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Assembly Options and Challenges for Electronic Products With Lead-Free Exemption

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ABSTRACT Due to safety and reliability concerns, various classes and/or applications of electronic products are excluded from the European Union's Restriction of Hazardous Substances (RoHS) regulations requiring the elimination of lead (Pb). However, the majority of electronic devices are now Pb-free. As a result, manufacturers attempting to maintain tin-lead (SnPb) based electronics face an increasing challenge to procure parts and products with Pb-based solder. This paper reviews the challenges of producing Pb-based electronic equipment, the reliability concerns with Pb-free electronics, and the options that manufacturers have for maintaining reliable, Pb-based production. In particular, the paper examines mixed soldering processes and the re-balling of Pb-free electronic parts. While Pb-free electronics present risks, it is our conclusion that the risks are manageable and are lower than those incurred by maintaining an increasingly obsolete Pb-based manufacturing process.

INDEX TERMS Mixed soldering, lead-free, PCB, re-balling, reliability, RoHS exempt, solder, tin-lead.

I. INTRODUCTION

In 2006, consumer electronics entering the European market were required to comply with the European Union's RoHS directive that was enacted in 2003. Among other requirements, the RoHS directive banned the intentional use of Pb and required that mechanically separable materials in products have a composition of less than 1000 ppm of Pb unless there was a specific exemption. The RoHS directive was updated in 2011. Under the revised RoHS directive, deadlines were set for all electronic products to comply with the material restrictions, except those specifically excluded from the directive.

While both the earlier and the later RoHS directives restricted European manufacturers, these regulations have caused the entire electronics supply chain to adapt to the Pb-free requirement. For electronic component manufacturers, this adaptation has meant the elimination of Pb from parts terminations and, in some cases, from use within parts. For most electronic component manufacturers, SnPb-finished terminals were replaced with tin-finished terminals. For ball grid array (BGA) packaged components that use solder balls for component terminations, the SnPb solder ball alloy was replaced with tin-silver-copper (SAC) solder ball alloy. For equipment manufacturers, compliance with the RoHS directives required replacing SnPb solder paste, which was commonly used to attach electronic components to printed wiring boards (PWBs), with a Pb-free alternative. For the majority of equipment manufacturers, the SAC alloy was selected for reflow and wave solder assembly [1].

While the EU RoHS regulation banned the use of Pb in most electronic equipment, the regulation specifically excluded electronic equipment used in specific applications, such as defense systems, transportation systems, and implantable medical devices [2]. Based on these exclusions, some electronic equipment manufacturers have continued to use Pb-based solder due to reliability concerns with the use of Pb-free solder. While automotive systems were excluded from the RoHS regulations, the use of Pb has been banned for solder attachment of electronic devices onto PWBs used in automotive systems through an update in the EU end-of-life vehicles directive [3]. As a result, the market for Pb-based solder has become very limited. For example, while aerospace products were excluded from RoHS regulation, these products account for less than 1% of the total electronic component market [4]. Hence, except for niche industries, electronic component manufacturers are producing parts that comply with the RoHS regulations. This conversion has made

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it increasingly difficult for non-RoHS-compliant electronics manufacturers to find Pb-based components.

For electronic equipment manufacturers of Pb-free exempt and excluded products, the current market is quite challenging. The risks and potential solutions facing non- RoHS-compliant product manufacturers are addressed in the remainder of this paper.

II. CONCERNS ASSOCIATED WITH PB-FREE ELECTRONICS

Pb-free electronics have been used for more than a decade, and problems associated with the use of Pb-free materials in electronics have been identified and largely addressed. The first three issues with Pb-free electronics revolve around the solder alloy used to replace SnPb solder. First, most Pb-free solders require a higher reflow assembly process temperature compared with SnPb solder, which can create quality issues due to part and board warpage [5], [6]. Second, not surprisingly, the fatigue and fracture behavior of alternative Pb-free solder materials is different than that of SnPb solder. In particular, solder joints of certain device package types created with the most popular Sn3.0Ag0.5Cu (SAC305) solder tend to have significantly lower durability under drop and shock loading conditions compared with joints formed with SnPb solder [7]. Third, the use of SAC alloy in wave solder operations can erode exposed copper, so care is needed in terms of the time copper surfaces are subjected to flowing SAC solder [8]. Another issue with Pb-free electronics is related to the surface finish materials used for terminals of packaged electronic devices. In this case, the elimination of Pb from terminal finishes of packaged electronic devices has raised concerns for product failure caused by tin whisker-induced electrical shorting [9].

As the name implies, tin whiskers are hair-like structures that spontaneously grow from thin tin film deposits. The incubation period for tin whisker growth can vary from seconds to years. Because tin whiskers are conductive, they can cause unintended electrical shorts by mechanically bridging gaps between closely spaced electrical conductors. Whisker growth on tin-finished surfaces was identified in the 1950s and was mitigated by adding Pb to the tin [10], [11]. However, failures in the 1980s resulted in the requirement of a minimum of 3% Pb in tin finishes for the most critical electronic applications such as space systems. The RoHS-driven adoption of tin by component manufacturers resulted in a flurry of research focused on tin whisker growth mechanisms and test methods, as well as tin whisker mitigation strategies. To address tin whisker concerns, standards bodies for the electronics industry created multiple standards to assess the whisker growth propensity of tin-coated structures [9], [12]–[17]. While no publicly announced recalls or failures from tin whiskers within Pb-free mandated electronics have occurred, the current standards make clear that whisker formation cannot be ruled out. As a result, manufacturers of products with low-risk tolerance are expected to apply whisker mitigation strategies. The SAE GIEA-STD-0005-2 standard provides a guide for mitigating the effects of tin whiskers [17].

The melting point of a Pb-free solder should be considered when replacing the SnPb solder. The melting point of the solder joint must be low enough that the solder remains in a pasty state during the reflow process, but also be high enough to withstand the operating temperature during the manufacturing process [18]. The operating temperature range could be very broad, such as –55°C to 150°C or higher [19], depending on the product applications, so the solidus temperature of the solder is recommended to be 25°C higher than the maximum service temperature [20], which in this case is 175°C. Pb is an effective additive to tin for reducing the melting point of tin and enhancing its physical properties without significantly changing the solder chemistry. However, none of the other additives are comparable to Pb for solder alloy improvement. The melting point of Pb-free solders, such as SAC305 alloy, is higher than that of traditional Sn37Pb solder. Table 1 summarizes the melting points and the solder compositions of several commercially available Pb-free solders. According to Table 1, the melting point of most Pb-free solders is above 200°C, and it can vary broadly depending on the category and weight percentage of the alloying elements. Therefore, manufacturers should refer to the expected applications when choosing alternative Pb-free solders with an appropriate melting point.

TABLE 1. Selected solders used in industry [1].

Symbol	Composition (Weight %)	Melting Point (°C)
Sn57Bi	Sn-57.0Bi	138 (eutectic)
Sn58Bi1Ag	Sn58.0Bi1.0Ag	133–137
Sn58Bi1Ag1In	Sn58.0Bi1.0Ag-1.0In	138–142
Sn37Pb	Sn37.0Pb	183 (eutectic)
Sn9Zn	Sn9.0Zn	198 (eutectic)
Sn15BiCu	Sn15.0Bi0.5Cu	190–200
Sn7Bi2Ag	Sn2.0Ag7.0Bi	190–215
Sn8Zn3Bi	Sn8.0Zn3.0Bi	189–199
S1XBIG58	Sn1.1Ag0.7Cu1.8Bi + Ni	211–223
S01XBIG58	Sn0.1Ag0.7Cu1.6Bi + Ni	211–227
SAC305	Sn3.0Ag0.5Cu	217–221
SAC405	Sn4.0Ag0.5Cu	217–221
M771	Sn0.7Cu1.0Ag + P	217–224
SACX plus 0807	Sn0.8Ag0.7Cu0.1Bi	217–225
SACm	Sn0.5Ag1.0Cu + Mn	217–225
SAC-R	Sn0.92Cu2.46Bi	221–227
SACX plus 0107	Sn0.1Ag0.7Cu	217–227
SACX plus 0307	Sn0.3Ag0.7Cu0.12Bi	217–227
M35	Sn0.7Cu0.3Ag + P	217–227
K100LD$^{®}$	Sn0.7Cu + Ni + Bi	227
SN100C	Sn0.7Cu + 0.05Ni + Ge	227 (eutectic)
SN100CV$^{®}$	Sn0.7Cu0.05Ni1.5Bi	221–225
SN995$^{®}$	Sn0.5Cu + Co	228

Higher assembly process temperatures can not only increase costs but can also lead to larger component warpage due to the increasing expansion differences between the materials. The coefficient of thermal expansion (CTE) mismatch can come from the silicon dies, metallization layers, underfill, substrates, and printed circuit boards (PCBs).

For example, one study [21] found that both the reflow temperature and die thickness can affect the warpage behavior in a flip chip package. Because electronic products, including laptops, smartphones, and wearable devices, have been shrinking, their electronic assemblies, such as CPUs, GPUs, memories, and PCBs, have also been getting thinner and smaller. These thinner assemblies are less resistant to the stresses induced by temperature change, which can lead to warpage during the reflow process and solder joint defects, including non-contact open, head-on-pillow, bridging, and non-wet open [6], [22]–[24]. A conceptual diagram for these defects is depicted in Figure 1. Warpages can be minimized by choosing new materials to minimize CTE mismatch or by introducing additional stiffeners. Board warpage can be minimized by balancing the copper distribution across PCB layers and by balancing the copper ratio in outrigger and board, both of which help reduce the CTE mismatch at reflow temperature [25]. These efforts might increase assembly costs arising from developing new materials, adopting a more labor-intensive manufacturing process, and performing more testing. One promising solution for reducing warpage is to lower the reflow process temperature. Various low-melting-temperature Pb-free solders have been developed, including Sn9Zn (198.5°C), Sn58Bi (138°C), and Bi33In (109°C) [26].

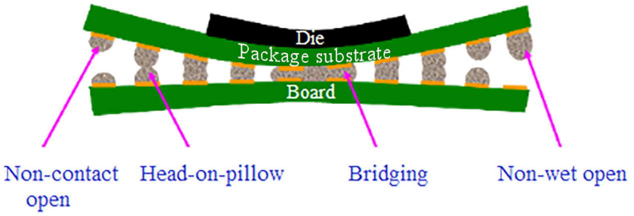


FIGURE 1. Typical solder joint defects induced by component warpage [24].

The trends for portable electronic products are higher speed, lighter weight, smaller size, and multiple functions. Solder interconnect reliability under both temperature cycling and drop conditions has attracted more attention within the electronics industry because of these trends [27]–[32]. Because the rapidly increasing popularity of portable electronics coincided with the Pb-free solder transition, SAC solders have been recognized as the mainstream solders for assemblies in electronic industries. The reliability of SAC solder joints can be affected by the Ag content, and their performance varies depending on the applied loading conditions. Several SAC solders with different Ag content, such as SAC105 and SAC305, have been developed and used in portable electronic products for various applications.

When portable electronic products are accidentally dropped, the electronic assemblies inside the product housing are susceptible to the impact induced by the PCB bending and mechanical shock inertia. Such events could lead to product failure due to solder interconnect cracking. The reliability of solder interconnects is related to the solder composition and the interfacial intermetallic compounds (IMCs) [33]–[35]. The failure of solder joints induced by dropping can occur within the bulk solder or at the interface between the solder and the terminal to which the solder is bonded. Other failure sites caused by the drop can be the copper trace, the pad-to-board laminate interface, or the board laminate material under the pad on the PCB. As can be seen from the trends in IEEE publications, presented in Figure 2, the interest in drop studies increased from 2004 to 2014.

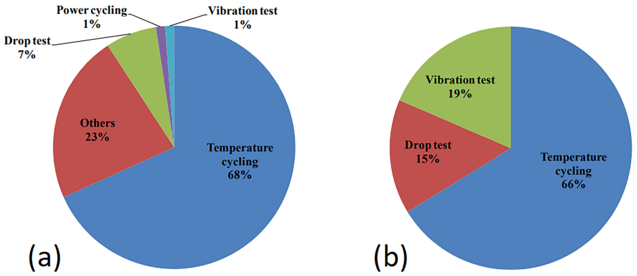


FIGURE 2. IEEE publications on solder interconnect durability, (a) 2004–2008, (b) 2008–2014 [36].

In particular, SAC305 solder interconnects have lower ductility and are prone to fail in the early cycle of drop conditions. For example, high Ag-content SAC alloys have been found to exhibit a higher probability of failure compared with SnPb interconnects under drop in mobile electronics due to their high rigidity [37]. For flip chip packages, high Ag-content SAC alloys (high-yield-strength Pb-free solder) can either cause delamination (identified as a white bump in scanning acoustic imaging) between the back-end-of-line (BEOL) layer or cracking within low-k dielectric in BEOL structure during the cooling stage after chip bonding reflow. Delamination is caused by the thermomechanical stress imposed on the BEOL structure due to the application of high-yield-strength Pb-free solder and CTE mismatch between the silicon chip and laminate. In order to mitigate delamination, high-creep-rate solders (low Ag and Cu) are preferred for solder bumps because they deform easily during chip joining and reduce stress transmitted to the BEOL layers [38].While lowering the Ag content of SAC solders can improve drop durability, it can also sacrifice thermomechanical fatigue durability.

According to literature reviews in the past 10 years [39]–[43], the promising solutions to improve the drop reliability of SAC solders without compromising their thermal fatigue reliability can be classified into two groups, including package structure enhancement and soldering materials adjustment. The package structure can be enhanced by dispensing underfill and corner staking. Corner staking is the application of silica-filled epoxy at four corners of the BGA packages. The soldering materials can be adjusted by changing their composition and adding elements that modify the bulk properties as well as the bonding interface [39].

Chen and Osterman [39] assessed the reliability of SAC305 BGA packages with corner staking under temperature cycling, harmonic vibration, and drop loadings. The results showed the characteristic life of corner-staked BGAs can be improved as much as 10 times compared to non-staked BGAs under 3000 G drop loading. Moreover, the characteristic lives of staked BGAs are double and 400 times that of non-staked BGAs under temperature cycling (–55 to 125°C) and 4G harmonic vibration, respectively. According to Chen and Osterman's study, corner staking is an ideal method to enhance the drop reliability of SAC305 BGA packages without sacrificing the temperature cycling reliability.

Singh *et al.* [40] studied the drop reliability of SAC105 BGA packages with partial underfill dispensing under thermal cycling (–40 to 125°C) and drop (1500 G) loadings. For the drop test, the first failure cycle in corner nets of the underfill samples was twice that of non-underfill samples. For the temperature cycling test, both the underfill and non-underfill samples showed good reliability performance and passed 1000 cycles. Chen and Zhang [41] investigated the drop reliability of SAC305 BGA packages by both experiment and simulation approaches under JEDEC drop loading (1500 G). The results showed that underfill dispensing can effectively reduce the stress level and significantly decrease the plastic strain to 1.31% compared with non-underfill samples (22.7%). Also, the underfill with higher elastic modulus showed it can better protect the solder joints. According to the above studies, underfill dispensing is an effective way to enhance the reliability of drop loading by sacrificing the thermal reliability because it acts as a stress-buffering layer and can redistribute the load to reduce the shear deformation.

To achieve a balance between the drop and thermal fatigue reliability of Pb-free solders, many studies have reported that adding a fourth minor alloying element (microalloy or dope), including Bi, Zn, In, Ti, and Ni, to the low Ag-content SAC solders can enhance their microstructure and mechanical properties. For example, one study [42], [43] found that the 2.0 wt.% addition of Zn in low Ag-content Sn1.0Ag0.3Cu (SAC103) solder would cause an excessive tensile strength and low ductility on the solders because of the effects of grain refinement and formation of coarse $(Cu,Ag)_5Zn_8$ IMCs. They also observed that SAC103 solder with 3.0 wt.% Zn exhibited the highest tensile strength and large ductility owing to the high volume percentage of fine $(Cu,Ag)_5Zn_8$ IMCs. According to El-Daly *et al.*'s [42], [43] studies, the addition of a fourth element should be carefully evaluated to achieve the most appropriate results.

The effects of aging on Pb-free solder joints are reliability concerns. During field operation, solder joints are exposed to aging conditions such as continuous use of electronic equipment, temperature storage, and on/off power cycles. The IMC layer at the board and package interface continues to grow, and microstructural coarsening of the solder joint occurs during aging. The IMC layer gets brittle as its thickness increases, eventually resulting in solder joint failure [44]. Studies were conducted to investigate the long-term reliability of SnPb, SAC105, and SAC305 solder alloys after aging at 125°C for 12 months [45]–[47]. It was found that package lifetime degradation after aging was severe for SAC alloys (56%) compared to SnPb alloys (35%). A significant reduction in the mechanical properties of aged solder joints was observed [48]–[50]. Critical factors affecting the solder joint reliability are IMC thickness and roughness [51]–[54]. Looking at the long-term aging effects of SAC alloys, electronic equipment manufacturers adhering to Pb-free requirements will find these alloys unfavorable, especially for automotive or supercomputer applications. Research has indicated that microalloying SAC alloys with elements such as Bi, Sb, In, Zn, Ni, Mn, and Co has significantly reduced package lifetime degradation and IMC growth after aging [1], [55]–[60]. The microalloying approach is an active and ongoing effort by solder paste manufacturers looking for performance improvement.

Soldering temperature-sensitive devices becomes an issue when industry completely transitions to Pb-free. Temperature-sensitive devices include crystals, oscillators, aluminum and tantalum capacitors, fuses, inductors, and other non-semiconductor components. For the mixed assembly process, the peak reflow temperature is restricted to less than 230°C to protect temperature-sensitive devices. Shifting to Pb-free technology requires these devices to withstand up to 260°C. The bill of materials (BOM) analysis is used to identify the temperature-sensitive devices along with moisture-sensitive devices. It is recommended that the identified temperature-sensitive devices are monitored through thermal profiling (during primary attach and rework) to ensure that the time above liquidus and peak temperature limits do not exceed as per J-STD-075 [61], [62]. Suppliers would need to develop new materials and assess their reliability to help improve performance. The separate assembly process of these devices after standard reflow, which increases assembly lead time, would be required until the supplier develops a reliable device to withstand high temperatures. The separate assembly process includes press-fit, hot bar soldering, laser soldering, hand soldering, or conductive adhesive attachment [63].

A final concern with alternative Pb-free solders is the dissolution of copper during the wave soldering process. When the copper pad on a PCB and the component terminations are in contact with a wave of molten solder, some of the copper dissolves into the solder wave, and the thickness of the copper pad is reduced. The amount of copper lost in a solder wave is a function of the solder composition, temperature, and flow rate [8]. For example, SAC solders such as SAC305 have been shown to dissolve substantially larger amounts of copper in the wave soldering process compared to SnPb. While more copper dissolves into the molten solder, the liquidus temperature of the solder increases, and the higher copper level makes the solder more sluggish, increasing hole-fill defects. Moreover, high copper dissolution can increase the downtime required to maintain the solder pot as well as the cost of adding more solder bars to regulate the copper level in the solder pot [1]. For surface mount assemblies, the amount of copper dissolution can limit rework times [64].

While the above issues are present with Pb-free solders, they do not necessarily prevent manufacturers from creating robust and durable electronics. Manufacturers should take advantage of the research conducted to identify and address potential problems.

III. MAINTAINING SnPb ASSEMBLY PROCESS

The availability of components with SnPb finished terminals has been dramatically reduced owing to the conversion to Pb-free electronics. Most electronic component manufacturers no longer provide parts with SnPb terminals. For electronic equipment manufacturers seeking to maintain a SnPb assembly process, the lack of parts with SnPb terminations gives rise to the concern of compatibility of Pb-free components with the SnPb assembly process as well as tin whisker failure risk. For leaded perimeter components with Pb-free coated terminations, assembly with SnPb solder does not represent a major concern. For leaded parts, the Pb-free finish results in a negligible change in composition in a SnPb solder joint. However, for area array components (BGA/CSP), the volume of the solder balls for the interconnect compared to the solder paste applied to the bonding pad is considerable, and this raises concerns. For Pb-free area array components, manufacturers face the choice of converting the Pb-free solder balls to SnPb solder balls in a process known as re-balling or addressing mixed solder assembly concerns.

A. MIXED SOLDER ASSEMBLY

Electronic equipment manufacturers exempted by RoHS face manufacturing challenges due to the limited availability of SnPb BGA packages. When SnPb BGA packages are not available, it may be necessary to use Pb-free BGAs with an existing SnPb assembly process. Assembling Pb-free BGAs in a SnPb assembly process is referred to as mixed alloy (SnPb paste/SAC BGA) or backward-compatible soldering. Mixed alloy assembly serves as an alternative to immediate or complete conversion to Pb-free manufacturing, but its implementation has been limited due to concerns about the long-term reliability of the mixed solder joints [65]. Many studies of the mixed soldering technique have focused on: (1) optimizing reflow profile parameters for acceptable mixed solder joints [66]–[70]; (2) evaluating Pb diffusion and its uniformity throughout the solder joint microstructure [69], [71]–[73]; (3) evaluating the reliability of mixed solder joints under different thermal cycling conditions [65], [72], [74]; (4) measuring the properties and failure modes of mixed solder joints under vibration and shock loadings [75]; and (5) evaluating the effect of the rework process on the mixed solder joints according to the peak reflow temperature and rework counts [76].

The reliability of mixed solder interconnects under thermal cycling conditions is related to the degree of Pb mixing and the formation of microstructures within the solders [77]. Completely mixed solder interconnects with Pb uniformly distributed throughout the microstructures and partially mixed joint showed their fatigue life was comparable with that of pure SnPb and Pb-free solder interconnects.

The peak reflow temperature and the time above liquidus are factors necessary to achieve complete mixing of the backward-compatible assembly. Figure 3 shows the reflow profile requirements for complete mixing of 0.8 mm (0.45 mm ball diameter), 1 mm (0.6 mm ball diameter), and 1.27 mm (0.75 mm ball diameter) pitch sizes [66]–[68]. Studies have shown that full mixing and uniform distribution of Pb is possible at peak temperature below 217°C [69], [71]–[73]. Snugovsky *et al.* [71] reported that the peak temperature depends on the solder ball alloy composition, SAC solder ball/SnPb solder paste volume ratio, dwell time, and package size. Based on the findings from the International Electronics Manufacturing Initiative (iNEMI) [74], full mixing was not a reliability prerequisite, and the mixed assembly reliability is package-dependent and can be better, equal, or worse than the fatigue life of SnPb and SAC. Larger BGA packages (23 mm and 45 mm), having incomplete mixing, survived 3500 temperature cycles (–40 to 125°C with 10-min dwell time) compared to smaller BGA packages (8 mm and 19 mm) with complete mixing. From the results, full mixing and homogeneous microstructure are needed for smaller BGA packages with low fatigue requirements. For larger BGA packages with long life requirements, complete solder mixing is not necessary. Snugovsky *et al.*'s findings [78] also agreed with the iNEMI results and further suggested that mixed reliability is sensitive to microstructure, which is sensitive to processing conditions and alloy composition.

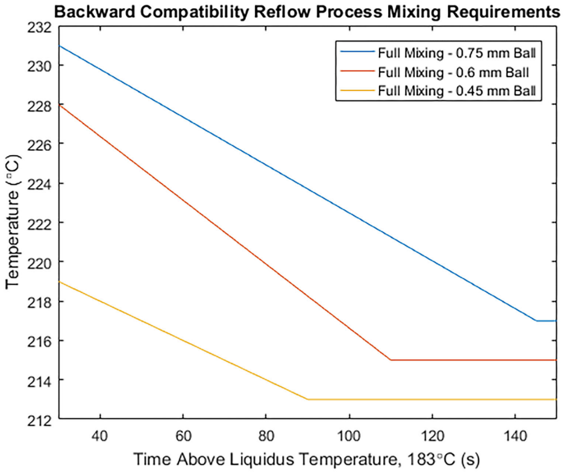


FIGURE 3. **Reflow process guidelines [66].**

Coyle *et al.* [65] performed a thermal cycling reliability comparison (0/100°C) between partially mixed (minimum 70%) and fully mixed assemblies (100%) for 21 mm BGAs (pitch size: 1 mm, ball diameter: 0.63 mm). The Pb mixing % was calculated using (1).

$$\%\text{Pb Mixing} = \left(\frac{H_1 - H_2}{H_1}\right) \times 100 \tag{1}$$

H_1 is the solder joint height, which is the distance from the top of the package land to the top of the board land. H_2 is calculated by measuring the distance from the top of the package land to the average height location of the Pb-mixed region [70]. Figure 4 shows how H_1 and H_2 are measured. The study was conducted under the assumption that full mixing is not always achievable in manufacturing, and partial mixing may be unavoidable in practice. They found that partially mixed solder alloy performed better than fully mixed and SnPb solder alloys. The presence of Pb did not change the failure mode, and there was no evidence to prove the correlation between Pb and the reduced thermal fatigue life. The effect on reliability depends on the interaction of solder microstructure and Pb morphology but not on the presence or absence of Pb.

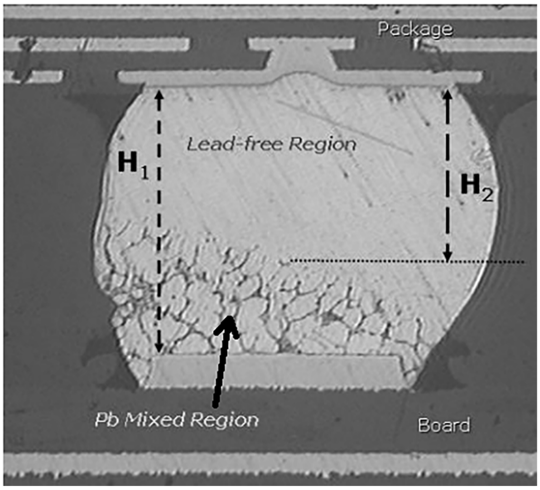


FIGURE 4. Cross-section of a mixed solder joint [70].

The previous study [65] did not address mixing below 70%. For large high-density BGA packages, mixing may be less than 50%. Kinyanjui *et al.* [70] developed the profile for backward compatibility of large high-density packages: 37.5 mm × 37.5 mm BGA (ball count: 1295, ball diameter: 0.6 mm, pitch: 1.162 mm), and 51 mm × 59.5 mm BGA (ball count: 3162, ball diameter: 0.56 mm, pitch: 1.5 mm) Thermal cycling test result [79] of 37.5 mm × 37.5 mm BGA (ball count: 1295, ball diameter: 0.6 mm, pitch: 1.162 mm) indicated that full mixing performed better than SAC405 solder, medium mixed (60%–75%), low mixed (>40%), and SnPb. This result contradicted the previous finding that partially mixed solder alloy performed better than fully mixed alloy. The better thermal fatigue performance of the fully mixed solder alloy was not due to the presence of Pb in the microstructure but to the mixed assembly profile and its resultant effect on solidification of the SAC solder. Another reason was that the size, morphology, and distribution of Ag_3Sn particles in the microstructure may be more resistant to particle coarsening. The Pb segregation at the PCB interface reduced the thermal fatigue life of medium mixed and low mixed solder alloys. It is possible to achieve acceptable reliability with a backward-compatible assembly if full Pb mixing is realized. The backward-compatible assembly process has a more limited process window than the standard surface mount assembly, and full Pb mixing is always preferred. Although favorable results were seen in partially mixed alloys, partially mixed assembly is not recommended. If required, extreme caution is necessary due to the possibility of Pb-assisted failure modes.

Choubey *et al.* [80] studied the microstructural changes and IMC thickness evolution of pure SnPb and mixed solder alloy. After aging for 350 h at 125°C, the Pb phase region for the mixed alloy decreased, but for pure SnPb solder joints, it increased. In other words, coarsening is higher for pure SnPb solder joints due to the higher quantity of Pb and the smaller separation distance between Pb phases, which produces enough concentration gradient. For mixed solder alloy, coarsening is not significant due to the insufficient concentration gradient between Pb phases due to large separation distance. Mixed solder alloy is therefore more durable than pure SnPb solder alloy in thermal loading. The IMC thickness of mixed solder alloy was found to be 30%–40% lower than pure SnPb and pure Pb-free alloy. The decrease in board IMC thickness was due to the presence of a Pb-rich layer, which acted as a diffusion barrier for copper. The thermal fatigue life of mixed alloy is comparable to pure Pb-free alloy if it is completely mixed.

Menon *et al.* [75] studied the vibration durability of mixed solder BGA assemblies with various solder ball/solder paste combinations, including SAC305/SnPb (mixed solder), SAC105/SAC305 (mixed Pb-free), SAC305/SAC305 (pure Pb-free), and SnPb/SnPb (pure SnPb). After the preconditioning (100°C, 24 h) and harmonic uni-directional vibration test, they found the cycles to failure of the Pb-contained solder combinations (SnPb/SnPb was the best) was higher than that of Pb-free combinations. Thus, they concluded that the vibration reliability of the solder interconnects can be enhanced by adding Pb to the solders. According to Menon *et al.*'s study, the cycles to failure of mixed solder was between that of pure SnPb and pure Pb-free, which means the reliability of mixed solder is acceptable under vibration applications.

The performance of the reworked packages should be considered when considering area array packages, which might experience multiple reflow processes due to rework demand. Nie *et al.* [76] studied the performance of two solder ball/solder paste combinations (SAC305/SAC305 and SAC305/Sn37Pb) under thermomechanical loading conditions for both non-reworked and reworked (1X and 3X) assemblies. These assemblies were then subjected to a temperature cycling environment (–55 to 125°C, 1 h per cycle) to collect the cycles-to-failure data. For Pb-free assemblies, the cycles to 0.1% failure decreased with the increasing counts of rework. On the other hand, the cycles to 0.1% failure of the reworked samples was larger than that of non-reworked samples for mixed solder assemblies. Nie *et al.* explained these two reversed trends in three points of view for the assemblies.

The first factor is the higher rework temperature. For SAC305/SAC305 combination, the solder joint standoff height decreased with the rework counts because of the higher reflow temperature during the rework process. The impact of fatigue life can be observed by referring to the Engelmaier fatigue life model [81]. In this model, the state of the shear strain can be expressed in (2). The h means the solder standoff height, so a smaller h would increase $\Delta\gamma$ (shear strain), and then reduce the cycles to failure.

$$\Delta\gamma = \frac{\Delta\alpha \times \Delta \mathrm{T} \times \mathrm{DNP}}{h} \tag{2}$$

The second factor is related to the interfacial IMC thickness. The IMC thickness was observed to get thicker with the rework times for both Pb-free and mixed solder assemblies. The thicker IMC also reduces the ductile solder region, which can be considered a reduction in standoff height. Combining the first two factors can explain the decreasing trend of cycles to failure for SAC305/SAC305 assemblies. For the SAC305/Sn37Pb assemblies, however, the third factor of the mixed microstructure should be considered. A more homogeneous distribution of the Pb-rich phase microstructure was observed in the reworked mixed solder assemblies. This distribution was attributed to the higher rework temperature compared with the original reflow temperature, which facilitated the inter-diffusion between the SAC305 and Sn37Pb solder. The Pb-rich phase can retard the progress of recrystallization and grain coarsening, enhancing fatigue durability. After considering the third factor, the higher cycles to 0.1% failure of the reworked SAC305/Sn37Pb assemblies can be explained (reworked 1X > 3X > non-reworked). Moreover, the homogeneous Pb-rich phase did not change after the first rework process, but the IMC thickness did. Therefore, the cycles to 0.1% failure of 1X rework was higher than that of 3X rework.

In addition to the above three factors, the copper pad dissolution of the PCB was also a key concern for the rework process of area array packages [64]. Although copper overconsumption trends were similar for both the Pb-free and mixed solder assemblies, the copper pad dissolution of the mixed solder assemblies was less than that of the Pb-free solder assemblies after 5X rework. When the Cu dissolves into bulk solder, the local Pb concentration in mixed solder assembly will increase at the IMC/bulk solder interface, which blocks Cu from being dissolved into bulk solder. Therefore, copper pad loss is less for mixed solder assemblies. Based on the result, rework count over 3 times was not recommended for BGA packages [64]. A similar recommendation was also proposed according to the concern with IMC thickness. After the packages were assembled, the IMC of Pb-free assemblies was thicker than that of mixed solder assemblies because the Pb presence in the mixed solder assemblies could retard the IMC growth [80] Nevertheless, after the 5X rework, the IMC thickness of these two kinds of assemblies was almost equivalent. The thinner copper pads and thicker IMC layers might lead to an open-circuit failure under real application loadings.

The terminal finishes used for leadframe packages are SnPb, pure (matte) tin, and high-tin alloy [82]. Due to the limited availability of SnPb-plated components, manufacturers are left with an option to choose components with tin finishes, which have a high tendency for tin whisker formation. Components with SnBi plating were proposed for backward compatibility assembly, but there is a limitation when choosing that plating [83]. A study done by Moon *et al.* [84] has found that the combination of Sn, Bi, and Pb could result in the formation of ternary eutectics Sn-Pb-Bi (Sn32Pb52Bi), which melts at 98°C. Snugovsky *et al.* [85] indicated that SnBi plating with less than 6% Bi does not result in the formation of ternary eutectic.

Zhang [83] showed that Sn3Bi plating has effectively reduced the whisker length compared with pure Sn finishes. Pull strength analysis of quad flat package (QFP) with SnPb finish/SnPb solder paste, Sn3Bi finish/SAC solder paste, and Sn3Bi finish/SnPb solder paste was done. There was no difference in pull strength before and after 1000 thermal cycles (–40 to 125°C with 30-min cycle) for Sn3Bi/SnPb solder paste and SnPb finish/SnPb solder paste. Vibration test of quad flat no-leads packages (QFN) was done to evaluate Sn finish/SnPb solder paste, Sn finish/SAC solder paste, Sn3Bi finish/SAC solder paste, and Sn3Bi finish/SnPb solder paste. Vibration test results have shown no difference in time to failure between Sn finish/SnPb solder paste, Sn3Bi finish/SnPb solder paste, and Sn finish/SAC solder paste. Based on the overall results, there were no reliability and solder joint integrity issues when Sn3Bi component plating was used with SnPb solder.

In conclusion, soldering Pb-free SAC305 BGA parts with SnPb solder can result in durable solder interconnects. However, the reflow temperature for the BGA is critical to obtain a uniform distribution of Pb throughout the solder joints. Without proper mixing, the solder interconnects durability can be compromised. Further, care must be taken in the number of rework operations conducted with SAC305 BGA parts. Component finish with SnBi plating is a feasible strategy for backward compatibility assembly because it mitigates tin whisker formation given the Bi content in the component finish is less than 6%.

B. RE-BALLING PROCESS

As an alternative to mixed solder assembly, non-RoHS-compliant manufacturers can choose to re-ball Pb-free BGA parts. BGA re-balling is the process of removing and replacing the solder balls on a BGA component. It has been used to restore the solderability of components that have been severely oxidized and to reclaim previously assembled BGA parts. For non-RoHS-compliant equipment manufacturers, re-balling can be used to replace Pb-free solder with SnPb solder balls. The re-balling process results in the parts being subjected to two additional elevated temperature excursions, one for solder ball removal and a second for solder ball reattachment.

The solder ball removal process strips the original solder balls from the component. Three approaches for solder ball removal are the solder wick process, solder wave process, and hot nitrogen vacuum deballing. In the solder wick process, the package is a fixture with the solder balls facing upward. The soldering iron is attached to a copper braid (wick), the heated braid wire is passed over solder balls melting and picking up the molten solder. The solder wick method is inexpensive and good for low-volume work. However, the process can damage the solder mask surrounding the solder ball pads on the BGA substrate. Damage to the solder mask can result in non-symmetric solder balls and solder bridging when solder balls are reattached [86].

In the solder wave process, the component is held with solder balls facing down and brought into a solder wave for a sufficient time to remove the solder balls. With robotic systems, the solder wave process can be performed simultaneously on multiple parts and with greater control than the manual solder wick removal process. Further, the lack of mechanical abrasion that can occur with the copper braid makes the wave approach less likely to damage the BGA substrate or solder mask [86].

The third solder ball removal process known as hot nitrogen vacuum deballing was introduced by Stoyanov *et al.* [87]. Deballing is done by hot nitrogen heating and partial vacuum removal of the solder ball from the BGA package. Figure 5a shows the deballing principle. The hot nitrogen (at 250°C) is injected through injectors integrated outside the nozzle so that they can produce a focused nitrogen flow jet capable of melting an individual solder ball in the package without the nozzle coming in contact with the solder ball. The nozzle aperture is chosen to be smaller than the solder ball. The hot nozzle is lowered from above the solder ball, and the focused nitrogen flow gradually heats and melts the solder material. Under the partial vacuum condition inside the nozzle tube, the liquid solder is taken from the pad as the nozzle moves back vertically and away from the package.

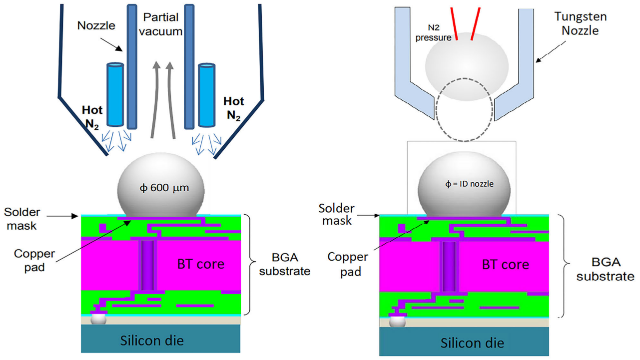


FIGURE 5. (a) Hot nitrogen vacuum deballing [87] (left), (b) laser re-balling process [88] (right).

After the solder balls are removed, a new set of solder balls can be attached. Water-solvable paper with solder balls located in a pattern matching the BGA's interconnect locations, known as BGA preforms, can be purchased to attach new solder balls when re-balling a BGA [86].

Alternatively, a metal stencil with an opening matching the BGA interconnect location pattern can be created with an opening sufficiently large to allow a single solder ball to fit through it. In addition to the stencil, a fixture is used that holds the stencil and BGA so that loose solder balls can be added to fill the openings. Once the solder balls are positioned over the pads on the BGA substrate, the parts are subjected to an over-reflow process so that the solder balls become mechanically attached to the pads on the BGA substrate. After attachment, the parts are cleaned and inspected. After passing inspection, parts are placed in processing trays for use on PWB assembly lines [86].

Laser re-balling is another method to attach a solder ball to a BGA package [88]. The laser re-balling principle is shown in Figure 5b. The dispensing disk releases a solder ball into the laser beam, and the solder ball blocks the aperture. This blockage increases the nitrogen pressure within the nozzle. The solder liquefies when hit by the laser pulse, and the nitrogen pressure expels the droplet. For a 0.5 mm ball diameter, the typical size of the nozzle would be in the range of 0.3 mm. The laser energy is chosen to heat the ball within the nozzle to around 500°C while in flight. This is typically one shot of the laser. The solder drop loses heat from the point where the laser pulse finishes. This process is very fast, at a rate of 1 s or less.

The re-balling process has been considered a preferred method to obtain components with SnPb solder balls for RoHS-exempt PCB manufacturers. Several concerns with the re-balling process should be considered before using it, including the impact on temperature cycling reliability of re-balled BGAs by different re-balling approaches and the attachment strength of the re-balled components. Previous studies focused on evaluating the attachment strength of re-balled BGAs, and few of them assessed the reliability performance of re-balled components. However, the performance of the re-balled Sn37Pb BGA packages is quite similar to the original Sn37Pb packages according to the literature discussed in the following two paragraphs. Therefore, well-performed re-balled BGA packages can be expected to exhibit comparable mechanical and reliability performance with traditional SnPb packages.

Nie *et al.* [86] measured the solder attachment strength of re-balled BGA packages by both ball shear test and cold bump pull (CBP) test to examine the re-balling process. The effects of different isothermal aging conditions on the re-balled BGAs were also considered. The results exhibited the solder attachment strength of the re-balled solder balls were at the same level under different re-balling methods and isothermal aging conditions. While they found the shear strength and the pull strength of re-balled Sn37Pb solder balls were lower than that of SAC solder balls, the strength distributions were smaller for the re-balled Sn37Pb parts compared to non-re-balled SAC305 parts. The strength difference was not unexpected, as other research has documented that SAC305 solder joints have higher strength [89], [90]. The tighter strength distribution for the re-balled Sn37Pb parts indicates a more uniform material and controlled and repeatable process compared to the SAC parts.

Further research [91] was conducted to evaluate the durability of re-balled Sn37Pb parts. For these packages, the original SAC305 solder balls were re-balled by Sn37Pb balls with different re-balling methods. The re-balled Sn37Pb parts were then assembled with Sn37Pb solder paste. For experimental reference, the non-re-balled assemblies, which were SAC305 solder balls/ Sn37Pb solder paste (mixed) and SAC305 solder balls/ SAC305 solder pastes (Pb-free) were also prepared. A temperature cycling test (–55°C to 125°C, 1 h per cycle) was applied to all assemblies to check the differences in durability. The results showed the mean cycles-to-failure rate of the re-balled assemblies was less than that of both Pb-free and mixed assemblies. The failure life difference between the Sn37Pb, mixed, and Pb-free assemblies was because of the properties of different bulk solders, not due to the re-balling process. Moreover, the temperature cycling reliability of the BGA assemblies with different re-balling methods was similar. In conclusion, the temperature cycling reliability of the re-balled BGA packages would not be affected by the re-balling process and was consistent between different re-balling methods.

From the research conducted on the re-balling of SAC305 BGAs with Sn37Pb solder balls, it can be observed that under well-controlled processes, re-balling is a viable approach for RoHS-exempt manufacturers. However, the process must be validated for each part type that is being subjected to a re-balling process. Changes to BGA construction may make this approach non-viable. Further, assemblers must always be cautious that the processing and handling of those parts do not introduce defective parts into production.

IV. COMPLETE CONVERSION TO PB-FREE

Pb-free solders have been successfully used in the electronics industry for more than 10 years. However, various product classes are not subjected to the ban on Pb in electronics. The exclusion exists in large part because of the risk of using Pb-free materials in applications that have long life (>10 years) requirements, that have harsh operating and environmental conditions, and that have safety- and mission-critical concerns. Due to these concerns, many companies continue to produce Pb-based electronics. However, with over 10 years of experience in Pb-free production, conversion to Pb-free production is recommended as a better solution than either re-balling or mixed soldering based on the market trends and expiration date of the Pb-free exemption. Most categories of products except in vitro diagnostic medical devices, industrial monitoring, and control instruments will not be exempt after 2021 [2]. The expiration for Pb-free exemption in automotive applications such as sensors, actuators, and engine control units (ECUs) has been extended to 2024 [92].

When companies plan to transfer their products to Pb-free, they should consider the maturity of the knowledge associated with the material, its availability, cost, and its existing regulations. A CALCE survey [36] of IEEE studies indicates the industry-favorite Pb-free solder, SAC305, is well researched. As such, the concerns associated with SAC305 are known and can be mitigated. Further, some promising alternative solders, including SAC alloys that contain low amounts of Ag (0.1, 0.3, 0.8, 1.0 wt.% Ag) and SnCu solders with dopants (Ni, Ge, Co, and Bi), have been subjects of research studies.

Pb-free solder should be supplied in multiple forms, including solder spheres, pastes, bars, and wires, to meet the requirements of assembly and repairing processes. However, the selection of Pb-free solders is restricted by a variety of regulations. For example, Cd is considered a hazardous substance and is restricted by the RoHS directive [2]. Cost is another major concern for companies. The prices of selected solder alloy are shown in Figure 6. They are calculated by recent metal prices listed in Table 2 [93]–[95]. In the list, Ag and In are the most expensive metals, and the alloy cost could be significantly increased by adding them to the solder. Therefore, companies should thoroughly investigate the Pb-free solders while planning their product conversion.

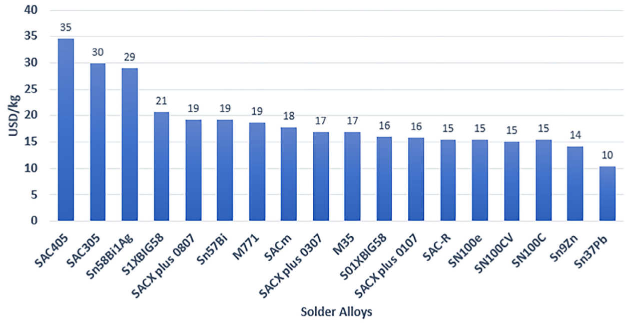


FIGURE 6. Selected solder prices.

TABLE 2. Metal Prices as of April 2020 [93]–[95].

Metal	USD/kg
Zn	1.89
Pb	1.67
Cu	5.11
Ni	11.72
Sn	15.43
Sb	5.67*
Co	29.49
Ag	497.05
Bi	22.04*
In	955*
Sn63Pb Solder	10.34
SAC305 Solder	29.83

*denotes metal prices in February 2020

TABLE 3. Physical and mechanical properties of typical high-Pb solders [118].

Solder Composition (%wt)	Melting Temperature (°C)	CTE (ppm/°C)	Elastic Modulus (GPa)	0.2% Yield Strength (MPa)
Pb85/Sn15	183–288	27.2	-	-
Pb88/Sn10/Ag2	268–290	29	-	15.5
Pb90/Sn10	275–302	29	19.0	13.9
Pb90/Sn5/Ag5	292	27	-	-
Pb92.5/Sn5/Ag2.5	287–296	25	13.8	-
Pb95/Sn5	308–312	28.4	-	13.3

Manufacturers also need to consider if the Pb-free solders can fulfill various requirements of their targeted applications, including mechanical loads and reliability performance. The solders should be able to sustain the expected mechanical loads to prevent failures during operation, including delamination between the metallization layers, redistribution layer (RDL) fracture, cracks between the solder and the IMCs, and bulk solder cracks [96]. Thus, qualification and reliability tests (including thermal cycling, vibration, and shock/drop tests) are necessary for the companies to collect data for their evaluation of various package types. Package type includes leadframe devices, BGAs, QFNs, and chip-scale packages (CSPs). In some cases, the solder interconnects may need to be reinforced using staking or underfill materials to meet mission and life requirements [39], [97].

In addition to solder, companies converting to Pb-free electronics must also specify Pb-free surface finishes for their PWBs. A survey conducted by IPC and NPL (National Physical Laboratory) in 2012 showed that surface finish solderability is the single most important contributor to PCB defects [98]. Many researchers have reported the impacts of different surface finishes on wettability, mechanical properties, ball pull strength, thermal cycle reliability, drop reliability, vibration reliability, and electromigration reliability of solder joints formed by various solder alloys [99], [100], [109], [101]–[108]. From the PCB manufacturers' perspective, the surface finish selection impacts the manufacturing cost, process, quality, and reliability of the product [110]. When companies prefer Pb-free solder pastes, the effects of different surface finishes should be considered and tested to evaluate the solderability and reliability of the corresponding Pb-free solder.

In addition to the solder interconnect durability issue, manufacturers must be sensitive to the tin whisker risk presented by the use of Pb-free materials. However, this concern also extends to manufacturers still using SnPb solder with Pb-free parts. To this end, manufacturers should use the SAE-GEIA-STD-0005-2 standard [17] to determine appropriate mitigation strategies. George and Pecht [111] analyzed the materials used in an automotive ECU from an automobile. They found tin whiskers in the pure tin finish with a nickel underlayer connector in the ECU. The tin whiskers raised additional reliability and safety concerns. However, using conformal coating to mitigate tin whiskers in electronic products has been reported [17], [112]–[114]. Conformal coatings on exposed electrically conductive surfaces are considered one of the most effective mitigation techniques for preventing electrical short failures caused by tin whiskers and are widely used by some electronic industries. Conformal coatings are thin non-conductive protection layers used to mitigate electrical failures on PCBs due to moisture [115], [116]. In Han *et al.*'s study [117], the mitigation of tin whisker formation on surface mount components differed with the effectiveness of the conformal coating material. They performed sequential experiments, including temperature cycling, corrosive gases, and temperature and humidity conditions, on the tin-plated QFPs coated with six materials of various thicknesses. They found the material types and coating coverage were the key factors for tin whisker growth. In their findings, whiskers were observed on the surface of a relatively thin layer of coating, and the extent of the whisker growth was different depending on the coating material. Conformal coating is recommended to mitigate the risks of the tin whiskers in safety- and mission-critical products, after carefully reviewing the coating materials and uniformly coating the materials.

Finally, companies that have high-temperature application needs should consider Pb-free alternatives. The high-melting-temperature solders used in this application are typically Pb-based alloys with at least 85% Pb. High-Pb solders are commonly used in the die attach process, heat sinks and lead pins attachment, internal connection of passive devices, flip chip assembly, as well as PCBs for automotive, oil and gas, avionics, and aerospace applications. Table 3 summarizes the melting temperatures and mechanical properties of the typical high-Pb solders in the industry. The melting temperatures of the high-Pb solders are generally higher than 250°C. Several key advantages, such as high melting temperature, thermal fatigue/electromigration/IMC formation resistances, and established long-term reliability data, make high-Pb solders popular in high-reliability and power/performance applications [118].

Because of the high-temperature applications, the thermal fatigue resistance of the interconnections is important to sustain the cyclic shear strain induced by the CTE mismatch between the materials and to prevent device failure. For high-power applications, higher electromigration resistance of solder joints is necessary because electromigration is considered as the primary failure mechanism for high current-carry interconnects. Moreover, high-Pb solders do not contain IMCs, so more ductile and reliable interconnection can be formed. The above factors should be looked upon and well evaluated when considering high-temperature alternatives to high-Pb solders. Menon *et al.* [118] summarized the alternative solder alloys for high-temperature applications, and these solders can be classified into four categories, including gold-, zinc-, bismuth-, and silver-based alloys.

Gold-based alloys are most common for high-temperature applications because of the ability of fluxless soldering, good mechanical and electrical properties, and low IMC growth rate while using Ni, Pd, or Pt as the dopants [119]–[121]. Because of high cost concerns with gold, silver-based alloys can be considered as another solution due to their high-temperature stability and good mechanical properties. Chuang and Lee [122] studied Ag80In20 solder to form void-free and uniformly thick solder joints under a relatively low process temperature (206°C). After annealing for 26 h at 145°C, the melting point of the Ag80In20 joints was reported between 765 and 780°C.

Zn-based alloys have become more popular in high-temperature applications because of their low cost. The melting point of zinc is 419.5°C, and the melting point of the Zn-based alloys can be adjusted to between 300 to 400°C by adding aluminum and tin. ZnSn solders are believed to be the best choice of high-temperature alternative solders because of the following two reasons. First, no IMC would form within the solder for the whole range of composition, so ZnSn solders are very ductile. Second, the thermal conductivity of ZnSn solders has been reported to be higher than of the solders with Au-Sn and SnPb systems. Moreover, Kim *et al.* [123]–[125] reported that ZnSn solders presented good shear strength, excellent electrical properties, and oxidation resistance in high-temperature/humidity environments. Among the bismuth alloys, BiAg solders are most popular. However, BiAg solders are brittle with low Ag content. Although increasing the Ag content can improve this situation, it also increases the cost. Song *et al.* [126] also reported the tensile strength and elongation properties could be enhanced by increasing the Ag content.

Many of these alternative Pb-free solders exhibit favorable characteristics for high-temperature applications, but more studies are needed to understand the thermal fatigue and long-term reliability performance. The fatigue reliability of these solders must be carefully evaluated according to the applications they are expected to be used for. On the other hand, the physics of failure of these solders should be well understood by further studying their long-term reliability. With the need for more reliability data on alternative solders, the general exemptions of high-Pb solders by RoHS and end-of-life vehicle (ELV) directives may be prolonged in some less reliable applications. Therefore, the manufacturers now within the exemptions have to prepare their unique requirements to extend the exemptions and collect the necessary reliability data for a complete conversion to Pb-free technology.

V. CONCLUSION

Since mid-2006, most electronic equipment has been produced with Pb-free materials to comply with government restrictions on the use of Pb. As a result, the electronics supply chain, particularly for consumers, information technology, and computer markets, has eliminated Pb. The availability of affordable Pb-based electronic parts and assemblies has significantly decreased owing to this manufacturing trend in electronics. Manufacturers of electronic products that are exempt or excluded from the Pb ban must procure obsolete parts, often from lower-quality alternative suppliers, while avoiding counterfeit parts. These manufacturers must also either adapt Pb-free parts for SnPb solder assembly (mixed solder) processes or convert to Pb-free production. The selection of the appropriate strategy will depend on life-cycle costs, risk tolerances, and customer requirements.

Based on market trends, conversion to Pb-free production is recommended over either re-balling or mixed soldering. However, the conversion to Pb-free production requires a top-to-bottom commitment to procurement, engineering, manufacturing, and quality control. For companies that use contract manufacturers, auditing the manufacturer to assure competence in Pb-free production, as well as basic capability maturity, is required. For those with captured production lines, training and planning are needed. For high-temperature applications, the selection of Pb-free alternative solders is a challenge because there is no drop-in solution so far. Alloys based on Au, Zn, Bi, and Ag elements are potential Pb-free solders. Nevertheless, these alternatives should be carefully evaluated case by case according to the expected application conditions and customer requirements. Moreover, key factors, including the cost, intended application, characteristics of IMCs, ease of manufacturing, and field performance, should be considered by the companies to determine appropriate alternative solders.

As an interim solution, manufacturers can maintain SnPb solder assembly by adapting Pb-free parts to the SnPb soldering (mixed soldering) assembly process. While either mixed soldering (assembling Pb-free parts with SnPb solder) or re-balling can be successful, the re-balling process is recommended over the mixed soldering process. For the mixed soldering process, definition and control of reflow process parameters, including reflow temperature, dwell time of peak temperature, alloy percentages, pasty range, and soldering environment are critical for each assembly design. If time and temperature are not sufficient, incomplete mixing of Pb into Pb-free solder balls of BGA components can result in early-life failures that may escape environmental stress screens. Alternatively, at too high a temperature or for too long of a reflow process, thermal damage to some components may occur, resulting in a reduction in yield or a shorter field life. For the re-balling process, the final assembly reflow process remains the standard SnPb profile, and levels of solder mixing are not a concern. When re-balling, manufacturers must define and control the complete re-balling process.

They must also verify that the part type can be successfully processed. Once established, strict control of the process must be maintained.

REFERENCES

[1] S. Cheng, C.-M. Huang, and M. Pecht, "A review of lead-free solders for electronics applications," *Microelectron. Rel.*, vol. 75, pp. 77–95, Aug. 2017, doi: 10.1016/J.MICROREL.2017.06.016.

[2] *Directive 2011/65/EU of the European Parliament and of the COUNCIL of 8 June 2011 on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment*, Official J. Eur. Union, Brussels, Belgium, 2011, pp. L174/88–L174/110. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011L0065&from=EN

[3] *Directive 2000/53/EC of the European Parliament and of the COUNCIL of 18 September 2000 on End-of Life Vehicles*, Official J. Eur. Union, Brussels, Belgium, 2000, pp. L269/34–L269/42. [Online]. Available: https://eur-lex.europa.eu/resource.html?uri=cellar:02fa83cf-bf28-4afc-8f9f-eb201bd61813.0005.02/DOC_1&format=PDF

[4] S. Stoyanov and C. Bailey, "Modelling the impact of refinishing processes on COTS components for use in aerospace applications," *Microelectron. Rel.*, vol. 55, nos. 9–10, pp. 1271–1279, Aug. 2015, doi: 10.1016/j.microrel.2015.07.030.

[5] R. S. Sidhu, R. Aspandiar, S. Vandervoort, D. Amir, and G. Murtagian, "Impact of processing conditions and solder materials on surface mount assembly defects," *JOM*, vol. 63, no. 10, pp. 47–51, Oct. 2011, doi: 10.1007/s11837-011-0174-3.

[6] L. Kondrachova, S. Aravamudhan, R. Sidhu, D. Amir, and R. Aspandiar, "Fundamentals of the non-wet open BGA solder joint defect formation," in *Proc. Int. Conf. Soldering Rel. (ICSR)*, 2012.

[7] X. Qu, Z. Chen, B. Qi, T. Lee, and J. Wang, "Board level drop test and simulation of leaded and lead-free BGA-PCB assembly," *Microelectron. Rel.*, vol. 47, no. 12, pp. 2197–2204, Dec. 2007, doi: 10.1016/j.microrel.2006.10.017.

[8] G. Izuta, T. Tanabe, and K. Suganuma, "Dissolution of copper on Sn-Ag-Cu system lead free solder," *Soldering Surf. Mount Technol.*, vol. 19, no. 2, pp. 4–11, Apr. 2007, doi: 10.1108/09540910810836484.

[9] T. Shibutani, M. Osterman, and M. Pecht, "Standards for tin whisker test methods on lead-free components," *IEEE Trans. Compon. Packag. Technol.*, vol. 32, no. 1, pp. 216–219, Mar. 2009, doi: 10.1109/TCAPT.2009.2013311.

[10] S. M. Arnold, "The growth and properties of metal whiskers," in *Proc. 43rd Annu. Conv. Amer. Electroplater's Soc.*, 1956, pp. 26–31.

[11] S. M. Arnold, "The growth of metal whiskers on electrical components," in *Proc. IEEE Electron. Compon. Conf.*, 1959, pp. 75–82.

[12] *Test Method for Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes*, JEDEC Standard JESD22A121A, 2008.

[13] *Environmental Acceptance Requirements for Tin Whisker Susceptibility of Tin and Tin Alloy Surface Finishes*, JEDEC Standard JESD201, 2006.

[14] *Whisker Test Methods on Components for Use in Electrical and Electronic Equipment*, JEITA Standard ET-7410, 2005.

[15] Whisker Test Methods on Connectors for Use in Electrical and Electronic Equipment, JEITA Standard RC-5241, 2007.

[16] *Whisker Test Methods for Electronic and electric components, Edition 1.0*, IEC Standard IEC60068-2-82, 2007.

[17] *Standard for mitigating the Effects of Tin Whiskers in Aerospace and High Performance Electronic Systems*, Standard GEIA-STD-0005-2, SAE International, 2012.

[18] M. R. Harrison, J. H. Vincent, and H. A. H. Steen, "Lead-free reflow soldering for electronics assembly," *Soldering Surf. Mount Technol.*, vol. 13, no. 3, pp. 21–38, Dec. 2001, doi: 10.1108/09540910110407388.

[19] K. Puttlitz and K. Stalter, *Handbook of Lead-Free Solder Technology for Microelectronic Assemblies*, 1st ed. Boca Raton, FL, USA: CRC Press, 2004.

[20] P. Vianco, "Solder technology for ultra high temperatures," *Weld. J.*, vol. 81, no. 10, pp. 51–54, 2002.

[21] A. T. Wu, C.-Y. Tsai, C.-L. Kao, M.-K. Shih, Y.-S. Lai, H.-Y. Lee, and C.-S. Ku, "*In situ* measurements of thermal and electrical effects of strain in flip-chip silicon dies using synchrotron radiation X-rays," *J. Electron. Mater.*, vol. 38, no. 11, pp. 2308–2313, Nov. 2009, doi: 10.1007/s11664-009-0934-9.

[22] D. Amir, R. Aspandiar, S. Buttars, W. W. Chin, and P. Gill, "Head–and–pillow SMT failure modes," in *Proc. SMTA Int.*, 2009, pp. 409–421.

[23] D. Amir, S. Walwadkar, S. Aravamudhan, and L. May, "The challenges of non wet open BGA solder defect," in *Proc. SMTA Int.*, 2012.

[24] W. Keat Loh, R. Kulterman, H. Fu, and M. Tsuriya, "Recent trends of package warpage and measurement metrologies," in *Proc. Int. Conf. Electron. Packag. (ICEP)*, Apr. 2016, pp. 89–93, doi: 10.1109/ICEP.2016.7486789.

[25] S. Aravamudhan, C. Combs, A. Prasad, and A. Abraham, "Multi-faceted approach to minimize printed circuit board warpage in board assembly process," in *Proc. SMTA Int.*, 2016, pp. 168–176.

[26] H. R. Kotadia, P. D. Howes, and S. H. Mannan, "A review: On the development of low melting temperature Pb-free solders," *Microelectron. Rel.*, vol. 54, nos. 6–7, pp. 1253–1273, Jun. 2014.

[27] D. Y. R. Chong, F. X. Che, J. H. L. Pang, K. Ng, J. Y. N. Tan, and P. T. H. Low, "Drop impact reliability testing for lead-free and lead-based soldered IC packages," *Microelectron. Rel.*, vol. 46, no. 7, pp. 1160–1171, Jul. 2006, doi: 10.1016/J.MICROREL.2005.10.011.

[28] H. Qi, Q. Zhang, E. C. Tinsley, M. Osterman, and M. G. Pecht, "High cycle cyclic torsion fatigue of PBGA Pb-free solder joints," *IEEE Trans. Compon. Packag. Technol.*, vol. 31, no. 2, pp. 309–314, Jun. 2008, doi: 10.1109/TCAPT.2007.898337.

[29] J. Varghese and A. Dasgupta, "Test methodology for durability estimation of surface mount interconnects under drop testing conditions," *Microelectron. Rel.*, vol. 47, no. 1, pp. 93–103, Jan. 2007, doi: 10.1016/J.MICROREL.2006.02.002.

[30] J. Varghese and A. Dasgupta, "Drop testing of printed wiring assemblies," in *Proc. IEEE Workshop Accelerated Stress Test. Rel. (ASTR)*, Oct. 2005, pp. 1591–1595.

[31] Y. Zhou, M. Al-Bassyiouni, and A. Dasgupta, "Vibration durability assessment of $Sn_{3.0}Ag_{0.5}Cu$ and Sn37Pb solders under harmonic excitation," *J. Electron. Packag.*, vol. 131, no. 1, Feb. 2009, Art. no. 011016, doi: 10.1115/1.3078195.

[32] S. C. O. Mathuna, P. Byrne, G. Duffy, W. Chen, M. Ludwig, T. O'Donnell, P. McCloskey, and M. Duffy, "Packaging and integration technologies for future high-frequency power supplies," *IEEE Trans. Ind. Electron.*, vol. 51, no. 6, pp. 1305–1312, Dec. 2004, doi: 10.1109/TIE.2004.837904.

[33] Y. Yao, L. M. Keer, and M. E. Fine, "Modeling the failure of intermetallic/solder interfaces," *Intermetallics*, vol. 18, no. 8, pp. 1603–1611, Aug. 2010, doi: 10.1016/J.INTERMET.2010.04.016.

[34] J.-W. Yoon, B.-I. Noh, J.-H. Yoon, H.-B. Kang, and S.-B. Jung, "Sequential interfacial intermetallic compound formation of Cu_6Sn_5 and Ni_3Sn_4 between Sn–Ag–Cu solder and ENEPIG substrate during a reflow process," *J. Alloys Compounds*, vol. 509, no. 9, pp. L153–L156, Mar. 2011, doi: 10.1016/J.JALLCOM.2011.01.015.

[35] *Board Level Drop Test Method of Components for Handheld Electronic Products*, JEDEC Standard JESD22-B111A, 2016.

[36] *Considerations for Implementing RoHS Compliant Electronics for Critical Applications*, CALCE, College Park, MD, USA, 2014.

[37] D. A. Shnawah, M. F. M. Sabri, and I. A. Badruddin, "A review on thermal cycling and drop impact reliability of SAC solder joint in portable electronic products," *Microelectron. Rel.*, vol. 52, no. 1, pp. 90–99, Jan. 2012, doi: 10.1016/J.MICROREL.2011.07.093.

[38] S.-K. Kang, D.-Y. Shih, and W. E. Bernier, "Flip-chip interconnections: Past, present, and future," in *Advanced Flip Chip Packaging*, H. Tong, Y. Lai, and C. Wong, Eds. Boston, MA, USA: Springer, 2013, pp. 85–154.

[39] D. Yun Chen and M. Osterman, "Reliability of corner staked surface mount packages," in *Proc. IEEE Accelerated Stress Test. Rel. Conf. (ASTR)*, Sep. 2016, pp. 1–6, doi: 10.1109/ASTR.2016.7762272.

[40] B. Singh, V. Smet, J. Lee, G. Menezes, M. Kobayashi, P. M. Raj, V. Sundaram, B. Roggeman, U. Ray, R. Radojcic, and R. Tummala, "First demonstration of drop-test reliability of ultra-thin glass BGA packages directly assembled on boards for smartphone applications," in *Proc. IEEE 65th Electron. Compon. Technol. Conf. (ECTC)*, May 2015, pp. 1566–1573, doi: 10.1109/ECTC.2015.7159806.

[41] Z. Chen and X. Zhang, "Investigation on reliability of embedded ultra-thin sensor chip in organic substrate under drop impact loading by stresses monitor and FEM simulation," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 4, no. 8, pp. 1309–1316, Aug. 2014, doi: 10.1109/TCPMT.2014.2328015.

[42] A. A. El-Daly, A. E. Hammad, G. S. Al-Ganainy, and M. Ragab, "Properties enhancement of low ag-content Sn–Ag–Cu lead-free solders containing small amount of zn," *J. Alloys Compounds*, vol. 614, pp. 20–28, Nov. 2014, doi: 10.1016/J.JALLCOM.2014.06.009.

[43] A. A. El-Daly, A. E. Hammad, G. S. Al-Ganainy, and M. Ragab, "Influence of zn addition on the microstructure, melt properties and creep behavior of low ag-content Sn–Ag–Cu lead-free solders," *Mater. Sci. Eng., A*, vol. 608, pp. 130–138, Jul. 2014, doi: 10.1016/J.MSEA.2014.04.070.

[44] A. Choubey, H. Yu, M. Osterman, M. Pecht, F. Yun, L. Yonghong, and X. Ming, "Intermetallics characterization of lead-free solder joints under isothermal aging," *J. Electron. Mater.*, vol. 37, no. 8, pp. 1130–1138, Aug. 2008, doi: 10.1007/s11664-008-0466-8.

[45] J. Zhang, Z. Hai, S. Thirugnanasambandam, J. L. Evans, M. J. Bozack, Y. Zhang, and J. C. Suhling, "Thermal aging effects on the thermal cycling reliability of lead-free fine pitch packages," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 3, no. 8, pp. 1348–1357, Aug. 2013, doi: 10.1109/TCPMT.2013.2251932.

[46] J. Zhang, Z. Hai, S. Thirugnanasambandam, J. L. Evans, M. Bozack, R. Sesek, Y. Zhang, and J. C. Suhling, "Correlation of aging effects on creep rate and reliability in lead free solder joints," *SMTA J.*, vol. 25, no. 3, pp. 19–28, 2012.

[47] T.-K. Lee, H. Ma, K.-C. Liu, and J. Xue, "Impact of isothermal aging on long-term reliability of fine-pitch ball grid array packages with Sn-Ag-Cu solder interconnects: Surface finish effects," *J. Electron. Mater.*, vol. 39, no. 12, pp. 2564–2573, Dec. 2010, doi: 10.1007/s11664-010-1352-8.

[48] H. Ma, T.-K. Lee, D. Hyun Kim, H. G. Park, S. Ha Kim, and K.-C. Liu, "Isothermal aging effects on the mechanical shock performance of lead-free solder joints," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 1, no. 5, pp. 714–721, May 2011, doi: 10.1109/TCPMT.2011.2118757.

[49] H. Ma, T.-K. Lee, D. H. Kim, S. H. Kim, H. G. Park, and K.-C. Liu, "Isothermal aging effects on the dynamic performance of lead-free solder joints," in *Proc. 59th Electron. Compon. Technol. Conf.*, May 2009, pp. 390–397, doi: 10.1109/ECTC.2009.5074044.

[50] R. J. Coyle, P. P. Solan, A. J. Serafino, and S. A. Gahr, "The influence of room temperature aging on ball shear strength and microstructure of area array solder balls," in *Proc. 50th Electron. Compon. Technol. Conf.*, May 2000, pp. 160–169, doi: 10.1109/ECTC.2000.853140.

[51] A. Raj, T. Sanders, S. Sridhar, J. L. Evans, M. J. Bozack, W. R. Johnson, and D. M. Carpenter, "Thermal shock reliability of isothermally aged doped lead-free solder with semiparametric estimation," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 9, no. 6, pp. 1082–1093, Jun. 2019, doi: 10.1109/TCPMT.2019.2909052.

[52] C. L. Rodekohr, M. J. Bozack, G. T. Flowers, J. C. Suhling, and D. A. Rodekohr, "The effects of surface finish roughness on intermetallic layer growth, intermetallic interface roughness, and solder joint reliability," in *Proc. 56th IEEE Holm Conf. Electr. Contacts*, Oct. 2010, pp. 1–5, doi: 10.1109/HOLM.2010.5619460.

[53] J. K. Shang and D. Yao, "Effect of interface roughness on fatigue crack growth in Sn-Pb solder joints," *J. Electron. Packag.*, vol. 118, no. 3, pp. 170–173, Sep. 1996, doi: 10.1115/1.2792148.

[54] H.-T. Lee, M.-H. Chen, H.-M. Jao, and T.-L. Liao, "Influence of interfacial intermetallic compound on fracture behavior of solder joints," *Mater. Sci. Eng. A*, vol. 358, nos. 1–2, pp. 134–141, Oct. 2003, doi: 10.1016/S0921-5093(03)00277-6.

[55] G. Henshall, R. Healey, and R. Pandher, "iNEMI pb-free alloy alternatives project report: State of the industry," *SMTA J.*, vol. 21, no. 4, pp. 11–23, 2008.

[56] Y. W. Wang and C. R. Kao, "Minimum Ni addition to lead-free solders for inhibiting Cu_3Sn thickness," *ASE Technol. J.*, vol. 2, no. 2, pp. 137–142, 2009.

[57] H. Watanabe, N. Hidaka, I. Shohji, and M. Ito, "Effect of Ni and Ag on interfacial reaction and microstructure of Sn-Ag-Cu-Ni-Ge lead-free solder," in *Proc. Mater. Sci. Technol. Conf. Exhib.*, 2006, pp. 135–146.

[58] D.-S. Jiang, Y.-P. Wang, and C. S. Hsiao, "Effect of minor doping elements on lead free solder joint quality," in *Proc. Electron. Packag. Technol. Conf.*, Dec. 2006, pp. 385–389, doi: 10.1109/EPTC.2006.342747.

[59] F. Gao, T. Takemoto, and H. Nishikawa, "Effects of Co and Ni addition on reactive diffusion between Sn–3.5Ag solder and Cu during soldering and annealing," *Mater. Sci. Eng., A*, vol. 420, nos. 1–2, pp. 39–46, Mar. 2006, doi: 10.1016/j.msea.2006.01.032.

[60] L. Gao, S. Xue, L. Zhang, Z. Sheng, F. Ji, W. Dai, S.-L. Yu, and G. Zeng, "Effect of alloying elements on properties and microstructures of SnAgCu solders," *Microelectron. Eng.*, vol. 87, no. 11, pp. 2025–2034, Nov. 2010, doi: 10.1016/j.mee.2010.04.007.

[61] *Classification of Non-IC Electronic Components for Assembly Processes*, JEDEC Standard J-STD-075A, 2018.

[62] L. G. Pymento, W. T. Davis, M. Kelly, M. Cole, J. Wilcox, P. Krystek, and C. Grosskopf, "Process development with temperature sensitive components in server applications," in *Proc. IPC APEX EXPO*, 2008, pp. 1–16.

[63] V. Eveloy, S. Ganesan, Y. Fukuda, J. Wu, and M. G. Pecht, "Are you ready for lead-free electronics?" *IEEE Trans. Compon. Packag. Technol.*, vol. 28, no. 4, pp. 884–894, Dec. 2005, doi: 10.1109/TCAPT.2005.859353.

[64] L. Nie, M. Osterman, and M. G. Pecht, "Copper Pad Dissolution and Microstructure Analysis of Reworked Plastic Grid Array Packages in Lead-free and Mixed Assemblies," *J. Surf. Mount Technol.*, vol. 22, no. 2, pp. 13–20, 2009.

[65] R. Coyle, P. Read, S. Kummerl, D. Fleming, R. Popowich, and I. Chatterji, "A comprehensive analysis of the thermal fatigue reliability of SnPb and Pb free plastic ball grid arrays (PBGA) using backward and forward compatible assembly processes," *SMTA J.*, vol. 21, no. 4, pp. 33–47, 2008.

[66] M. Logterman and L. Gopalakrishnan, "A product feasibility study of assembling Pb-free BGAs in a eutectic Sn/Pb process," in *Proc. 59th Electron. Compon. Technol. Conf.*, May 2009, pp. 742–751, doi: 10.1109/ECTC.2009.5074096.

[67] J. Nguyen, D. Geiger, D. Rooney, and D. Shangguan, "Solder joint characteristics and reliability of lead-free area array packages assembled at various tin–lead soldering process conditions," *IEEE Trans. Electron. Packag. Manuf.*, vol. 31, no. 3, pp. 227–239, Jul. 2008, doi: 10.1109/TEPM.2008.926282.

[68] A. R. Zbrzezny, P. Snugovsky, T. Lindsay, and R. Lau, "Reliability investigation of mixed BGA assemblies," *IEEE Trans. Electron. Packag. Manuf.*, vol. 29, no. 3, pp. 211–216, Jul. 2006, doi: 10.1109/TEPM.2006.881985.

[69] B. Nandagopal, D. Chiang, S. Teng, P. Thune, L. Anderson, R. Jay, and J. Bath, "Study on assembly, rework process, microstructures and mechanical strength of backward compatible assembly," in *Proc. SMTA Int.*, 2005, pp. 861–870.

[70] R. Kinyanjui, R. Aspandiar, R. Coyle, V. Vasudevan, S. Tisdale, J. Arellano, and S. Parupalli, "Challenges in reflow profiling large and high density ball grid array (BGA) packages using backward compatible assembly processes," in *Proc. IPC APEX EXPO Tech. Conf.*, vol. 2010, pp. 2957–3002.

[71] P. Snugovsky, A. R. Zbrzezny, M. Kelly, and M. Romansky, "Theory and practice of lead-free BGA assembly using SnPb solder," in *Proc. CMAP (Centre Microelectron. Assem. Packag. Canada) Int. Conf. Lead-Free Soldering*, 2005.

[72] J. Bath, S. Sethuraman, X. Zhou, D. Willie, K. Hyland, K. Newman, L. Hu, D. Love, H. Reynolds, K. Kocki, D. Chiang, V. Chin, S. Teng, M. Ahmed, G. Henshall, V. Schroeder, Q. Nguyen, A. Maheswari, M. J. Lee, J. P. Clech, J. Cannis, J. Lau, and C. Gibson, "Reliability evaluation of lead-free SnAgCu PBGA676 components using tin-lead and lead-free SnAgCu solder paste," in *Proc. SMTA Int.*, 2005, pp. 891–901.

[73] B. Nandagopal, Z. Mei, and S. Teng, "Microstructure and thermal fatigue life of BGAs with eutectic Sn-Ag-Cu balls assembled at 210 C with eutectic sn-pb solder paste," in *Proc. 56th Electron. Compon. Technol. Conf.*, 2006, pp. 875–883, doi: 10.1109/ECTC.2006.1645759.

[74] R. Kinyanjui, Q. Chu, P. Snugovsky, and R. Coyle, "Solder joint reliability of Pb-free Sn-Ag-Cu ball grid array (BGA) components in Sn-Pb assembly process," in *Proc. IPC Printed Circuits Expo, APEX Designers Summit*, 2008, pp. 972–987.

[75] S. Menon, M. Osterman, and M. G. Pecht, "Vibration durability of mixed solder ball grid array assemblies," in *Proc. Electron. Syst. Technol. Conf.*, 2013.

[76] L. Nie, M. Osterman, and M. G. Pecht, "Microstructural analysis of reworked ball grid array assemblies under thermomechanical loading conditions," *IEEE Trans. Device Mater. Rel.*, vol. 10, no. 2, pp. 276–286, Jun. 2010, doi: 10.1109/TDMR.2010.2048327.

[77] P. Snugovsky, H. McCormick, S. Bagheri, Z. Bagheri, C. Hamilton, and M. Romansky, "Microstructure, defects, and reliability of mixed Pb-free/Sn-Pb assemblies," *J. Electron. Mater.*, vol. 38, no. 2, pp. 292–302, Feb. 2009, doi: 10.1007/s11664-008-0592-3.

[78] P. Snugovsky, H. McCormick, S. Bagheri, Z. Bagheri, A. C. Hamilton, and M. Romansky, "Microstructure, defects, and reliability of mixed Pb free/SnPb assemblies," in *Supplemental Proceedings: Materials Processing and Properties TMS*, vol. 1. Warrendale, PA, USA: The Minerals, Metals & Materials Society (TMS), 2008, pp. 631–642.

[79] R. Coyle, R. Aspandiar, V. Vasudevan, S. Tisdale, I. Muntele, R. Popowich, D. Fleming, and P. Read, "The effect of Pb mixing levels on solder joint reliability and failure mode of backward compatible, high density ball grid array assemblies," in *Proc. SMTA Int.*, 2013, pp. 403–414.

[80] A. Choubey, M. Osterman, and M. Pecht, "Microstructure and intermetallic formation in SnAgCu BGA components attached with SnPb solder under isothermal aging," *IEEE Trans. Device Mater. Rel.*, vol. 8, no. 1, pp. 160–167, Mar. 2008, doi: 10.1109/TDMR.2007.915049.

[81] P. Chauhan, M. Pecht, M. Osterman, and S. W. R. Lee, "Critical review of the Engelmaier model for solder joint creep fatigue reliability," *IEEE Trans. Compon. Packag. Technol.*, vol. 32, no. 3, pp. 693–700, Sep. 2009, doi: 10.1109/TCAPT.2009.2030983.

[82] Y. Fukuda, M. Osterman, and M. Pecht, "The effect of annealing on tin whisker growth," *IEEE Trans. Electron. Packag. Manuf.*, vol. 29, no. 4, pp. 252–258, Oct. 2006, doi: 10.1109/TEPM.2006.887390.

[83] R. Zhang, J. Zhang, J. Evans, W. Johnson, J. Vardaman, I. Fujimura, A. Tseng, and J. Knight, "Tin-bismuth plating for component finishes," in *Proc. IEEE 61st Electron. Compon. Technol. Conf. (ECTC)*, May 2011, pp. 2060–2066, doi: 10.1109/ECTC.2011.5898801.

[84] K.-W. Moon, W. J. Boettinger, U. R. Kattner, C. A. Handwerker, and D.-J. Lee, "The effect of Pb contamination on the solidification behavior of Sn-Bi solders," *J. Electron. Mater.*, vol. 30, no. 1, pp. 45–52, Jan. 2001, doi: 10.1007/s11664-001-0213-x.

[85] P. Snugovsky, J. McMahon, M. Romansky, L. Snugovsky, D. Perovic, and J. Rutter, "Microstructure and properties of Sn-Pb solder joints with Sn-Bi finished components," in *Proc. IPC Printed Circuits Expo, APEX Designers Summit*, vol. 2006, pp. S28-01-1–S28-01-13.

[86] L. Nie, M. Osterman, F. Song, J. Lo, S. W. R. Lee, and M. Pecht, "Solder ball attachment assessment of reballed plastic ball grid array packages," *IEEE Trans. Compon. Packag. Technol.*, vol. 32, no. 4, pp. 901–908, Dec. 2009.

[87] S. Stoyanov, A. Dabek, and C. Bailey, "Hot nitrogen deballing of ball grid arrays," in *Proc. 37th Int. Spring Seminar Electron. Technol.*, 2014, pp. 44–49, doi: 10.1109/ISSE.2014.6887559.

[88] S. Stoyanov, A. Dabek, and C. Bailey, "Thermo-mechanical impact of laser-induced solder ball attach process on ball grid arrays," in *Proc. 5th Electron. Syst.-Integr. Technol. Conf. (ESTC)*, Sep. 2014, pp. 1–6.

[89] C. L. Hernandez, P. T. Vianco, and J. A. Rejent, "Effect of interface microstructure on the mechanical properties of Pb-free hybrid microcircuit solder joints," in *Proc. IPC/SMTA Electron. Assem. Expo*, 1998, pp. 1–10, doi: 10.2172/676869.

[90] I. Ahmad, A. Jalar, B. Y. Majlis, and R. Wagiran, "Reliability of SAC405 and SAC387 as lead-free solder ball material for ball grid array packages," *Int. J. Eng. Technol.*, vol. 4, no. 1, pp. 123–133, 2007.

[91] L. Nie, M. Mueller, M. Osterman, and M. Pecht, "Microstructural analysis of reballed tin-lead, lead-free, and mixed ball grid array assemblies under temperature cycling test," *J. Electron. Mater.*, vol. 39, no. 8, pp. 1218–1232, Aug. 2010, doi: 10.1007/s11664-010-1209-1.

[92] *Annex III to Directive 2011/65/EU of the European Parliament and of the Council as Regards an Exemption for Lead in Solders Used in Certain Combustion Engines*, Off. J. Eur. Union, Brussels, Belgium, 2019, pp. L283/41–L283/43. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L1846&from=EN

[93] (2020). *InfoMine*. [Online]. Available: https://www.infomine.com/investment/metal-prices/

[94] (2020). *MineralPrices.Com*. [Online]. Available: https://www.mineralprices.com/

[95] (2020). *London Metal Exchange*. [Online]. Available: https://www.lme.com/

[96] M. Huang, N. Zhao, S. Liu, and Y. He, "Drop failure modes of Sn–3.0Ag–0.5Cu solder joints in wafer level chip scale package," *Trans. Nonferrous Met. Soc. China*, vol. 26, no. 6, pp. 1663–1669, Jun. 2016, doi: 10.1016/S1003-6326(16)64272-3.

[97] M. Mostofizadeh, M. Najari, D. Das, M. Pecht, and L. Frisk, "Effect of epoxy flux underfill on thermal cycling reliability of Sn–8Zn–3Bi lead-free solder in a sensor application," in *Proc. IEEE 66th Electron. Compon. Technol. Conf. (ECTC)*, May 2016, pp. 2169–2175, doi: 10.1109/ECTC.2016.209.

[98] R. Puthota. (2013). PCB Vs PCBA Process Challenges & Solutions. Alent Plc Company. Accessed: Apr. 17, 2020. [Online]. Available: http://www.smta.org/chapters/files/India_SMTA_Kick-off_PCB_Vs_PCBA_Process_Challenges_n_Solutions.pdf

[99] D. Y. R. Chong, K. Ng, J. Y. N. Tan, P. T. H. Low, J. H. L. Pang, and F. X. Che, "Drop test reliability assessment of leaded & lead-free solder joints for IC packages," in *Proc. 6th Electron. Packag. Technol. Conf. (EPTC)*, Dec. 2004, pp. 210–217.

[100] F. Song, S. W. R. Lee, K. Newman, B. Sykes, and S. Clark, "High-speed solder ball shear and pull tests vs. Board level mechanical drop tests: Correlation of failure mode and loading speed," in *Proc. 57th Electron. Compon. Technol. Conf.*, 2007, pp. 1504–1513, doi: 10.1109/ECTC.2007.373994.

[101] R. Berni, M. Catelani, C. Fiesoli, and V. L. Scarano, "A comparison of alloy-surface finish combinations considering different component package types and their impact on soldering reliability," *IEEE Trans. Rel.*, vol. 65, no. 1, pp. 272–281, Mar. 2016, doi: 10.1109/TR.2015.2455973.

[102] S.-M. Lee, J.-W. Yoon, and S.-B. Jung, "Board level drop reliability of epoxy-containing Sn-58 mass% Bi solder joints with various surface finishes," *Mater. Trans.*, vol. 57, no. 3, pp. 466–471, 2016, doi: 10.2320/matertrans.M2015260.

[103] C. Yang, F. Song, and S. W. Ricky Lee, "Comparison of ball pull strength among various Sn-Cu-Ni solder joints with different pad surface finishes," *J. Electron. Packag.*, vol. 136, no. 1, Mar. 2014, Art. no. 0110031, doi: 10.1115/1.4025915.

[104] B. Arfaei, F. Mutuku, K. Sweatman, N.-C. Lee, E. Cotts, and R. Coyle, "Dependence of solder joint reliability on solder volume, composition and printed circuit board surface finish," in *Proc. IEEE 64th Electron. Compon. Technol. Conf. (ECTC)*, May 2014, pp. 655–665, doi: 10.1109/ECTC.2014.6897356.

[105] K.-H. Kim, J. Koike, J.-W. Yoon, and S. Yoo, "Effect of plasma surface finish on wettability and mechanical properties of SAC305 solder joints," *J. Electron. Mater.*, vol. 45, no. 12, pp. 6184–6191, Dec. 2016, doi: 10.1007/s11664-016-4908-4.

[106] J.-H. Kim, Y.-C. Lee, S.-M. Lee, and S.-B. Jung, "Effect of surface finishes on electromigration reliability in eutectic Sn–58Bi solder joints," *Microelectron. Eng.*, vol. 120, pp. 77–84, May 2014, doi: 10.1016/J.MEE.2013.12.006.

[107] A. Siewiorek, A. Kudyba, N. Sobczak, M. Homa, Z. Huber, Z. Adamek, and J. Wojewoda-Budka, "Effects of PCB substrate surface finish and flux on solderability of lead-free SAC305 alloy," *J. Mater. Eng. Perform.*, vol. 22, no. 8, pp. 2247–2252, Aug. 2013, doi: 10.1007/s11665-013-0492-4.

[108] R. J. Coyle, K. Sweatman, and B. Arfaei, "Thermal fatigue evaluation of Pb-free solder joints: Results, lessons learned, and future trends," *JOM*, vol. 67, no. 10, pp. 2394–2415, Oct. 2015, doi: 10.1007/s11837-015-1595-1.

[109] S. Menon, A. Pearl, M. Osterman, and M. Pecht, "Effect of ENEPIG surface finish on the vibration reliability of solder interconnects," *Int. Symp. Microelectron.*, vol. 2013, no. 1, pp. 115–119, 2013, doi: 10.4071/isom-2013-TA44.

[110] R. Schueller, "Considerations for selecting a printed circuit board surface finish," in *Proc. SMTA Int.*, 2010. [Online]. Available: https://www.smta.org/knowledge/proceedings_abstract.cfm?PROC_ID=4295

[111] E. George and M. Pecht, "Tin whisker analysis of an automotive engine control unit," *Microelectron. Rel.*, vol. 54, no. 1, pp. 214–219, Jan. 2014, doi: 10.1016/J.MICROREL.2013.07.134.

[112] T. Fang, M. Osterman, S. Mathew, and M. Pecht, "Tin whisker risk assessment," *Circuit World*, vol. 32, no. 3, pp. 25–29, Sep. 2006, doi: 10.1108/03056120610663371.

[113] M. E. McDowell, "Tin whiskers: A case study," in *IEEE Aerosp. Appl. Conf. Dig.*, Jan/Feb. 1993, pp. 207–215, doi: 10.1109/AERO.1993.255322.

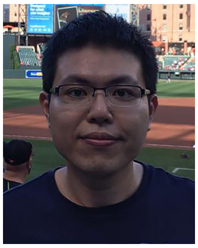
[114] E. M. Russick and G. E. Thayer, "Conformal coating value/risk assessment for Sandia satellite programs," Sandia Nat. Lab., Albuquerque, NM, USA, Tech. Rep. SAND2008-1125, 2008, doi: 10.2172/929522.

[115] M. G. Pecht, E. M. Bumiller, D. A. Douthit, and J. Pecht, *Contamination of Electronic Assemblies*, 1st ed. Boca Raton, FL, USA: CRC Press, 2002.

[116] S. Zhan, M. H. Azarian, and M. G. Pecht, "Surface insulation resistance of conformally coated printed circuit boards processed with no-clean flux," *IEEE Trans. Electron. Packag. Manuf.*, vol. 29, no. 3, pp. 217–223, Jul. 2006, doi: 10.1109/TEPM.2006.882496.

[117] S. Han, M. Osterman, S. Meschter, and M. Pecht, "Evaluation of effectiveness of conformal coatings as tin whisker mitigation," *J. Electron. Mater.*, vol. 41, no. 9, pp. 2508–2518, Sep. 2012, doi: 10.1007/s11664-012-2179-2.

[118] S. Menon, E. George, M. Osterman, and M. Pecht, "High lead solder (over 85%) solder in the electronics industry: RoHS exemptions and alternatives," *J. Mater. Science: Mater. Electron.*, vol. 26, no. 6, pp. 4021–4030, Jun. 2015, doi: 10.1007/s10854-015-2940-4.
[119] D. G. Ivey, "Microstructural characterization of Au/Sn solder for packaging in optoelectronic applications," *Micron*, vol. 29, no. 4, pp. 281–287, Aug. 1998, doi: 10.1016/S0968-4328(97)00057-7.
[120] W. Kim, Q. Wang, K. Jung, J. Hwang, and C. Moon, "Application of Au-Sn eutectic bonding in hermetic RF MEMS wafer level packaging," in *Proc. 1st IEEE Consum. Commun. Netw. Conf.*, Mar. 2004, pp. 215–219, doi: 10.1109/ISAPM.2004.1288016.
[121] J. Doesburg and D. Ivey, "Microstructure and preferred orientation of Au–Sn alloy plated deposits," *Mater. Sci. Eng. B*, vol. 78, no. 1, pp. 44–52, Oct. 2000, doi: 10.1016/S0921-5107(00)00515-8.
[122] R. W. Chuang and C. C. Lee, "Silver-indium joints produced at low temperature for high temperature devices," *IEEE Trans. Compon. Packag. Technol.*, vol. 25, no. 3, pp. 453–458, Sep. 2002, doi: 10.1109/TCAPT.2002.801113.
[123] S. Kim, K.-S. Kim, S.-S. Kim, and K. Suganuma, "Interfacial reaction and die attach properties of Zn-Sn high-temperature solders," *J. Electron. Mater.*, vol. 38, no. 2, pp. 266–272, Feb. 2009, doi: 10.1007/s11664-008-0550-0.
[124] S. Kim, K.-S. Kim, S.-S. Kim, K. Suganuma, and G. Izuta, "Improving the reliability of Si Die attachment with Zn-Sn-based high-temperature Pb-free solder using a TiN diffusion barrier," *J. Electron. Mater.*, vol. 38, no. 12, p. 2668, 2009, doi: 10.1007/s11664-009-0928-7.
[125] S. Kim, K.-S. Kim, G. Izuta, and K. Suganuma, "Reliability of die attached AlN-DBC module using Zn-Sn high temperature lead-free solders," in *Proc. 2nd Electron. Systemintegr. Technol. Conf.*, Sep. 2008, pp. 411–416, doi: 10.1109/ESTC.2008.4684383.
[126] J.-M. Song, H.-Y. Chuang, and T.-X. Wen, "Thermal and tensile properties of bi-ag alloys," *Metall. Mater. Trans. A*, vol. 38, no. 6, pp. 1371–1375, Jul. 2007, doi: 10.1007/s11661-007-9138-1.



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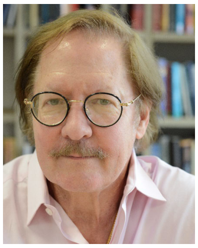

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