Innovative Material Reinforcement Strategies for Advanced Packaging Solutions in Automotive Electronics

Anna Lifton, Kennedy Fox, Paul Salerno, Ebad Rehman
MacDermid Alpha Electronic Solution
New Jersey, USA

ABSTRACT

The growing integration of larger Ball Grid Arrays (BGAs), ceramic packages, and Wafer-Level Chip Scale Packages (WLCSPs) into automotive and other harsh-environment electronic systems necessitates enhanced reliability in printed circuit board (PCB) assemblies. These demanding environments—characterized by elevated thermal loads, mechanical stresses such as vibration and shock, and stringent operational requirements—pose significant challenges to the structural integrity and performance of electronic components. As advanced packaging technologies continue to evolve and design tolerances become more stringent, the selection and qualification of reinforcement materials, including underfills and Edgebond adhesives, have become increasingly critical. To meet the elevated reliability standards required in these conditions, advanced reinforcement strategies are being adopted, including the use of high-reliability solder alloys, flowable underfills, and no-flow Edgebond materials. Flowable underfills provide mechanical stability by fully encapsulating the interstitial spaces beneath components, while Edgebond materials are applied along the periphery of packages to enhance edge support and streamline assembly processes. The optimal reinforcement approach is influenced by multiple factors, including device architecture, warpage behavior, I/O pitch, and production throughput constraints.

This study presents a comparative analysis of high-reliability solder alloys in combination with underfill and Edgebond materials to enhance the mechanical and thermomechanical durability of BGAs and WLCSPs for use in automotive and other high-stress environments. The evaluation encompasses a range of package sizes, I/O pitches, and warpage profiles, subjected to two distinct thermal cycling regimes. Mechanical reliability is assessed through vibration and mechanical shock testing, while thermomechanical performance is evaluated via thermal cycling. The results highlight the efficacy of specific material combinations and reinforcement strategies in improving the structural robustness of advanced electronic packages. These findings contribute to the development of next-generation packaging solutions capable of withstanding the rigorous demands of high-reliability applications in the automotive and industrial sectors.

Key words: BLR (Board level Reliability), Reinforcement, Underfill and Edgebond, BGA, Drop Shock, Thermocycling.

INTRODUCTION

The rapid growth of advanced electronic control units (ECUs) in automotive, aerospace, and industrial markets has driven demand for highly reliable electronic assemblies capable of withstanding harsh operating conditions. Applications such as electric vehicle battery management systems, advanced driver assistance systems (ADAS), and industrial automation require miniaturized, high-performance components with uncompromising reliability. These applications are characterized by prolonged exposure to harsh environmental conditions, including:

- Elevated thermal loads from high-power operation and variable ambient conditions [1]
- Dynamic mechanical stresses from vibration, shock, and impact
- Stringent operational lifetimes exceeding decades in some cases.

Among the critical packaging technologies, Ball Grid Arrays (BGAs), Wafer-Level Chip Scale Packages (WLCSPs), and ceramic-based modules are widely used due to their high I/O density and excellent electrical performance. However, these packages are increasingly vulnerable to mechanical and thermal fatigue, particularly under cyclic temperature exposure and board-level dynamic stresses. The failures due to mismatch in CTE (Coefficient of Thermal Expansion) are often a function of the size of the substrate, i.e., the larger the substrate the larger the differential forces between the substrate material, the smaller soldered components and solder joints caused by temperature variation:

E= (l_o) (alpha) (delta T), where *E* is elongation; l_o is the initial length, *alpha* is the thermal coefficient of expansion; and *delta T* is the change in temperature – hence, the larger the substrate compared to the components, the larger the stresses generated in the solder joints and components. Failures often manifest as solder joint cracking, pad lift, or package fracture, leading to catastrophic system-level malfunction [2].

The combination of fine-pitch interconnects, thin substrates, and much larger package dimensions creates susceptibility to solder joint fatigue, warpage-induced stress, and early-life failures. As packaging complexity grows and design tolerances tighten, traditional soldering and assembly techniques alone are insufficient to meet the reliability demands of harsh environments. To mitigate such reliability risks, reinforcement strategies particularly underfill and Edgebond adhesives have gained popularities [3]. By redistributing stress, constraining package warpage, and enhancing mechanical anchoring, these materials substantially extend the life of interconnects under aggressive reliability testing. There is significant industry evidence available showing mechanical improvement when reinforcement materials are used [4]. Understanding of Underfill and Edgebond behavior, properties and composition, its influence onto the reliability improvement of advanced packages and system is critical to meet reliability specification.

Underfill is a polymeric material used to fill the gap between the IC chip and the organic board, encapsulating the solder joints. It enhances device reliability by distributing thermo-mechanical stresses caused by the coefficient of thermal expansion (CTE) mismatch between chip and board evenly over the whole package. Underfill absorbs the CTE mismatch and therefore reduces significantly stress to a more uniform distribution on solder joints. Historically, the target properties of underfills can be generally summarized as high glass transition temperature (Tg), high modulus (E) and matched coefficient of thermal expansion (CTE) to solder.

In principle, BGA packages have complex structure and CTE of the device will be affected by the Die to component body ratio, molding compound, lead frame design, etc., while the WLCSP design is much simpler. It is typically a silicon chip with solder balls on a thin dielectric and copper redistribution layer (RDL) stack and the effective CTE of the WLCSP is close to silicon (3 ppm/°C). The effective CTE of the PCB is much larger and typically 13-19 ppm/°C in x-y direction and even higher in z (60-80 ppm/°C) with FR-4 epoxy glass multilayer laminates. PCB CTE will depend on the design, structure and dielectric materials. All that CTE mismatch will concentrate the stresses to the solder joint interfaces and affect reliability of assemblies. Larger WLCSP die packages would allow penetration into new device (e.g., processor) and system level (e.g., automotive, server) markets including Lately with advancement in High Power Computing (HPC), Artificial intelligence (AI) and ADAS.

In a prior work presented [5] underfill and Edgebond materials evaluation and several criteria were investigated which included underfill flow rate, flux compatibility, electrochemical reliability. Selection of the material is very critical to insure high reliability of the final assembly. Understanding and testing interaction and potential compatibility issues becoming a common practice in no clean solder paste development and reinforcement materials formulation and properties. This paper conducts a deeper and wider study on the underfill/flux compatibility issues. The present work explores the synergy between high-reliability solder alloy and reinforcement materials, with a focus on optimizing strategies for harsh-environment deployment.

EXPERIMENTAL PROCEDURE.

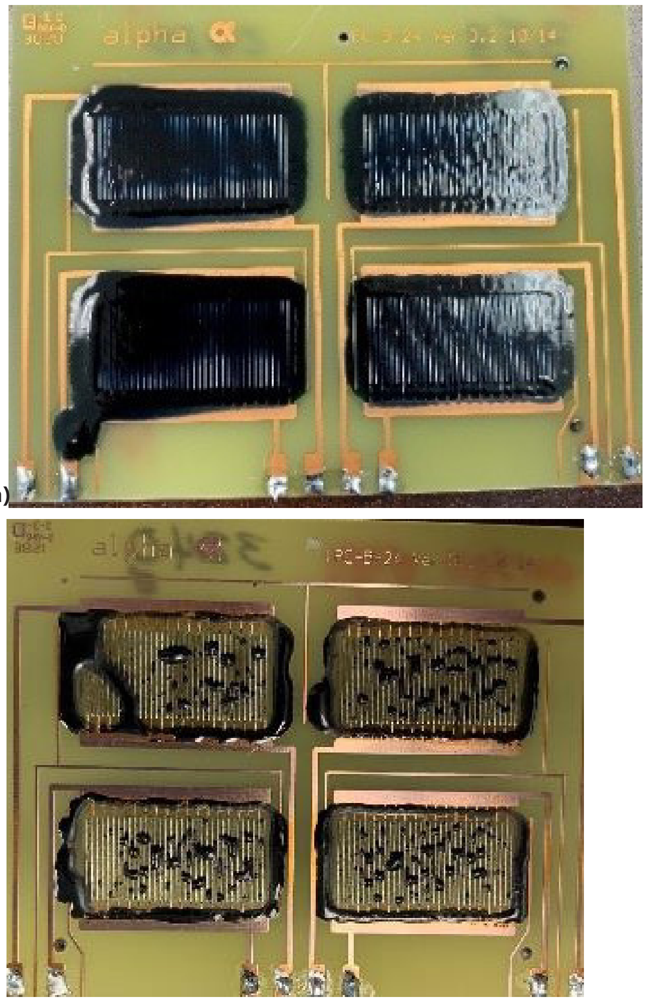
The focus is on the reliability enhancement is Wafer-Level Chip-Scale Packages (WLCSPs). WLCSPs offer advantages in electrical characteristics, faster signal transmission, and lower manufacturing cost but their direct interconnection to the printed circuit board (PCB), without an interposer, introduces significant stress. Use of higher reliability alloys or polymer reinforcements can effectively address these challenges. This strategy helps managing thermal stress and enhancing thermomechanical durability by mitigating CTE mismatch effects and preventing damage to solder joints. Conventional SAC305 or similar solder alloys, while robust under consumer-grade conditions, exhibit premature fatigue failures in automotive-grade cycling . Selection of the correct solder alloy is critical to achieve acceptable reliability.

Selection of the flowable Underfill or no-flow Edgebond for specific application is also extremely critical for achieving required reliability in specific application. Flowable underfills improve solder joint fatigue life but require longer process and may reduce Reworkability. Edgebond adhesives provide simplified dispensing along package peripheries but offer less comprehensive encapsulation depending on the component construction. The objective of this study was to evaluate and assess compatibility and effect on reliability of leading solder paste with various reinforcement materials such as underfills (UF) and Edgebonds (EB) which are commonly used to improve Board Level Reliability (BLR). The requirement for the assemblies and components with enhanced environmental robustness, ensuring functional reliability under extreme operating conditions such as thermal excursions, sustained high-humidity exposure and corrosive environments, as well as mechanical shock and vibrational loading becoming a complex materials selection task.

Reinforcement Materials Selection:

Prior to assessing effect of the reinforcement onto the mechanical and thermomechanical (TCT) reliability, electrochemical (ECM) reliability of the systems was assessed. When underfill materials are applied to assembled circuit boards, residual flux can affect reliability through two primary mechanisms. First, flux residues present on solder bumps, die surfaces, or substrates may form thin interfacial films that reduce surface energy and significantly weaken adhesion between the underfill and solder surfaces. Second, flux residues can obstruct underfill flow. Accumulation of residue within the narrow gaps between solder bumps or between the die and substrate reduces effective clearance, impeding capillary flow. This can result in preferential edge flow, air entrapment, and subsequent void formation. Achieving void-free encapsulation requires uniform wetting of all interfacial surfaces during underfill dispensing. Incomplete or non-uniform wetting increases the likelihood that voids formed during cure will persist, ultimately reducing long-term package reliability. Improved flux–underfill compatibility minimizes void incidence by enhancing interfacial adhesion and promoting uniform capillary flow [6]. Underfill material was dispensed onto the IPC B-24 coupon reflowed with various solder pastes. Assumption was made that if solder paste flux residue and underfill have lower surface energy, it will insure better flow and lower voiding under the components. Figure 1 shows the surface of the as cured underfill A and underfill B on the surface of the coupon reflowed with the same solder paste. As a part of underfill selection process, cross section of the final assembly was done to confirm the absence of outgassing voids and delamination around solder ball due to presence of flux residue. Figure 2 shows those types of defects.

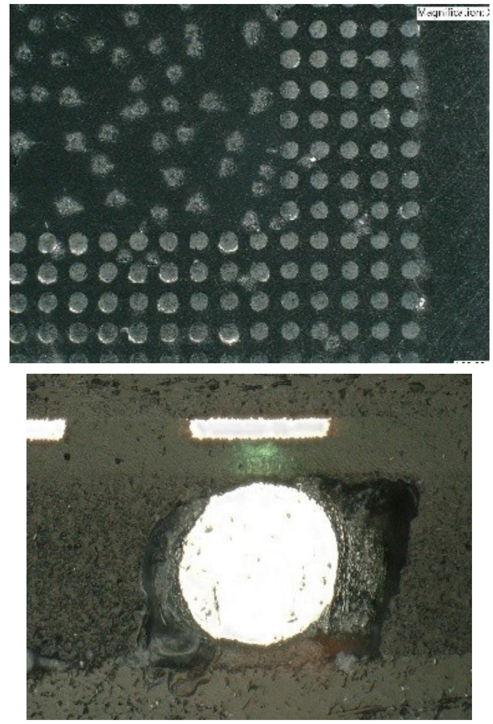
(a)



(b)

Figure 1: Boards appearance Paste A (a) and Paste B (b).

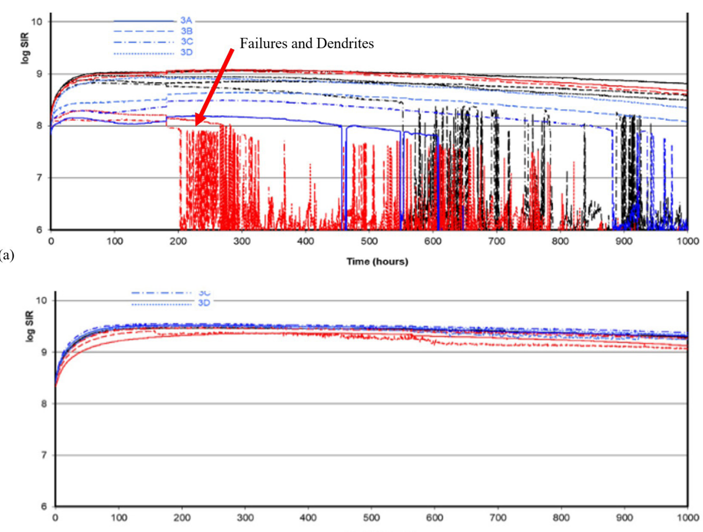
(a)



(b)

Figure 2: A planar cross section of the assemblies with outgassing voids (a) and delamination around solder ball (b).

Curing kinetics was confirmed using DSC to ensure compatibility of the solder paste flux residue and underfill materials. complete cure. While assessing thermo mechanical reliability of the system, it is needed to ensure that there is no compromise in electrochemical reliability. Figure 3 shows SIR curves of the same material tested at 85°C/85%RH at 12.5V for 1000 hours. The material which was fully cured performs well in SIR testing while partially cured material shows dendritic growth and failure within 200 hours.



(a)

(b)

Figure 3: SIR performance of the partially cured material (a) and fully cured material (b)

Thermomechanical Reliability.

A representative automotive-type test vehicle was developed to evaluate reinforcement effects on solder joint reliability and test vehicle was designed to have integral copper 'loading' representative of production PCBs and component types. Copper OSP was used as a surface finish. Thickness of the 6-layer board was about 1.6 mm. High Tg laminate material was used to avoid any decomposition, warpage or degradation at higher test temperatures. Several different components (details are in Table 1) were selected for evaluation because they had very specific size and pitch. As a result of component design and materials used to fabricate, warp signature was very different. Assembled boards with and without reinforcement were subjected to thermocycling at -40°C to +125°C with 20 min dwell time (Figure 4). Slower transition rate was chosen because it offers the toughest challenge i.e., allows longer time for plastic deformation to occur in the solder joint. Resistance values of the I/O connections of the assemblies were monitored in-situ. Increase in resistance was indicative of solder joints failure/cracking. All assemblies were tested for up to 4000 cycles. Increase in resistance by 20% in five consecutive measurements was a failure [7,8].

Table 1: Components details.

Available components	Body size	BGA pitch	Ball diameter
BGA228	12x12 mm	0.5 mm	0.30
BGA360	10x10 mm	0.4 mm	0.25
WLP400-05	10x10 mm	0.5 mm	0.30
WLP400-04	8x8 mm	0.4 mm	0.25

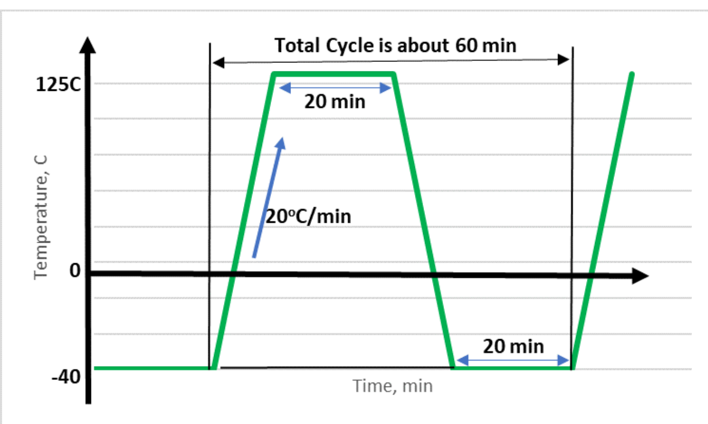


Figure 4: Thermocycling profile.

RESULTS AND DISCUSSION

Reinforcement materials were carefully selected to avoid any generation and introduction of additional stress onto the system. Underfill and Edgebond were applied and cured at recommended conditions. Quality and uniformity of the reinforcement materials was evaluated, and the fillet height was from 50% or up to 100% of the substrate height. To investigate thermal fatigue, assembled boards—with and without polymer reinforcement—were subjected to accelerated thermal cycling at -40 °C to +125 °C with 20 min dwell at each temperature extreme. As it was mentioned earlier, two component types were selected for comparative evaluation conventional BGAs and WLCSP. Both component types had similar pitch and comparable dimensions but differed in structural design and warpage behavior. In our previous studies [5], it was reported that package warpage emerged as a decisive factor in reinforcement effectiveness: Figure 5 shows concave warpage packages and Underfill reinforcement produced the highest improvement in solder joint life. While Edgebond also extended reliability compared with the baseline SAC305 condition, its effect was less pronounced. Figure 6 convex warpage packages, both underfill and Edgebond materials delivered comparable improvements. These observations confirm that reinforcement strategies must be tailored to package geometry and stress distribution to maximize reliability gains. In this study, focus was on comparison of the performance of conventional BGA packages and WLCSPs of similar size and pitch, reflecting differences in package stiffness and warpage. The study further compared three solder alloys—SAC305 and two high-reliability alternatives—across BGA and WLCSP assemblies. Table 2 shows alloy description.

Table 2: Generic description of the alloys

Alloy ID	Generic Description
SAC305	Sn-Ag-Cu
High Rel I	Sn-Ag-Bi-Sb-Cu-Ni
High Rel MXE	Sn-Ag-Bi-Sb-Cu-X

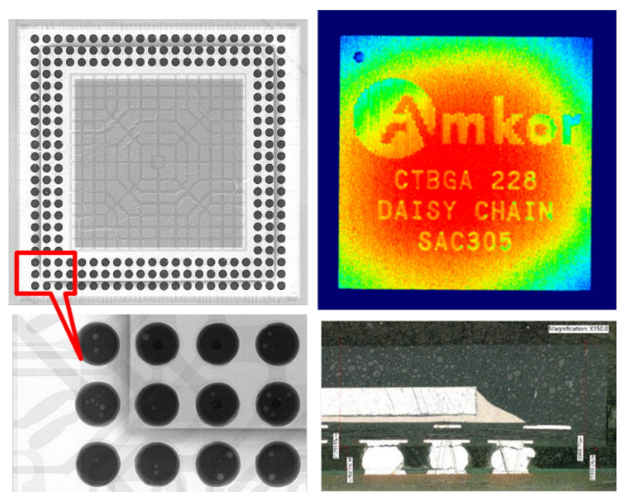


Figure 5: Details of the larger die BGA component

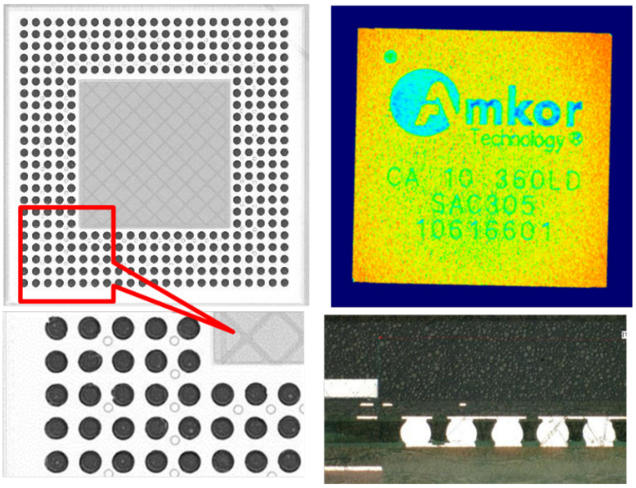


Figure 6: Details of the smaller die BGA component

Characteristic life of the assemblies (total of 16 datapoints) build with various alloy with and without reinforcement are shown in Figure 7. There is a clear reliability improvement when BGA was used compared to WLCSP and components stiffness and warpage plays significant role reliability level. Reliability of the WLCSP was almost ten times lower compared to BGA package. Even the use of the higher reliability alloys does not improve reliability sufficiently enough to meet requirements. Also, for smaller pitch WLCSP characteristic life was even smaller, indicating that smaller standoff height in combination with high CTE mismatch increase overall system stress resulting in failure within 300 cycles. SEM images shown in Figure 8 illustrate the degree of cracking in BGA SAC305 assemblies without reinforcement. After 4000 cycles cracks propagate through most of the balls. Very different pictures could be observed in case when BGA SAC305 assemblies are reinforced (Figure 9). Very few cracks were observed even after 4000 cycles in the underfilled assembly.

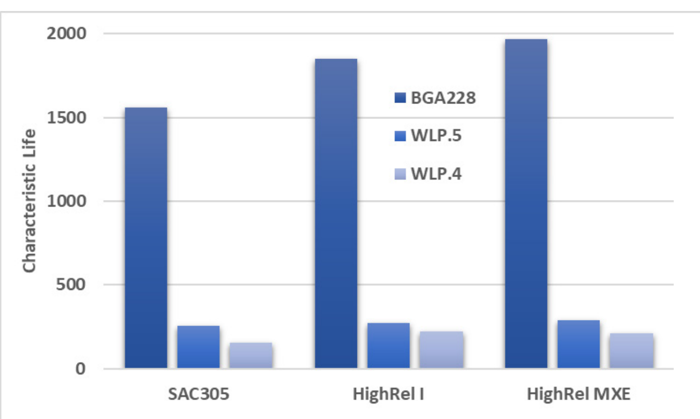


Figure 7: Characteristic life of the BGA and WLCSP assemblies build with different alloys

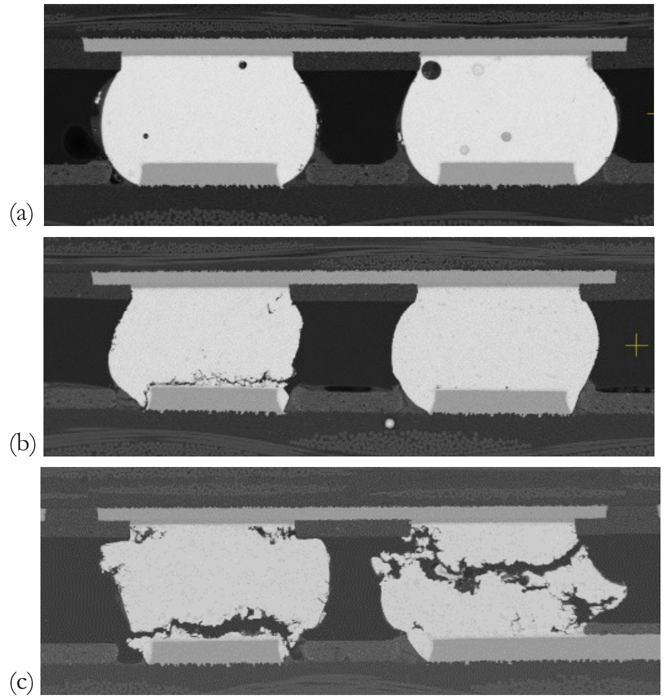


Figure 8: SEM images of the SAC305 BGA assemblies without reinforcement (a) as assembled), (b) after 2000 cycles and (c) after 4000 cycles.

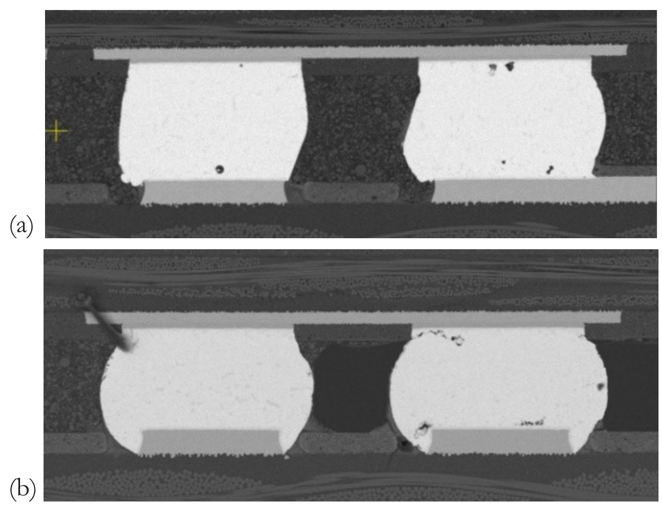


Figure 9: SEM images of the SAC305 BGA assemblies with reinforcement (a) 2000 cycles Edgebonded and (b) 4000 cycles underfilled

Characteristic life of the reinforced with Edgebond material assemblies are shown in Figure 10. At the minimum characteristic life was increased by 50 percent compared to alloys only configuration. Even for highly stressed by CTE mismatch WLCS packages, much higher characteristic life was observed.

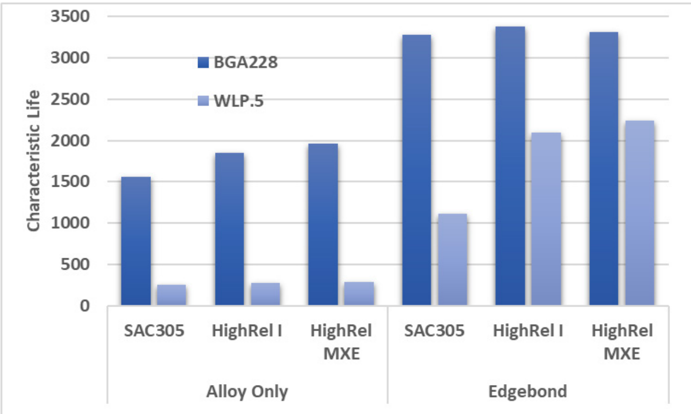


Figure 10: Comparison of the characteristic life of the BGA and WLP 0.5 mm pitch assemblies with and without reinforcement.

Thermocycling was terminated at 5000 cycles. The same BGAs and WLCSP assemblies were reinforced with underfill material but at 5000 cycles there was not enough failures to generate Weibull plot and calculate characteristic life for BGA assemblies with all alloys and WLCS packages build with high reliability alloys. Figure 11 shows characteristic life of reinforced with Edgebond and Underfill WLCS packages. As shown before, smaller bitch and lower standoff component showed worst performance compared to the larger pitch ones. Also, the observation was made that higher reliability alloy showed slightly lower characteristic life when it was underfilled.

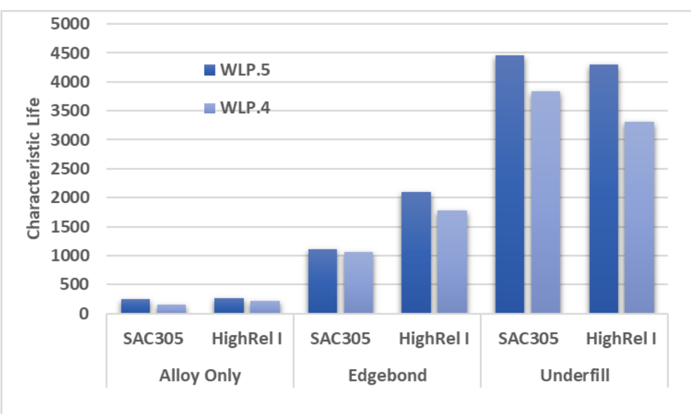


Figure 11: Comparison of the characteristic life of two different pitch WLCSP assemblies with and without reinforcement .

Failure mode analysis initially showed no differences in crack location or propagation pattern. Figure 12 shows SEM images of the cross sectioned WLCSP build with SAC305 material. Most of the cracks were observed near component and solder sphere interface. Use of Edgebond or underfill reinforcement materials drastically improved reliability of the assemblies but did not change much crack location, it was still through the bulk solder alloy closer to the component solder interface. No other defect modes such as pad cratering, cracking through IMC or other types of failures were observed [9]. Failure analysis of the thermal cycled assemblies showed significant damage of the solder joints especially at the corners. Further investigation into the differences in reversed reliability of the SAC305 and high reliability alloy with underfill versus Edgebond material was conducted.

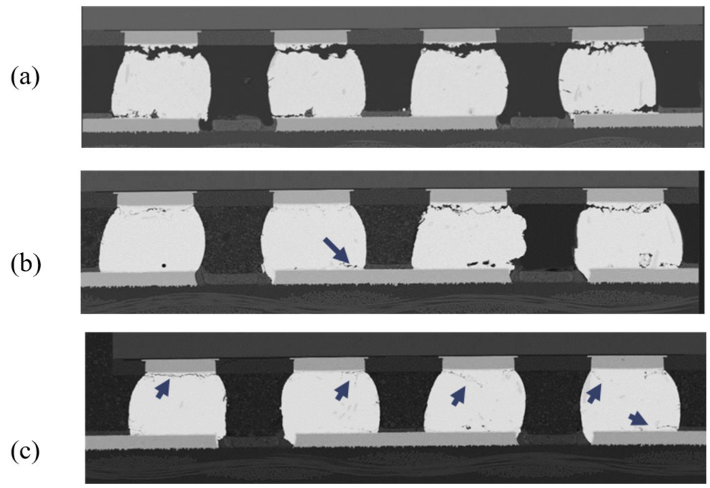


Figure 12: SEM images of the SAC305 WLCSP 0.5mm pitch after thermocycling assembled (a) without reinforcement, (b) with Edgebond and (c) Underfill.

X-Ray analysis of the assemblies after thermocycling was conducted in order to identify potential root cause of the slightly lower characteristic life of the high reliability alloy tested with underfill. Solder extrusion was observed on the assemblies build with SAC305 alloy. Figure 13 shows X-ray image of BGA package and planar section of SAC305 planar cross section. No such phenomenon was observed when high reliability alloy was examined. As a part of this evaluation, various underfills were tested and the observation was made that higher degree of extrusion was observed with higher CTE underfills and SAC305 alloy.

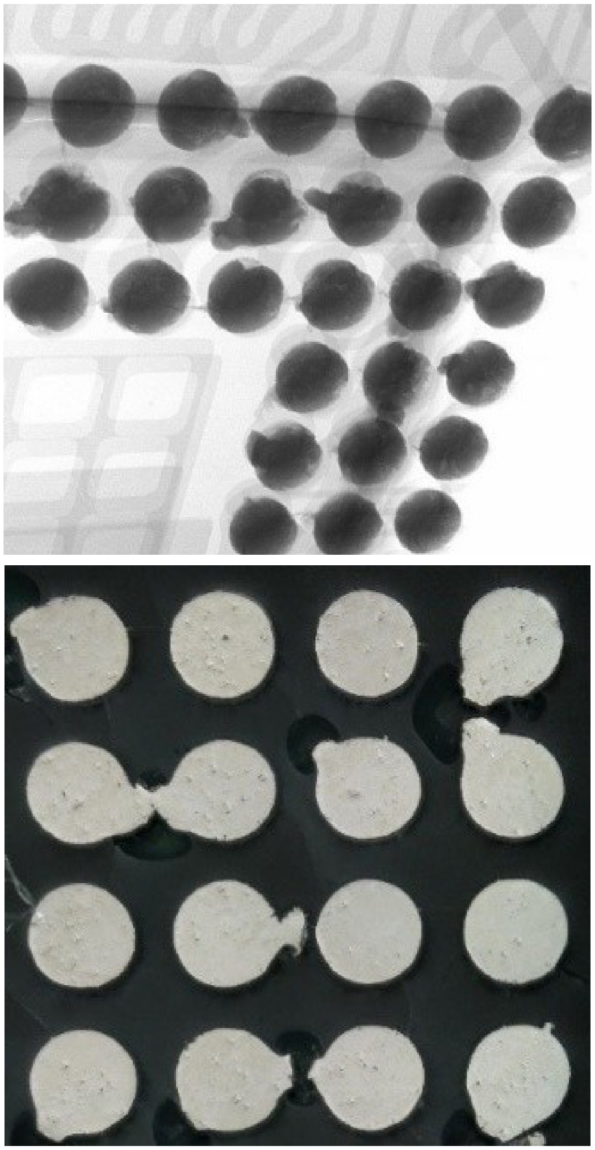

(a)
(b)

Figure 13: SAC305 assembly after thermocycling (a) X-Ray image of the BGA package and (b) planar cross section of the SAC305 WLCSP assembly.

The hypothesis was proposed to explain and understand this phenomenon [10, 11]. During thermocycling, there is a change in microstructure, recrystallization, grain and IMC growth in conjunction with externally applied compressive stresses by the underfill plus CTE mismatch results in material extrusion.

The question was why it is happening with SAC305 and not with high reliability alloys? The addition of micro-alloying elements in high reliability alloy (Bi, Sb, Ni) results in a finer microstructure and increased toughness, suppressing grain growth. As a result, alloying elements are inhibiting stress. Also, high reliability alloys have significantly higher yield stress, tensile strength, and creep resistance than SAC305. This hardness is advantageous for component reliability but makes the material more difficult to deform and extrude.

SAC305 has a lower tensile strength and is a less stiff material than high reliability alloy so it requires less internal force to be extruded. This translates to a less energy-intensive extrusion process. Figure 14 shows cross sectioned extruded material and Ag_3Sn precipitate could be observed within the extruded structure.

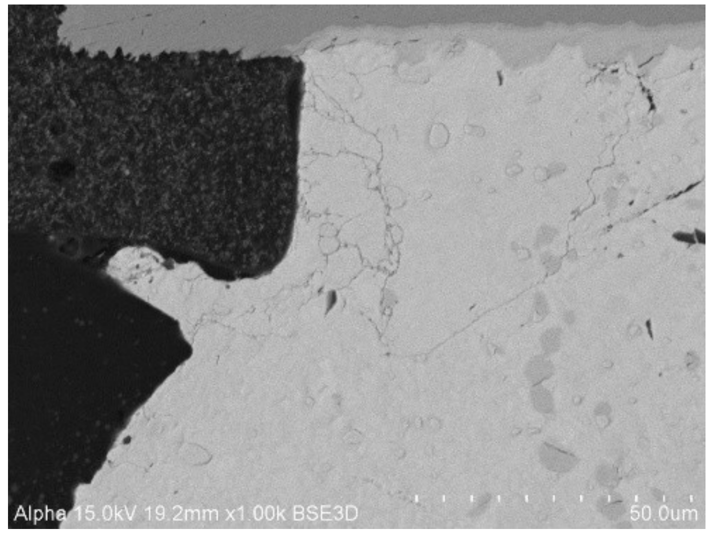


Figure 14: A cross section of the SAC305 BGA assembly after thermocycling showing SAC305 extrusion.

SUMMARY AND CONCLUSIONS

The use of Edgebond and Underfill materials has shown a substantial improvement in the thermal cycling performance of SAC305 assemblies. These reinforcements mitigate the impact of thermal expansion mismatches between the different materials, reducing the strain experienced by the solder joints and thereby extending their characteristic life. The enhanced thermal fatigue resistance provided by these reinforcements is critical for applications where electronic assemblies are subject to harsh thermal environments, ensuring greater long-term reliability and durability of the overall system. The study also highlights that under harsher environmental conditions, such as exposure to elevated temperatures, the need for reinforcement materials becomes even more critical. Selecting reinforcement materials with precisely tailored mechanical properties ensures that they are suitable for specific applications, ultimately contributing to the system's overall durability and robustness.

This study demonstrates reinforcement materials are essential for extending solder joint reliability in harsh thermal environments. Warpage behavior governs reinforcement effectiveness—concave packages benefit most from full underfill, whereas convex packages can be effectively supported by either Edgebond or underfill. High-reliability solder alloys enhance performance, but reinforcement is still required to meet automotive-grade durability standards for specific packages.

High-reliability solder alloys contribute to improvements but in some cases cannot independently meet harsh-environment standards. Their synergy with reinforcement materials is essential to achieve balanced performance.

From a manufacturing perspective, Edgebond solutions offer throughput and rework advantages, while underfills require additional process time and curing but deliver superior fatigue life. Hybrid strategies may represent the most robust path forward, particularly in safety-critical automotive electronics where both fatigue and impact resistance are mandatory.

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