Criteria for Solder Alloy Adoption

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ABSTRACT

Solder is a critical component in modern electronic systems – past, present, and future. While solder is used within packaged electrical devices, the highest volume of solder is used for fabrication of printed circuit board assemblies. Historically, tin-lead solder was the dominant solder used in printed circuit board assemblies. However, tin-silver-copper solder replaced tin-lead solder starting in 2006 after European Union regulations banned the use of lead for a wide range of electronic products. Despite the successful transition to tin-silver-copper lead-free solder and over fifteen years of high volume lead-free electronic production, a number of aerospace and defense products have not converted to tin-silver-copper or other lead-free solders over reliability concerns. Reliability should be a concern for all product manufacturers and end-users. This begs the question, what has convinced industries that are currently producing lead-free products that the reliability was sufficient and what is keeping defense and aerospace electronic equipment manufacturers from adopting lead-free solder. This paper reviews decision processes for adopting solder for printed circuit board assembly.

Key words: ROHS, Solder, Assembly, Reliability, Fatigue.

INTRODUCTION

In 2002, the European Union introduced the Restriction of Hazardous Substance (RoHS) directive that called for the elimination of six hazardous substances found in specific categories of electrical and electronic equipment for product introduced into the European Union marketplace after July 2006 [1]. The leadup to this directive and the issuance of the directive started the clock for electronics manufacturers to find an alternative to the eutectic tin-lead solder alloy that had been used.

Solder provides electrical, thermal, and mechanical connections between electronic components and printed circuit boards. Eutectic tin-lead alloy has been the preferred solder material due to its melting temperature, resistance to tin whisker formation, and reliability under mechanical, thermal, and electrical loads. The restriction of lead use prohibited the majority use of tin-lead solders in commercial electronics and limited the lead-containing components.

In efforts of finding a replacement for tin-lead solder in the early 2000s, near eutectic tin-silver-copper alloys (SAC405, SAC396, and SAC387) were examined. Through a continuing study of the effects of silver concentration in near eutectic SAC alloys, SAC305 alloy became the preferred lead-free solder replacement for SnPb. While the temperature cycling performance of SAC305 and these other higher silver SAC solders are generally superior to SnPb, their drop performance was identified as an issue. In the late 2000s, the popularity of portable electronics further increased attention on SAC305 performance under mechanical loads, primarily vibration and drop/shock. Tin rich lead-free solders with lower silver contents such as SAC105, SAC205, SAC0307, and SN100C were studied [2]. It was found that reducing silver content in SAC improved the drop performance, although the temperature cycling reliability is compromised slightly [3].

Since then, solder alloy research has focused on: 1) solders with high reliability for aerospace, defense, medical, and automobile industries, and (2) solders that have low melting temperatures in the range 130°C to 200°C, well below SAC solder melting temperature, and meet the reliability requirements for commercial microelectronics. For the most demanding applications, design of high performance solders has focused on making SAC solders stronger and more creep resistant by microalloying of bismuth, antimony, nickel, and indium to fulfill the need for higher temperature cycling and improved mechanical reliability [4][5]. The goal of low melting temperature solders (LTS) is to reduce the reflow temperature by lowering the melting temperature of the solder alloy, and thus to reduce warpage-induced defects while also meeting the reliability requirement for commercial microelectronics. Research has been focusing on near eutectic bismuth-tin (Bi-Sn) alloys and Bi-Sn with alloying additions, which all have melting temperatures near 139°C [6][7].

Although many lead-free alloys are available commercially, commercial microelectronic industries adopted SAC305 as the international standard solder about 15 years ago. As a result, SAC305 has been the most studied, widely accepted, and widely used lead-free solder in global microelectronics. Defense and aerospace industries are still hesitant to switch to lead-free solder. Not all the industries had to go to Pb-free at once, according to RoHS. The question is what persuaded the commercial industries to adopt SAC305 and what factors contributed to the SAC305 adoption. This paper examines the adoption for SAC305 and factors in adopting the next solder alloy.

With Packaged Electronic Devices

Any solder that is selected for printed circuit board assembly must be compatible with terminal finish and terminal base material to which the solder is expected to bond. Currently, copper or copper alloys make up the bulk of base materials for terminations of lead-framed based packaged electronic devices. Other terminal base materials include iron-nickel and nickel. For many array parts, such as ball-grid array parts (BGA), terminations are formed with solder spheres on the component side with SAC305 being the most prevalent solder used for solder spheres. When parts with solder spheres are assembled, paste is used on the board-side. Thus, if the solder paste and the solder sphere are of different alloys, compatibility becomes an issue, and the mixing ratio in heterogeneous solder plays an important role in solder joint quality.

As is widely known, SAC305 is not a "drop-in" replacement for Sn-Pb eutectic solder. One of the dominant factors is the reflow temperature. The melting temperature of SnPb is 183°C while the melting temperature of SAC305 is 217°C. The increase in melting temperature of solder requires higher reflow temperature during assembly, increasing from approximately 220°C to 250°C. For SnPb based assemblies, a thin layer of SnPb (known as a "surface finish") is electroplated on Cu pads on printed circuit boards to protect the Cu surfaces from environmental contamination and maintain solderability. With the ban on the use of Pb, lead-free assemblies require alternative surface finishes to SnPb, such as tin, silver, electroless nickel – immersion gold (ENIG), and electroless nickel – electroless palladium – immersion gold (ENEPIG) [8]-[10].

One issue that arose from increasing reflow temperature is excess warpage in components due to the coefficient of thermal expansion (CTE) mismatch between the encapsulation material and the substrate, as shown in Figure 1. Consequently, the reflow process can yield bridging solder joints, where adjacent solder joints are merged into a large solder joint, and head-in-pillow, where the solder balls of BGAs do not fully consolidate with the solder paste on the copper pad. Bridging solder joint creates unwanted shorts between IOs while head-in-pillow solder joint creates stress concentration on the solder joint, leading to reliability problems. To mitigate solder joint issues due to excess package warpage, methods have been developed to measure the warpage of packages during the reflow process [11]-[14].

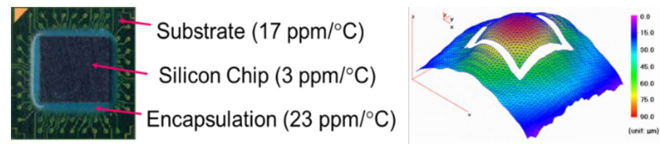

Figure 1: Warpage of Electronic Package at High Temperature During Reflow

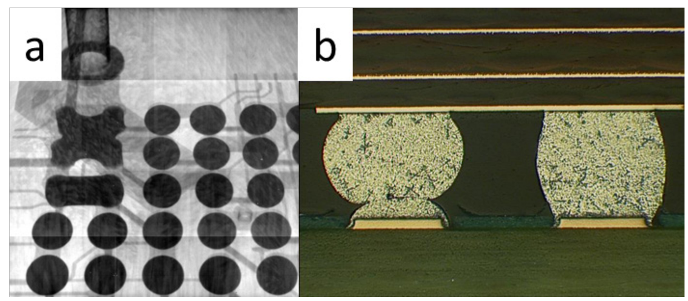

Figure 2: Warpage Defects a) Bridging Solder Joint, b) Head-in-Pillow Solder Joint

Provide Low and Stable Electrical Resistance for the Defined Life Time of the PCBA

The electrical performance of solder joints is based on electrical resistivity and the degradation of resistivity over time during operation. SAC alloys, with the presence of silver and copper have lower resistivity compared to SnPb, 13μΩ*cm compared to 14.5μΩ*cm [15]. Further, SAC solder experiences a small change in resistance under mechanical load and temperature cycling loads until failure [16]. This allows SAC305 solder to be accepted without much change to electrical performance consideration.

Survive Operation and Field Temperature Excursions for the Defined Life Time of the PCBA

Solder joints, in application, primarily experience two types of thermal excursions, heat generation from power cycle and environmental temperature. Under cyclic temperature excursions, temperature cycling or power cycling, the CTE mismatch between the package on the PCB or the thermal gradient causes cyclic strains on the solder joint. In addition, solder can creep when stressed at above homologous temperature (40% of the melting temperature in Kelvin) and continues to deform plastically without additional stress. The presence of both cyclic instantaneous plasticity and creep causes microstructural change, crack initiation, and crack propagation in solder joints [17]-[19].

Although the apparent failures of SAC solder and SnPb solder joints are complete cracks in the solder joints. The failure mechanism of SAC alloy and SnPb alloy are slightly different under cyclic thermal excursion, as shown in Figure 3. Under temperature cycling, the Sn phase and Pb phase in SnPb enlarge near the high stress regions and the crack propagates between the enlarged phases. On the other hand, SAC solder joints under temperature form new small grains near the high stress regions through recrystallization and the crack propagation occurs between these newly formed finer grains.

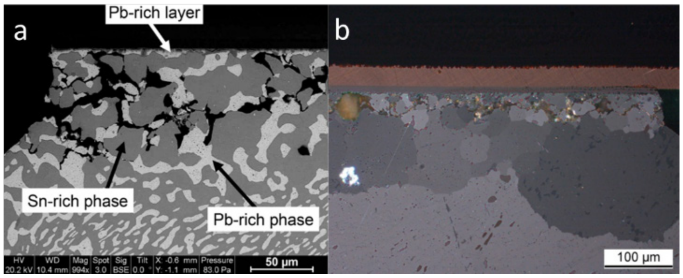

Figure 3: Temperature cycling failure mechanism: a) Tin and Lead phase enlargement for SnPb, b) recrystallization and small grain nucleation at high stress region for SAC305 solder

Despite the differences in failure mechanisms between SAC solder and SnPb, the reliability performance of SAC solder joints was one of the major points leading to SAC solder adoptions. Under accelerated temperature cycling tests, SAC305 solder outperforms SnPb solder every majority of the temperature cycling conditions listed in JEDEC standard except for extremely severe conditions where SnPb solder joints perform equally or better than SAC305 solder joints [20].

Although the temperature cycling reliability performance of SAC305 meets the need or surpasses SnPb in accelerated life tests, the question is how does SAC305 solder joint perform in real applications. To answer this question, fatigue models were developed to estimate the time to failure or reliability performance of solder joints in the field using existing accelerated life tests in the literature. Currently, there are three main fatigue life modeling approaches that are either a variation of Coffin-Manson's model [21] or Morrow's model [22]. One approach is the Norris-Landzberg model, that analytically calculates the acceleration factor between the field and test condition using environmental temperature conditions [23]. Another approach is Engelmaier's model, which estimates the fatigue lives of solder joints using the extrinsic and intrinsic properties of materials in the assembly and temperature cycling profiles [24]. Lastly, finite element analysis (FEA) approach, this approach estimates the strain or strain energy density in the solder joints using FEA shown in Figure 4 and correlate the strain and strain energy density with time to failure [25]. Regardless of the approaches, the available test data, fatigue models, and the understanding failure behavior of SAC helped the commercial industry to adopt SAC305.

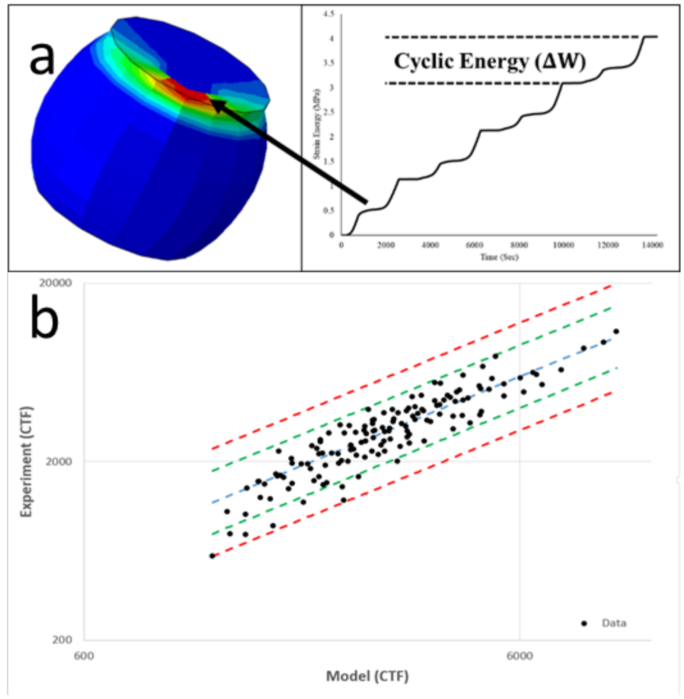

Figure 4: a) Strain energy density extraction from temperature cycling FEA, b) Model prediction vs test data

Surviving Operation and Field Mechanical Loads for the Defined Life Time of the PCBA

In addition to thermal excursions, solder joints can also experience mechanical loads such as vibration, shock/drop, torsion, and bending. Under mechanical loads, the stiffness differences between packages and the PCBs cause strains on solder joints. Such repetitive strain can lead crack initiation and crack propagation in solder joints. Furthermore, SAC305 solder is sensitive to strain rate, the rate at which strain is applied, increasing strain can increase the stiffness of the material. Increased stiffness in SAC305 solder joints relocates the weak link from solder joints to locations such as solder to copper pad intermetallic compound, copper traces, and PCB resin, as shown in Figure 5 [26]. While mixed failures such as bulk solder failure, IMC failure, copper trace failure, and pad cratering can be found in SAC305 interconnect under vibration loads, IMC, copper trace failure, and PCB pad cratering are the major failures found in SAC305 assemblies.

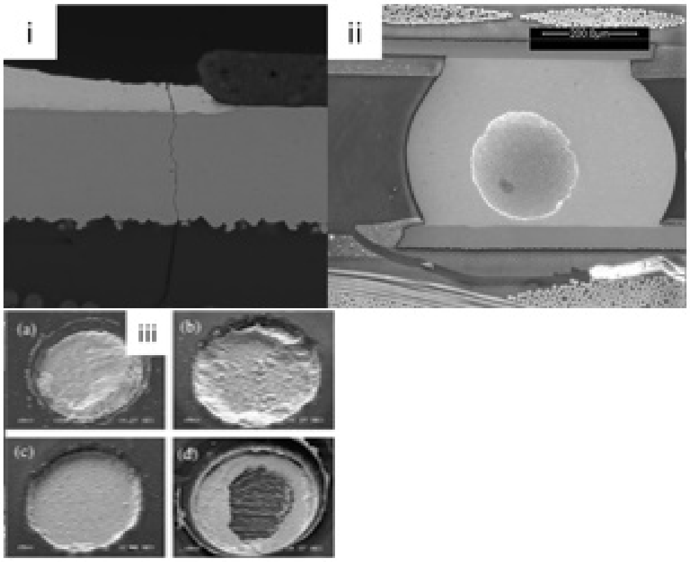

Figure 5: (i) Copper trace failure, (ii) PCB pad cratering, (iii) IMC failure under high strain rate mechanical tests

For SnPb solder and SAC solders, the majority of the reliability prediction methods are based on generalized Coffin Manson fatigue model [21][28]. Generally, drop, shock, bending, torsion yield failure due to low cycle fatigue and vibration yields failure under high cycle fatigue. Due to the complexity and the length scale of solder joints, the stress and strain on solder joints are estimated through finite element analysis while matching PCB strain between the FEA and the experiment. Fatigue model constants for both SnPb and SAC305 are well studied in the literature for both high cycle and low cycle fatigue [29].

One of the drawbacks of fatigue life estimation using FEA is time consuming. Thus, analytical models such as the Steinberg equation were developed for high cycle fatigue by assuming pure elastic deformation in solder [30]. Further, the IPC standard and MIL handbook suggest acceleration factor models that only consider the load levels, acceleration (G) or power spectral density, and high cycle fatigue model exponents [31][32]. The model constants are also available in the literature for SAC305 solder.

In general, SAC305 and SnPb perform similarly under high cycle fatigue or vibration loads, and SAC305 performs worse than SnPb under low cycle fatigue, particularly drop or shock [20]. The reason for the reduced low cycle fatigue life of SAC305 is its higher stiffness compared to SnPb, shifting failure sites to IMC, copper trace, and PCB. Studies were done in the late 2000s to improve shock reliability of SAC solders by reducing silver content, but the tradeoff was lowered temperature cycling fatigue life [33]. Another method of mitigating mechanical shock failures was using underfill or corner staking, where the correct selection of underfill and corner staking could significantly improve the mechanical shock reliability of SAC305 PCB assemblies [34].

Cornerstone Project

The United States Partnership for Assured Electronics (USPAE) has created the Defense Electronics Consortium (DEC) to address microelectronics research needs for the Department of Defense and the defense industrial base, including the aerospace electronics industry. The Solder Performance and Reliability Assurance (SPRA) project funded by Cornerstone OTA through the Industrial Base Analysis and Sustainment (IBAS) program is the first DEC project. The SPRA brings together the University of Maryland, Auburn University, Purdue University, and Binghamton University along with Collins Aerospace, Plexus, and STI Electronics, do develop a solder agnostic approach for qualifying solders for use in defense application. This five-year program will establish and demonstrate the process for qualifying solders for assembly and reliability with the development of life/acceleration models. In addition, the program will develop use case definitions with solder reliability qualification methods. The output of the program will be a solder users handbook and solder performance specification

CONCLUSION

This paper discussed the criteria for the adoption of SAC305 in the commercial microelectronic industry, including compatibility of SAC305 with the rest of the assembly and electrical performance and reliability under mechanical and thermal loads. The key factor for SAC305 adoption is superior or comparable fatigue performance of SAC305 compared to SnPb on top of the availability of fatigue life data and fatigue model constants for SAC305. Further, high strain rate failure mitigation methods such as underfill and corner staking help to improve the mechanical reliability of lead-free assemblies.

To adopt a new generation of lead-free solder, factors such as assembly compatibility, electrical performance, mechanical performance, thermal performance, and long-term reliability should be considered. Since the majority of the new generation solders for aerospace and defense industries are based on SAC alloys with additives, the melting temperature remains near 220°C, adopting a newer generation of solder requires less effort when it comes to PCBA compatibility. The major concern for new generation solders will be their reliability under various types of loads and this requires a large set of test data to provide the confidence for new solder adoption.

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