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Holistic Lead-free Reliability

After the initial stages of lead-free conversion, lead-free electronics manufacturing has become reality. However, one prevalent mega-question is whether lead-free is reliable enough for all products, particularly for harsh-environment or mission-critical electronics.

When product reliability is paramount, lead-free conversion must start with plan-for-reliability, which comprises design-, material-selection-, and manufacturing-for-reliability. Crucial aspects cover fundamental scientific principles, practical real-world manufacturing, exemplary test data, and reliability performance criteria.

Solder Joint Reliability

Solder joint life essentially is associated with creep and fatigue interaction and/or intermetallic development, as well as microstructural evolution under electronics' service conditions. Service conditions may drive a creep-dominant fatigue or fatigue-dominant creep damage mechanism. How this damage mechanism progresses in a solder joint is associated directly with the elemental makeup and microstructure evolution of the solder joint in question. In contrast to a typical fatigue failure, other conditions such as an overload, high G force, or mechanical shock also could cause failure.

For tin/lead eutectic, the common thermal fatigue failure for solder interconnections is initiated in the lead-rich phase. This phase cannot be strengthened effectively by tin-solute atoms due to limited solubility and tin precipitation. At room temperature, the limited solubility of lead in tin matrix renders it incapable to improve the plastic deformation slip. Under temperature-cycling conditions, this lead-rich phase tends to coarsen and eventually leads to solder joint cracks. In the absence of lead, intrinsic solder composition, which in turn makes up metallurgical phases, governs creep and fatigue behavior.

To illustrate the relative performance among the common lead-free solder compositions, the stress vs. strain curves[1] (25°C, 6.2×10^{-4}/sec.) are aggregated in Figure 1. Solder joint integrity also can be affected by substrates it contacts, the solder-making process, joint design, and configuration. Another important factor is system thermal management. Active IC packages face increasing challenges in managing heat dissipation. The integrity and service life of the system can depend on the efficiency of heat dissipation, in addition to external temperature. The heat generated during functioning must be carried away from the die to the package surface and then to the ambient environment. Design and materials of the package and board all contribute to heat dissipation.

Key characteristics in fatigue include that fatigue fracture usually occurs at lower stresses than would be required for monotonic loading. It often starts at the free surface and is sensitive to stress raisers such as surface flaws and defects that promote localized flow in their vicinity; fatigue strength decreases with increasing temperature; and fatigue properties correlate well with tensile strength. The solder joint must possess adequate tensile strength over the entire temperature span during service life. This does not mean that tensile strength accounts for all fatigue behaviors, due to the complexity of fatigue process and the localized nature. Nonetheless, thermal fatigue resistance is related directly to fatigue strength and thermal conductivity, but inversely related to elastic modulus and linear thermal expansion coefficient. Fundamentals behind fatigue strength are that fatigue strength is proportional directly to the difficulty of dislocation cross slip. Certain strengthening mechanisms are expected to enhance tensile strength and fatigue resistance; others are not.[2] Consequently, distinct strengthening mechanisms in designing tin-based solder differentiate solder joint performance in harsh environments.

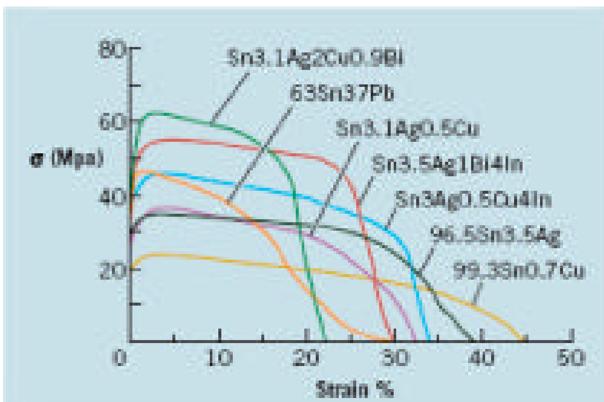

Figure 1. Comparative stress vs. strain curves of common lead-free alloys.

Differentiating Test Methodology

Available tests, from temperature cycling and aging to mechanical shock and vibration, are plentiful. Selecting relevant tests and defining testing parameters for a specific methodology dictate the outcome, and should be set considering the intrinsic properties of a solder material. For example, tin/silver/copper (Sn/Ag/Cu — near eutectic) alloys may be vulnerable to high-stress or high-strain rate conditions (drop test) and tin/lead (eutectic or near eutectic) or tin/silver/copper/indium (Sn/Ag/Cu/In — near eutectic) alloys are not. The effort also is to determine how many and which tests should be performed, and the validity of selected test parameters. Tests and corresponding parameters should have the capability to differentiate different levels of performance.

In a study of failure mechanisms in tin/lead and SAC solder bumps for flip chip assembly,[3] the assembly's consecutive exposure to high-temperature aging (150°C, 3,000 hours) and temperature cycling (-55° to +125°C, 2 cycles/hour) revealed the solder joint's different behaviors and different performance levels between tin/lead and SAC. Figures 2, 6, and 7 exhibit fatigue cracks in a SAC bump after 1,000 cycles. The equivalent tin/lead solder joints remain intact without incurring any detectable cracks after 2,500 cycles.

Figure 2. Fatigue crack in SAC bump after 1000 temperature cycles.

Assess Solder Joint Reliability

Among these various tests, fatigue life is a necessary gauge of solder joint reliability. Fatigue life is measured by a low-cycle isothermal fatigue mode or a thermomechanical mode as imposed by temperature-cycling conditions. Low-cycle isothermal fatigue is performed at a constant temperature, and thermomechanical fatigue is conducted under a continuous spectrum of temperature cycles between two related extremes. In temperature cycling, the boundaries of the influential parameters include upper temperature (T_{upper}), temperature amplitude, lower temperature (T_{lower}), dwell at T_{upper}, dwell at T_{lower}, wave form, strain amplitude, and ramp rate. Each can affect test results and the interpretation of results.

Low-cycle fatigue is a more convenient method, since it is more straightforward to relate the fatigue phenomenon to fundamental material behavior at a fixed temperature. Although not as convenient, thermomechanical test mode more closely replicates actual service conditions of electronic packages and assemblies. From a material point of view, a thermomechanical test integrates the deformation mechanisms generated at all temperatures within the set lower and upper limits. However, selection of the temperature-cycling parameters takes good judgment, knowledge, and experience.

Fatigue lives under low-cycle isothermal and thermomechanical testing modes are expected to be comparable in most cases. However, disparity in solder joint fatigue obtained by these two methods is observed. A true comparison between low-cycle and thermal cycling needs to be performed in a continuous integration manner, i.e., integrating the isothermal fatigue lives at a fixed strain range over the entire temperature limits of the cycle.

With a similar operative mechanism, low-cycle fatigue life or fatigue resistance is expected to compare relatively to that under thermal cycling when the testing temperature of low-cycle fatigue is equivalent to the maximum temperature of the thermal cycling. As the operative mechanism is different between these two test schemes, such comparable performance may not exist. This primarily is the result of thermodynamic and kinetic development under the effect of operating temperature, leading to different micro or sub-micro events as reflected in the evolution of microstructure. Overall, either low-cycle isothermal or thermomechanical testing mode can be effectively used for performance comparison purpose. Figure 3 compares the isothermal low-cycle fatigue between Sn3.0Ag0.5Cu, Sn4.1Ag0.5Cu4.0In, and Sn4.1Ag0.5Cu7.0In at 125°C (triangle wave, 5 µm/sec. ramp rate, life defined as 20% drop from initial load). Sn4.1Ag0.5Cu4.0In and Sn4.1Ag0.5Cu7.0In solders have a better fatigue life than Sn3.0Ag0.5Cu.[4]

As shown in Figure 6, the steady creep rate of Sn3.0Ag0.5Cu is faster than that of Sn4.1Ag0.5Cu4.0In and Sn4.1Ag0.5Cu7.0In at 25°C over a range of stress, indicating that Sn3.0Ag0.5Cu imparts an inferior creep resistance. However at 125°C, the steady creep rate of Sn 3.0Ag0.5Cu is similar to that of Sn4.1Ag0.5Cu4.0In and Sn4.1Ag0.5Cu7.0In.[4]

Combined results under the two fatigue test modes, in conjunction with the results under creep test and the relationship of monotonic stress vs. strain, will lead to an understanding of the predominant operative mechanism, and thus a reliability assessment. A system that demonstrates high thermomechanical fatigue life, but inferior ambient low-cycle fatigue life, implies that a thermally activated micro event may be predominant, directing a favorable microstructural evolution at a high temperature. However, if a system has high thermal fatigue resistance and high creep resistance, it may suggest that a sub-micro event involving the development of fine precipitates and dispersion may be prevailing. The result of good low-cycle fatigue resistance at ambient temperature but poor thermal fatigue resistance may suggest deleterious development of microstructures at elevated temperatures.

Another example, under temperature cycling (-25° to +125°C, dwell 20 min., 55 min./cycle, 1,000 cycles), the SAC BGA solder ball exhibited solder joint cracks[5] (Figure 5). Under the same testing conditions, the solder joint made of SnAgCuIn did not show any detectable crack. Refer the intrinsic material properties of SAC and Sn/Ag/Cu/In to Figure 1.

Having the test results is not the final step. Actually, it is the beginning of drawing conclusions. Most important are to integrate results from the tests that were conducted and to interpret data and phenomena. In many instances, the conclusion is directly related to test design, parameters, selected criteria, and how the assembly is processed.

Before drawing a conclusion, consider the design and process. Solder joint integrity and assembly reliability depend not only on the materials and components, but also on the connection process.

There is no single test that can determine reliability unless it is a known system. The integrated data and the damaging mechanism that is in congruence with the scientific principles get to the rationalization of reliability. Both fundamental material property testing and accelerated testing are a part of reliability assessment equations.

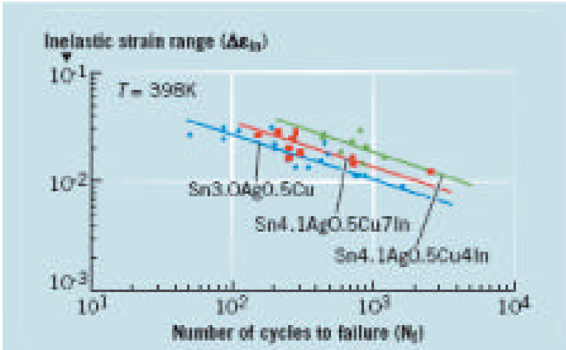

Figure 3. Isothermal low-cycle fatigue of Sn3.0Ag0.5Cu, Sn4.1Ag0.5Cu4.0In, and Sn4.1Ag0.5Cu7.0In at 125°C.

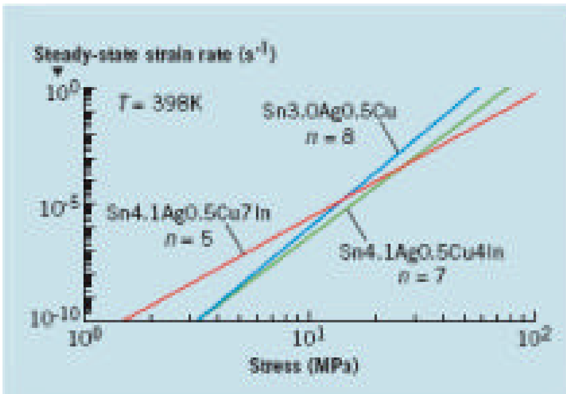

Figure 4. Steady creep rate vs. stress (MPa).

Universal Rules

The top three tactics to maximum solder joint reliability are to minimize the mismatch of the coefficient of thermal expansion (CTE) between components and the PCB; make the component as pliable as practical; and boost a solder joint alloy's durability.

Solder joint strain primarily comes from external stress or CTE mismatch. The mismatched CTE imposes the most damaging cyclic strain to solder joints, causing fatigue degradation. The higher temperature excursion results in a higher percentage of joint strain development in a typical CTE-mismatched assembly. CTE-matched assembly is ideal. However, under increased functional demands and other design requirements, the idealized CTE match may not be practically feasible. Then the tactic goes to the second most potent factor, the components. With tight design constraints, desirable components with long and flexible leads often are not suitable to fit–for-design and use. As the design takes on shorter leads or lead-less structure — CSP, BGA, LGA — functional/service conditions are expected to pose higher strain levels to the solder joint. In practice, when the first two tactics are not feasible, solder joint durability can only be increased by enhanced intrinsic performance of a solder alloy.

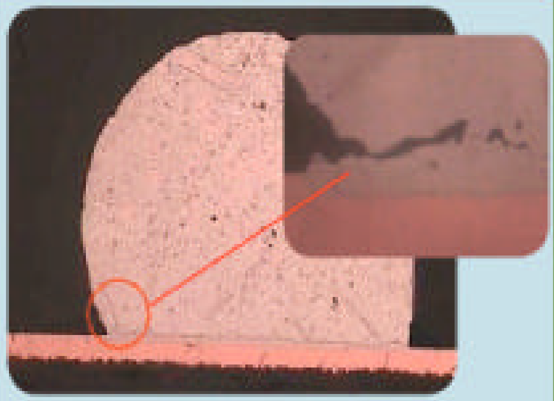

Figure 5. Fatigue cracks in a SAC-formula solder ball under temperature cycling.

Microstructure

If constraints on PCB design and component selection due to desired functionality are limiting, maximizing solder joint reliability is key. As a reference point, tin/lead's microstructure is made of tin-rich phase and lead-rich phase. For lead-free solders, the microstructure comprises the primary metallurgical phases and second phases, depending on the composition of the solder alloy. This in turn reveals each solder's specific strengthening mechanisms or lack thereof.

The microstructure that is more stable during service life offers higher fatigue resistance. High fatigue resistance can be achieved by homogenizing slip deformation and eschewing local concentrations of plastic deformation. Further, the microstructure that facilitates the formation of fine precipitates, particle dispersion, homogenization, and granulation tends to favor fatigue resistance and those conditions that generate needle morphology, brittle phases, weak inter-phase interfaces, excessive voids, surface crack, and stress concentration sites. Controlling microstructure to promote homogenous slip with small regions of plastic deformation increases the fatigue strength, as opposed to a small number of regions of extensive slip.

Some commercial solder alloys are specifically designed for high fatigue strength.[1] Solder joint fatigue failures, tin/lead or lead-free, are expected and have been observed to undergo ductile fatigue fracture, not a brittle fracture. The elastic limit of solder alloys is a low value and is related to the motion of a few hundred dislocations. In the event that a brittle fracture is observed, extraneous phenomenon predominates and precedes the intrinsic fatigue. This could be due to undesirable intermetallic-related fracture either at the interface or in the bulk of the solder joint or the intermetallic second phase as observed in SAC alloys at temperatures below -45°C.

A factor that may complicate the solder joint failure phenomena and mechanism is the interfacial boundary and its vicinity area, which in turn is affected by the nature of the substrate surface (such as PCB surface finish and component coating), soldering process, and the service conditions.

One should note that the interfacial boundary of a solder joint could play a role in a solder failure mechanism. When the interfacial band's mechanical behavior separates from that of bulk solder composition, the failure mechanism may alter and fatigue life would suffer.

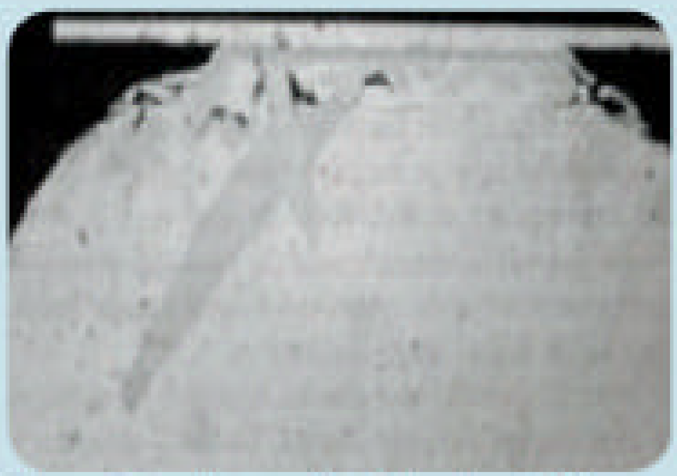

Figure 6. Crack caused by fatigue in a SAC bump.

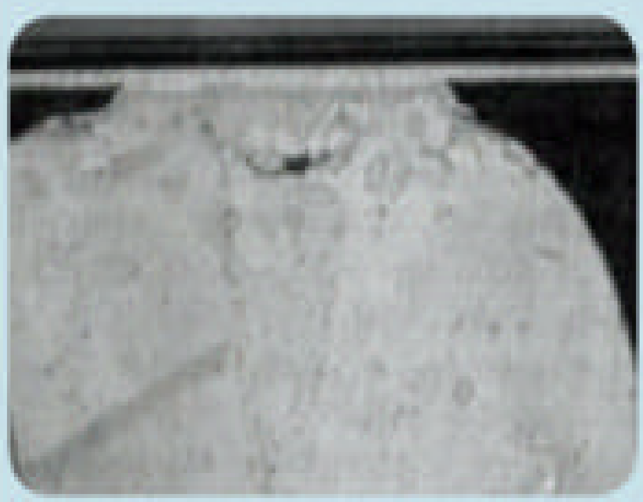

Figure 7. Fatigue crack in the center of a SAC bump after 1,000 cycles.

PCB Integrity

Solder joints are critical mechanical, thermal, and electrical connections. But solder joints per se do not account for all aspects of PCB assembly integrity. PCB assembly integrity is linked closely with process temperature. An increased process (soldering) temperature over the tin/lead system to any minor degree is expected to require a more thermally resistant PCB in order to maintain the same level of integrity. That means to have a higher glass transition temperature (T_g), higher decomposition temperature (T_d), increased dimensional stability, lower CTE, lower moisture absorption, higher threshold of copper plating thickness, more robust circuit structural design.

Under a higher process temperature, common problematic or failure phenomena include PCB delamination, blistering, warpage, thru-hole barrel crack, Z-axis thermal expansion, connector plastic housing changes, large PCB assembly sagging during reflow, increased residual stress, potential heat-sensitive component damages on IC components, BGA solder ball drop, coplanarity degradation of BGAs, black pad, moisture sensitivity aggravation, higher solder joint voids, and higher propensity to tin whisker. Potential detrimental effects on the internal solder joints of modules and subassemblies and more demanding rework are other areas of concern.

There are insidious effects that a higher process temperature could exert onto a PCB assembly. Without doubt, if reliability is top priority, the process temperature should be kept as low as feasible. But the process temperature should not marginalize the process window required for delivering quality and consistent wetting across all components. A low-temperature process therefore must be made available for the industry.[6]

BGA Joint Reliability

The prevalent questions to ask are: What are additional potential BGA lead-free issues, if any?; Should BGA solder balls become molten during reflow?; How does the process affect production yield and defects?; How does the process affect assembly reliability?; Can SAC ball and tin/lead solder paste, or vice versa, work well?; Can SAC ball and other lead-free solder paste work well?; Can SAC ball and SAC solder paste work for harsh environment electronics? These topics are covered in the upcoming seminars.

Evolution of Lead-free Alloys

The more one understands the past, the better one can look into the future. The initial lead-free systematic R&D starting in the late 1980s was not driven by legislation or regulations, rather by the mission of advancing solder material above and beyond tin/lead. Before the research started, it was recognized that any working lead-free alloy for electronics must be tin-based for fundamental scientific reasons.

Naturally, conventional wisdom calls for as simple a system as is feasible and practical. However, none of the binary alloys could suit all surface mount soldering, and a ternary system could not do the job under the established manufacturing infrastructure. As the result of systematic research in conjunction with the verification on actual production floors, it was becoming clear that a ternary alloy from the groups of tin/copper/bismuth (Sn/Ag/Bi), Sn/Ag/Cu, zinc- (Zn-) or magnesium (Mg-) containing and many other ternary systems would be unable to fulfill the goal of maintaining the existing manufacturing infrastructure and deliver desired reliability. Consequently, R&D extended to higher-element systems — quaternary and pentanary alloys.

Despite all disparities and debates for last five years, time will tell. After a few years of actual lead-free manufacturing, an increasing number of commercial solder alloys incorporate more elements into a binary or a ternary alloy, albeit often in small dosages. These additional elements make today's commercial solder alloys quaternary and pentanary, as recommended at the outset.[2, 6]

Conclusion

Understanding fundamental material properties is as important as working on fracture mechanics. These properties provide a baseline of comparative performance. Compositional makeup dominates the microstructure, and the microstructure directs atomic dynamics, thus the failure mode. Intrinsically inferior materials cannot deliver superior solder joint performance.

As to designing a test scheme and formulating its parameters, knowledge of the underlying strengthening mechanism for each material system is key. The anticipated evolution of a microstructure through the testing/service environment must be considered. Recognizing the different levels of reliability and integrity required for PCB assemblies and the need of manufacturing within practical SMT constraints, the industry needs choices — a fit-for-use choice. There are two process choices, which are essentially distinguished by the soldering temperature along with the designed alloy choices, which dictate the solder joint performance. The choice should be based on the production and reliability requirements.

The fact that alloy performance has proved congruent with the principles and teachings of materials science and metallurgical engineering is an unequivocal comfort. And the fact that the real-world production results coincide well with the experience and knowledge that have been learned during the 28 years of SMT manufacturing is welcome. Ultimately, a PCB assembly's performance relies on not only solder joint reliability but also PCB integrity. To ensure integrity, eschew any higher process temperature during assembly. The sweet spot of lead-free reliability for harsh environments is the performance latitude, which is dictated by the enduring microstructural/metallurgical solder joint properties in response to harsh conditions. The performance latitude that accommodates the anticipated and the unanticipated stressful conditions works for the lower probability of failure, thus higher reliability. SMT

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Jennie S. Hwang, Ph.D., an *SMT* Advisory Board member, is elected to the National Academy of Engineering, inducted to the WIT International Hall of Fame, and named an R&D-Stars-to-Watch. During the 28-year SMT manufacturing establishment, Dr. Hwang has helped improve SMT production yield and solved challenging reliability issues. She is a member of the U.S. Commerce Department’s Export Council, and serves on the board of Fortune 500 NYSE companies and civic and university boards. In addition to technical publications, she is an international speaker and author on trade, business, education, and social issues. She may be contacted at (216) 839-1000; JennieHwang@aol.com.

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