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Methodology for Implementation of Pb-free Materials in Aerospace & Defense Electronics

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ABSTRACT

The Aerospace & Defense (A & D) industries maintain a high level of interest in the expansive amount of work performed in developing and qualifying Pb-free solder alloys. The three main areas of interest continue to be thermal cycle, mechanical shock, and vibration. The past twenty years have seen an unprecedented increase in alloy development such that the concepts of "generations of solders and "families of solders" have been coined to help manage the numerous individual alloys on the market today. The efforts of industry, academia, and the U.S. Department of Defense have resulted in developing standards, handbooks, and guidelines as well as an immense amount of data all benefiting a rigorous risk management framework. This paper will discuss the Pb-free challenges (also considered risks) and the "building blocks" generated which provide a methodology to allow cautious and responsible implementation of Pb-free materials in high performance products.

Key words: Pb-free, lead-free, solder, Aerospace & Defense.

INTRODUCTION

The European Union RoHS (Restriction on the use of hazardous substances) Directive was the driving force in the electronics industry for the conversion from manufacturing with eutectic tin-lead (63Sn37Pb) solder to manufacturing with Pb-free solder [1]. The initial implementation for the high volume, consumer electronics market was mandated in 2006. As the high-volume market segments transitioned to Pb-free manufacturing, high reliability electronic equipment suppliers continued to manufacture and support tin-lead (SnPb) electronic products by using the European Union Pb-in-solder exemption. In parallel, considerable research was being conducted to evaluate the quality and reliability of Pb-free electronic assemblies. As exemptions neared expiration, high reliability manufacturers in telecom, medical, and automotive markets developed the confidence to convert many of their products successfully to Pb-free manufacturing. However, the aerospace & defense (A & D) industries that have characteristically stricter mission critical reliability requirements, continue to widely use SnPb solder manufacturing processes.

The A & D industries recognized the worldwide supply chain implications imposed by implementation of the RoHS Directive. They have been engaged in a joint endeavor to survey all technological aspects of Pb-free solder manufacturing in anticipation of a measured and systematic conversion to Pb-free manufacturing. The overall objective is to develop strategies for reliability risk assessments and supply base challenges specific to the industries' rigorous requirements and unique environmental service and storage conditions. Most of these conditions and requirements consist of various combinations of thermal cycling, thermal shock, vibration, and high strain rate mechanical shock.

These efforts have resulted in a technology assessment and gap analysis of the most widely used Pb-free materials to enable development of strategies and tools needed for risk mitigation. A considerable amount of supporting information can be found in the open literature on identification of the risks, potential failures and shortfalls if the risks are realized. Many of the technical papers, handbooks, standards, and specifications that are referenced in this paper can be used as comprehensive guidance and recommendations to mitigate these risks [2-5].

In an earlier paper, the author, along with four of his colleagues, presented a comprehensive review of Pb-free research performed to date and a list of standards, handbooks, and guides to help engineers address Pb-free challenges when such materials are forcefully integrated into Aerospace & Defense (A&D) design [10]. The combination of the data and documentation can be thought of as a "toolbox" for engineers developing, designing, and producing high performance products and systems with Pb-free solders and finishes. The purpose of this paper is to present these "building blocks" or "tools" in a user-friendly, methodological manner. Recent EU activity to consider the placement of elemental Pb on the REACH Authorisation only increases the sense of urgency in understanding Pb-free materials as alternatives. Note that in many high reliability cases, SnPb is still the preferred interconnection material of choice and extreme care should be taken when considering Pb-free for interconnection technology.

An effective methodology relies on a solid set of resources. For the purposes of this discussion, we consider two "buckets" of resources: Data and Guidance (standards, specifications, and handbooks).

DATA

The Pb-free technical data base (e.g. open literature) is abundant with a variety of data categories and, due to the immense amount of information, only summaries and some specific examples are discussed here. To bound this discussion, two applications of the data are provided: interconnections and tin whiskers.

Interconnections

The open literature is abundant with data and information on both SnPb and Pb-free as interconnection materials as well as surface finishes. Several years prior to enactment of RoHS (Restriction of Hazardous Substances) in 2006, research on both material technologies was rampant to understand comparisons and shortfalls. It has been said that the industry learned more about SnPb than previously known during the comparative studies to Pb-free. Moreover, given that Pb-free is an extremely wide group of materials, characterizing these materials becomes a formidable as well as never-ending task.

When understanding the impact of Pb-free on A&D products, one needs to comprehend two high-level challenges (previously termed “risk” but in the spirit of positive thinking we use the term challenges). They are 1) reliability of a Pb-free solder interconnection and (Figure 1) and 2) deleterious effects from formation of tin whiskers (Figure 2).

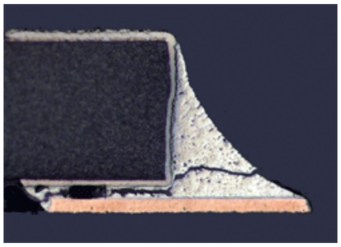


Figure 1: A Pb-free solder joint can fail earlier than an SnPb solder joint when subjected to mechanical vibration or shock in the field (courtesy of Dr. Craig Hillman, DfR Solutions.)

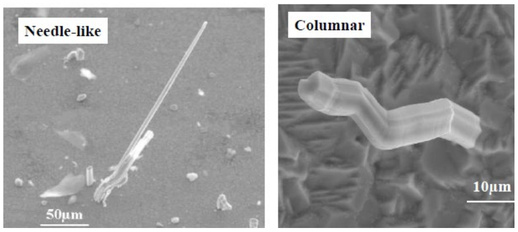


Figure 2. Examples of whiskers observed in CALCE (University of Maryland) experiments. Left: Needle-like whisker structure, Right: Columnar-like whisker structure. (Courtesy of Center for Advanced Life Cycle Engineering [CALCE])

(There is a third high-level challenge which is configuration management of Pb-free built product primarily concerned that commercial suppliers not required to notify customers of material changes. However, this risk is not within the scope of this paper.)

The ability of solder to provide a sound interconnection between component and printed board depends on the mechanical/physical properties of the solder, the termination finishes, and the environment/conditions to which the circuit card assembly will experience.

When characterizing mechanical properties of Pb-free solders, two things should be noted: 1) there is an overwhelming number of different alloys and 2) all testing should be compared to eutectic SnPb to benefit application to A&D use. At this point, it is important to establish the following ground rule regarding the scope of this paper from hereon in: While there are cross-over similarities in aerospace and defense service conditions, for brevity, the remainder of this discussion will be limited to latter applications (although an analogous if not similar methodology can be used for the former).

In general, performance of equipment in defense conditions may subjected (but not be limited) to thermal cycling, thermal shock, vibration and mechanical shock. (Other conditions such as humidity, salt fog, sand/dust, radiation, etc. are also a concern and can be dealt with in a similar manner.) When determining reliability of equipment under any/all of these four conditions, analytical and/or modeling approaches will require use of basic material properties (and in some cases other physical properties). Examples of these properties include yield strength, ultimate tensile strength, shear strength, elastic modulus, stress relaxation, and creep rate (among others). Finding replacement solder alloys for SnPb presents a challenge in that the candidate alloys represent much different material properties (See Figures 3 and 4) than the benchmark creating a scenario of many possibilities requiring many analytical and modeling iterations.

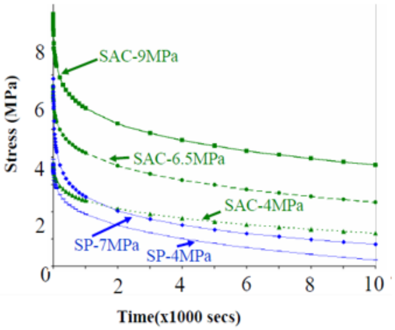


Figure 3. Differing creep rates between SAC 305 and SnPb (denoted as SP) alloys for varying stress levels: slower in SAC. (Figure courtesy of Auburn University CAVE[3]).

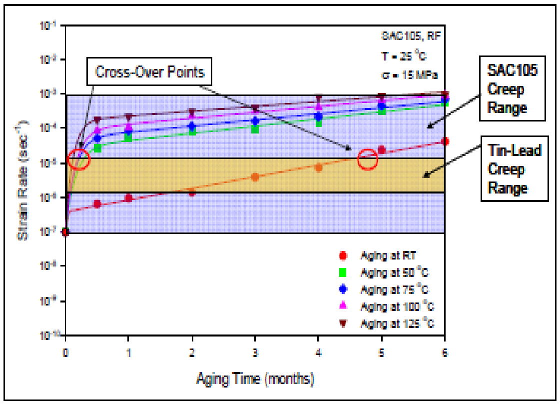


Figure 4. Comparison of creep rates between SAC and SnPb for varying temperatures. (Figure courtesy of SMTA and Auburn University CAVE[3]).

Figure 5 provides an example of how these material differences can lead to changes in service conditions, e.g. thermal cycle behavior of SAC 305 versus eutectic SnPb.

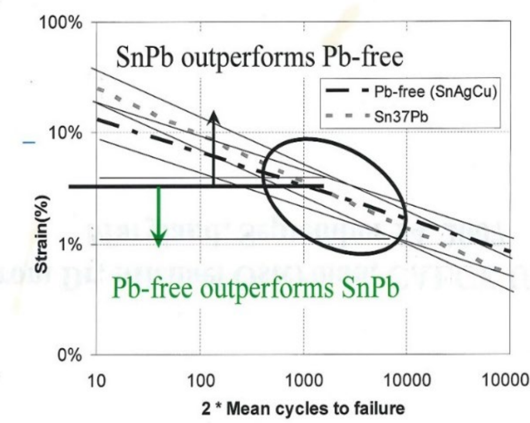


Figure 5. Presenting the thermal cycling comparison from a percentage strain aspect. At extreme strain conditions (extreme temperatures), SnPb outperforms SAC but the opposite occurs for less extremes (courtesy of M. Osterman, University of Maryland Center for Advanced Life Cycle Engineering)

Likewise, Pb-free alloys differ in mechanical shock (drop) and vibration thereby posing similar challenges in evaluating reliability for these service conditions as well [11, 12]. See Figure 6.

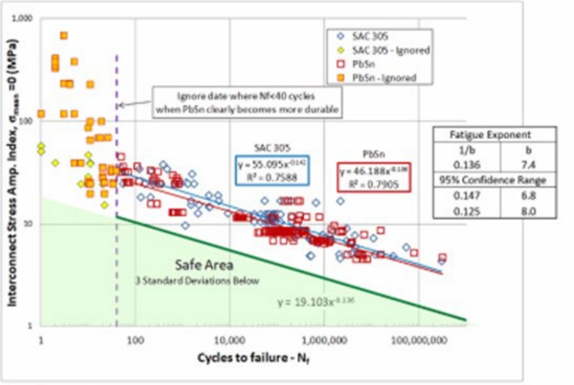


Figure 6. Example shown for vibration data – at high strain rate (i.e. shock) and high vibration levels, Pb-free (SAC 305 in this case) tends to be less durable than SnPb. The data can be used to develop mitigations. (Courtesy CALCE/University of Maryland)

Tin Whiskers.

The conversion to Pb-free has also affected trends in electronic surface finishes and plating materials, i.e. the recent focus on tin whiskers. Tin whiskers are defined as electrically conductive crystalline structures that originate on surfaces containing tin as the final finish. Dimensionally, they can grow to within several millimeters and, rarely, can exceed ten (10) millimeters. They pose risk of causing electrical shorts between component leads and/or printed circuit board traces. Failure analysis can be challenging as in some cases, a whisker can be completely disintegrated after shorting thereby eliminating evidence of its existence. Whisker formation is not limited to just pure tin as other finishes (zinc, cadmium, indium, antimony, and silver) can produce the phenomenon as well [13].

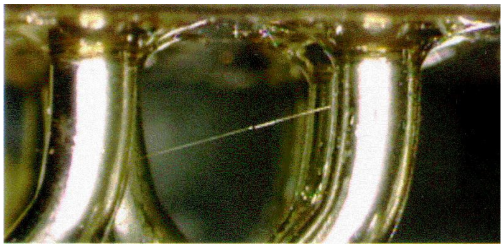


Figure 7. Tin whisker growing between pure tin-plated hook terminals of an electromagnetic relay (courtesy of NASA Goddard - https://nepp.nasa.gov/WHISKER/background/index.htm)

Addressing tin whisker risk has resulted in the development and implementation of mitigation strategies to minimize effects. These mitigations include (but are not limited to) increased lead spacings, coatings, and re-finishing (e.g., re-balling for ball grid arrays, re-tinning for leaded components).

GUIDANCE

July 1, 2006 saw the onset of the first of many global regulations, i.e. the European Union Restriction of Hazardous Substances (RoHS) Directive [14] which was then followed by the more comprehensive REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) directive [15]. Today, many nations have developed their own interpretations or "flavors" or RoHS and REACH which adds to the challenge of manufacturers providing compliant products in these markets. Approximately, ten years prior to enactment of original RoHS regulation, the U.S. Department of Defense and its major contractors initiated discussions on identifying associated risks of a Pb-free transition and how to address the impacts, i.e. mitigations. Both DoD and industry working groups were formed to corroborate and collaborate resources to work issues, risks, and strategies finally resulting in the IPC Pb-Free Electronics Risk Mitigation Council as it is known today [16]. Through the efforts of the council, along with contributions from other industry/academia/DoD groups, a suite of standards, handbooks and guidelines have been established to help defense contractors incorporate Pb-free materials into the design and manufacture of high performance equipment. These documents are as shown in Table 1:

Table 1. Standards Handbooks, Guidelines to Facilitate Pb-free Implementation in A&D Products

Document Number	Document Title
SAE GEIA-STD-0005-1	Standard for Developing a Lead-free Control Plan to Manage the Risks of Lead-free Solders and Finishes in Aerospace, Defense, and High Performance Soldered Electronic Products
SAE GEIA-STD-0005-2	Standard for Mitigating the Effects of Tin in Aerospace and High Performance Electronic Systems
SAE GEIA-STD-0005-3	Performance Testing for Aerospace and High Performance Electronics Containing Pb-free Solder and Finishes
SAE GEIA-HB-0005-1	Program Management / Systems Engineering Guidelines for Managing the Transition to Pb-free Electronics
SAE GEIA-HB-0005-2	Technical Guidelines for Aerospace and High Performance Electronic Systems Containing Pb-free Solder
SAE GEIA-HB-0005-3	Rework and Repair Handbook To Address the Implications of Pb-free Electronics and Mixed Assemblies in Aerospace and High Performance Electronic Systems
SAE GEIA-STD-0006	Requirements for Using Robotic Hot Solder Dip to Replace the Finish on Electronic Piece Parts
IPC/PERM-2901	Pb-free Design & Assembly Implementation Guide

SAE GEIA-STD-0005-1 presents elements of lead-free control plan (LFCP), i.e. a tool for tracking and verifying a minimum set of requirements to reduce performance risk in A&D systems and products. The latest version (Revision B about to be released) will feature the concept of risk areas based on feedback and lessons learned from users of previous versions. Each risk area includes three high level requirement categories, again based on usage data and lessons learned [17].

SAE GEIA-STD-0005-2 establishes processes for documenting the mitigating steps taken to reduce the harmful effects of Pb-free tin finishes in electronic systems. Its scope includes electronic parts and mechanical hardware used on or in the proximity electronics. The cited mitigations are meant to support designers, operations, and test personnel in execution of actions in their disciplines providing a menu of options as well as collaborative opportunities fostering an integrated product team (IPT) approach to product development.

SAE GEIA-STD-0005-3 was developed in 2008 and subsequently updated in 2012. The rather quick interval between revisions represented the rapid pace of industry/academia research conducted to quickly learn about the unique characteristics of Pb-free materials. The document defines 1. a default method and 2. a protocol method. The thought process was that with Pb-free being a new material in the A&D use community, some guidance was necessary to answer the question "How do I test Pb-free built product?"

The default method is a conservative (biased toward minimizing the risk to users of AHP electronic equipment) approach intended for users who, for a variety of reasons, may be unable to develop methods specific to their own products and applications. It is to be used when little or no other information is available to define, conduct, and interpret results from reliability, qualification, or other tests for electronic equipment containing Pb-free solder.

The protocol method is intended for use by manufacturers or repair facilities that have the necessary resources to design and conduct tests specific to their products, operating conditions, and applications. Users of the protocol are expected to have the necessary knowledge, experience, and data to customize their own methods for designing, conducting, and interpreting results from the data. They should also have a firm understanding of all material properties for the Pb-free material in question as well as knowledge of package- and board-level attributes.

SAE GEIA-HB-0005-1 was generated to assist a program in assuring the performance, reliability, airworthiness, safety, and certifiability of product(s) containing Pb-free materials (i.e. as interconnections or finishes). While not limited to these roles, the handbook is steered to program managers, systems engineers, and quality assurance engineers. Content includes general concerns as well as impacts on reliability, cost/schedule, system engineering, supply chain, and configuration control. It essentially is a support tool for SAE GEIA-STD-0005-1 and its content contributes significantly to development of an effect LFCP.

SAE GEIA-HB-0005-2 is a compendium of technical information including (but not limited to) Pb-free solder behavior and its relation to system level service environments, high performance electronics test, solder joint reliability, piece parts, printed circuit boards (PCBs), PCB assembly, module assembly, wiring/cabling, rework/repair, and life test. Released in 2007, the knowledge base has drastically increased since its release but the consideration topics are still valid as is the guidance insight into use of Pb. Results from the U.S. DoD-funded Solder Performance and Reliability Assurance (SPRA) program, under the United States Partnership for Assured Electronics (USPAE), will enhance the industry data base as well as provide a performance specification and test handbook applicable to any solder alloy, i.e. solder agnostic [18].

SAE GEIA-HB-0005-3 was generated to provide technical background, procurement guidance, engineering procedures, guidance to users who rework/repair A&D electronic systems assembled or previously reworked/repaired using 1) SnPb, 2) Pb-free alloys, or 3) a combination of both. Focus is on the removal and replacement of piece parts.

SAE GEIA STD 006 was generated to standardize the requirements for using robotic hot solder dip to replace the finish on certain electronic piece parts. Subsequently, hot solder dip is one of the mitigation techniques cited in SAE GEIA-STD-0005-2. There are two major reasons to solder dip piece parts: solderability concerns and tin whisker mitigation. Since Solder dip for tin-whisker mitigation differs from solder dip for solderability in that the former requires the termination be coated over its entire length, i.e., up to the package surface. This standard includes requirements for this successful application.

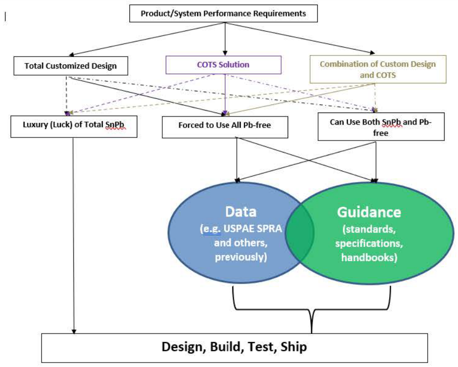
IPC/PERM 2901 was developed to assist design engineers in developing electronics that are completely Pb-free and meet the demanding requirements of ADHP systems and products. One way to describe its content is that the information provided is a delta to the SnPb knowledge base, i.e. data/information that applies to both SnPb and Pb-free is not included. Put another way, the assumption is design engineers using this guide are competent and experienced with SnPb based electronics but not as familiar with the unique aspects/traits of Pb-free materials, components, and processes or their associated influence on performance.

Note that all of these documents are intended (as applicable) for use by those procuring, designing, building or repairing electronic assemblies for A&D use.

METHODOLOGY

As a result of years of testing, observations, analysis, and collaboration, this author has developed a vision for an engineering methodology to implement Pb-free technology in A & D systems. The approach involves five (5) key elemental levels for consideration in compliant product design with Pb-free (Figure 8).

First, the engineer must understand the customer's needs, i.e. the product/system performance requirements. Any successful engineering design, and subsequent build, must comply with specified expectations. Second, consideration is given to how the designs will be generated in terms of product/system components considering such factors as (but not limited to) required functionality, cost and schedule. Trade studies are usually employed to assess the priority of these factors the results of which create decision paths as shown in Figure 8: 1) completely customized design, 2) design heavily reliant on commercial-off-the-shelf (COTS), and 3) a combination of the two.



Key: Solid Line = Likely, Dash-Dot = Somewhat Likely, Dash = Unlikely

Figure 8. A proposed methodology for implementation of Pb-free into A&D products/systems.

The third element of the methodology considers availability of interconnection material and finish(es) in the Supply Chain. At the time of this writing, some solder suppliers still stocked SnPb solder but with increasing activity by global regulatory groups (e.g. European Union and REACH), there is concern that SnPb materials may either be outlawed or may require Authorisation (very constraining option within REACH regulations) resulting in problematic supply acquisition.

However, Figure 8 does reveal some recourse in addressing the dilemma. Barring the rare luxury of using all SnPb technology in the electronic designs, there are resources to support the designer in selecting the all Pb-free or combined

SnPb/Pb-free approach. An immense amount of Pb-free data has been generated by many research groups including (but not limited to) CALCE (University of Maryland), CAVE3 (Auburn University), and Binghamton University [19-21]. Representing ten to fifteen years of knowledge, this data was processed into a set of standards, handbooks, and guidelines to support engineers in various disciplines of design, development, test, and manufacture including repair/rework (Table 1). These resources represent the fourth element in the framework. It should be noted that the knowledge base will be bolstered with the work on the U.S. Department of Defense (DoD) Solder Performance and Reliability Assurance (SPRA) project [22, 23]. Final deliverables include an agnostic solder performance specification along with a handbook providing guidance in testing and evaluation to supplement the specification. Starting in 2021, the SPRA has generated milestone reports in a building-block approach to generating the deliverables. These milestones include (but are not limited to) test plans, use cases, gap analyses, and test demonstrators. Despite a projected end date of January 2026, data is being generated presently which will help this methodology. The fifth and final element is the completion of the design and build of the product.

CONCLUSIONS

The A&D industry has impressively advanced in its recognition, acknowledgement, and acclimation with Pb-free materials, i.e., as interconnects and finishes. However, for certain high reliability applications (e.g., space systems, missile systems) total acceptance will still require a considerable amount of verification and validation time. Therefore, during this time, such conditions will continue to require SnPb solder until a suitable replacement material is found. Yet, the partnership between the DoD and industry (USPAE) provides hope on providing a long-needed approach to responsible and effective selection of solder alloys for high performance conditions. With the anticipation of the USPAE SPRA deliverables, a disciplined evaluation process, for using Pb-free materials, is a valid mid-term goal. Given the body of work completed to date (industry/academic generated data, GEIA suite of tools, etc.), a methodology for risk mitigation has been proposed. The USPAE deliverables should provide a means to enhance this proposed methodology. In addition, the author anticipates and welcomes many variations and revisions to this approach with the ultimate goal of ensuring reliable systems for the warfighter.

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