Surface Finishes", Presentation at the ASME (American Society of Mechanical Engineers) International Mechanical Engineering Congress and Exposition, Chicago, IL, Nov. 5-10, (2006)

[56] Wickham, M., Zou, L., Dusek, M., Hunt, C., "Measuring the Reliability of Electronics Assemblies During the Transition Period to Lead-Free Soldering", NPL Report DEPC MPR 030, National Physical Laboratory, UK August (2005)

[57] Frear, D.R., Jones, W. B., Kinsman, K. R., "Solder Mechanics: A State of the Art Assessment", Minerals, Metals & Materials Society, 1990

[58] Shade, G. "PCB Pad Cratering", Intel Lead Free Symposium Sponsored by IPC, Scottsdale, AZ, March 15-16 2006

[59] Woodrow, T.A., "JCAA/JG-PP Lead-Free Solder Project: -55 to +125 °C Thermal Shock Test; March 1, 2006. Also published in The Proceedings of SMTA International Conference, Rosemont, IL, September 24-28, 2006

[60] Woodrow, T.A., "JCAA/JG-PP Lead-Free Solder Project: -20 to +80 °C Thermal Cycling Test", SMTA International Conference Proceedings, Rosemont, IL, September 24-28, 2006

[61] Borgesen, P., 2005 Year End Report Unovis Area Array Consortium (formerly Universal Instruments Consortium)

[62] Chung, C.K., Aspandiar, R., Leong, K.F., Tay, C.S., "The Interactions of Lead (Pb) in Lead Free Solder (Sn/Ag/Cu) System", Electronics Components and Technology Conference Proceedings (2002)

[63] Maire, O., Munier, C., Bousquet, S., Chastenet, C., Jeremias, M., "Backward Compatibility of Lead-Free BGA: Microstructural Characterization and Reliability", IPC Soldertec, Malmo, Sweden 2006

[64] Snugovsky, P., Zbrzezny, A., Kelly, M., Romansky, M. "Theory and Practice of Lead-Free BGA Assembly Using Sn-Pb Solder," CMAP (Centre for Microelectronics Assembly and Packaging in Canada) International Conference on Lead-free Soldering, University of Toronto, Toronto, ON Canada, May 2005

[65] Hunt, C., Wickham, M., "Impact of Lead Contamination on Reliability of Lead Free Alloys", 2006 IPC Printed Circuits Expo (2006)

[66] Hampshire, W.; "Solders"; Electronic Materials Handbook, Volume 1, Packaging; ASM International (1989)

[67] Marshall, J. (Lau, J., editor); Solder Joint Reliability, Theory and Applications; Van Nostrand Reinhold, 1992; p218

[68] W.J. Boettinger et. al, "Whisker and Hillock Formation on Sn, Sn-Cu and Sn-Pb Electrodeposites," Acta Materialia, Vol. 53, No. 19, November 2005

[69] Williams, M.E., Moon, K.-W., Boettinger, W.J., Josell, D., Deal, A.D., "Hillock and Whisker Growth on Sn and SnCu Electrodeposits on a Substrate not Forming Interfacial Compounds", Journal of Electronic Materials Vol. 36, No.3 (2007) pp. 214-219

[70] Abbott, Romm, Lange; "A Nickel-Palladium-Gold Integrated Circuit Lead Finish and Its Potential for Solder-Joint Embrittlement", Application Report SZZA031; Texas Instruments, 2001

[71] Finley, D. W, et. al., "Assessment of NiPd Finished Components for Surface Mount Assembly Applications", Surface Mount International Conference Proceedings, (SMTA, Edina, MN), 1995 pp. 941 – 953

[72] Mason, J. F., "RoHS is here — with 29 Exemptions, and Counting", EDN Magazine September 12, 2006

[73] Momokawa, Y., and Ishizuka, N., "Delamination by Reheating in SMD Solder Joint Using Lead-Free Solder," NEC Res & Devlop., Vol. 44, No. 3, July (2003) pp. 251 – 255

[74] Woodrow, T.A., "The Effects of Trace Amounts of Lead on the Reliability of Six Lead-Free Solders", Proceedings of the 3rd International Conference on Lead-Free Components and Assemblies, San Jose, CA April 23-24 (2003)

[75] Kariya, Y., Hirata, Y. and Otsuka, M., "Effect of Thermal Cycles on the Mechanical Strength of Quad Flat Pack Leads/Sn-3.5Ag-X (X = Bi and Cu) Solder Joints", Journal of Electronic Materials, Vol. 28, No 11, (1999)

[76] Hillman, D., "Surface Mount Solder Joint Integrity Issues for Lead-free Soldering Concerning Lead and Bismuth Interactions", CMAP (Centre for Microelectronics Assembly and Packaging in Canada) International Conference on Lead-free Soldering, University of Toronto, Toronto, ON Canada, May 2006

[77] Ki-Hwan Park, Nam-Seog Kim, and Se-Yong Oh, "Reliability of SnBi Lead Finished Lead-Free Product", IEEE International Symposium on Electronic Materials and Packaging 2002

[78] NEC Corp. Semiconductor Device Mount Manual, Chapter 5 Solder Joint Reliability Section 5.5 Combinations of device plating and solder material Solder Joint Reliability SnBi Lead finishes – NEC web site http://www.necel.com/pkg/en/mount/CHAPTER5_E.pdf and http://www.necel.com/pkg/en/pb_free/images/F0706_l.gif

[79] Snugovsky, P., McMahon J., Romansky, M., Snugovsky, L., Perovic, D., Rutter, J., "Microstructure and Properties of Sn-Pb Solder Joints with Sn-Bi Finished Components", IPC Apex Conference Proceedings (2006)

[80] Recommendations on Lead-Free Finishes for Piece-parts Used in High Reliability Products ", iNEMI Tin Whisker User Group, Herndon, VA USA, Version 4, Updated December 2006

[81] Moon, K.-W., Kattner, U., and Handwerker, C.A., "The Effect of Bi Contamination on the Solidification Behavior of Sn-Pb Solders," J. Electronic Materials, Vol. 36, No. 6 (2007) pp. 676 – 681

[82] Bradford, J. JCAA/JG-PP Lead-Free Solder Project: Combined Environment Test, August 15, 2005

[83] Clech, J-P., "Lead-free and Mixed Assembly Solder Joint Reliability Trends," Proceedings (CD-ROM), APEX 2004, Anaheim, CA, Paper S28-3, pp. 1-14

[84] Osterman, M., "Strain Range Approximation for Estimating Fatigue Life of Lead-free Solder Interconnects Under Temperature Cycle Loading", CALCE Research Paper (2006) in the JCAA/JGPP Modeling section, http://acqp2.nasa.gov/LFS/CALCEJGPPTCPaper.pdf

[85] Hillman, C., "Assessment of Pb-Free Norris-Landzberg Model to JG-PP Test Data", February 21, 2006 in the JCAA/JGPP Modeling section, http://acqp2.nasa.gov/LFS/CALCEJGPPTCPaper.pdf

[86] Glazer, J., Kramer, P.A., and Morris, J.W. Jr., "Effect of Gold on the Reliability of Fine Pitch Surface Mount Solder Joints," SMTA and IPC Surface Mount International Conference, San Jose, California, August 1991

[87] Chen, H.T., Wang, C.Q., Yan, C., Huang, Y., Tian, Y.H., "Effects of Solder Volume on Formation and Redeposition of Au-Containing Intermetallics in Ni/Au-SnAgCu-Ni(P) Solder Joints," J. Electronic Materials, Vol. 36 No. 1 (2007) pp. 33-39

[88] Brusse, J., "Zinc Whiskers: Could Zinc Whiskers Be Impacting Your Electronics?" NASA Goddard Space Flight Center April 2, 2003 http://nepp.nasa.gov/whisker/reference/tech_papers/Brusse2003-Zinc-Whisker-Awareness.pdf

[89] Sengupta, S., Das, D., Ganesan, S., Pecht, M., "Effects of Re-finishing of Terminations by Solder Dipping on Plastic Quad Flatpack Electronic Parts", Electronics Packaging Technology Conference, IEEE (2005) pp. 768-773

[90] Minter, C., "Robotic Solder Dip – A Key Technique for Mitigating Reliability Risk Posed by Tin Whiskers", DoD Diminishing Manufacturing Sources and Material Shortages (DMSMS) Workshop, San Antonio, Texas, 14-15 Dec 2005

[91] Winslow, R., Iyler, G., Cruz, M., Selvaduray, G., "Hot Solder Dip and Minimizing Thermal Gradients", International Microelectronics and Packaging Society Conference Proceedings, San Diego, CA, October 2006, pp. 513-520

[92] INEMI High-Reliability Task Force, "Pb-Free Manufacturing Requirements for High-Complexity, Thermally Challenging Electronic Assemblies", iNEMI, Herndon, VA, February 16, (2006)

[93] Smetana, J., Ogle, K., "Via (Plated Through Hole) Integrity with Lead-Free Soldering", IPC APEX Conference Proceedings February 2006

[94] Snugovsky, L., Ruggiero, M. A., Perovic, D. D., and Rutter, J. W., "Experiments on interaction of liquid Tin with solid Copper", Materials Science and Technology, Vol. 19, (2003) pp. 866-874

[95] Yin, L., Meschter, S.J., Singler, T.J., "Wetting in the Au-Sn System", Acta Materialia, Vol. 52, No. 10, (2004) pp. 2873-2889

[96] Huang, M. L., Loeher, T., Ostmann, A. and Reichl, H., "Role of Cu in dissolution kinetics of Cu metallization in molten Sn-based solders", Applied Physics Letters 86, 181808 (2005)

[97] Alam, M. O., Chan, Y. C., Tu, K. N., "Effect of 0.5 wt % Cu addition in Sn-3.5%Ag solder on the dissolution rate of Cu metallization", J. Applied Physics, 94 (12), pp. 7904-7909 (2003)

[98] de Sousa, I., Henderson, D., Patry, L., Martel, R., "Characterization and reliability of increased Cu levels in SAC alloys", IPC/JEDEC Global Conference on Lead-free Reliability, April 10-12, 2007

[99] W.G. Bader, "Dissolution of Au, Ag, Pd, Pt, Cu and Ni in a molten Sn-Lead Solder", Welding Journal 48, 551s-557s (1969)

[100] Klein-Wassink, R.J., *Soldering in Electronics*, Section 4.6 Dissolution of Base Metals, Electrochemical Publications, Isle of Man, British Isles (1989)

[101] Howes, M.A.H., and Saperstein, Z.P., "The Reaction of Lead-Tin Solders with Copper Alloys", Welding Research Supplement, February 1969, pp. 80s – 85s

[102] Hamilton, C. "A Study of Copper Dissolution during Pb-free PTH Rework" CMAP (Centre for Microelectronics Assembly and Packaging in Canada) International Conference on Lead-free Soldering, University of Toronto, Toronto, ON Canada May 2006

[103] Hamilton, C., Snugovsky, P., Kelly, M., "A Study of Copper Dissolution During Lead-Free PTH Rework using a Thermally Massive Test Vehicle", SMTA International Conference Proceedings, Chicago September 2006

[104] Jones, W. and Roggeman, B., Unovis Area Array Consortium (formerly Universal Instruments Consortium) Progress Meeting, Binghamton, NY, October 2006

[105] Tsal, C.M., et. al. "Cross-Interaction of Under-bump Metallurgy and Surface Finish in Flip-Chip Solder Joints," J. Electronic Materials, Vol. 33 No 12 (2004) pp. 1424-1428]

[106] Chen, S.-W., Wu, S.-H. and Lee, S.-W., "Interfacial reactions in the Sn-(Cu)/Ni, Sn-(Ni)/Cu and Sn/(Cu,Ni) Systems", J. Elec. Materials, Vol. 32 No. 11, (2003) pp. 1188-1194

[107] Mattlila, T.T., Vuorinen, V., Kivilahti, J.K., "Impact of Printed Wiring Board Coatings on the Reliability of Lead-Free Chip-scale Package Interconnections", J. Materials Research, Vol. 19, No. 11 (2004) pp. 3214-3223

[108] Dasgupta, A., University of Maryland CALCE Center, Private Communication (2006)

[109] Chada, S. and Bradley, E., “Investigation of Immersion Silver PCB finishes for portable product applications”, SMTA International Conference Proceedings (2001)

[110] Verdi, F., “GEIA Tin Whisker Industry Standard”, Empfasis News Letter, National Electronics Manufacturing Center of Excellence, Philadephia, PA, March 2006

[111] Figure E-18 SnAgCu Solder; OSP Finish in J-STD-001D

[112] “Lead Free: How Will IPC Standards Change?” IPC Designer’s Council Newsletter “Route”, September 2005

[113] Wilcoxon, R. and Hillman, D., “Effects of Thermal Interface Material on Solder Joint Reliability”, SMTA International Conference Proceedings, 2003

[114] Woodrow, T. A., and Ledbury, E.A., “Evaluation of Conformal Coatings as a Tin Whisker Mitigation Strategy”, IPC/JEDEC 8th International Conference on Lead-Free Electronic Components and Assemblies, San Jose, CA, April 18-20 (2005)

[115] Woodrow, T.A. and Ledbury, E.A., “Evaluation of Conformal Coatings as a Tin Whisker Mitigation Strategy, Part II” SMTA International Conference Proceedings (2006)

[116] Teghall, P.-E., and Dunn, B.D., “Assessment of the Reliability of Solder Joints to Ball and Column Grid Array Packages for Space Applications”, ESA STM 266, ESA Publication Division, Noordwijk, The Netherlands September 2001

[117] Wild, R., “Fatigue Properties of Solder Joints”, Supplement to the Welding Journal, November (1972) pp. 521 – 526

[118] Richardson, J.H., and Lasley, B.R., "Tin Whisker Initiated Vacuum Metal Arcing in Spacecraft Electronics", Proceedings of the Government Microcircuit Applications Conference, Vol. 18, pp. 119 – 122, November 10 – 12, 1992

[119] Hwang, J.S., Implementing Lead-Free Electronics, McGraw-Hill Professional Engineering, NY, NY, 2004

[120] Puttlitz. K., and Stalter, K., *Handbook of Pb-Free Solder Technology for Microelectronic Assemblies*, Marcel-Dekker, NY, NY 2004

[121] Lau, J. H., Wong, C.P., Lee, N.-C., Lee, S.W., *Electronics Manufacturing: with Lead-Free, Halogen-Free, and Conductive-Adhesive Materials*, McGraw-Hill, NY, NY, 2003

[122] Parrish, M. “Lead Free Solder Process Compatibility”, Wiring Harness News, Nov/Dec 2002

[123] Colfax, R., O’Keefe, M. J., Amick, P., Kleine, D., Vetter, S., Murry, D., “Perspectives on Repaired Lead-Free Solder Joints”, IPC/APEX proceedings, February 2005

[124] Perez,M., O’Keefe, M., Colfax, R., Vetter, S., Murry, D., Smith, J., Kleine, D., and Amick, P., “Vibration Testing of Repaired Lead-Tin/Lead-Free Solder Joints,” ECTC Conf. 2006

[125] O’Keefe, M., et.al, “The Effect of Mechanical Vibration on Thermally Cycled, Lead-Free and Mixed Alloy Solder Joints,” IPC APEX Conference 2007

[126] Gleason, J., Reynolds, C., Bath, J., Chu, Q., Kelly, M., Lyjak, K., Roubaud, P., "Pb-free Assembly, Rework and Reliability Analysis of IPC Class 2 Assemblies" IEEE Electronic Components and Technology Conference, June 2005

[127] McCall, P. "Lead-free Solder and the Rework Process", Surface Mount Technology (SMT) Magazine, April 2006

[128] Donaldson, A., and Aspandiar, R., "Hot Air Lead-Free Rework of BGA Packages & Sockets," SMTA International Conference Proceedings (2004)

[129] Pepe, S., Whiteman. L., "Environmental Exposure of JG-PP/JCAA Test PWAs", January 2005. See NASA JCAA/JGPP Joint Test Report http://acqp2.nasa.gov/JTR.htm

[130] Downs, W.R., "Apollo Experience Report – Detection and Minimization of Ignition Hazards from Water/Glycol Contamination of Silver-Clad Electrical Circuitry" NASA TECHNICAL NOTE NASA TN D-8177, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION WASHINGTON, D.C., MARCH 1976

[131] Stevens, H. D., "Chemically induced fires in aircraft electrical circuitry by glycol/water solutions. Hazard analysis and elimination methods", Final Engineering Report, 28 Jun. 1974 – 17 Jan. 1975, General Dynamics/Fort Worth, TX., Published by NASA Scientific and Technical Information (STI) Office, January 1975

[132] Brizoux, M., Leclerc, A., Maia, W., "Long term reliability of 'x' BGA solder joints drastically depends on PCB raw material & design," EMPC June 12-15, Brugge, Belgium, (2005)

[133] W.R. Lewis, "Tin Solders at Low Temperatures," ITIR Pub. No. 93 (Notes on Soldering), 1968

[134] Binary Alloy Phase Diagrams," T.B. Massalski Editor-in-Chief, ASM Intl., October 1986

[135] S.M. Arnold, "The Growth of Metal Whiskers on Electrical Piece-parts," Proc. of IEEE ECC, pp. 75-82, 1959

[136] V.K. Glazunova and N.T. Kudryavtsev, "An Investigation of the Conditions of Spontaneous Growth of Filiform Crystals on Electrolytic Coatings," translated from Zhurnal Prikladnoi Khimiii, Vol. 36, No. 3, pp. 543-550, March 1963

[137] I. Yanada, "Electroplating of Lead-Free Solder Alloys Composed of Sn-Bi and Sn-Ag," Proc. of IPC Printed Circuits Expo, Long Beach, USA, pp. S11-2 to 27, April 1998

[138] S.C. Britton, "Spontaneous Growth of Whiskers on Tin Coatings: 20 Years of Observation," Trans. of Institute of Metal Finishing, Vol. 52, pp. 95-102, April 1974

[139] C.E. Homer and H. Plummer, J. Inst. Met., Vol. 64, p. 169, 1939

[140] L. Snugovsky et al., "The Solid Solubility of Ag and Cu in the Sn Phase of Eutectic and Near-Eutectic Sn-Ag-Cu Solder Alloys," J. Electro. Mats, Vol. 33, No. 11, pp. 1313-1315, 2004

[141] G.T.T. Sheng et al., "Tin Whiskers Studied by Focused Ion Beam Imaging and Transmission Electron Microscopy," J. Appl. Phys., Vol. 92, No. 1, pp.64-69, July 2002

[142] S.M. Arnold, "Repressing The Growth of Tin Whiskers," Plating, pp. 96-99, January 1966

[143] K. Chen and G. Wilcox, "Observations of the Spontaneous Growth of Tin Whiskers on Tin-Manganese Alloy Electrodeposits," Physical Review Letters 94, 066104, February 2005

[144] K. Whitlaw and J. Crosby, "An empirical study into whisker-growth of Tin and Tin alloy electrodeposits," in Proc. 2002 AESF SUR/FIN Conf., Jun. 2002, pp. 19–30

[145] D.C. Abbott et al., "Whisker Evaluation of Lead-free Component Leads," Texas Instruments Corp. Appl. Report No. SZZA051B, August 2005

[146] M. Tanimoto et al., "Pb-free Plating for Electronic Components," Furukawa Co. report, 1999

[147] K-W. Moon et al., "Observed Correlation of Sn Oxide Film to Sn Whisker Growth in Sn-Cu Electrodeposit for Pb-Free Solders," J. Electronic Materials, Vol. 34, No. 9, (2005) pp. L31-L33

[148] Cole, M. et.al, "Lead-free Card Assembly and Rework for Column Grid Arrays", SMTA Journal Vol. 17-1 (2004)

[149] Karl Seelig and David Suraski "Lead Contamination in Lead-free Electronics Assembly", White paper AIM Solder

[150] Sinn-Wen Chen, Shou-Wei Lee and Ming-Chuen Yip, "Mechanical Properties and intermetallic compound formation at the Sn/Ni and Sn-0.7wt% Cu/Ni Joints", J. Elec. Materials, Vol. 32 No. 11, (2003) pp. 1284-1289

[151] Chien-Sheng Huang, Guh-Yaw Jang and Jenq-Gong Duh, Interfacial Reaction in the Edge of Pb-Sn Flip Chip Solder Bumps on Ni-Cu Under-bump metallization, J. Elec. Materials, Vol. 32 No. 11, (2003) pp. 1273-1277

[152] Smetana, J., Horsley, R., Lau, J., Snowdon, K., Shangguan, D. Gleason, J., Memis, I, Love, D., Dauksher, W., Sullivan, B., "HDPUG's Lead-Free Design, Materials and Process of High Density Packages", IPC SMEMA Council APEX (2003)

[153] National Institute of Standards and Technology (NIST) & Colorado School of Mines, Database for Solder Properties with Emphasis on New Lead-free Solders – Properties of Lead-Free Solders (http://www.metallurgy.nist.gov/solder/NIST_LeadfreeSolder_v4.pdf)

[154] IEC/TS 62647-21:2013, *Process management for avionics – Aerospace and defence electronic systems containing lead free-solder – Part 21: Program management – Systems engineering guidelines for managing the transition to lead-free electronics*

[155] IEC/TS 62647-23, *Process management for avionics – Aerospace and defence electronic systems containing lead free-solder – Part 23: Rework and repair guideline to address the implications of lead-free electronics and mixed assemblies*[5]

[156] GEIA-STD-0005-1, Performance standard for aerospace and high performance electronic systems containing lead-free solder

[157] GEIA-STD-0005-2, Standard for mitigating the effects of tin in aerospace and high performance electronic systems

5 Based on GEIA-HB-0005-3.

[158] MIL-I-46058, Insulating Compound, Electrical (for coating printed circuit assemblies), Inactive for new design

[159] GEIA-HB-0005-3, Rework and repair handbook to address the implications of lead-free electronics and mixed assemblies in aerospace and high performance electronic systems

[160] GEIA-STD-0006, Requirements for Using Solder Dip to Replace the Finish on Electronic Components

[161] ARINC Project Paper 671, Guidelines for Lead-free Soldering, Repair, and Rework

[162] ASTM B117-3, Standard Practice for Operating Salt Spray (Fog) Apparatus

[163] ASTM G85:2011, Standard Practice for Modified Salt Spray (Fog) Testing, Annex A4 Salt/SO2 Spray (Fog) Testing

[164] IPC-A-610, Acceptability of Electronic Assemblies

[165] IPC-CC-830, Qualification and Performance of Electrical Insulating Compound for Printed Wiring Assemblies

[166] IPC-TM-650, Test Methods Manual – Method 2.6.25 Conductive Anodic Filament (CAF) Resistance Test: X-Y Axis

[167] IPC-TM-650, Test Methods Manual – Method 2.4.24.1 Time to Delamination (TMA Method)

[168] IPC J-STD-001, Requirements for Soldered Electrical and Electronic Assemblies

[169] IPC/ECA J-STD-002, Solderability Tests for Component Leads, Terminations, Lugs, Terminals and Wires

[170] IPC J-STD-006B:2009, Requirements for Electronic Grade Solder Alloys and Fluxed and Not Fluxed Solders for Electronic Soldering Applications

[171] IPC/JEDEC J-STD-020, Moisture/Reflow Sensitivity Classification for Non-hermetic Solid State Surface Mount Devices

[172] IPC/JEDEC J-STD-033, Handling, Packing, Shipping and Use of Moisture/Reflow Sensitive Surface Mount Devices

[173] IPC/JEDEC J-STD-609A:2010, Marking and Labeling of Components, PCBs and PCBAs to Identify Lead (Pb), Lead-Free (Pb-Free) and Other Attributes

[174] IPC-2221, Generic Standard on Printed Board Design

[175] IPC-4552, Specification for Electroless Nickel/Immersion Gold (ENIG) Plating for Printed Circuit Boards

[176] IPC-4553, Specification for Immersion Silver Plating for Printed Circuit Boards

[177] IPC-4554, Specification for Immersion Tin Plating for Printed Circuit Boards

[178] IPC-6011, Generic Performance Specification for Printed Boards

[179] IPC-6012, Qualification and Performance Specification for Rigid Printed Boards

[180] IPC-7095B:2008, Design and Assembly Process Implementation for BGAs

[181] IPC-9201, Surface Insulation Resistance Handbook

[182] JESD97, Marking, Symbols, and Labels for Identification of Lead (Pb) Free Assemblies, Components, and Devices

[183] RoHS Directive Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (commonly known as the RoHS (Restriction of Hazardous Substances Directive). [http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:037:0019:0023:en:PDF]

[184] RoHS Directive Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast; commonly known as RoHS 2). [http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:174:0088:0110:en:PDF]

[185] WEEE Directive Directive 2003/108/EC of the European Parliament and of the Council of 8 December 2003 amending Directive 2002/96/EC on waste electrical and electronic equipment (WEEE) [http://www.environ.ie/en/Legislation/Environment/Waste/WEEE/FileDownLoad,1358,en.pdf]

[186] JEDEC JESD201:2006, Environmental acceptance requirements for tin whisker susceptibility of tin and tin alloy surface finishes

[187] IPC-1752, Materials Declaration Management

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

3, rue de Varembé
PO Box 131
CH-1211 Geneva 20
Switzerland

Tel: + 41 22 919 02 11
Fax: + 41 22 919 03 00
info@iec.ch
www.iec.ch