



TECHNICAL REPORT

GEIA-HB-0005-02

Issued 2007-11
Reaffirmed 2016-06

Technical Guidelines for Aerospace and High Performance
Electronic Systems Containing Lead-free Solder and Finishes

NOTICE

This document has been taken directly from the original TechAmerica document and contains only minor editorial and format changes required to bring it into conformance with the publishing requirements of SAE Technical Standards. The release of this document is intended to replace the original with the SAE International document. Any numbers established by the original document remain unchanged.

The original document was adopted as an SAE publication under the provisions of the SAE Technical Standards Board (TSB) Rules and Regulations (TSB 001) pertaining to accelerated adoption of specifications and standards. TSB rules provide for (a) the publication of portions of unrevised specifications and standards without consensus voting at the SAE committee level, and (b) the use of the existing specification or standard format.

SAE Technical Standards Board Rules provide that: "This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user."

SAE reviews each technical report at least every five years at which time it may be revised, reaffirmed, stabilized, or cancelled. SAE invites your written comments and suggestions.

Copyright © 2014 SAE International

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of SAE.

TO PLACE A DOCUMENT ORDER: Tel: 877-606-7323 (inside USA and Canada)
Tel: +1 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
http://www.sae.org

SAE WEB ADDRESS:

Full document details: SAE GEIAHB0005_2

SAE values your input. To provide feedback on this Technical Report, please visit http://www.sae.org/technical/standards/GEIAHB0005_2

Documents

Document Sharing Hub

TechAmerica Engineering Bulletin

Technical Guidelines for Aerospace and High Performance Electronic Systems Containing Lead-free Solder and Finishes

GEIA-HB-0005-2

November 2007



NOTICE

TechAmerica Engineering Standards and Publications are designed to serve the public interest by eliminating misunderstandings between manufacturers and purchasers, facilitating interchangeability and improvement of products, and assisting the purchasers in selecting and obtaining with minimum delay the proper product for their particular needs. Existence of such Standards and Publications shall not in any respect preclude any member or nonmember of TechAmerica from manufacturing or selling products not conforming to such Standards and Publications, nor shall the existence of such Standards and Publications preclude their voluntary use by those other than TechAmerica members, whether the standard is to be used either domestically or internationally.

Standards and Publications are adopted by TechAmerica in accordance with the American National Standards Institute (ANSI) patent policy. By such action, TechAmerica does not assume any liability to any patent owner, nor does it assume any obligation whatever to parties adopting the Standard or Publication.

Technical Publications are distinguished from TechAmerica Standards in that they contain a compilation of engineering data or information useful to the technical community and represent approaches to good engineering practices that are suggested by the formulating committee.

This Bulletin is not intended to preclude or discourage other approaches that similarly represent good engineering practice, or that may be acceptable to, or have been accepted by, appropriate bodies. Parties who wish to bring other approaches to the attention of the formulating committee to be considered for inclusion in future revisions of this publication are encouraged to do so. It is the intention of the formulating committee to revise and update this publication from time to time as may be occasioned by changes in technology, industry practice, or government regulations, or for other appropriate reasons.

(Formulated under the cognizance of the TechAmerica (APMC) Avionics Process Management Committee and the (G-12) Solid State Devices Committee. This is a joint activity of the Aerospace Industries Association (AIA), Avionics Maintenance Conference (AMC), and TechAmerica, to address aerospace issues related to the global elimination of lead from electrical and electronic equipment put on the market after July 1, 2006. Formed in 2004, this coalition includes all stakeholders (market segments, supply chain, geographic regions.))

Published by

© 2010 TechAmerica
Standards & Technology Department
601 Pennsylvania Ave., NW
North Building, Suite 600
Washington, DC 20004-2650
All rights reserved - Printed in U.S.A.

PLEASE!
DON'T VIOLATE
THE
LAW!

This document is copyrighted by TechAmerica and may not be reproduced without permission.

Organizations may obtain permission to reproduce a limited number of copies by entering into a license agreement with our distributors.

For distributor information please see our web site www.techamerica.org/ or contact TechAmerica at 703-284-5355

TechAmerica

**Technical Guidelines for Aerospace and High Performance Electronic
Systems Containing Lead-free Solder and Finishes**

GEIA-HB-0005-2

Revision	Description of change	Date
-	Initial Release	Nov 2007

TABLE OF CONTENTS

Section	Page
1. Scope	1
2. References.....	1
3. Terms and definitions	11
4. Approach	15
5. General Pb-Free Solder Alloy Behavior.....	15
5.1 Elevated Temperature	16
5.2 Low Temperatures	16
5.3 Temperature Cycling	19
5.4 Rapid Mechanical Loading (Vibration/Shock).....	21
6. System Level Service Environment.....	22
7. High Performance Electronics Testing.....	24
8. Solder Joint Reliability Considerations	25
8.1 Mixing of Solder Alloys and Finishes	26
8.2 Pb-free Terminations in Tin-Lead joints.....	27
8.3 Tin-Lead Terminations in Pb-free joints.....	31
8.4 Bismuth Effects.....	31
8.5 JCAA/JGPP Testing of Mixed Alloy Combinations	33
8.6 Pb-Free Solder and Mixed Metallurgy Modeling.....	34
9.0 Piece-parts.....	41
9.1 Materials	41
9.2 Temperature Rating	41
9.3 Special considerations.....	41
9.4 Plastic Encapsulated Microcircuit (PEM) Moisture Sensitivity Level (MSL)	41
9.5 Terminal Finish.....	42
9.6 Assembly stresses	43
9.7 Hot Solder Dipping.....	43
10. Printed Circuit Boards.....	44
10.1 Plated Through Holes	44
10.2 Copper Dissolution	45
10.3 PCB Laminate Materials.....	46
10.4 Surface Finish	47
10.5 Pb-Free PCB Qualification	49
10.6 PCB artwork and Design Considerations for Pb-Free solder applications	50
11. Printed Circuit Board Assembly	50
11.1 PCB Process Indicator Coupons	50
11.2 Solder Inspection Criterion.....	50
11.3 Fluxes, Residues, Cleaning and SIR issues	51
12. Module Assembly Considerations	58
12.1 Connectors and Sockets	58
12.2 Heatsinks/Modules.....	58
12.3 Conformal Coating.....	58
13. Manufacturing Resources	59
14. Aerospace Wiring/Cabling Considerations.....	60
14.1 Insulation Temperature Rating	60

14.2 Cable Connectors	60
14.3 Wire Terminals	60
14.4. Splices	60
14.5 Sleeving	60
15. Rework/Repair	60
15.1 Piece Part Rework	62
15.1.1 Area Array Rework	62
15.1.2 Surface Mount Capacitor/Resistor Rework	63
15.1.3 Through-Hole Piece Part Rework	63
15.2 Depot Level Repair	63
15.3 Mixed Solder Rework Temperature Profiles	64
15.5 Rework / Repair Cleaning Process	65
15.6 Inspection requirements	65
16. Generic Life Testing	65
16.1 Thermal Cycling, Vibration, and Shock Testing	65
16.2 Other Environments	66
16.2.4 Generic Humidity	66
17. Similarity Analysis	66
Appendix A: Equipment Service Environmental Definition	68
A1. Steady Temperature Service Environments	68
A2. Service Cyclic Temperature Environments	68

Foreword

This handbook is intended for use by Aerospace and High Performance (AHP) electronics system customers, i.e., aerospace and military vehicle integrators, operators, and regulatory organizations, and their suppliers, i.e., system original equipment manufacturers (OEMs) and system maintenance facilities as they incorporate Lead-free (Pb-free) solder or Pb-free piece-parts and board finishes.

The Aerospace Industries Association (AIA), the Avionics Maintenance Conference (AMC), and Government Electronics and Information Technology Association (GEIA) formed the Lead-free Electronics in Aerospace Project Working Group (LEAP WG) to generate a series of industry documents for the use and handling of Pb-free solder, piece parts and boards in AHP. This handbook was prepared by the LEAP WG; and was balloted and approved by GEIA G-12 (Solid State Subcommittee) and the GEIA Avionics Process Management Committee.

This handbook is intended to work in concert with the Lead-free performance standard (GEIA-STD-0005-1), the program management/systems engineering guidelines (GEIA-HB-0005-1), and the tin whisker mitigation standard (GEIA-STD-0005-2). Part way through this documents creation, it was evident that three additional documents were needed. As a result, the performance test standard (GEIA-STD-0005-3), the rework and repair handbook (GEIA-HB-0005-3) and the reliability assessment handbook (GEIA-HB-0005-4) have been added to address testing, rework, and reliability prediction respectively.

This handbook may be referenced in proposals, requests for proposals, work statements, contracts, and other aerospace and high performance industry documents.

Introduction

The global transition to Pb-Free electronics impacts the aerospace and other industries having high reliability applications in various ways. 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 will need to be able to withstand higher manufacturing process temperatures.
- Printed circuit boards will need to have robust solderable 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 20+ year life.

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 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 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 are the facts 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 Pb-Free alloy must have predictable performance when mixed with heritage Tin-Lead alloys. Pb-Free alloys containing elements such as Bismuth (Bi) or Indium (In) that can form alloys having melting points within the equipments operating temperature range must be considered very carefully before use. Although 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].

The majority of the Pb-Free solder alloys being considered have higher melting temperatures than Tin-Lead eutectic solder. In order to make use of the Pb-Free solders, changes to the molding compound, die attach and printed circuit board insulation systems are being introduced to accommodate the 30 to 40 °C higher (54 to 72 °F higher) processing temperature. Thus, not only is the 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 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 Pb-Free solder will perform adequately for their products. Creep resistance of 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 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 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., 305 and 405) Pb-Free thermal cycling, there is less information regarding 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 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.

1. Scope

This document is intended for use as technical guidance by Aerospace system suppliers, e.g., Aerospace system Original Equipment Manufacturers (OEMs) and Aerospace system maintenance facilities, in developing and implementing designs and processes to assure the continued performance, quality, reliability, safety, airworthiness, configuration control, affordability, maintainability, and supportability of high performance aerospace systems (subsequently referred to as AHP) both during and after the transition to Pb-Free electronics.

This document is intended for application to aerospace products; however, it may also be applied, at the discretion of the user, to other products with similar characteristics, e.g., low-volume, rugged use environments, high reliability, long lifetime, and reparability. If other industries wish to use this document, they may substitute the name of their industry for the word “Aerospace” in this document.

The guidelines may be used by the OEMs and maintenance facilities to implement the methodologies they use to assure the performance, reliability, airworthiness, safety, and certifiability of their products, in accordance with Document GEIA-STD-0005-1, “Performance Standard for High Performance Electronic Systems Containing Pb-Free Solder.”

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.

2. References

Standards:

GEIA-STD-0005-1, *Performance Standard for Aerospace and High Performance Electronic Systems Containing Lead-Free Solder*

GEIA-STD-0005-2, *Standard for Mitigating the Effects of Tin Whiskers in Aerospace and High Performance Electronic Systems.*

GEIA-STD-0005-3, *Performance Testing for Aerospace and High Performance Electronic Interconnects Containing Lead-Free Solder.*

GEIA-HB-0005-1, *Program Management/Systems Engineering Guidelines For Managing The Transition To Lead-Free Electronics*

GEIA-HB-0005-3, *Rework and Repair of Aerospace and High Performance Electronics Containing Lead Free Solder*

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

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

ARINC Project Paper 671: *Guidelines for Lead-free Soldering, Repair, and Rework*, March 16, 2006.

ASTM B117-3 *Standard Practice for Operating Salt Spray (Fog) Apparatus*, October 2003

ASTM G85 *Standard Practice for Modified Salt Spray (Fog) Testing*, Annex A4 Salt/SO₂ Spray (Fog) Testing 2002.

MIL-I-46058C *Insulating Compound, Electrical (for coating printed circuit assemblies)*, Inactive for new design. July (1982)

IPC/JEDEC JP002, *Current Tin Whiskers Theory and Mitigation Practices Guideline*, March 2006.

IPC/JEDEC J-STD-001D, *Requirements for Soldered Electrical and Electronic Assemblies*, Feb. 2005.

IPC/JEDEC J-STD-002B, *Solderability Tests for Component Leads, Terminations, Lugs, Terminals and Wires*, February 2003

IPC/JEDEC J-STD-006B, *Requirements for Electronic Grade Solder Alloys and Fluxed and Not Fluxed Solders for Electronic Soldering Applications*, January 2006.

IPC/JEDEC J-STD-020C, *Moisture/Reflow Sensitivity Classification for Non-hermetic Solid State Surface Mount Devices*, July 2004.

IPC/JEDEC J-STD-033B, *Handling, Packing, Shipping and Use of Moisture/Reflow Sensitive Surface Mount Devices*, October 2005

IPC/JEDEC J-STD-609, *Marking of Symbols and Labels of PCB Assemblies and Piece Parts to Identify Lead (Pb) and other Materials*

IPC-A-610, *Acceptability of Electronic Assemblies*, Revision D, February (2005)

IPC-CC-830, *Qualification and Performance of Electrical Insulating Compound for Printed Wiring Assemblies*, Revision B, August (2002)

IPC-TM-650, *Test Methods Manual Method 2.6.25 Conductive Anodic Filament (CAF) Resistance Test: X-Y Axis* November 2003

IPC-1066 *Marking, Symbols and Labels for Identification of Lead-Free and Other Reportable Materials in Lead-Free Assemblies, Components and Devices*, January 2005

IPC-1752 *Materials Declaration Management*, February 2006

IPC-2221A, *Generic Standard on Printed Board Design*, May 2003.

IPC-4552, *Specification for Electroless Nickel/Immersion Gold (ENIG) Plating for Printed Circuit Boards*, October 2002.

IPC-4553, *Specification for Immersion Silver Plating for Printed Circuit Boards*, June 2005.

IPC-4554, *Specification for Immersion Tin Plating for Printed Circuit Boards*

IPC-7095A, *Design and Assembly Process Implementation for BGAs*, October, 2004.

IPC-9701 *Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments*, January 2002, and *Lead-Free Appendix B*

JESD97 Marking, Symbols, and Labels for Identification of Lead (Pb) Free Assemblies, Components, and Devices, May 2004

Technical Books and Papers:

- [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*, Shangguan, D., Ed., ASM International, Materails 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 Ag₃Sn 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., Zavaliy, 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., Vandeveld, 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/Solderotec 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 Technology 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. Shangquan, 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., "Solderability 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 Solderotec, 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 Electrodeposits," 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 & Develop., 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_1.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, Philadelphia, 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 Aspdindar, 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).

Summary of selected references cited in the tables:

- (1) W.R. Lewis, "Tin Solders at Low Temperatures," ITIR Pub. No. 93 (Notes on Soldering), 1968.
- (2) J.H. Becker, "On the Quality of Gray Tin Crystals and Their Rate of Growth," J. Appl. Phys., Vol. 29, No. 7, pp. 1110-1121, July 1958.
- (3) A. Bornemann, "Tin Disease in Solder Type Alloys," ASTM Spec. Techn. Publ. 189, pp. 129-148, 1956.
- (4) W.L. Williams, "Gray Tin Formation in Soldered Joints Stored at Low Temperatures," ASTM Spec. Techn. Publ. 189, pp. 149-159, 1956.
- (5) C.L. Mantell, "Tin-Its Mining, Production, Technology and Applications," The Chemical Catalog Company, Inc., New York, 1929.
- (6) "Binary Alloy Phase Diagrams," T.B. Massalski Editor-in-Chief, ASM Intl., October 1986.
- (7) S.M. Arnold, "The Growth of Metal Whiskers on Electrical Piece-parts," Proc. of IEEE ECC, pp. 75-82, 1959.
- (8) 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
- (9) 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.
- (10) W.J. Boettinger et. al, "Whisker and Hillock Formation on Sn, Sn-Cu and Sn-Pb Electrodeposits," Acta Materialia, Vol. 53, No. 19, November 2005.
- (11) 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.
- (12) C.E. Homer and H. Plummer, J. Inst. Met., Vol. 64, p. 169, 1939.
- (13) 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.
- (14) 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.
- (15) K. Sweatman et al., "Suppression of Tin Pest in Lead-free Solders," JEDEX 2005.
- (16) S.M. Arnold, "Repressing The Growth of Tin Whiskers," Plating, pp. 96-99, January 1966.
- (17) J. Spergel, "Tin Transformation of Tinned Copper Wire," ASTM Spec. Techn. Publ. 319, pp. 83-92, 1962.
- (18) 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.
- (19) H.J. Plenderleith and R.M. Organ, "The Decay and Conservation of Museum Objects of Tin," Intl. Institute for Conservation of Historic and Artistic Works, Vol. 1, pp. 63-72, 1952.
- (20) 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.
- (21) D.C. Abbott et al., "Whisker Evaluation of Lead-free Component Leads," Texas Instruments Corp. Appl. Report No. SZZA051B, August 2005.
- (22) M. Tanimoto et al., "Pb-free Plating for Electronic Components," Furukawa Co. report, 1999.

- (23) 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
- (24) M. Williams et al., "Hillock and Whisker Growth on Sn and SnCu Electrodeposits on a Substrate Not Forming Interfacial Intermetallic Compounds
- (25) Cole, M. et.al, "Lead-free Card Assembly and Rework for Column Grid Arrays", SMTA Journal Vol. 17-1 (2004).
- (26) W.J. Boettinger et.al, "Whisker and Hillock Formation on Sn, Sn-Cu and Sn-Pb Electrodeposits," Acta Materialia, Vol. 53, No. 19, November 2005.
- (27) 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.
- (28) Karl Seelig and David Suraski "Lead Contamination in Lead-free Electronics Assembly", White paper AIM Solder.
- (29) 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
- (30) 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
- (31) 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

3. Terms and definitions

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

Alloy Composition - All alloy compositions are stated as weight percent. For instance 63Sn-37Pb corresponds to a mixture of 63 % by weight of Tin(Sn) and 37 % by weight of Lead(Pb).

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

Ag, Au, Bi, Cu, Ge, In, Ni, Pb, Sb, and Sn refer to the elements Silver, Gold, Bismuth, Copper, Germanium, Indium, Nickel, Lead, Antimony, and Tin, respectively.

AHP: Aerospace, High Performance Systems

Assemblies are electronic items that require electrical attachments, including soldering of wires or component terminations; examples include circuit cards and wire harnesses.

AR Acrylic resin conformal coating.

CAF refers to Conductive Anodic Filaments that form in printed wiring boards. See IPC-TM-650 Method 2.6.25.

CALCE: The University of Maryland Center for Advanced Life Cycle Engineering (CALCE) consortium.

CLCC refers to a Ceramic Leadless Chip Carrier electronic package.

Critical item or function, if defective, will result in the system's inability to retain operational capability, meet primary objective, or affect safety.

Creep refers to time dependent strain occurring under stress.

CSAM refers to C-Mode scanning acoustic microscopy, which is a method for evaluating electronic packages for internal delamination using high frequency sound waves.

CTE refers to the coefficient of thermal expansion of a material. PCB CTE (x-y) 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 during thermal cycling. CTE(z) is measured in the "thickness" direction and is typically used to quantify plated through hole stress.

Customer refers to an entity or organization that (a) integrates a piece part, soldered assembly, unit, or system into a higher level system, (b) operates the higher level system, or (c) certifies the system for use. For example, this may include end item users, integrators, regulatory agencies, operators, original equipment manufacturers (OEMs), and subcontractors.

Dicy Cure refers to the use of dicyandiamide (dicy), as a curing agent for epoxy resins.

EM refers to electromigration of the PCB metallization. Resistance to electromigration testing is typically performed between electrically biased conductors at elevated humidity and temperature.

ENIG refers to Electroless Nickel Immersion Gold Printed Wiring Board Finish.

ER Epoxy resin conformal coating.

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

FR4 refers to Flame Retardant laminate made from woven glass fiber material impregnated with epoxy resin.

Fick's Law refers to the classic diffusive mass transport model where the mass diffusion is proportional to the concentration gradient in the material.

Fillet Lifting refers to a separation that occurs between a solder fillet and a PCB pad where the solder fillet has the appearance that it has lifted off the PCB pad. 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 pad results in a layer that allows the solidified solder above it to pull off the PCB pad [38] [73].

High Performance System or Product requires continued performance or performance on demand, or equipment down time cannot be tolerated, or end-use environment may be uncommonly harsh, and the equipment must function when required, such as life support or other critical systems.

HALT and HAST refers to highly accelerated life test and highly accelerated stress test, respectively.

HASL refers to the Hot Air Solder Level PCB surface finish

Incubation Period in the context of Tin Pest formation refers to the time required at cold temperature to initially form the brittle gray (α) Tin phase from the ductile white (β) Tin phase.

Inoculation in the context of Tin Pest formation refers to 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.

ICP refers to Inductively Coupled Plasma/Mass Spectrometry based chemical analysis.

Imm Ag or Im Ag refers to an immersion silver printed circuit board finish

JCAA refers to the Joint Council of Aging Aircraft Organization within the US Department of Defense. JCAA and JGPP have performed extensive Pb-free solder reliability testing.

JGPP refers to the NASA lead Joint Group on Pollution Prevention. The NASA JGPP group began the Pb-free solder testing that was completed with the support of JCAA.

Kirkendall void formation refers to voids induced in a diffusion couple between two metals that have different interdiffusion coefficients..

Lead: 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.

Lead-Free or Pb-Free is defined as less than 0.1% by weight of Lead (Pb) in accordance with Waste Electrical and Electronic Equipment (WEEE) guidelines.

LRU is a line replaceable electronic unit.

May indicates a course of action that is permissible within the limits of this document.

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

Non-Eutectic: See Eutectic mixture definition

OSP refers to Organic Solderability Preservative finishes used on PCBs.

PCB stands for Printed circuit board, which is also commonly referred to as a Printed Wiring Board (PWB).

PEM refers to a plastic encapsulated microcircuit

Peritectic: In a peritectic reaction, a solid phase and a liquid phase react on cooling to produce a new solid phase.

Piece-part is defined as an electronic piece part that is not normally disassembled without destruction and is normally attached to a printed wiring board to perform an electrical function.

PWB stands for Printed Wiring Board, which is also commonly referred to as a Printed Circuit Board (PCB).

PTH stands for the plated through holes used on printed circuit boards for interconnecting between layers and for component attachment.

Repair is the act of restoring the functional capability of a defective article in a manner that precludes compliance of the article with applicable drawings or specifications.

Rework is 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.

RMA refers to solder flux type: Rosin, Mildly Activated.

RoHS refers to the legislation enacted by the European Union on the Restriction of Hazardous Substances, EU Directive 2002/95/EC, which places a restriction on the use of certain hazardous substances in electrical or electronic equipment sold or used in the European Union after July 1, 2006. These substances are lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls, and polybrominated diphenyl ethers.

SAC refers to the family of Pb-Free alloys containing Tin, Silver and Copper used in surface mount technology or sometimes in wave solder processes. The alloys typically have a composition near the eutectic (Sn - 3.5Ag - 0.9Cu).

SAC-L refers to low Silver content SAC alloys that are not eutectic compositions. These alloys have increasingly been used for BGA interconnects.

Should indicates that, among several possibilities, one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not

necessarily required; or that (in the negative form) a certain course of action is deprecated but not prohibited.

SIR refers the Surface Insulation Resistance measurements performed on PCBs. These electrical resistance measurements are often performed after periods of humidity exposure.

SMT refers to surface mount technology circuit card assembly technology

SMTA refers to the Surface Mount Technology Association, with headquarters in Edina, MN.

Sn-Cu solder or alloy refers to Pb-Free alloys that are comprised of Tin-Copper (Sn-0.7Cu)

Sn-Cu-(Ni) solder or alloy refers to Pb-Free Tin-Copper with trace Nickel concentration alloy (Sn-0.7Cu-0.05Ni). Some formulations also include other minor additions such as Ge.

Sn-Pb solder generally refers 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).

Solder ball technology identifies a family of components that employ solder balls or bumps to make mechanical and electrical connections between components and printed circuit boards. Examples are ball grid arrays (BGA), flip chip, and chip scale interconnections.

Soldered Assembly is an assembly of two or more basic parts interconnected by a solder alloy. 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.

Supplier refers to an entity or organization that designs, manufactures, repairs, reworks, or maintains a piece part, unit, or system. For example, this includes original equipment manufacturers (OEMs), repair and rework facilities, subcontractors, and piece part manufacturers.

System is defined as one or more units that perform electrical function(s).

T_d is the decomposition temperature of a PWB laminate.

T_g is the glass transition temperature of a PWB laminate.

Tin Whisker is a spontaneous crystal growth that emanates from a Tin surface. They may be cylindrical, kinked, or twisted. Typically they have an aspect ratio (length/width) greater than two, with shorter growths referred to as nodules or odd-shaped eruptions (OSEs).

TSOP refers to a thin small shrink outline electronic device package.

um is a unit of length measure defined to be a micro-meter or one millionth of a meter and is commonly referred to as a micron.

Unit is defined as one or more assemblies within a chassis to perform electrical function(s).

UR: Urethane resin conformal coating.

XY: Paraxylylene resin conformal coating (Also known by the trade name Parylene).