LIVING WITH PB-FREE IN HIGH PERFORMANCE ENGINEERING DESIGN

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ABSTRACT

As Pb-free technology increasingly becomes the standard for electronic interconnects and finishes, engineers must cope with the various challenges posed by this material. Summarizing at a high level, these challenges represent risks associated with 1) durability of the interconnection and 2) deleterious effects of tin whiskers. Subsequently, IPC Task Group 8-81D (Research Coordination and Technical Guidance), of the IPC PERM COUNCIL, has undertaken an assignment to generate an industry-wide guide to aid engineers in designing with Pb-free technology. The focus is to provide insight and information such that the design will maintain performance requirements for aerospace, defense, and high-performance (ADHP) products and systems. Having started out as a "laundry list" of Pb-free concerns and challenges identified by the ADHP industry, the guide is structured such that those “delta” considerations, i.e. technical knowledge gaps with Pb-free technology are brought to the designer’s attention. Furthermore, the guide highlights Pb-free concerns, as they are encountered in the phases which generally reflect the product development cycle used by Aerospace, Defense, and High-Performance systems industries. This paper presents a summary of efforts from document inception to document release.

Key words: Pb-free, lead-free, design guidance, PERM

INTRODUCTION AND BACKGROUND

Since the mid-1990’s, in anticipation of enactment of the July 2006 European Union Restriction of Hazardous Substances regulation [1], the aerospace, defense, and other high performance (ADHP) electronics industries have been working to address the challenges of incorporating Pb-free (elemental lead-free) materials in electronics, i.e. as interconnection media (solder joints) and for surface finishes (e.g. pure tin). While these companies continue to be excluded from the restrictions, the impact is still significant since the commercial supply chain has converted to Pb-free solder for the majority of their products.

ADHP industry dependence on commercial-off-the-shelf (COTS) products has led to concerns as to how these products will perform under the harsh service, environmental, and storage conditions typical of many system life cycles. Prior to Pb-free solder, tin-lead (Sn-Pb) solders were the standard interconnection material for most electronics. A substantial database was generated to help predict performance behavior thus facilitating design and manufacture of ADHP products. Pb-free performance characteristics in ADHP applications are, to date, minimal or unknown thereby warranting generation and comprehension of a new performance database. Given the variety of Pb-free choices in the marketplace, generating this database is an overwhelming task. While some suppliers continue to provide tin-lead products, this “luxury” is viewed as a limited resource since consumer market demands may force reduction/termination of lead-based production lines. New products (as well as updates to traditional parts) are being introduced exclusively in Pb-free form. Figure 1 illustrates ADHP dependence upon the global supply chain. In general, ADHP companies must address two major concerns with the inception of Pb-free technology: 1. performance of the soldered interconnection and 2. potential deleterious effects of tin whisker formation from Pb-free finishes using pure tin. The first concern becomes more complex expanding into a long term issue that centers around the use of Pb-free and mixed Pb-free assemblies and the ability to sustain systems that use them. For example, when using mixed technology in repairing assemblies, remember that the Pb-free solder may require higher reflow temperatures. Thus, in addition to concern about Pb-free performance, one also needs to consider how much of the life time is impacted as a result of exposure to the higher temperature [2]. Thus, the first concern results in a third concern of long term sustainment of Pb-free and mixed assemblies.

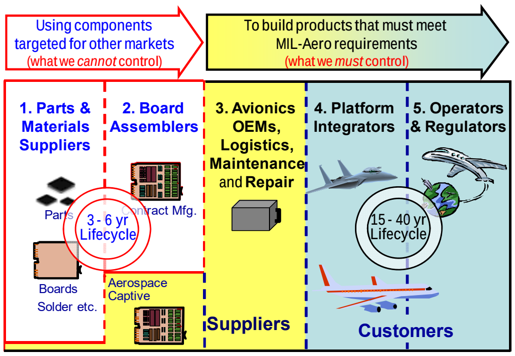

Figure 1. The Global Military and Aerospace Supply Chain [2] (Courtesy of Mr. Lloyd Condra, BOEING Company.)

Therefore, in order aid the designer in "tolerating" the impact of a Pb-free supply chain, the IPC PERM Council and its Research Coordination/Technical Guidance team initiated an effort to generate a guide with the sole purpose of alerting users to the properties, impact, effects, and challenges (risks) associated with Pb-free materials as interconnection media and plating finishes.

WHY A DESIGN GUIDE?

Establishment of a baseline, at any level, is critical to ensuring a design and product that will comply with service requirements. For close to seventy-years (70), and perhaps even longer, tin-lead (Sn-Pb) solder was the standard material for joining electronic components to printed circuit boards. The enactment of the RoHS regulations, and subsequent reaction by the supply chain, created a disruptive effect in high reliability electronics, i.e. the incorporation of new materials with no understanding of their ability to meet the traditional requirements of ADHP products and systems. It just stands to reason that the incorporation of any new (and some cases exotic) material into a high reliability design, without sufficient evaluation, produces concerns and risks with the product's performance and reliability.

New materials present a potential to behave differently than baselined materials (i.e. eutectic tin-lead which will hereby be denoted as SnPb). The case of Pb-free is no different. For example, two (out of several) areas in which noticeable material property behaviors are manifested are 1) creep and stress relaxation (significant parameters when gauging durability under service conditions) [3] and 2) aging effects under stress (which influence strength assessments). For the former property, the tin-silver-copper (SAC) family of Pb-free solders has demonstrated significantly longer times to stabilize as compared to SnPb [3]. (See Figure 2.)

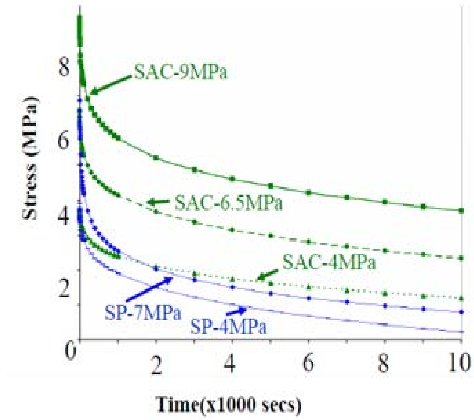

Figure 2. Graph shows a slower creep rate in SAC solders as compared to SnPb (denoted as SP here). For a given initial stress, SAC relaxes, in this case, only 60%, whereas SnPb relaxes almost completely at 80% [4]. (Courtesy of Gayatri Cuddalorepatta, Center for Advanced Life Cycle Engineering [CALCE]).

Considering aging effects, studies have shown that aging induced changes in the creep strain rates of SAC alloys are much larger than analogous changes observed for conventional eutectic Sn-37Pb solder [4, 5]. (See Figure 3.)

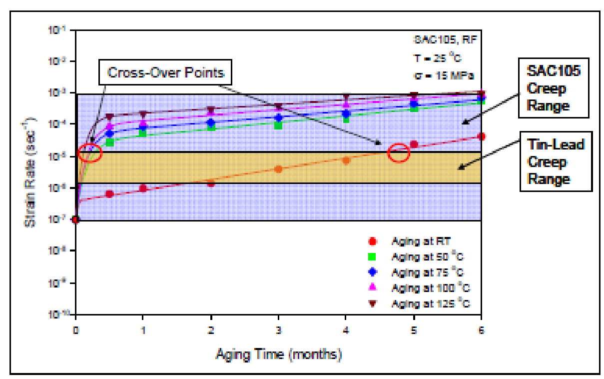

Figure 3. Graph showing creep rate changes dramatically with elevated temperature aging relative to Sn-37Pbsolder immediately after reflow (zero aging) but the creep rate changes dramatically with elevated temperature aging relative to Sn-37Pb. (Courtesy of SMTA and Auburn University.)

Furthermore, the case can be made for other types of attributes. For example, several Pb-free alloy families (e.g. SAC), require higher reflow temperatures than SnPb (e.g. 217C vs 183C), resulting in vulnerability of component package damage prior to shipment [6].

Therefore, the differences between Pb-free alloys and SnPb is a very well-known issue today. A web-based search for any and all types of attribute differences will easily result in tens of thousands of "hits" (over 61,000 at the time of this writing). Subsequently, it is in a designer's best interest to understand the effects of selecting electronic components containing these new alloys, either as surface finishes and/or as interconnection media.

HIGH-LEVEL APPROACH – DESIGN STRATEGIES

Since the inception of the RoHS regulations in 2006, this author has presented and discussed several high-level strategies to mitigate risk when forced to design using Pb-free materials.

1. Aggressive preventative maintenance (PM)

   This approach is similar to designing redundancy. If one assumes that Pb-free interconnections will maintain performance over a specified period of time, then perhaps one should plan to swap out modules (or line replaceable units) with new units and check the originals for signs of potential failure. Analysis and assessment is required to establish a suitable "mean-time-to-swap-out" (MTTSO). Overall, the benefit is that failure can be prevented by consistently integrated newer, fresher product. The drawback, obviously, is cost to provide additional (spares) units as well as storing them.

2. Ruggedization

   This approach targets deficiencies associated with certain Pb-free materials and designs to mitigate the specific risks. For example, some Pb-free solders do not perform well under mechanical shock and vibration so to compensate, one would consider including dampening and/or stiffening components at or around the solder joints. One example approach would be application of underfills to surface mount components to mitigate vibration (and perhaps shock) damage. As many aerospace & defense programs impose MIL-STD-883 (vibration) and MIL-S-901 (mechanical shock) requirements on their systems, ruggedization has become a popular technique for compliance. The benefit is that potential performance shortfalls are "designed out" but additional cost is needed for the additional materials as well as the processes to apply them.

3. Service Condition Constraints

   Perhaps the most unpopular approach is limiting the service conditions (usage and storage) of Pb-free built product. For example, if the Pb-free materials used in certain products have limited temperature ranges for optimal performance, then the ultimate usage and storage environments will need to be similarly limited. Such products, upon completion of production, may need to be shipped directly to their environmentally controlled usage areas (e.g. combat control centers in marine platforms). Spares will require storage in similarly controlled areas (presenting added cost and other logistical challenges to the end user). The advantage here is that the Pb-free-built product will be limited to use under conditions that will not stress material property limits. A disadvantage, particularly pointed to the military market, is that product interchangeability is hampered and would lead to additional cost if additional, similarly functional products must be acquired and ruggedized for harsher use conditions.

No doubt there are other strategies being developed but in all cases, trade studies will be necessary to evaluate the best approach from a cost, schedule, and, more importantly, risk point of view.

DESIGN GUIDE OVERVIEW

No matter which strategy is selected, designers will require guidance with their designs. Insight and advice into selection of parts (including finishes, solders, and other materials), printed circuit boards, connectors, and other components will help mitigate inadvertent effects on performance and reliability.

The design guide serves to address the following key areas affecting performance, reliability and service life and offers guidelines on dealing with the associated risks:

1. Pb-free Solders and Solder Joints
2. Tin Whiskers
3. Printed Board Defects
4. Product Qualification
5. Manufacturing Processes
6. Supply Chain Control
7. Obsolescence Management
8. COTS Assembly, Selection and Use
9. Configuration Management

Background information will be provided for each of the areas to give the designer a basic understanding of the underlying issues. References are included for those designers looking for more in-depth understanding. The design guide includes recommendations for addressing the limitations and risks associated with Pb-free materials.

The intent is to assist design engineers in developing electronics that are completely Pb-free and meet the demanding requirements of ADHP systems and products. It is assumed that the design engineers using this guide are competent and experienced with tin-lead based electronics but may not be fully conversant with the detailed vagaries of Pb-free materials, components or manufacturing processes or how these impact equipment reliability and longevity.

ADHP systems and products have a broad range of performance requirements, operating environments and service life. The guidelines presented in this document may not provide solutions for all products. Currently, not all Pb-free material risks have solutions that reduce the risk to acceptable levels. On-going research targeted for the ADHP industry and experience with Pb-free materials in commercial and industrial products continue to improve the knowledge base.

DESIGN GUIDE BREAKDOWN

Sections 1.0 and 2.0 consist of Introduction and Scope, respectively. Section 3.0, entitled Technical Background and Guidance, is the heart of the guide as it presents the current body of knowledge necessary to give the designer a solid awareness of Pb-free solder and finishes within the context of the nine (9) risk areas mentioned above. The next nine paragraphs summarize guide content in these areas.

Pb-free solders and solder joints present a set of challenges that the ADHP industry continues to address to this day. The primary concern is the low amount of confidence that these materials can withstand the harsh service conditions encountered in ADHP environments. Laboratory evaluations have shown that many of these materials are not comparable to SnPb baseline products under such conditions as thermal cycle, vibration, and mechanical shock [7]. (See Figure 4.) Furthermore, the lack of field data, under harsh conditions, prohibits effective reliability modeling.

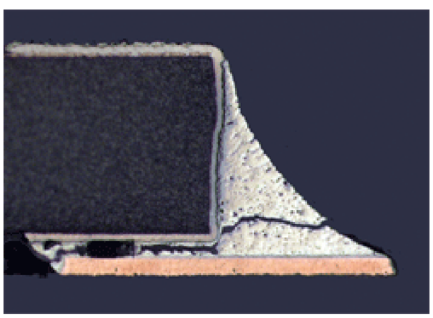

Figure 4. A Pb-free solder joint can fail earlier than an SnPb solder joint when subjected to mechanical vibration or shock in the field (courtesy of Dr. Craig Hillman, DfR Solutions.)

Tin Whiskers presents its own set of challenges. The causes and influential mechanisms are beyond the scope of this paper but can be found in many sources (e.g. Reference 6). The challenges include the deleterious effects that these structures can cause such as a) foreign object debris, b) potential RF effects (acting as antennae), and c) electrical shorting and arcing (the most damaging of effects) [8,9]. See Figures 5 and 6.

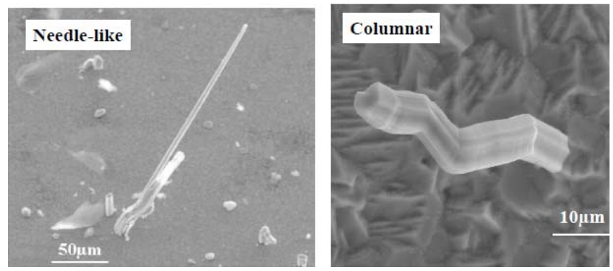

Figure 5. Examples of whiskers observed in CALCE (University of Maryland) experiments. a). Needle-like whisker structure, b). Columnar-like whisker structure. (Courtesy of Center for Advanced Life Cycle Engineering [CALCE])

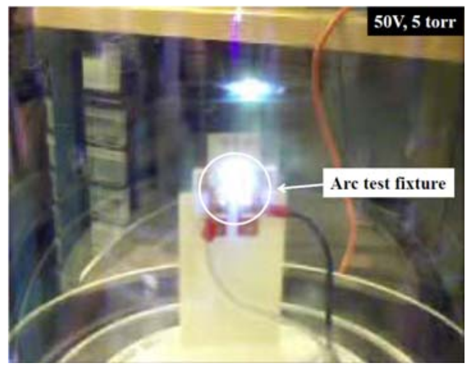

Figure 6. Example of a tin whisker initiating an electrical arc as shown in a CALCE experiment. (Courtesy of Center for Advanced Life Cycle Engineering [CALCE])

With respect to printed circuit boards and potential defects, the higher soldering process temperatures required with Pb-free solder does mean that the substrate is now much more vulnerable to damage. It is understood that this condition is not necessarily restricted to only Pb-free conditions but, none the less, it would be helpful to the designer to be aware of the potential for issues on the board.

The term "qualification" can have several meanings to different users. Given that the context of this guide is product design, qualification is defined as the ability of a product design to comply with its requirements. In the section product qualification section, guidance is presented at for assessing at component and assembly level. Use of GEIA-STD-0005-3 [10] is highly encouraged as it provides insight into testing product built with Pb-free solder and finishes.


TechAmerica
Standard

Performance Testing for Aerospace and
High Performance Electronic
Interconnects Containing Pb-free
Solder and Finishes

GEIA-STD-0005-3-REV A

December 2012

TechAmerica

Figure 7. GEIA-STD-0005-3, Revision A defines: 1. A default method for those companies that require a pre-defined approach and 2. A protocol for those companies that wish to develop their own test methods. Its content support product qualification. (Courtesy of SAE, G-24 Committee).

The section on manufacturing processes is provided to give the designer an awareness of how material and part selection can influence production "down-the-line". Two examples are as follows: 1) Selection of Pb-free parts will influence reflow temperatures. For some Pb-free materials, the reflow temperatures are higher than traditional SnPb so some concern is needed for component exposure to these temperatures. 2) Selection of certain conformal coatings will mitigate tin whisker risks. (GEIA-STD-0005-2, Revision A, "Standard for Mitigating the Effects of Tin Whiskers in Aerospace, Defense, and High Performance Electronic Systems" provides excellent insight into coatings as a mitigator [11]).

The supply chain should be considered in design as well. Selection of critical parts may entail use of new or different suppliers and, as such, assessment of these suppliers is important in minimizing negative product impact. Part libraries and other organizational collaborative tools can be helpful in this regard.

Pb-free impacts obsolescence management as traditional SnPb processed components will continually disappear from stock sources forcing the designer to perform trades on replacements.

COTS assembly, selection, and use similarly should be executed with care and diligence. Remember, COTS are "selected" as opposed to "designed" and evaluating their ability to meet ADHP performance needs should be on the designer's mind during the selection process.

Finally, configuration management should be a design concern. Many commercial suppliers do not notify customers of material changes on stock parts posing a risk that commonly used components purchased now may have some performance differences as compared to the same component purchased one year ago. Managing commercial parts through an in-house vendor item description system could help alleviate risk.

Sections 4.0 and 5.0 of the guide discuss Product Design and Design Process Flow, respectively. At the time of this writing, the guide development team is deciding a suitable course of action for the Product Design section. Some ideas include creation of design checklists or perhaps a collection of lessons learned. In any case, the section would leverage the technical information presented in Section 3.0. Section 5.0 is a high-level flow chart analogous to a product development process common across many ADHP organizations. Its content is high-level and generic steering away from proprietary information. Its purpose is to sensitize the designer that compliance to customer requirements is greatly affected even at a materials level and that guidance in Pb-free design is crucial to product success.

FINAL COMMENTS AND CLOSURE

While the Pb-free movement may appear ominous and challenging, there are tools and resources available to the designer. These have been developed over the past several years thanks to the efforts of the IPC Pb-free Electronics Risk Mitigation (PERM) Council [12].

Some key resources include the following set of standards and handbooks developed for working with Pb-free materials in various electronics applications:

- GEIA-STD-0005-1, Revision A, "Performance Standard for Aerospace and High Performance Electronic Systems Containing Pb-free Solder"
- GEIA-STD-0005-2, Revision A, "Standard for Mitigating the Effects of Tin in Aerospace and High Performance Electronic Systems"
- GEIA-STD-0005-3, Revision A, "Performance Testing for Aerospace and High Performance Electronics Containing Pb-free Solder and Finishes"
- GEIA-HB-0005-1, Revision A, "Program Management / Systems Engineering Guidelines for Managing the Transition to Pb-free Electronics"
- GEIA-HB-0005-2 "Technical Guidelines for Aerospace and High Performance Electronic Systems Containing Pb-free Solder"
- 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"

Each of these is now owned and administered by the G-24 Committee of the Society of Automotive Engineers (SAE).

Other resources include work performed in 2009 to benchmark the Pb-free technical knowledge base as well as develop a roadmap and plan to close those technical data gaps [13, 14]. The plan included a list of tasks necessary to provide ADHP engineers sufficient information to minimize risks associated with Pb-free solders and finishes. Upon reviewing these plans, several research consortiums and organizations embraced the plan and, to date, have addressed many of the technical needs although the significant effort of obtaining sufficient data to develop Pb-free reliability models still remains unanswered [15]. Finally, a good number of texts and a continuously increasing amount of data is now available in the open literature. Engineers will need to "act like engineers" in order to comprehend this information and apply it to their needs.

In conclusion, the Aerospace, Defense, and High Performance (ADHP) industries are at a technology cross-roads. With a heavy dependence on COTS to maintain a competitive edge, the industry is heavily influenced by the commercial supply chain and its increasing use of Pb-free materials. While considerable progress has been made in closing Pb-free knowledge gaps, the challenge of characterizing performance and reliability still needs to be addressed. It will take a combination of high-level design strategies and an effective set of guidelines to enable the ADHP engineer to develop mission-successful products and systems.

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