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Microstructural Investigation of Solder Joint Failure in Heavy Duty Trucks

Master's thesis in Materials Engineering

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Abstract

The reliability of electronic control units (ECUs) used in heavy-duty vehicles is strongly influenced by the thermo-mechanical behaviour of Ball Grid Array (BGA) solder joints. This study investigates the microstructural evolution of SAC305 BGA solder joints subjected to accelerated environmental loading and compares laboratory-aged samples with a field-retained component.

SAC305 solder joints were investigated after thermal shock testing for 1000 and 2000 cycles, vibration testing, combined thermal cycling and vibration, and field service. The samples were characterized using polarized optical microscopy (POM), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), and quantitative Image analysis. The investigation focused on Ag_3Sn particle evolution and interfacial intermetallic compound (IMC) layers.

The results showed measurable microstructural evolution, including changes in Ag_3Sn particle morphology and distribution and variations in IMC thickness. The PCB-side IMC was generally thicker than the package-side IMC. No visible fatigue cracks or interfacial delamination were observed after 1000 or 2000 thermal cycles, indicating an early stage of solder degradation. The vibration and combined loading samples also exhibited microstructural changes, although the individual effects of thermal and mechanical loading could not be separated conclusively.

Comparison with the field-retained component showed differences in Ag_3Sn morphology and IMC characteristics, demonstrating that laboratory thermal shock alone cannot fully reproduce the complexity of field ageing.

Keywords: SAC305, BGA solder joints, microstructure, thermal shock, vibration, IMC, Ag_3Sn , solder reliability

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Bhushan Sudhakar, Gothenburg, September 2026

List of Acronyms

Below is the list of acronyms used throughout this thesis, listed in alphabetical order.

BGA	Ball grid array
DNP	Distance from neutral point
ECU	Electronic control unit
EBSD	Electron backscatter diffraction
EDS	Energy dispersive spectroscopy
IMC	Intermetallic compound
OM	Optical microscopy
PCBA	Printed circuit board assembly
POM	Polarized optical microscopy
ROI	Region of interest
SAC305	Sn-Ag-Cu 305 solder alloy
SEM	Scanning electron microscopy
XRD	X-ray diffraction

Nomenclature

$\Delta\alpha$	Coefficient of thermal expansion
ΔT	Temperature difference
T_m	Melting temperature
T_c	Creep temperature
h	Height of solder

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1

Introduction

The increasing use of electronic control systems in modern automotive applications has significantly increased the importance of reliability in electronic packaging assemblies. Heavy-duty vehicles rely extensively on electronic control units (ECUs), sensors, and advanced driver assistance systems (ADAS), which operate under harsh environmental conditions involving temperature variations, vibration loading, humidity, and mechanical stress[1]. Among the various components of electronic assemblies, solder joints are considered one of the most critical interconnections because they provide both electrical continuity and mechanical support between semiconductor packages and printed circuit boards (PCBs). Therefore, the reliability of solder joints plays an important role in determining the operational lifetime of automotive electronic systems[2],[3]. Ball Grid Array (BGA) packaging has become widely used in automotive electronics due to its high input/output density, compact structure, and improved electrical performance. However, differences in the coefficient of thermal expansion (CTE) between the component package, solder material, and PCB substrate generate Shear stresses during heating and cooling cycles[4]. Repeated thermal loading produces cyclic strain within solder joints, which gradually leads to fatigue damage, crack initiation, and crack propagation[2],[5]. Over time, these degradation mechanisms can reduce the structural integrity of solder interconnections and eventually result in electrical failure of the assembly. Thermal cycling and vibration loading are among the primary environmental conditions affecting solder joint reliability in automotive applications. In addition to temperature-induced fatigue, vibration loading also contributes to solder joint degradation through dynamic mechanical stresses and resonance effects[6]. The combined influence of thermal and mechanical loading conditions makes the reliability assessment of automotive electronic assemblies increasingly important.

The transition from conventional SnPb solder alloys to lead-free solder materials such as SnAgCu (SAC) alloys has further increased the importance of understanding solder joint reliability behaviour[7]. Environmental regulations such as the Restriction of Hazardous Substances (RoHS) directive accelerated the replacement of lead-based solders in electronic assemblies. Although SAC alloys provide improved environmental compatibility and good mechanical properties, their thermo-mechanical behaviour differs significantly from conventional SnPb solder systems, particularly under cyclic thermal and mechanical loading conditions[7]. Accelerated environmental testing methods such as thermal shock and vibration testing are widely used to evaluate the reliability of automotive electronic assemblies within a practical laboratory timescale. Although these methods successfully

reproduce many thermo-mechanical loading conditions experienced during service, it is important to understand how well the degradation mechanisms generated during laboratory testing correlate with those observed in field-returned electronic control units. Establishing this relationship improves confidence in accelerated reliability assessment and contributes to the development of more representative qualification methods for automotive electronic assemblies.[1]

Aim of the Thesis:

The main aim of this thesis is to investigate the reliability behaviour and microstructural evolution of SAC305 BGA solder joints subjected to accelerated environmental loading conditions.

The objectives of this study are:

1. To evaluate how well accelerated laboratory testing reproduces the degradation mechanisms observed in field-returned electronic control units, thereby improving the reliability assessment of automotive electronic assemblies.
2. To investigate the microstructural changes occurring in SAC305 solder joints after temperature cycling and vibration.
3. To analyse crack initiation, crack propagation behavior, and degradation mechanisms in thermally exposed solder joints.
4. Comparing the influence of thermal and mechanical loading conditions on solder joint reliability behaviour.
5. To improve the understanding of thermo-mechanical fatigue mechanisms affecting automotive BGA solder joint reliability.

2

Theory

This section consists of the packing structure of BGA, factors which affect the microstructure and the typical morphology of the microstructure of the SAC 305 solder alloy.

2.1 PCBA/BGA Design Parameters

The reliability of Ball Grid Array (BGA) solder joints is strongly influenced by the design and material properties of the electronic package. A typical BGA assembly consists of multiple materials with different mechanical and thermal properties, including the semiconductor package, solder joints and printed circuit board (PCB). The interaction between these components determines the distribution of stress within the solder joints during service. This section introduces the BGA package structure, copper pad design and PCB surface finishes, which influence solder joint reliability under thermo-mechanical loading.

2.1.1 BGA Package Structure

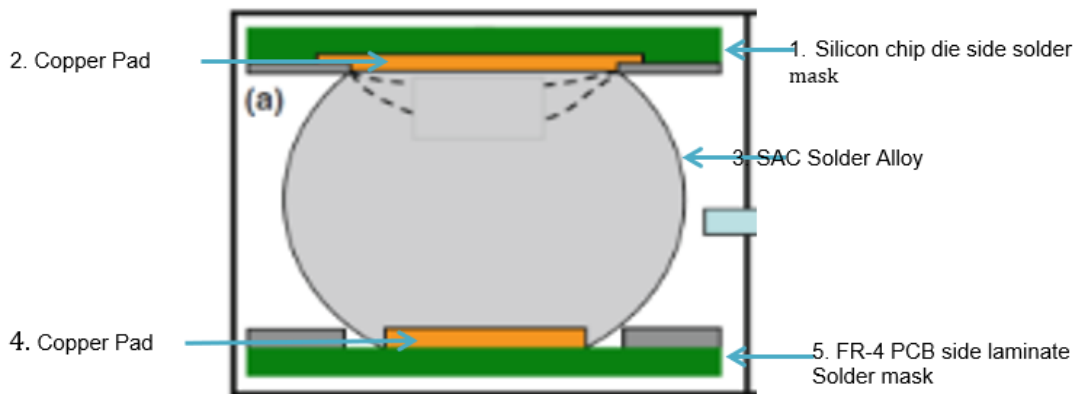


Figure 2.1: Structure of BGA Packaging [1]

Fig 2.1 depicts a typical BGA assembly consists of multiple material layers with different thermal and mechanical properties. These layers include the silicon die, package substrate, copper pads, solder balls, PCB pads, and the FR-4 printed circuit board. Each of these materials has a different coefficient of thermal expansion (CTE).

During temperature variations, the mismatch between the expansion behavior of these materials generates Shear Stresses within the solder joints. During repeated thermal cycling, the cyclic shear stresses cause dislocation motion within the solder. Progressive accumulation of these dislocations produces localized plastic deformation, eventually leading to crack initiation and propagation. However, continuous cyclic loading reduces their ability to accommodate deformation, resulting in fatigue damage over time. The definition of the solder pad geometry also influences the mechanical behaviour and reliability of BGA solder joints[1].

2.1.2 PCB Copper Pad Design (SMD and NSMD)

Fig 2.1 also shows two common pad designs are solder mask defined (SMD) and non-solder mask defined (NSMD) pads. In SMD pads, the solder mask opening is smaller than the copper pad, causing part of the pad edge to be covered by the solder mask. In contrast, NSMD pads have a solder mask opening larger than the copper pad, leaving the entire copper pad exposed for solder wetting[1].

The pad design influences the final geometry of the solder joint and the distribution of thermo-mechanical strain during service. Although SMD pads provide better mechanical adhesion between the copper pad and the substrate, reliability studies have shown that NSMD pads generally exhibit superior fatigue resistance under thermal cycling. This is because NSMD pads produce a solder joint geometry with a larger diameter near the pad interface, reducing local strain concentration. In contrast, SMD pads introduce stress concentration at the solder mask edge, where fatigue cracks can initiate and propagate more readily. For BGA components, SMD pads are often used on the package substrate to reduce the risk of copper pad lift-off, whereas NSMD pads are commonly preferred on the PCB because they generally provide improved solder joint fatigue life[1].

2.1.3 PCB Surface Finish

Fig 2.2 shows how PCB surface finish plays an important role in determining the microstructural characteristics and reliability of solder joints. Common PCB surface finishes include OSP (Organic Solderability Preservative), ENIG (Electroless Nickel Immersion Gold), and immersion silver. The type of surface finish influences diffusion behaviour, intermetallic compound formation, cooling characteristics, and the resulting solder microstructure. Nickel-based surface finishes act as diffusion barriers that suppress excessive copper migration from the PCB pad into the solder joint. As a result, the growth of Cu-containing intermetallic compounds is reduced and interfacial reactions become more controlled during thermal exposure. In contrast, copper-based OSP finishes allow easier diffusion of Cu into the solder, promoting formation of Cu_6Sn_5 intermetallic phases within both the interface and bulk solder microstructure. Studies reported that solder joints formed on OSP finishes exhibited finer Ag_3Sn dispersions, whereas joints on NiAu finishes showed coarser Ag_3Sn particles due to slower cooling behaviour associated with the higher thermal resistance of the Ni barrier layer. Excessive intermetallic growth and coarsening of Ag_3Sn particles may increase local brittleness and reduce the fatigue resistance of

solder joints during long-term thermo-mechanical loading[8].

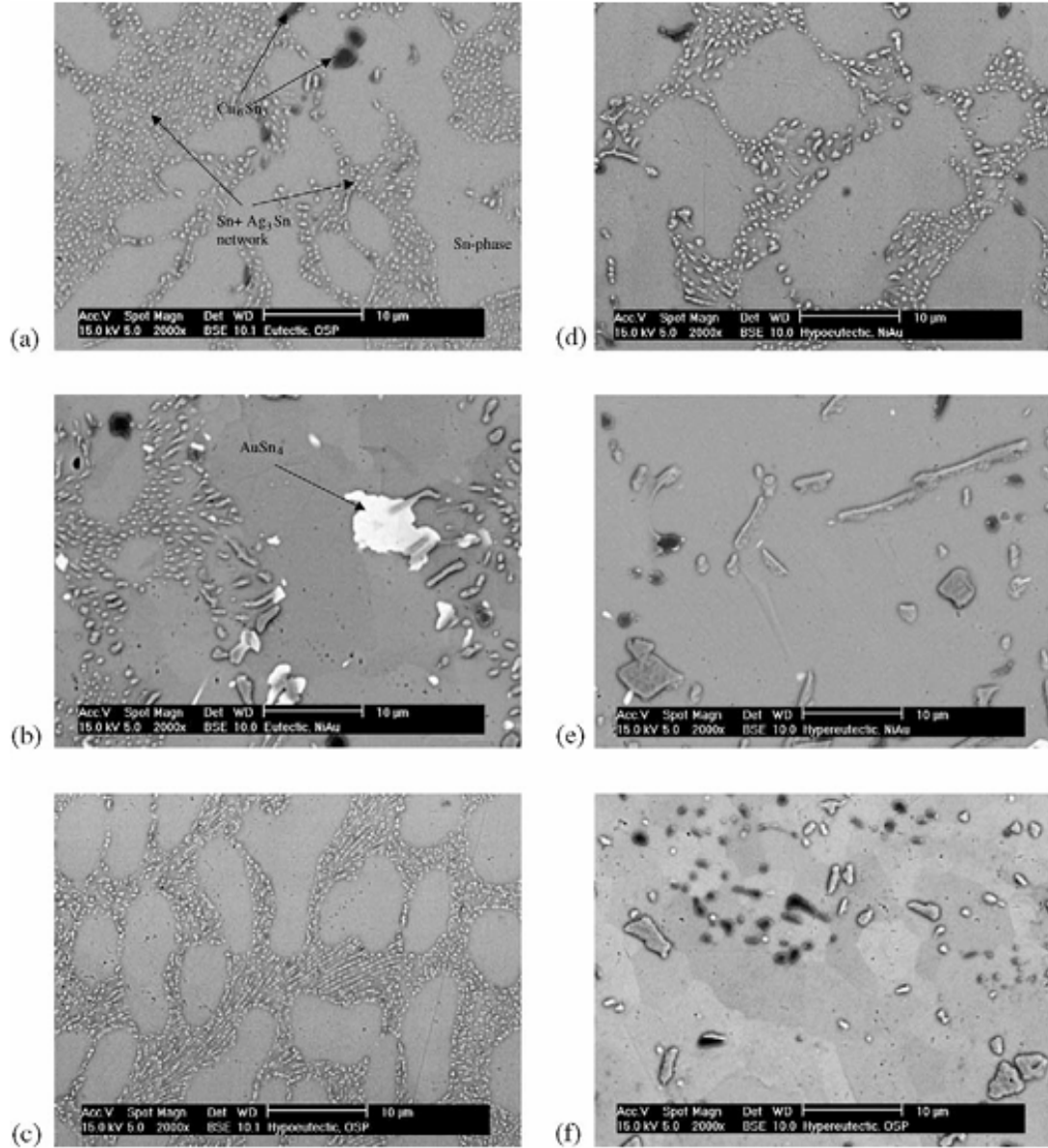


Figure 2.2: The dependence of the size of Ag₃Sn dispersions from the PCB surface finish and SnAgCu composition. (a) Eutectic SnAgCu on OSP; (b) eutectic SnAgCu on NiAu; (c) hypoeutectic SnAgCu on OSP; (d) hypoeutectic SnAgCu on NiAu; (e) hypereutectic SnAgCu on OSP; (f) hypereutectic SnAgCu on NiAu[8]

While the design and material selection of the BGA assembly influence its mechanical behaviour, the external operating conditions determine the magnitude and nature of the stresses experienced during service. The following section describes the environmental loads responsible for thermo-mechanical degradation of solder joints.

2.2 Environmental Loads

Electronic control units (ECUs) used in heavy-duty vehicles are exposed to various environmental loading conditions throughout their service life. The magnitude and type of loading depend on the installation location of the ECU and the operating conditions of the vehicle. In this study, the investigated ECU is installed near the rear axle, where it is subjected to significant temperature variations and road-induced mechanical vibrations. These environmental loads generate thermo-mechanical stresses within the BGA solder joints, leading to microstructural evolution and eventually fatigue damage. The following sections describe the influence of thermal and mechanical loading on solder joint reliability.

2.2.1 Thermal Loading

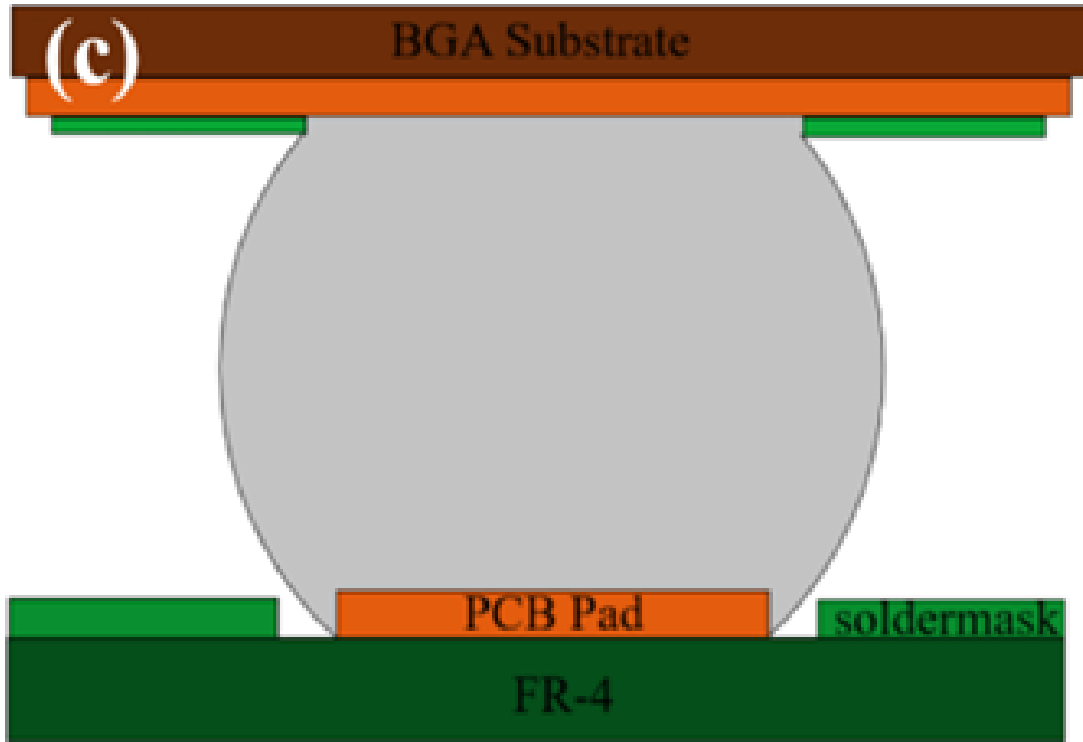


Figure 2.3: Single solder ball diagram[5]

The coefficient of thermal expansion mismatch between electronic packaging materials is one of the major causes of solder joint failure during thermal cycling. When the temperature changes, each material expands or contracts at a different rate depending on its CTE value and fig 2.3 shows how different materials are stacked together. This difference generates cyclic shear strain within the solder joints.

For example, silicon typically has a CTE of approximately 2.6 ppm/°C, while FR-4 PCB materials have CTE values in the range of 14–17 ppm/°C. This large mismatch

produces significant thermomechanical strain during temperature cycling between low and high temperature extremes. Repeated accumulation of this strain eventually leads to fatigue failure of solder joints[1], [4], [5].

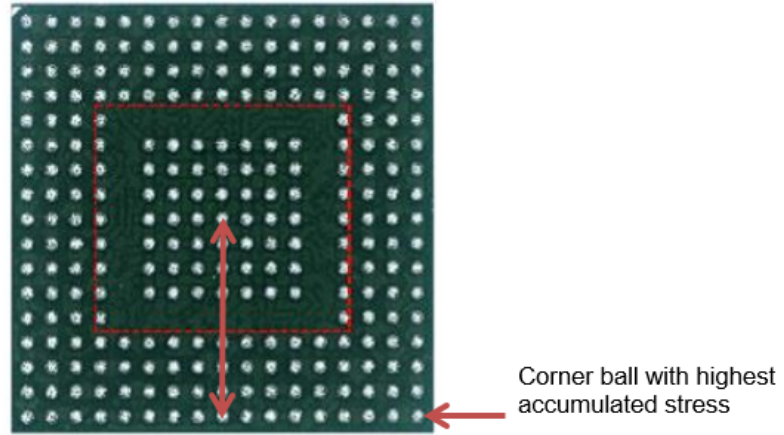


Figure 2.4: Depiction of DNP from neutral point[3]

The distance from neutral point (DNP) is an important parameter used to estimate the magnitude of shear strain experienced by solder joints in area array packages such as BGA assemblies as seen in fig 2.4. The neutral point represents the location within the package where no relative displacement occurs during thermal expansion. Solder joints located farther from the neutral point experience larger displacement and therefore higher strain compared to joints located near the center of the package. The shear strain experienced by a solder joint can be approximated as:

$$\gamma = \frac{DNP \Delta \alpha \Delta T}{h}$$

where, DNP = distance from neutral point , $\Delta \alpha$ = CTE mismatch between 2 materials, ΔT = temperature range, h = solder joint height . This relationship explains why corner solder joints are more susceptible to fatigue failure compared to central joints[9].

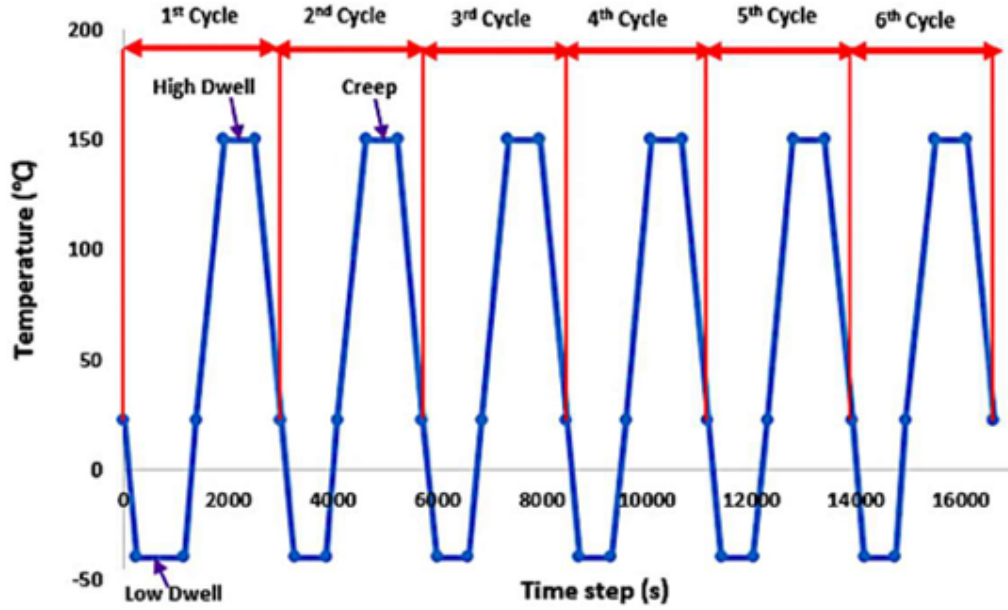


Figure 2.5: Thermal cycle with high and low dwell regions[10]

Fig 2.5 illustrates a typical thermal cycling profile consisting of a heating stage, high-temperature dwell, cooling stage and low-temperature dwell. During each cycle, the solder joint repeatedly expands and contracts due to the coefficient of thermal expansion (CTE) mismatch between the package, solder joint and PCB. These cyclic dimensional changes generate thermo-mechanical stresses within the solder joint, which contribute to the accumulation of fatigue damage during repeated thermal cycling.

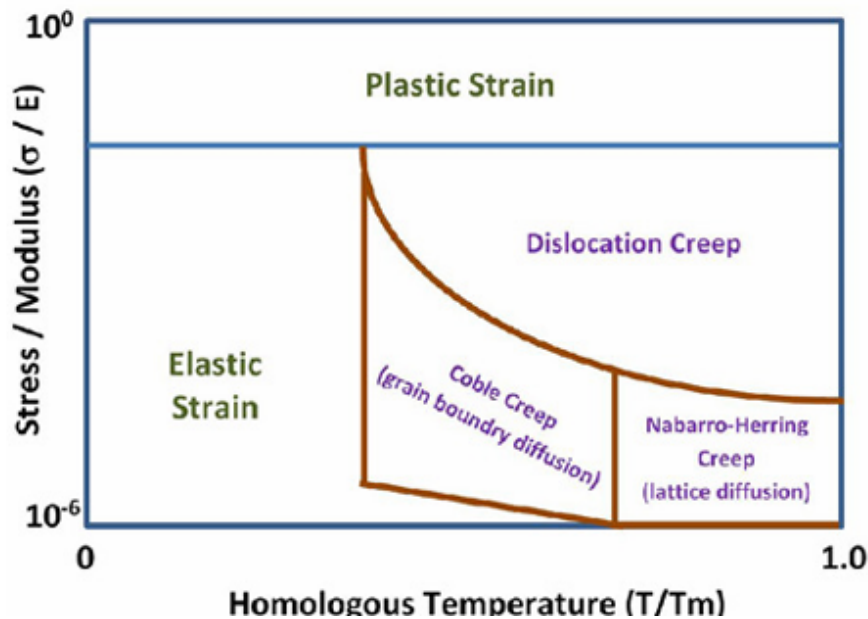


Figure 2.6: A representative schematic of a deformation map showing the various mechanisms that can induce damage during cyclic fatigue[11]

Fig 2.6 presents a deformation mechanism map illustrating the dominant deformation mechanisms in solder materials as a function of homologous temperature and applied stress. At relatively low homologous temperatures and applied stresses, the solder undergoes elastic deformation, which is fully recoverable upon removal of the applied load. As the homologous temperature increases, the elastic modulus and yield strength of the solder decrease, making the material more susceptible to permanent deformation. Consequently, the dominant deformation mechanism gradually shifts from elastic deformation to creep, as shown in Figure 2.6. Since SAC305 solder operates at a relatively high homologous temperature during thermal cycling, creep becomes the primary deformation mechanism. Creep is a time-dependent plastic deformation mechanism that results in the gradual accumulation of permanent strain under sustained thermo-mechanical loading. This accumulated strain contributes to microstructural evolution and eventually promotes fatigue damage in solder joints. The homologous temperature (T_h) is defined as the ratio of the operating temperature (T) to the melting temperature (T_m), both expressed in Kelvin:

$$T_h = T_{\text{Operating}} / T_{\text{Melting}}$$

When the homologous temperature exceeds approximately 0.4, diffusion-controlled creep becomes increasingly significant in SAC305 solder. During the heating stage of thermal cycling, creep deformation accumulates because of the combined effects of elevated temperature and thermo-mechanical stresses arising from CTE mismatch. During cooling, contraction of the assembly reverses the direction of the thermo-mechanical stresses; however, the accumulated creep strain is not fully recovered. Consequently, repeated thermal cycling results in progressive strain accumulation, microstructural evolution and eventually fatigue crack initiation[11].

2.2.2 Mechanical/Vibrational Loading

In addition to thermal loading, automotive electronic control units (ECUs) are subjected to mechanical vibrations during normal vehicle operation. These vibrations originate from road irregularities, engine operation, braking events and chassis dynamics, producing cyclic bending and deformation of the printed circuit board (PCB). As the PCB deforms, cyclic mechanical stresses are transferred to the BGA solder joints, which can contribute to fatigue damage. Although vibration alone may not always initiate solder joint failure, it can accelerate crack initiation and propagation, particularly in joints that have already experienced thermo-mechanical degradation. Consequently, vibration testing is commonly performed during reliability evaluation to assess the mechanical durability of electronic assemblies operating under automotive service conditions. In practical applications, BGA solder joints are often exposed to both thermal and mechanical loading throughout their service life. The combined effect of these loading conditions influences the long-term reliability of solder joints and is therefore considered during automotive reliability testing[6].

2.3 Microstructure of SAC305

The microstructure of SAC305 solder joints plays an important role in determining the mechanical behaviour and long-term reliability of electronic assemblies under

thermo-mechanical loading conditions. During thermal cycling, vibration, and thermal aging exposure, the solder joint undergoes continuous microstructural evolution due to cyclic stresses, creep deformation, and diffusion-controlled reactions. These microstructural changes influence the mechanical strength, ductility, fatigue resistance, and crack propagation behaviour of the solder joint. SAC305 solder joints mainly consist of a β -Sn matrix together with intermetallic compounds such as Ag_3Sn and Cu_6Sn_5 , whose morphology and distribution strongly affect reliability performance. In addition, phenomena such as intermetallic compound growth, recrystallization, grain coarsening, and void formation contribute and indicate degradation.

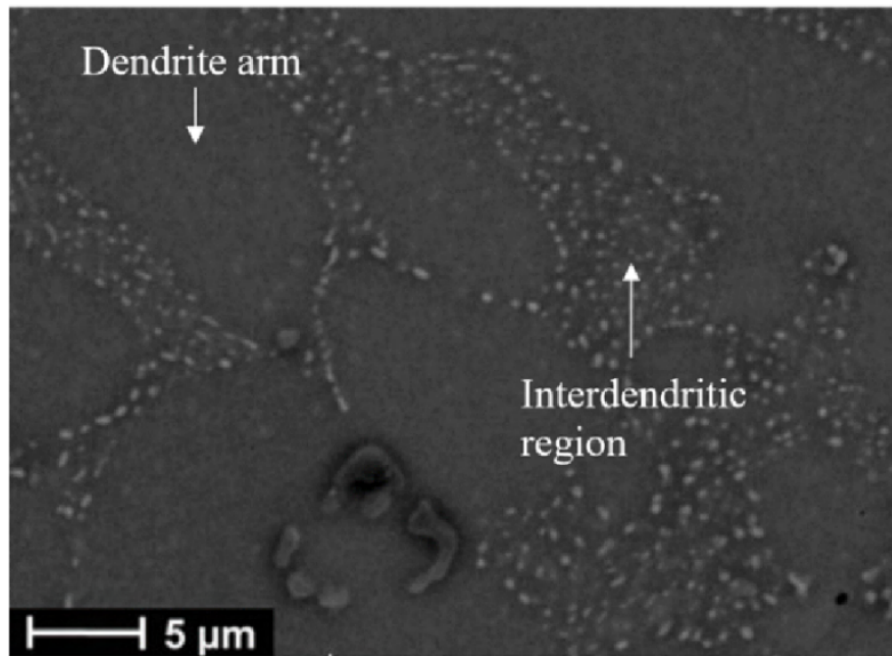


Figure 2.7: Microstructure of solder joint showing dendrite arms and interdendritic regions[1]

SAC305 is one of the most widely used lead-free solder alloys in electronic packaging applications due to its relatively low melting temperature, good mechanical properties, and compatibility with microelectronic assemblies. The microstructure of SAC305 solder joints primarily consists of a β -Sn matrix together with intermetallic compounds (IMCs) such as Ag_3Sn and Cu_6Sn_5 as seen in Fig 2.7 . The morphology, size, and distribution of these phases strongly influence the thermo-mechanical reliability and fatigue behaviour of solder joints under thermal and mechanical loading conditions[1], [4].

2.3.1 Grain Structure and Anisotropy of β -Sn

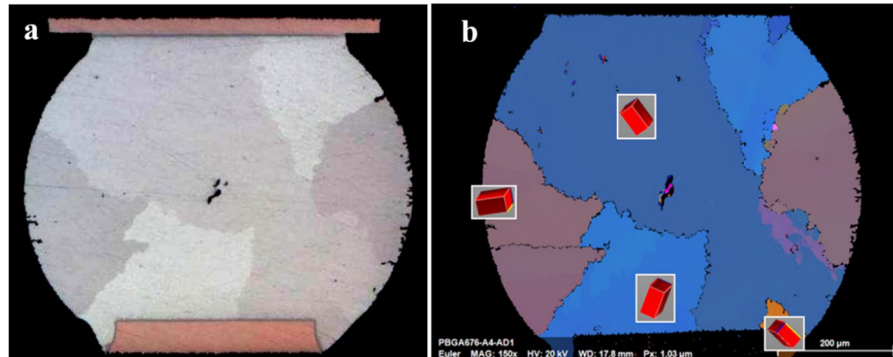


Figure 2.8: SAC solder joint to a BGA676 component examined using (a) polarised light and (b) electron backscatter diffraction showing a cyclic twin structure. Grains with the same orientation have the same colour[1]

The thermomechanical behaviour and reliability of SAC solder joints are strongly influenced by the crystallographic orientation of β -Sn grains. Due to the body-centered tetragonal crystal structure of β -Sn, its thermal and mechanical properties exhibit significant anisotropy. The coefficient of thermal expansion and elastic modulus vary depending on crystallographic direction, resulting in non-uniform strain accumulation during thermal cycling exposure. Studies reported that solder joints containing β -Sn grains with the c-axis oriented nearly parallel to the substrate experienced higher thermo-mechanical stresses and exhibited earlier crack initiation compared to neighbouring joints with different orientations[12].

Polarized light microscopy is commonly used to examine β -Sn grain orientation because differently oriented grains interact differently with polarized light and appear with varying colours or contrast as seen in Fig 2.8 . Large single-grain structures and cyclic twinning morphologies such as “Kara’s Beach Ball” microstructures are commonly observed in SAC solder joints[1], [12].

2.4 Microstructure Evolution

During service, SAC305 solder joints undergo continuous microstructural changes because of thermo-mechanical loading. Repeated thermal cycling and mechanical vibration promote diffusion, plastic deformation and creep within the solder joint, leading to progressive changes in the intermetallic compound (IMC) layer and solder microstructure. These microstructural changes include IMC growth, Ag_3Sn particle coarsening, recrystallization and fatigue crack initiation, all of which influence the long-term reliability of BGA solder joints. The following sections describe these degradation mechanisms and their contribution to solder joint failure.

2.4.1 Intermetallic Compound (IMC) Formation and Growth

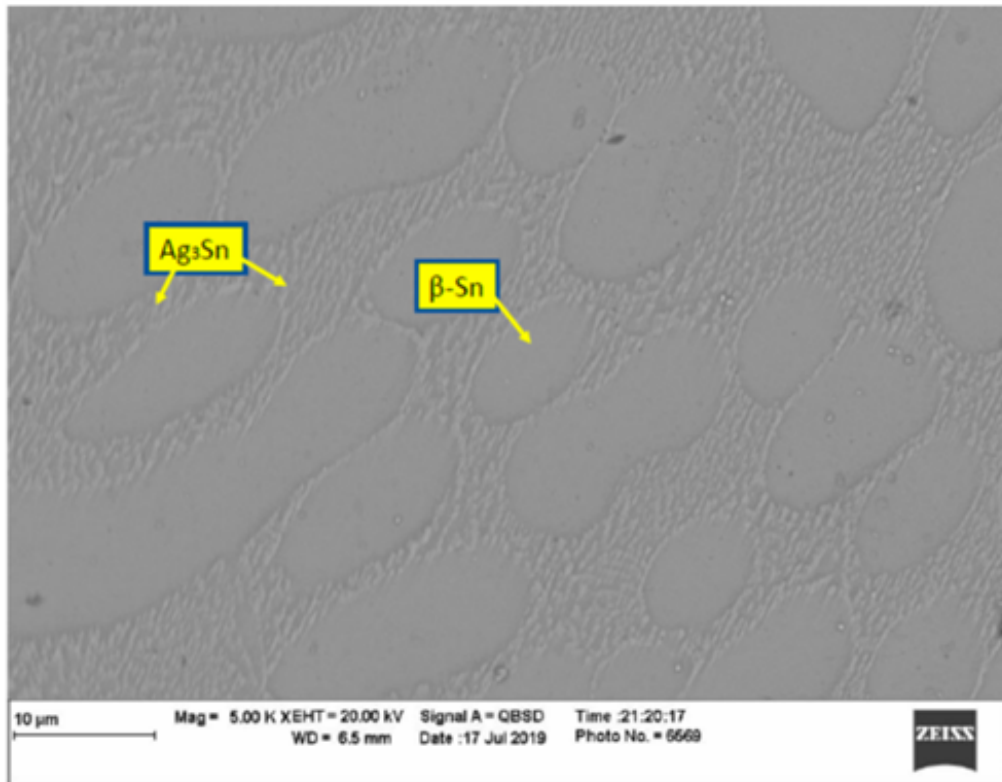


Figure 2.9: Microstructure of SAC305 as prepared (no aging)[13]

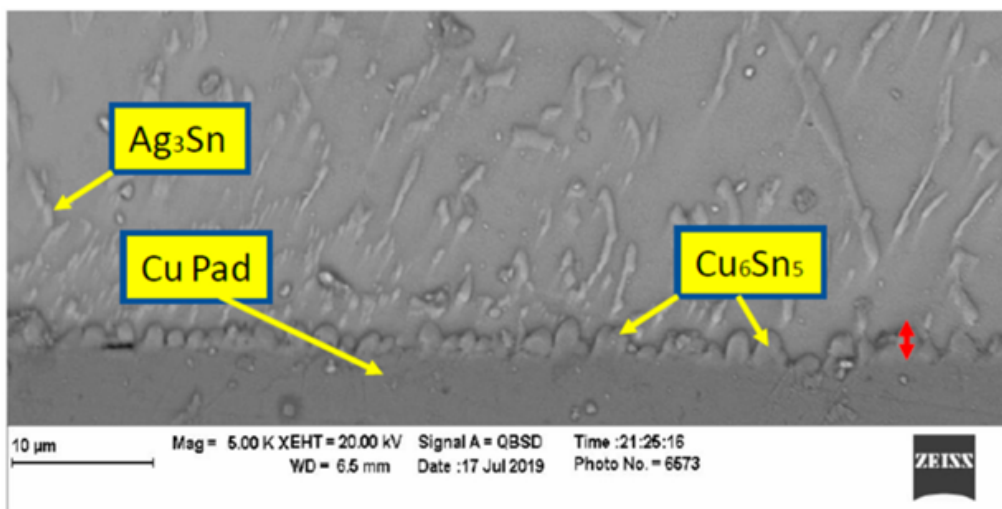


Figure 2.10: Microstructure of SAC305 fused to a copper pad as prepared (no aging)[13]

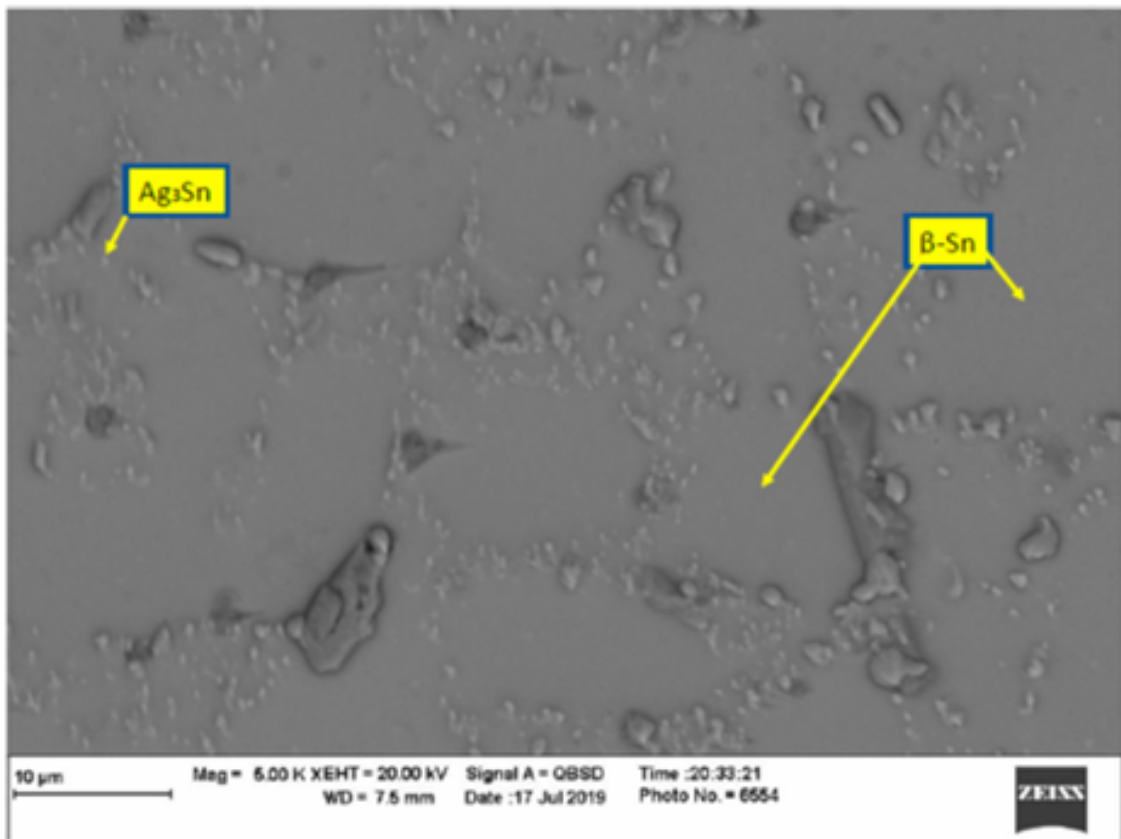


Figure 2.11: Microstructure of SAC305 thermally aged at 150 °C for 1000 h[13]

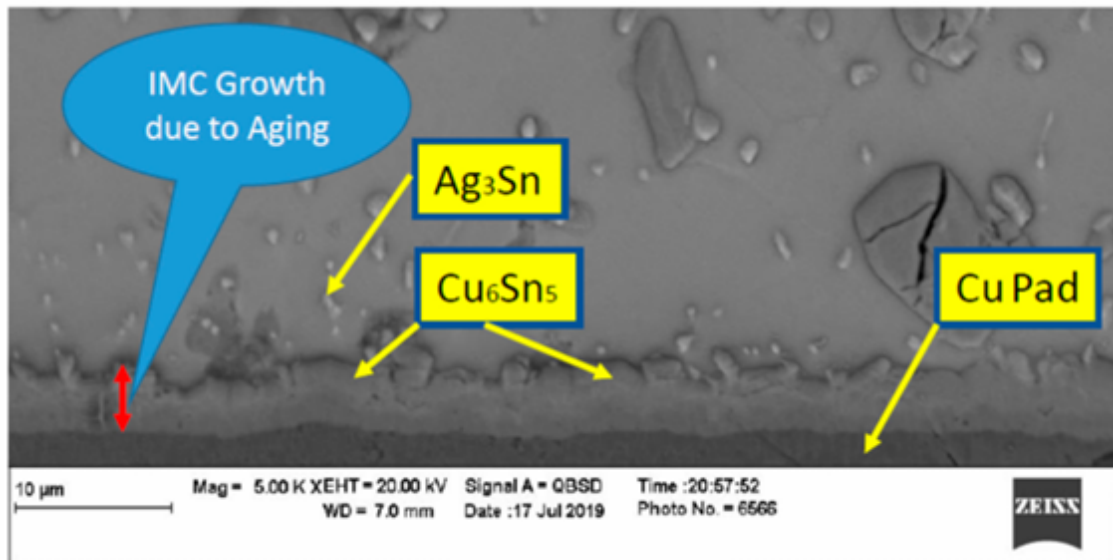


Figure 2.12: Microstructure of SAC305 fused to a copper pad and then thermally aged at 150 °C for 1000 h[13]

During soldering and thermal exposure, diffusion-controlled reactions occur continuously at the solder–substrate interface, resulting in the formation and growth

of intermetallic compounds that can be seen from Figs 2.9 to 2.12. In SAC305 solder joints, Cu_6Sn_5 commonly forms at the solder–copper interface, while Cu_3Sn may develop during prolonged thermal exposure. Initially, thin IMC layers improve metallurgical bonding between the solder and substrate materials. However, excessive IMC growth increases interfacial brittleness and reduces solder joint ductility[13].

2.4.2 Ag_3Sn Morphology and Mechanical Behaviour

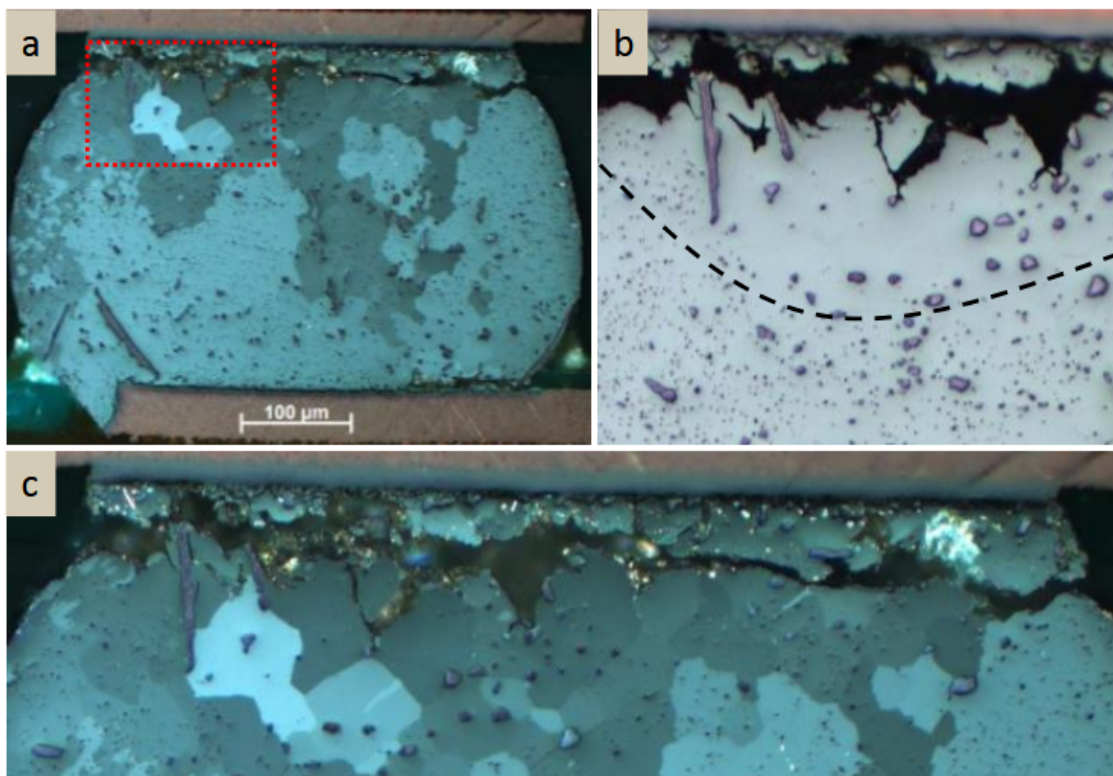


Figure 2.13: Optical micrographs of a solder joint after thermal cycling, 0/100°C : (a) cross-polarized (b) bright field, of the same joint. In the recrystallized region above the dashed line, larger and fewer precipitates are evident. (c) The intergranular fatigue crack can be seen at higher magnification[2]

Ag_3Sn intermetallic compounds may appear in different morphologies such as spheroids, needles, and platelets depending on solidification conditions and alloy composition which can be seen in Fig 2.13 . Although Ag_3Sn particles contribute to mechanical strength and hardness, they are relatively brittle compared to the surrounding β -Sn matrix. Coarse Ag_3Sn particles therefore act as stress concentration sites under cyclic thermo-mechanical loading and may accelerate fatigue crack initiation within the solder joint[2], [6], [7].

2.4.3 Recrystallization and Grain Coarsening

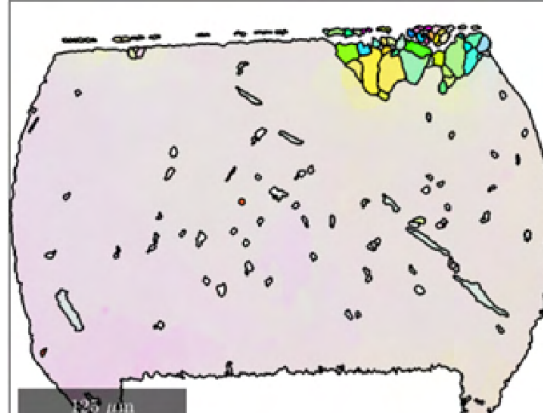


Figure 2.14: EBSD image of a cross-section of a solder joint to a BGA component showing a recrystallized region at the upper right corner[1]

Repeated thermo-mechanical loading during thermal cycling results in cyclic plastic deformation and dislocation accumulation within the β -Sn matrix. As stored strain energy increases, recrystallization occurs within highly strained regions of the solder joint, particularly near solder-IMC interfaces and crack-tip regions as seen in Fig 2.14 . Newly formed recrystallized grain boundaries often act as preferred crack propagation paths because of their lower resistance to fatigue crack growth. Recrystallization can be characterized quantitatively using Electron Backscatter Diffraction (EBSD), while cross-polarized optical microscopy (POM) provides a qualitative indication of grain structure and orientation through changes in optical contrast. Thermal ageing also promotes grain coarsening and precipitate coarsening, reducing the ability of the solder material to accommodate cyclic deformation[1].

The degradation of SAC305 solder joints during thermal cycling occurs progressively rather than through immediate fracture. Fatigue failure is generally preceded by a sequence of microstructural changes, including precipitate coarsening, recrystallization and finally crack initiation and propagation. These stages are influenced by cyclic thermo-mechanical loading and diffusion processes occurring within the solder joint. The overall fatigue process can be described as the sum of the individual microstructural stages:

$$N_{\{failure\}} = N_{\{coars\}} + N_{\{recr\}} + N_{\{crack\ growth\}}$$

where:

N_{coars} - represents the number of thermal cycles required for Ag_3Sn particle coarsening;

N_{recr} - represents the number of cycles required for recrystallization;

$N_{crack\ growth}$ - represents the number of cycles required for crack initiation and subsequent crack propagation[1].

2.4.4 Void Formation in BGA Solder Joints

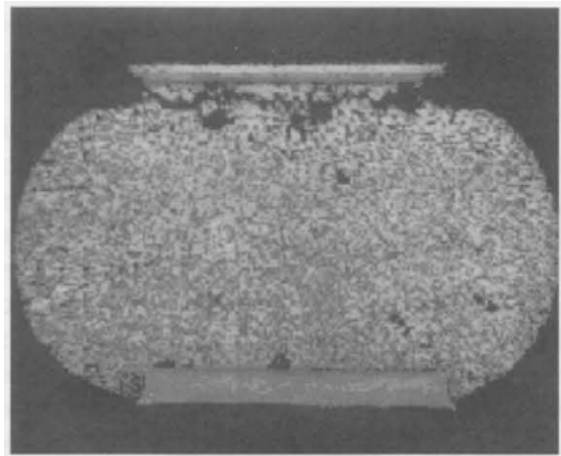


Figure 2.15: Failure with few voids[14]

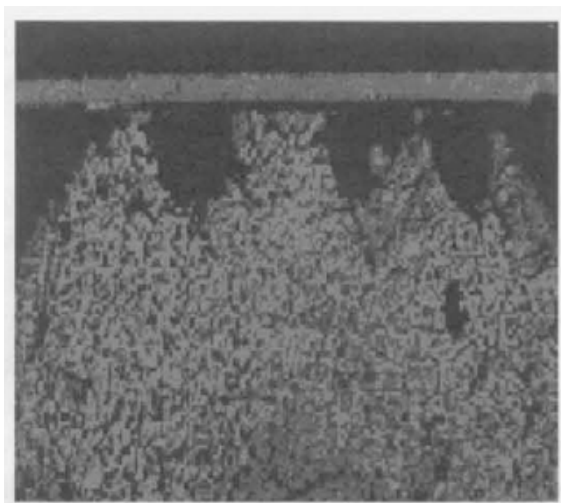


Figure 2.16: Failure with dominant voids[14]

Voids are cavities or gas-filled bubbles trapped within the solder joint during the reflow process. Void formation may occur due to flux outgassing, oxidation, moisture contamination, solder paste composition, reflow profile, and attachment metallurgy. Most voids observed in BGA solder joints are spherical in shape because gases trapped inside molten solder minimize surface energy during solidification as seen in Fig 2.15 . Large voids located near highly stressed regions may act as stress concentration sites and accelerate fatigue crack initiation and propagation during thermal cycling exposure as seen in Fig 2.16[14].

3

Methods

This chapter describes the experimental procedures used to investigate the reliability of BGA solder joints subjected to thermal shock and mechanical vibration. The test methodology included determination of ECU thermal equilibrium and dwell time, thermal shock testing, vibration testing, functional verification, and metallographic sample preparation. The experimental procedures and test conditions used throughout the study are described in the following sections.

3.1 Determination of ECU Thermal Equilibrium and Dwell Time

To determine an appropriate dwell time for the thermal shock test, temperature measurements were performed on the ECU assemblies using thermocouples connected to a Dewesoft data acquisition system. The objective was to determine the time required for the ECU to reach thermal equilibrium at the high- and low-temperature extremes (100°C and -40°C).

Thermocouples were attached to the BGA package Centre, BGA package edge, PCB Centre, and chamber air locations. The measured temperature data were used to evaluate the thermal response of the ECU during heating and cooling transitions and to determine the actual stabilization time at each temperature extreme.

3. Methods

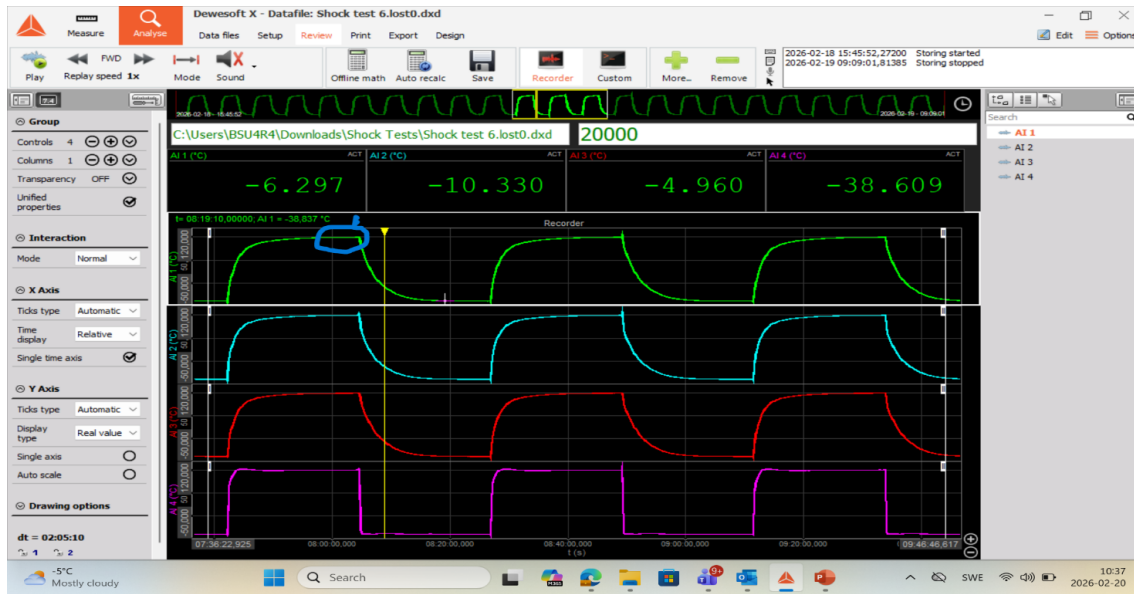


Figure 3.1: Temperature curve of thermocouple sensors A1 to A4

Calibration runs were conducted using a chamber dwell setting of 20 minutes. The chamber air temperature reached the target temperature as seen in Fig 3.1 (Sensor A4) rapidly because of its low thermal mass. However, the BGA package and PCB required additional time to reach thermal equilibrium.

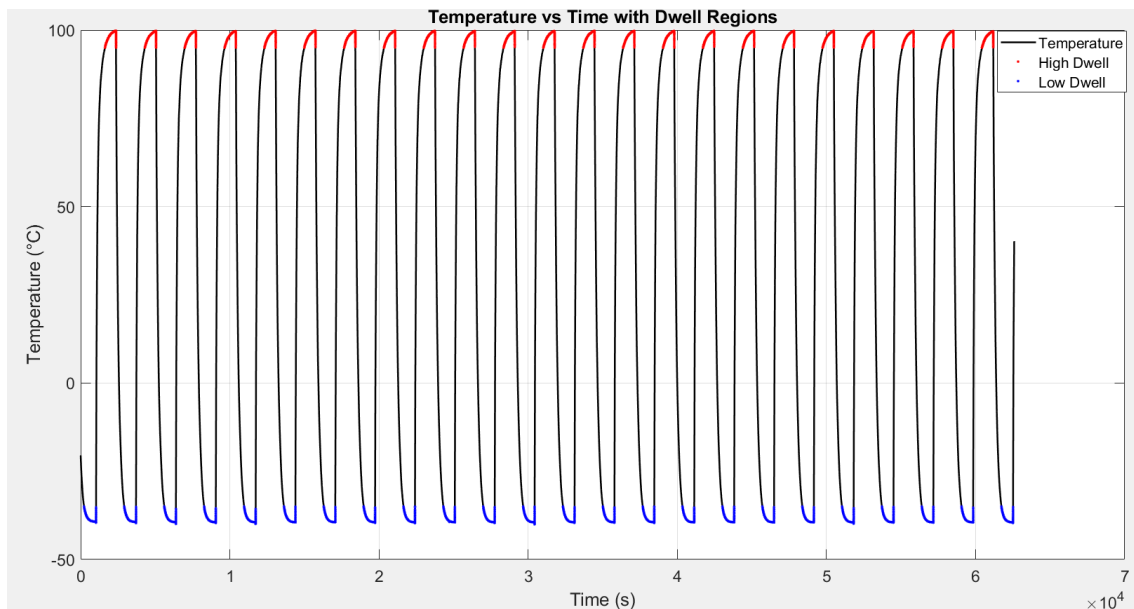


Figure 3.2: Temperature vs time plot with highlighted dwell regions

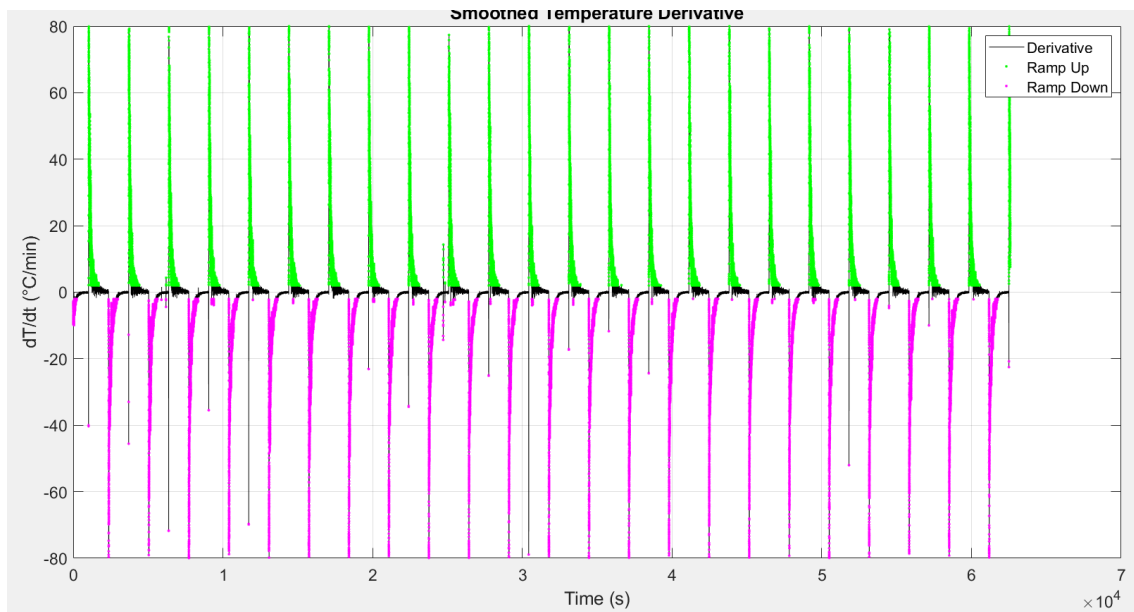
Fig 3.2 shows the temperature response of the BGA center during thermal cycling. The temperature data were analyzed using MATLAB to determine the time required for the ECU assemblies to reach thermal equilibrium at the high- and low-temperature extremes. The results are summarized in Table 3.1.

Table 3.1: Thermal equilibrium and cycle parameters obtained during calibration measurements.

Parameter	Value
Average Delta T	139.41°C
Average High Dwell	753.16 seconds
Average Low Dwell	777.52 seconds
Average Cycle Duration	44.54 minutes
Cycles per hour	1.35

The average stabilization time at the high-temperature extreme was 753.16 s, while the average stabilization time at the low-temperature extreme was 777.52 s. These values correspond to approximately 12–13 minutes and indicate that the ECU assemblies reached thermal equilibrium within the programmed 20-minute dwell period.

The calibration results indicated that the ECU assemblies reached thermal equilibrium within the programmed chamber dwell period. Based on these results, a dwell time of 12 minutes was selected for the subsequent thermal shock testing.

**Figure 3.3:** Temperature derivative vs time plot

The heating and cooling behaviour of the chamber was further evaluated using the temperature derivative obtained from MATLAB analysis. As shown in Fig 3.3 and summarized in Table 3.2, the average heating rate was 14.61 °C/min and the average cooling rate was 13.93 °C/min. smoothing of curve was done to reduce noise and artificial peaks. The measured ramp rates demonstrated stable and repeatable chamber performance throughout the calibration study.

Table 3.2: Heating and cooling rate characteristics obtained from calibration measurements.

Parameter	Value
Average Ramp Up	14.61°C/min
Average Ramp Down	13.93°C/min

3.2 Thermal Shock Test Run

Thermal shock testing was performed using six ECU assemblies in a thermal shock chamber operating between -40°C and 100°C. Based on the thermal equilibrium measurements described in Section 3.1, a dwell time of 12 minutes was selected for the test.

Three ECU assemblies were subjected to 1000 thermal shock cycles, while the remaining three assemblies were tested for 2000 cycles. Following completion of the first 1000 cycles, three samples were removed from the test and the remaining samples continued for an additional 1000 cycles.

The ECU assemblies were arranged inside the chamber as described below. Samples 1 and 2 were positioned closer to the chamber door and mounted horizontally, whereas Samples 3 and 4 were positioned closer to the chamber fan and mounted vertically. This arrangement allowed the influence of sample position and orientation on the thermal response to be evaluated.

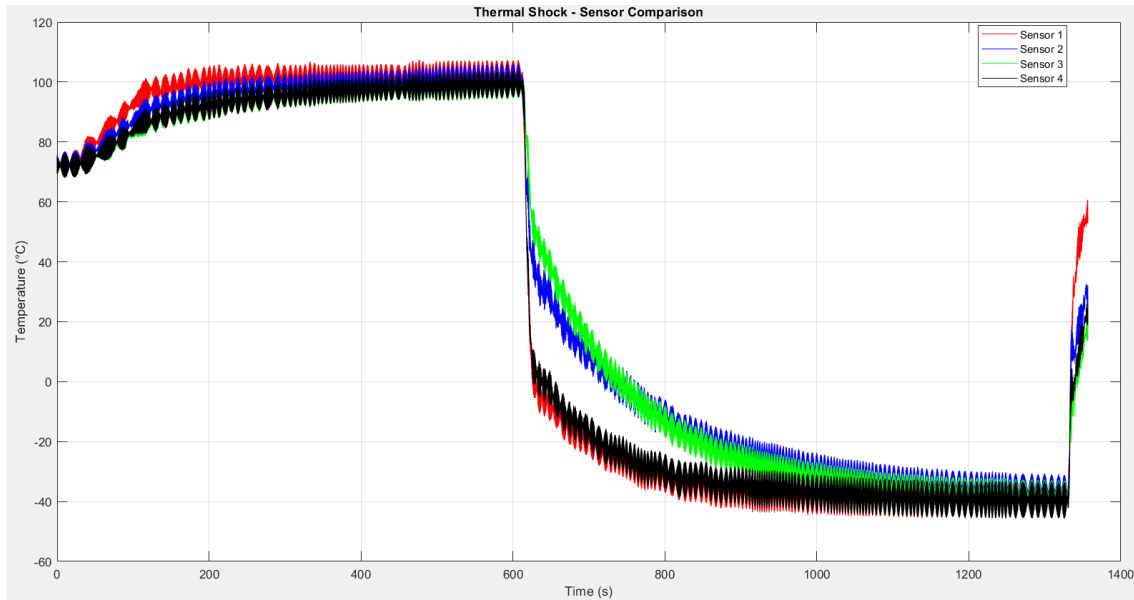


Figure 3.4: Temperature curve of thermocouple sensors

Since the initial calibration study was performed using a single ECU assembly, additional temperature measurements were conducted during the 1000-cycle thermal shock test to verify that all tested assemblies reached thermal equilibrium within the selected dwell period. The measured temperature profiles are presented in Fig 3.4 .

Although differences in the transient heating and cooling responses were observed due to sample position and orientation within the chamber, all monitored samples reached the target temperatures and achieved thermal equilibrium within the selected dwell period. These results confirmed that the selected dwell time was appropriate for the thermal shock testing performed in this study.

3.3 Vibration Testing

Mechanical vibration testing was performed on a separate set of ECU assemblies to after thermal shock test to evaluate their structural integrity under vibration loading. The tests were conducted using laboratory vibration equipment in accordance with Scania test requirements. Owing to confidentiality restrictions, the detailed vibration parameters cannot be presented in this report. Functional verification was performed before and after testing to confirm continued ECU operation.

3.4 Functional Testing

Functional testing was performed before and after environmental testing to verify the operational status of the ECU assemblies. Communication with the ECU was established through the CAN interface, and diagnostic fault codes (DTCs) were checked using the designated diagnostic software. The test confirmed that all ECU assemblies remained operational and no new fault codes were detected following testing.

3.5 Sample Preparation for Metallographic Analysis

Following completion of thermal shock, vibration, and functional testing, selected ECU assemblies were prepared for metallographic analysis. The objective of the sample preparation procedure was to expose the BGA solder joints for microscopic examination while preserving the microstructural features and damage mechanisms generated during testing. The preparation procedure consisted of cross-sectioning, epoxy mounting, grinding, polishing, and SEM preparation, as described in the following sections.

3.5.1 Cross-Sectioning

Following completion of thermal shock and vibration testing, selected ECU assemblies were prepared for metallographic analysis. The objective was to expose multiple BGA solder joints within a single cross-section to enable efficient inspection of crack initiation, crack propagation, and solder joint degradation. The cross-section locations were selected to allow simultaneous examination of several solder joints. Initial sectioning was performed using an accurate cutting machine, followed by precision cutting with a diamond cutting disc. Cutting parameters were selected

to minimize mechanical deformation of the solder joints and preserve the post-test condition of the samples. The cutting orientation was chosen to maximize the number of visible solder joints within each mounted specimen and facilitate comparison between laboratory-tested and field-returned samples.

3.5.2 Cold Mounting in Epoxy



Figure 3.5: Sample cold mounted in Epoxy

After sectioning, the samples were mounted in epoxy resin using a cold-mounting process as seen in Fig 3.5 . Cold mounting was selected because elevated temperatures used during hot mounting may alter the solder joint microstructure, increase intermetallic compound growth, or modify existing fatigue cracks. The mounting orientation was selected to ensure that multiple solder joints could be observed simultaneously during microscopy.

3.5.3 Grinding and Polishing

Following mounting, the samples were prepared using a multi-stage grinding and polishing procedure. The complete preparation sequence and process parameters are summarized in Fig 3.6 .

Step	Surface	Lubricant	RPM	Force	Time
PG	SiC-Foil 320	Water	300/150	25 N	1 min × 2
FG1	MD-Largo	DiaPro Allegro/Largo 9	150/150	25 N	7.5 min
FG2	MD-Dur	DiaProDur 3	150/150	25 N	5 min
FG3	MD-Dur	DiaProDur 3	150/150	10 N	5 min
FG4	MD-Nap 1 μm	DiaPro Nap B1	150/150	10 N	5 min
FG5	MD-Nap 1/4 μm	DiaPro Nap 1/4	150/150	10 N	5 min
FG6	MD-Nap 1/4 μm	DiaPro Nap 1/4	150/150	5 N	2 min

Figure 3.6: Grinding and polishing parameters used for metallographic sample preparation

The preparation started with planar grinding using SiC-Foil 320 with water as the lubricant, at 25 N and 300/150 rpm for two 1-minute steps. This was followed by fine grinding using MD-Largo with DiaPro Allegro/Largo at 25 N and 150/150 rpm for 7.5 minutes. Further grinding was performed using MD-Dur with DiaPro Dur3 at 25 N for 5 minutes, followed by a second MD-Dur step at a reduced force of 10 N for 5 minutes.

Polishing was subsequently performed using MD-Nap 1 μm with DiaPro Nap B1 at 10 N for 5 minutes. This was followed by polishing with MD-Nap 1/4 μm using DiaPro Nap 1/4 at 10 N for 5 minutes. A final polishing step was performed using the same MD-Nap 1/4 μm and DiaPro Nap 1/4 combination at a reduced force of 5 N for 2 minutes. The multi-stage procedure was used to progressively remove surface deformation and obtain a suitable surface for metallographic examination of the solder microstructure. After the 3, 1 and 1/4 μm steps: rinse only with ethanol. The final two steps are run against each other.

3.6 Analysis Methodology

Following sample preparation, the solder joints were characterized using complementary microscopy and analytical techniques to investigate their microstructure, elemental distribution, and phase composition. Optical microscopy, SEM, EDS, XRD and ImageJ analysis were employed to provide qualitative and quantitative information regarding the effect of thermal shock, vibration and field service on the solder joints.

3.6.1 Optical Microscopy

Following sample preparation, the cross-sections were initially examined using optical microscopy (OM). Optical microscopy was used to evaluate the overall quality of the sample preparation, identify solder joint locations, and perform a preliminary assessment of crack formation and microstructural features. Representative optical micrographs were recorded for further analysis.

3.6.2 Polarized optical microscopy

Polarized optical microscopy (POM) was used to examine the solder joint microstructure based on crystallographic orientation contrast. POM images provided qualitative

information regarding grain structure, recrystallized regions and general microstructural features prior to detailed SEM examination.

3.6.3 Scanning Electron Microscopy (SEM)

Detailed examination of the solder joints was performed using scanning electron microscopy (SEM). SEM provides higher magnification and improved image resolution compared to optical microscopy, enabling detailed observation of fatigue cracks, intermetallic compound layers, and solder microstructural features. Prior to SEM imaging, the samples were coated with a 10 nm platinum layer to reduce charging effects and improve image quality.

3.6.4 Image Analysis

SEM micrographs were analyzed using ImageJ software to obtain quantitative information on the Ag_3Sn intermetallic particles within the solder matrix. The ROIs were selected from comparable regions on the PCB-side solder matrix and were kept as similar in dimensions as practically possible. Minor differences in ROI dimensions occurred for some samples and are therefore considered a source of uncertainty in the ImageJ comparison.

3.6.5 EDS

Energy dispersive spectroscopy (EDS) was performed in conjunction with SEM to determine the elemental composition and distribution within the solder joints. Elemental mapping, point analysis and line scans were conducted to identify the distribution of Sn, Ag, Cu and Ni, and to examine the intermetallic compound (IMC) layer at the solder interfaces.

3.6.6 X-ray Diffraction

X-ray diffraction (XRD) analysis was performed to identify the crystalline phases present within the solder joint and confirm the phase composition observed during SEM and EDS analysis. The diffraction patterns were compared with reference diffraction data from the literature to verify the identified phases.

4

Results

4.1 Analysis from POM

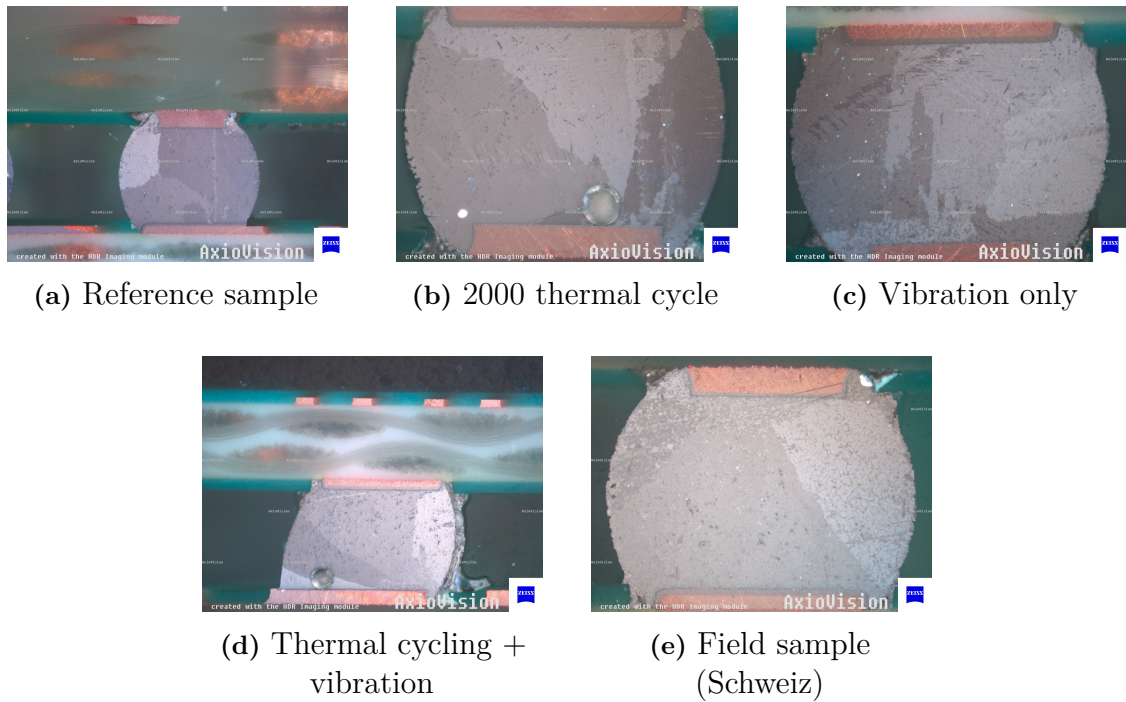


Figure 4.1: Polarized optical microscopy (POM) images of SAC305 solder joints

Figure 4.1 presents the overall grain morphology of the SAC305 solder joints under different ageing conditions and the morphology seen in the above picture is also termed as Beach Ball structure. The reference sample exhibited large β -Sn grains with relatively uniform contrast. The laboratory-aged and field-aged samples showed varying degrees of contrast variation, indicating microstructural evolution following service or laboratory exposure. No definitive evidence of recrystallization could be confirmed using POM alone therefore, definitive confirmation of recrystallization requires EBSD. The Schweiz field-returned sample was selected for the final POM comparison because the Finland field sample had been used during the development and optimization of the sample-preparation procedure. Only one corner solder ball remained available from the Finland sample after this process, and it was subsequently used for SEM preparation and coating-method evaluation. Although the Finland sample had approximately twice the mileage, it was not available in a suitable

condition for consistent comparative POM analysis. Therefore, the Switzerland sample was selected as the representative field sample for the comparative POM analysis.

Table 4.1 summarizes the qualitative comparison of the grain morphology observed in the POM images for the different ageing conditions. In the table Contrast variation refers to the variation in optical intensity observed between different regions or grains in the POM images. Low contrast variation indicates a relatively uniform optical appearance across the observed solder microstructure, whereas moderate or moderate-high contrast variation indicates increased differences in brightness between neighbouring grains or regions. This qualitative assessment was used to describe changes in optical contrast relative to the reference sample.

Table 4.1: Comparison of the grain morphology observed in POM images for the different ageing conditions.

Sample	Grain morphology	Contrast variation	Observation
Reference	Large β -Sn grains	Low	Uniform grain appearance
2000 cycles	Large β -Sn grains	Moderate	Increased variation in grain contrast compared with the reference.
Vibration	Similar to reference	Low	Grain morphology appears similar to the reference.
TC + Vibration	Large β -Sn grains	Moderate-High	More contrast variation than the vibration-only sample.
Field	Large β -Sn grains	Moderate	Grain morphology comparable to laboratory-aged samples.

4.2 SEM Analysis

Scanning electron microscopy (SEM) was used to investigate the evolution of the interfacial intermetallic compounds (IMCs) and Ag_3Sn particles after different ageing conditions. Particular attention was given to the PCB and package interfaces because these regions are most susceptible to diffusion-controlled microstructural changes.

4.2.1 Reference Sample

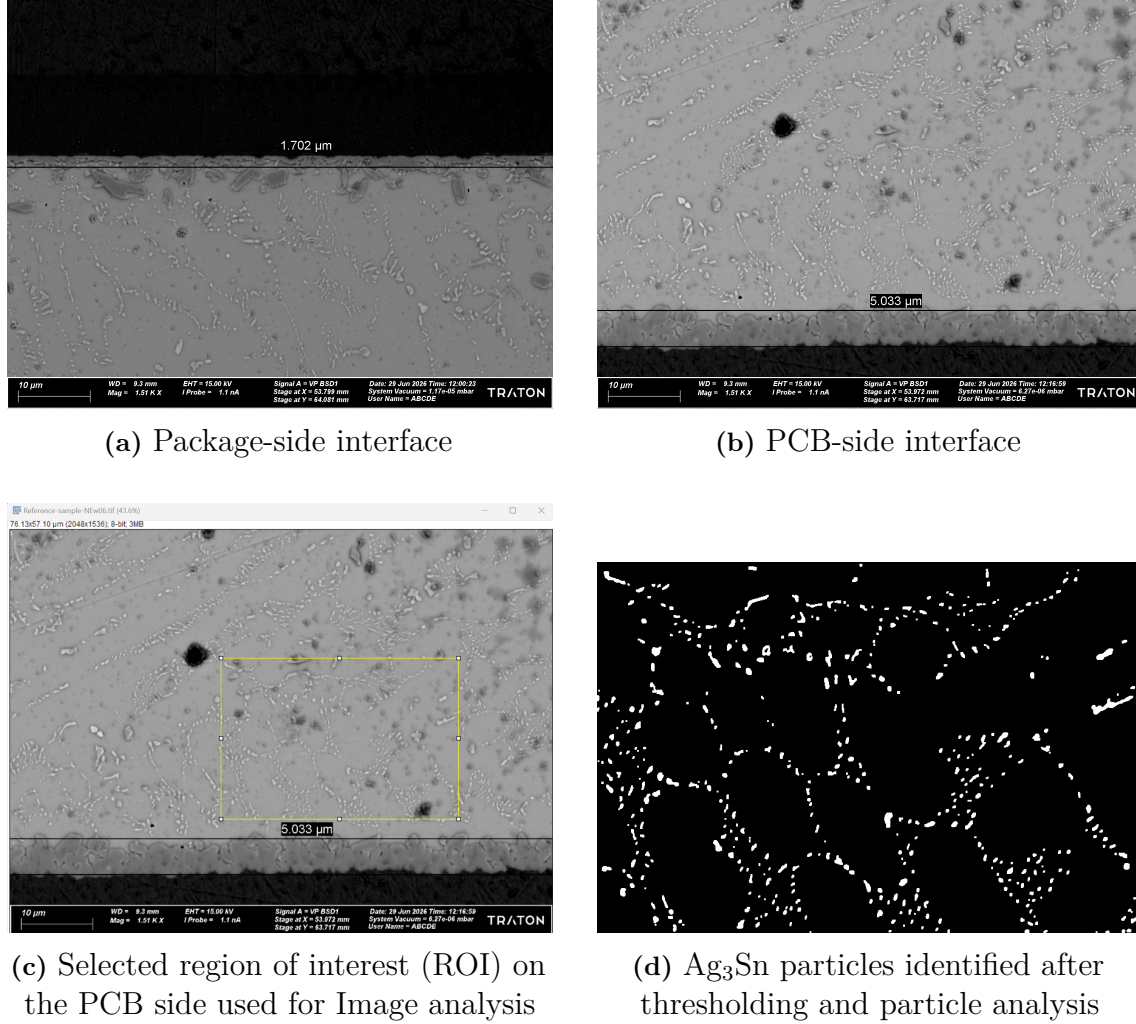


Figure 4.2: SEM micrographs of the reference SAC305 solder joint

Figure 4.2 shows representative SEM images of the reference sample. A continuous IMC layer was observed at both interfaces without cracks or delamination. The IMC thickness measured approximately $1.70\ \mu\text{m}$ on the package side and $5.03\ \mu\text{m}$ on the PCB side. Ag_3Sn particles were observed throughout the $\beta\text{-Sn}$ matrix. ImageJ analysis identified 208 particles with a mean particle area of $0.103\ \mu\text{m}^2$ and a mean Feret diameter of $0.534\ \mu\text{m}$. A continuous dark band was found between copper pad and IMC on the package side.

4.2.2 1000 cycles sample

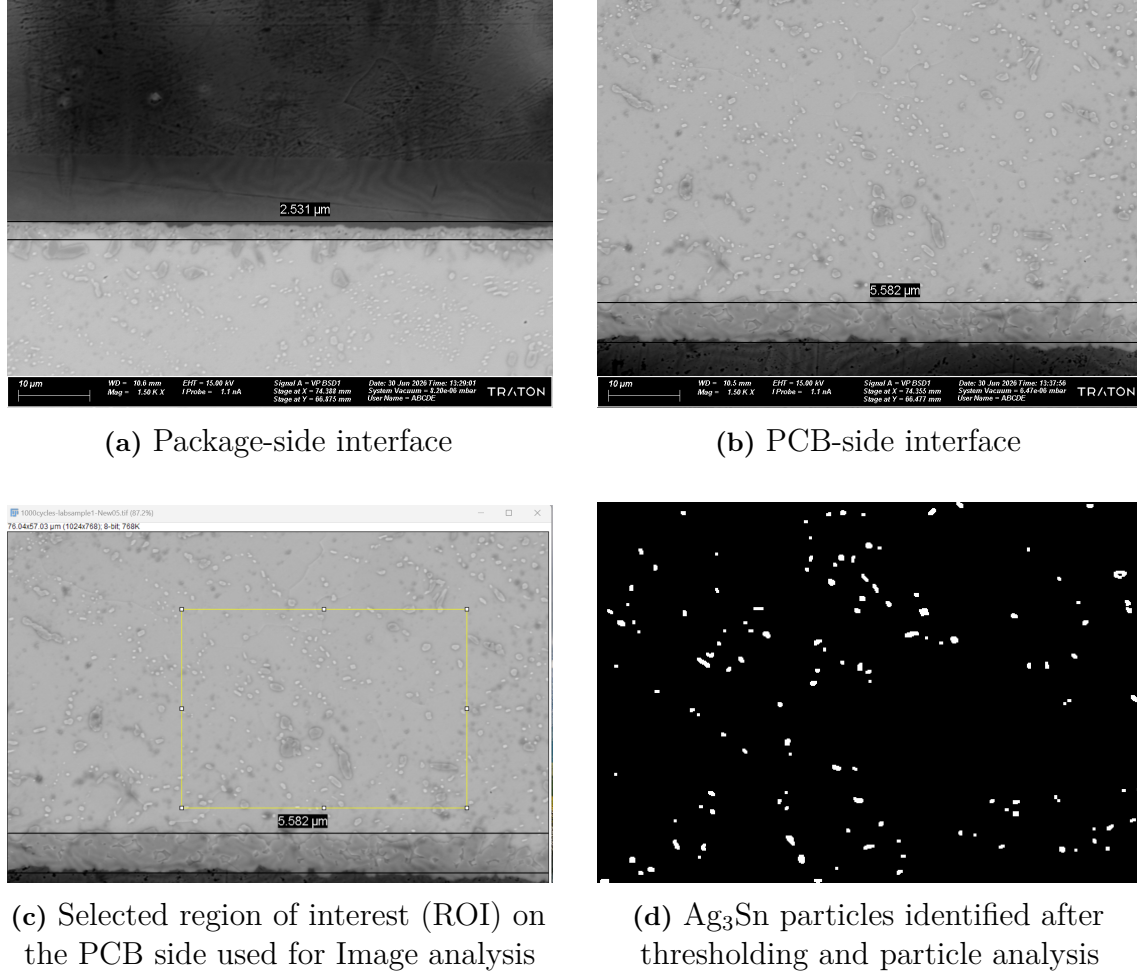


Figure 4.3: SEM micrographs of the SAC305 solder joint after 1000 thermal cycles

Figure 4.3 presents SEM images of the SAC305 solder joint after 1000 thermal cycles. The IMC remained continuous at both interfaces, with an average thickness of $2.53 \mu\text{m}$ on the package side and $5.58 \mu\text{m}$ on the PCB side. Ag_3Sn particles were distributed throughout the solder matrix. ImageJ analysis identified 103 particles, with a mean particle area of $0.143 \mu\text{m}^2$ and a mean Feret diameter of $0.569 \mu\text{m}$. A continuous dark band was found between copper pad and IMC on the package side.

4.2.3 2000 cycles sample

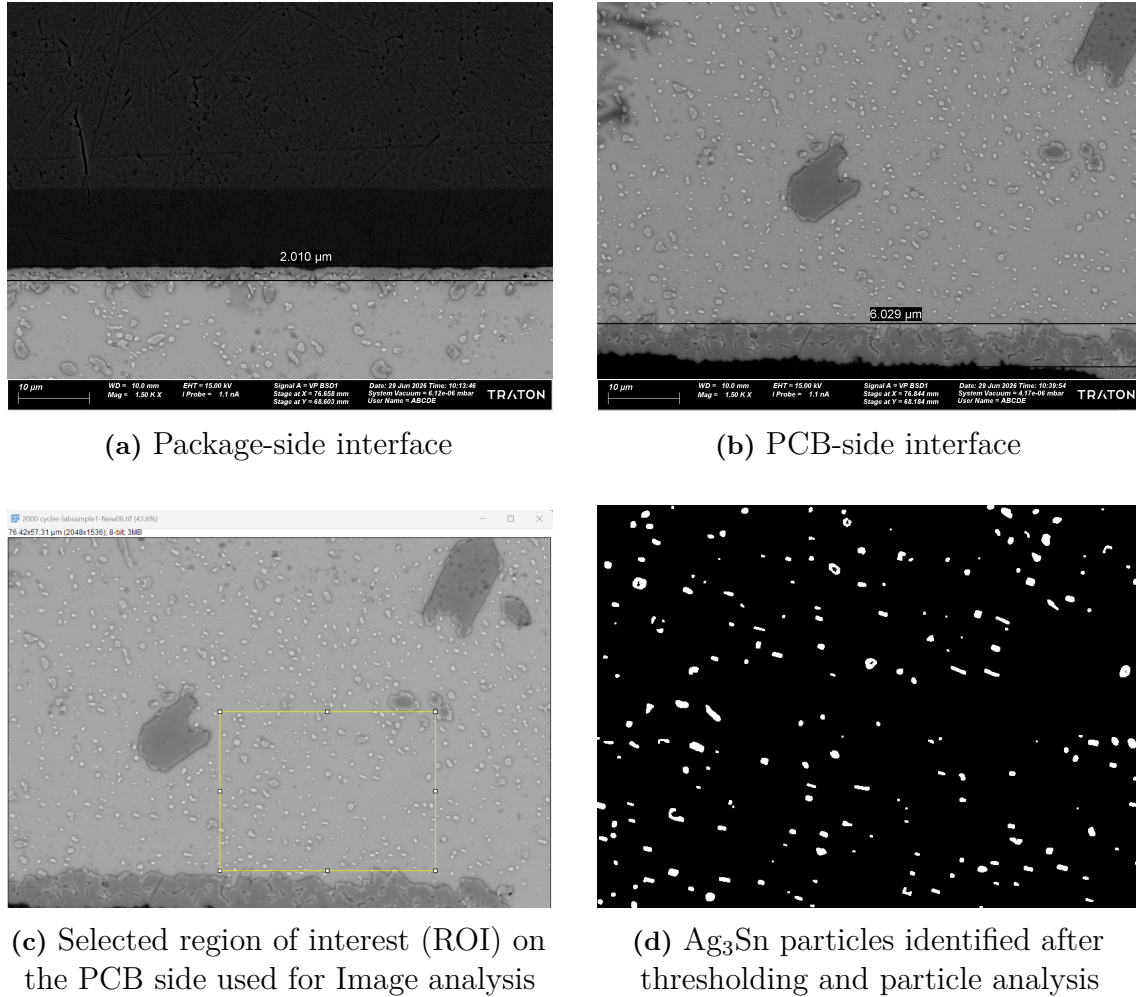


Figure 4.4: SEM micrographs of the SAC305 solder joint after 2000 thermal cycles

Fig 4.4 presents SEM images after 2000 thermal cycles. Continuous IMC layers were observed at both interfaces. The PCB-side IMC measured approximately $6.03 \mu\text{m}$, while the measured package-side IMC was approximately $2.01 \mu\text{m}$ in the analyzed region. ImageJ analysis identified 132 particles, with a mean particle area of $0.125 \mu\text{m}^2$ and a mean Feret diameter of $0.533 \mu\text{m}$. A continuous dark band was found between copper pad and IMC on the package side.

4.2.4 Thermal cycling with vibration sample

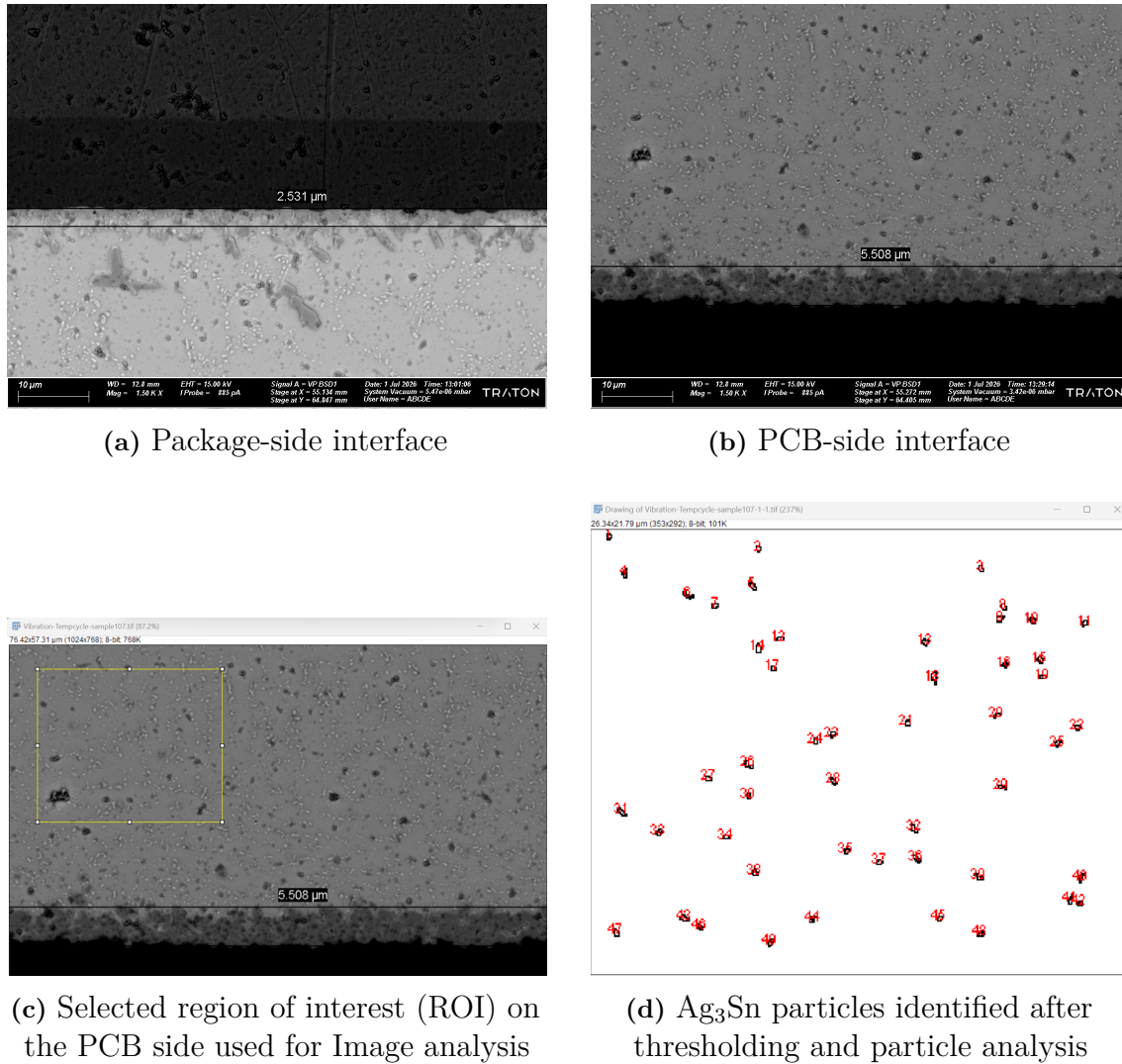
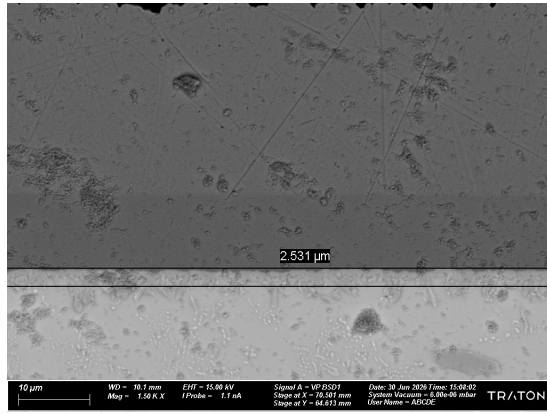


Figure 4.5: SEM micrographs of the SAC305 solder joint after thermal cycling followed by vibration showing

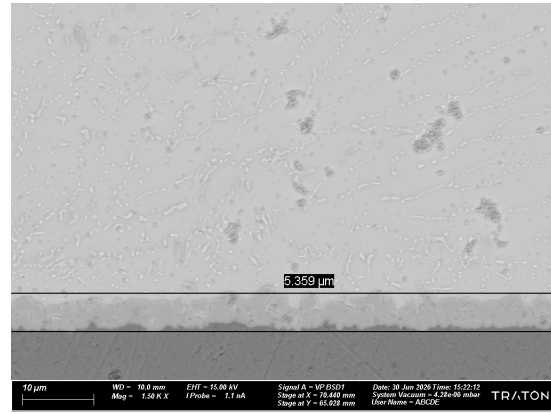
Fig 4.5 presents the thermal cycling followed by vibration sample. Continuous IMC layers were observed at both interfaces. Ag_3Sn particles were observed throughout the solder matrix. Small dark spots were also observed within the solder matrix. EDS analysis indicated the presence of platinum at these locations. Since the samples were coated with Pt prior to SEM/EDS analysis, these dark features are attributed to local variations in the sputtered Pt coating rather than to a distinct solder or intermetallic phase. The PCB-side IMC measured approximately $5.508 \mu\text{m}$, while the measured package-side IMC was approximately $2.531 \mu\text{m}$ in the analyzed region. ImageJ analysis identified 49 particles, with a mean particle area of $0.059 \mu\text{m}^2$ and a mean Feret diameter of $0.412 \mu\text{m}$. A continuous dark band was found between copper pad and IMC on the package side. It should be noted that the ImageJ thresholding procedure did not identify all Ag_3Sn particles visible in the original SEM micrographs.

Particle detection depends on image contrast, particle morphology and the selected threshold range, and some particles may therefore remain undetected or be excluded from the analysis. Consequently, the particle count and size parameters obtained from ImageJ should be considered representative of the particles detected within the selected ROI rather than an absolute count of all Ag_3Sn particles present.”

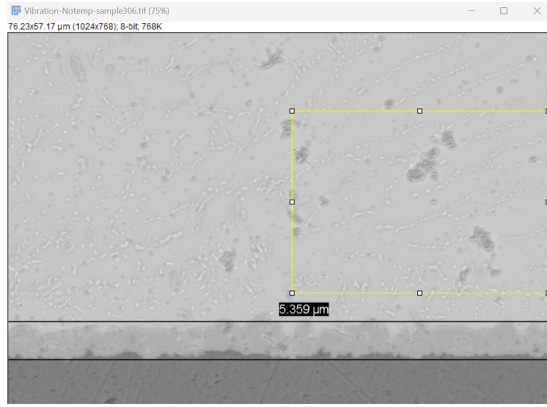
4.2.5 Vibration sample



(a) Package-side interface



(b) PCB-side interface



(c) Selected region of interest (ROI) on the PCB side used for Image analysis



(d) Ag_3Sn particles identified after thresholding and particle analysis

Figure 4.6: SEM micrographs of the vibration-only SAC305 solder joint

Fig4.6 shows the vibration-only sample. Continuous IMC layers were observed at both interfaces. Ag_3Sn particles were distributed throughout the solder matrix. The PCB-side IMC measured approximately $5.4 \mu\text{m}$, while the measured package-side IMC was approximately $2.531 \mu\text{m}$ in the analyzed region. ImageJ analysis identified 138 particles, with a mean particle area of $0.114 \mu\text{m}^2$ and a mean Feret diameter of $0.634 \mu\text{m}$. A continuous dark band was found between copper pad and IMC on the package side.

4.2.6 Field sample

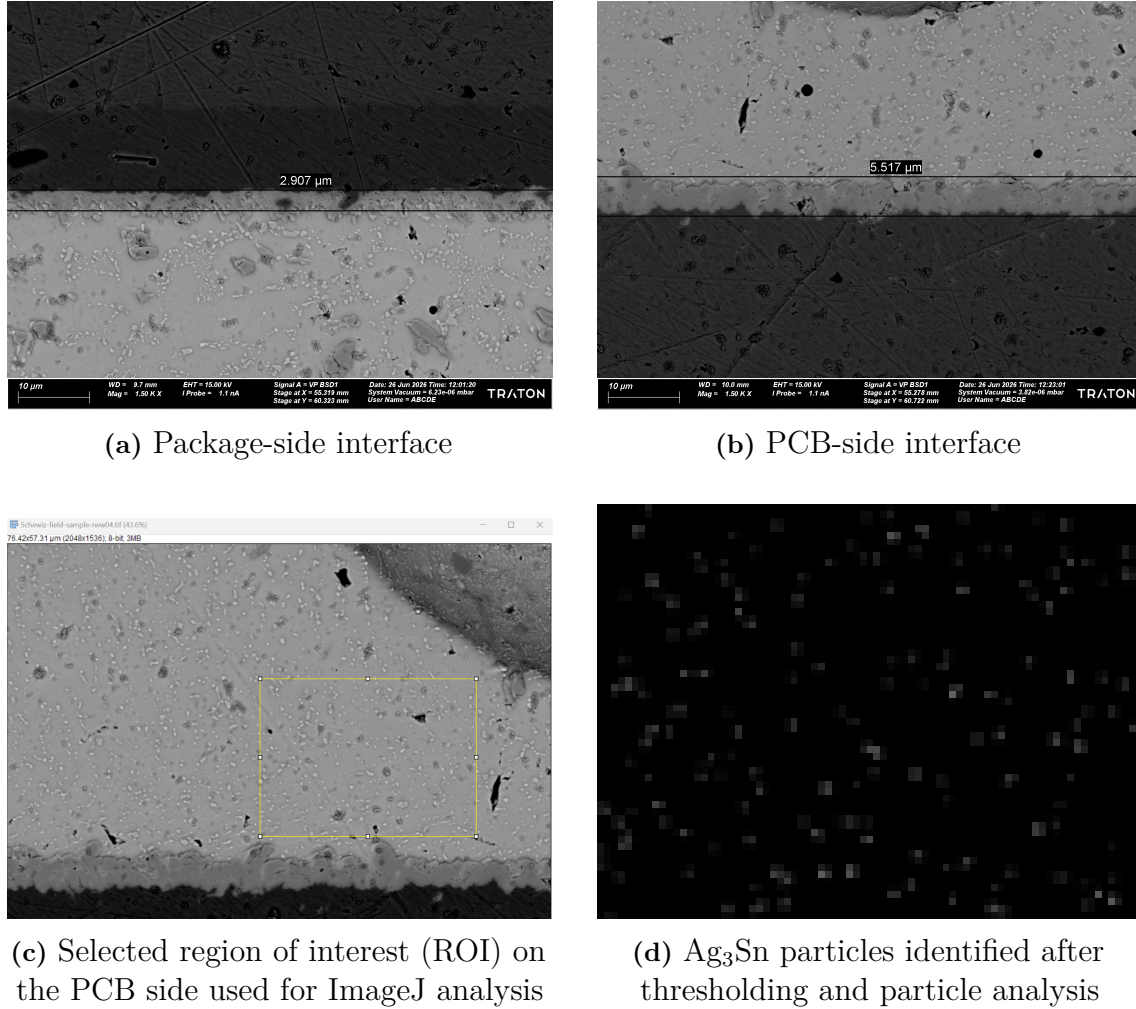


Figure 4.7: SEM micrographs of the field-aged SAC305 solder joint

Fig 4.7 shows the field-aged solder joint. Continuous IMC layers were observed at both interfaces. Ag_3Sn particles were distributed throughout the solder matrix. The PCB-side IMC measured approximately $5.517 \mu\text{m}$, while the measured package-side IMC was approximately $2.9 \mu\text{m}$ in the analyzed region. ImageJ analysis identified 165 particles, with a mean particle area of $0.036 \mu\text{m}^2$ and a mean Feret diameter of $0.279 \mu\text{m}$. A continuous dark band was found between copper pad and IMC on the package side.

The reported particle characteristics should be interpreted as representative measurements of the selected regions rather than as fully statistically representative values for the entire solder joint. The summary of the analysis can be seen in the table below.

Table 4.2: Summary of the ImageJ analysis of Ag_3Sn particles for all investigated samples. Differences in particle count, mean particle area and mean Feret diameter were observed between the reference, laboratory-aged, vibration-aged and field samples.

Sample	Count	Mean Area (μm^2)	Mean Feret Diameter (μm)
Reference	208	0.103	0.534
1000 cycles	103	0.143	0.569
2000 cycles	132	0.125	0.543
Temperature cycling + vibration	49	0.059	0.412
Vibration sample	138	0.114	0.634
Field sample	165	0.036	0.279

The ImageJ results show a slight decrease in the measured mean Ag_3Sn particle area and Feret diameter from 1000 to 2000 thermal cycles. This apparent decrease should not be interpreted as evidence of particle refinement with increasing thermal cycling. The measured values can be influenced by the local distribution of Ag_3Sn particles within the selected ROI, minor differences in ROI dimensions, and the thresholding procedure used for particle detection. In addition, only one ROI was analysed for each sample and no repeated measurements were performed; therefore, a statistical uncertainty could not be determined. The results are consequently considered representative of the analysed regions rather than sufficient to establish a definitive trend in Ag_3Sn particle coarsening.

The table below shows differences between the package-side and PCB-side interfaces across the investigated ageing conditions. The PCB-side IMC was generally thicker than the package-side IMC, consistent with the different metallization systems present at the two interfaces. The tabulated values provide a direct comparison of IMC development between the reference, laboratory-aged, vibration and field-aged samples.

Table 4.3: Measured IMC thicknesses at the package-side and PCB-side interfaces for the investigated solder joints.

Sample	Package-side IMC thickness (μm)	PCB-side IMC thickness (μm)
Reference	1.7	5.03
1000 cycles	2.53	5.58
2000 cycles	2.01	6.03
Thermal shock + vibration	2.531	5.508
Vibration	2.531	5.4
Field	2.9	5.517

4.3 EDS Analysis

Energy dispersive spectroscopy (EDS) was performed to investigate the elemental distribution and chemical composition of the solder joints after thermal shock testing. Elemental mapping was used to identify the spatial distribution of the major elements, while point analysis was performed to determine the composition of selected microstructural features. Line scan analysis was further carried out across the solder joint interface to examine elemental variations and the presence of interfacial layers. These analyses complement the SEM observations by providing chemical information regarding the solder matrix, intermetallic compounds and interface.

4.3.1 Elemental Mapping

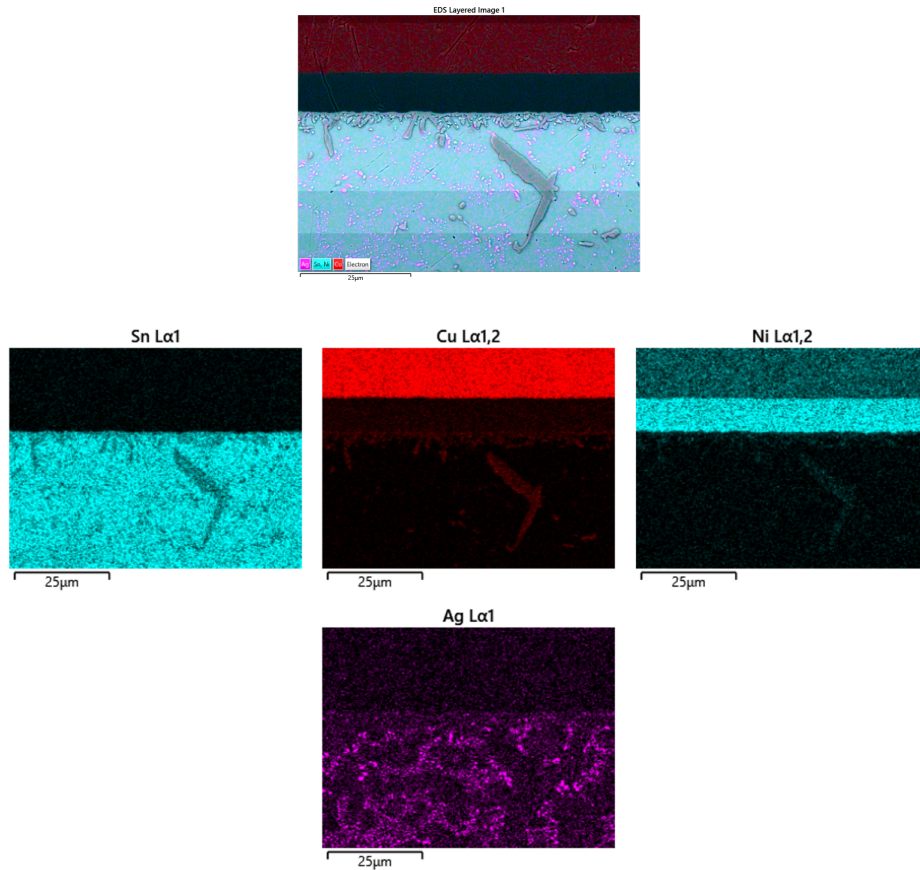
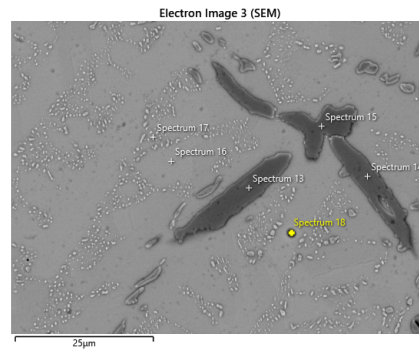


Figure 4.8: EDS elemental mapping of the package-side interface of the SAC305 solder joint after 1000 thermal cycles, showing (a) a global elemental map, (b) Sn distribution, (c) Cu distribution, (d) Ni distribution, and (e) Ag distribution.

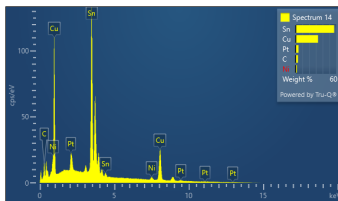
Fig 4.8 shows the elemental distribution within the 1000-cycle laboratory sample. Tin (Sn) was uniformly distributed throughout the solder matrix, whereas silver (Ag) appeared as discrete particles dispersed within the solder. Copper (Cu) was mainly concentrated within larger intermetallic particles and near the interface. On

the package side, a continuous Ni-rich layer was observed between the copper pad and the solder, indicating the presence of a nickel diffusion barrier.

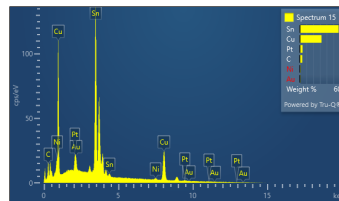
4.3.2 Point Analysis



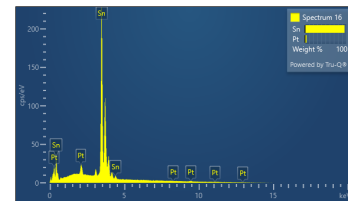
(a) SEM micrograph showing the selected locations for EDS point analysis



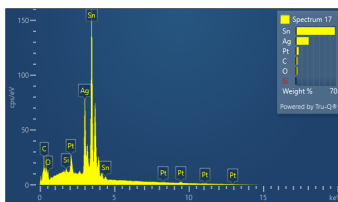
(b) Spectrum 14



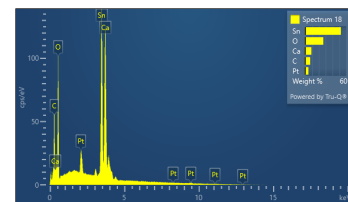
(c) Spectrum 15



(d) Spectrum 16



(e) Spectrum 17



(f) Spectrum 18

Figure 4.9: SEM micrograph showing the locations selected for EDS point analysis within the SAC305 solder joint and the respective EDS spectra

Fig 4.9 shows the EDS point analysis confirmed that the solder matrix primarily consisted of Sn, whereas the fine precipitates were enriched in Ag, indicating Ag_3Sn particles. The larger elongated particles contained relatively higher Cu contents, suggesting Cu-rich intermetallic compounds. Minor oxygen and carbon peaks were detected in some spectra and are attributed to surface oxidation, polishing residues or mounting material. Table 4.4 below shows the main elements identified by EDS analysis.

4. Results

Table 4.4: Summary of EDS point analysis showing the major elements detected at each selected spectrum location within the SAC305 solder joint.

Spectrum	Region	Main Elements	Interpretation
14	Particle	Sn + Cu	Cu-rich IMC
15	Particle	Sn + Cu	Cu-rich IMC
16	Matrix	Sn	β -Sn matrix
17	Small particle	Sn + Ag	Ag_3Sn precipitate
18	Matrix/contamination	Sn, Ca, O	Matrix with polishing residue or oxide

4.3.3 Line Scan

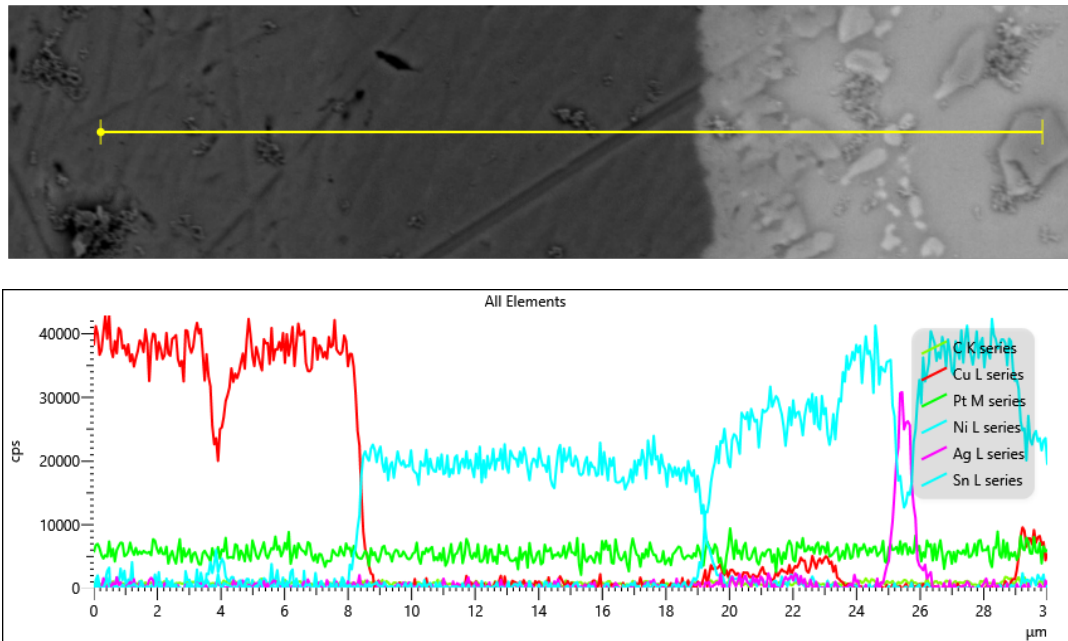


Figure 4.10: SEM image showing the location of the EDS line scan performed across the solder joint interface at the package side together with the corresponding elemental intensity profiles of Cu, Ni, Ag and Sn.

Figs 4.10 presents the EDS line scan performed across the solder joint interface. Tin remained the dominant element within the solder region, while copper intensity increased close to the interfacial region. Nickel exhibited a localized peak corresponding to the interfacial layer, confirming the presence of a nickel-containing diffusion barrier. Silver was mainly detected within the solder matrix as discrete precipitates.

4.4 XRD Analysis

X-ray diffraction (XRD) analysis was performed to confirm the crystalline phases present in the SAC305 solder alloy. Unlike the SEM and EDS analyses, XRD was conducted only as a phase identification technique and was not used for comparison between the different ageing conditions. The identified phases were compared with the reference patterns generated by the XRD software and with published literature.

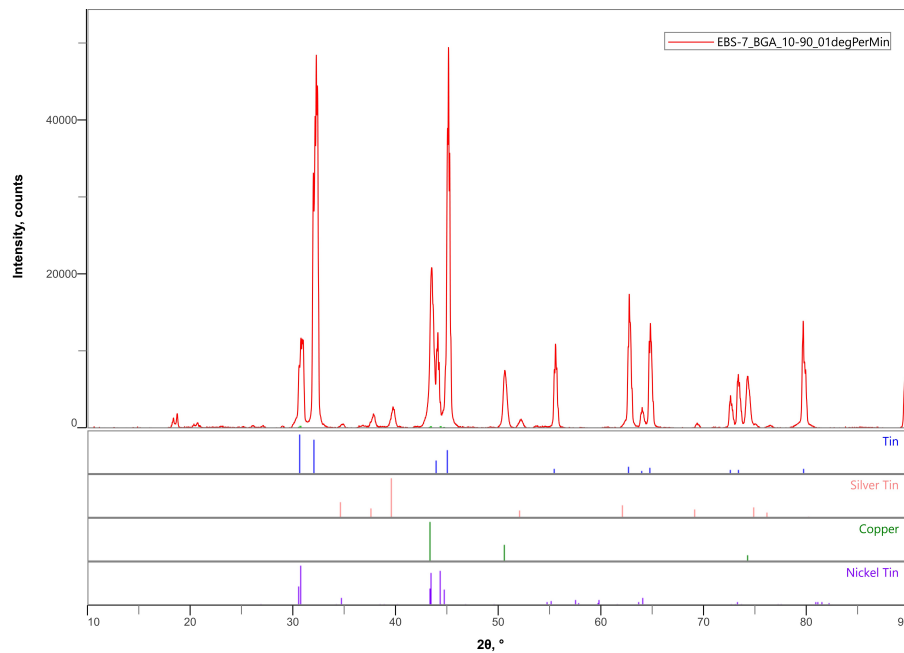


Figure 4.11: XRD diffraction pattern of the SAC305 solder alloy showing the experimental diffraction pattern together with the reference phase markers for β -Sn, Ag-Sn, Cu and Ni-Sn.

Fig 4.11 presents the XRD diffraction pattern obtained from the SAC305 solder alloy. The diffraction pattern is dominated by peaks corresponding to the β -Sn phase, confirming that β -Sn is the primary constituent of the solder matrix. Additional diffraction peaks corresponding to Ag-Sn, Cu and Ni-Sn reference phases were also identified by the software-generated phase matching. The presence of β -Sn and Ag-Sn phases is consistent with published studies on SAC305 solder alloys, where β -Sn forms the matrix and Ag-containing intermetallic compounds are present as secondary phases. In the present work, Cu and Ni-containing phases were also identified. The detection of a Ni-containing phase is consistent with the nickel-containing metallization observed during EDS analysis at the package interface. Since XRD was performed only for phase confirmation, detailed interpretation of phase evolution between different ageing conditions was not carried out.

Table 4.5: Crystalline phases identified from the XRD analysis of the SAC305 solder alloy.

Phase identified	XRD observation	Supporting evidence
β -Sn	Dominant phase	SEM shows β -Sn matrix
Ag ₃ Sn	Present	SEM/ImageJ identified Ag ₃ Sn particles
Cu	Present	EDS detected Cu at the interface
Ni-Sn	Present	EDS mapping showed a Ni-rich layer at the package side

Table 4.5 summarizes the crystalline phases identified from the XRD analysis. The diffraction pattern is dominated by β -Sn, confirming that it is the primary phase in the SAC305 solder alloy. Secondary diffraction peaks corresponding to Ag₃Sn, Cu and Ni-Sn were also identified. The identified β -Sn and Ag₃Sn phases are consistent with previous studies on SAC305 solder alloys.

5

Discussions

5.1 Comparison between laboratory-aged and field-retained SAC305 solder joints

The primary objective of this study was to compare the microstructural characteristics of laboratory-aged and field-retained SAC305 BGA solder joints used in heavy-duty truck electronic control units. Laboratory thermal shock testing provides a controlled method for accelerating thermal ageing, whereas field components experience a combination of thermal cycling, mechanical vibration, varying environmental conditions and operational loading. Therefore, although both laboratory and field samples exhibited similar constituent phases, differences in microstructural evolution were expected due to the different ageing histories.

SEM observations showed that all investigated samples retained continuous solder joints without visible cracks or interfacial delamination. Similarly, XRD confirmed the presence of the characteristic phases of SAC305 solder, while EDS verified the elemental distribution within the solder matrix and at the interfaces. Although catastrophic failure was not observed after 1000 or 2000 thermal cycles, measurable microstructural changes were identified through SEM and ImageJ analysis, indicating that thermal ageing had already influenced the solder microstructure.

The laboratory-aged samples exhibited measurable changes in interfacial IMC thickness with increasing thermal shock exposure. The PCB-side IMC increased from approximately $5.03\ \mu\text{m}$ in the reference sample to $5.58\ \mu\text{m}$ after 1000 cycles and $6.03\ \mu\text{m}$ after 2000 cycles. The package-side IMC also increased from approximately $1.70\ \mu\text{m}$ in the reference sample, although the measured thickness did not show a strictly increasing trend between 1000 and 2000 cycles. These observations indicate progressive interfacial reactions during thermal exposure, while the variation between individual samples should be considered when interpreting the thickness measurements.

Laboratory thermal shock testing provides a reproducible and controlled ageing environment, making it suitable for investigating the influence of cyclic temperature changes on solder joint reliability. Field ageing, however, represents the combined effects of thermal, mechanical and environmental loading. Consequently, the laboratory samples are valuable for understanding individual ageing mechanisms, whereas the field-retained component reflects the actual service behaviour of the solder joint. The comparison demonstrates that laboratory thermal shock testing successfully reproduced several of the microstructural characteristics observed in service-aged solder joints while also highlighting the limitations of accelerated laboratory testing

in reproducing the full complexity of field operating conditions.

5.2 Evolution of Ag_3Sn particles during thermal ageing

One of the most noticeable microstructural changes observed in the present study was the evolution of the Ag_3Sn particles within the β -Sn solder matrix. Ag_3Sn is an important strengthening phase in SAC305 solder because it contributes to the mechanical properties and creep resistance of the solder joint. Thermal exposure during laboratory ageing and long-term field service can alter the morphology, size and distribution of these particles, thereby influencing the long-term reliability of the solder joint.

SEM examination showed that Ag_3Sn particles were present in all investigated samples, including the reference, laboratory-aged, vibration and field-retained solder joints. The reference sample exhibited a relatively fine and homogeneous particle distribution throughout the β -Sn matrix. Following thermal ageing, differences in particle morphology and distribution were observed. Although no abrupt microstructural transformation occurred after 1000 and 2000 thermal cycles, the particles appeared to exhibit local variations in size and distribution compared with the reference condition.

The vibration-only sample also showed Ag_3Sn particles distributed throughout the β -Sn matrix, with a measured mean particle area of $0.114 \mu\text{m}^2$ and mean Feret diameter of $0.634 \mu\text{m}$. Compared with the reference sample, the vibration-aged sample showed a similar overall particle distribution in the qualitative SEM observations, although local differences in particle size and distribution were observed. Since vibration testing introduces cyclic mechanical loading rather than prolonged high-temperature exposure, the observed particle morphology cannot be attributed to thermal ageing alone. The results therefore suggest that vibration contributed to the overall microstructural condition of the solder joint, but the present analysis does not allow the specific contribution of vibration to Ag_3Sn coarsening to be quantified independently.

The qualitative SEM observations were supported by ImageJ analysis, which provided a semi-quantitative comparison of Ag_3Sn particle characteristics. The reference sample contained the highest particle count (208 particles), whereas the thermally aged samples generally exhibited fewer detected particles together with variations in mean particle area and Feret diameter. These measurements indicate that thermal exposure influenced particle morphology, although the magnitude of the changes differed between the ageing conditions investigated.

The observed changes are consistent with the thermal evolution of Ag_3Sn particles reported for SAC305 solders. At the elevated homologous temperatures experienced during thermal cycling, atomic diffusion becomes more active. Smaller Ag_3Sn particles possess higher surface energy than larger particles and are therefore thermodynamically less stable. Over time, silver atoms diffuse from smaller particles to larger particles, resulting in particle growth and changes in particle spacing. This process, commonly referred to as Ostwald ripening, has been widely reported during

thermal ageing of Sn–Ag–Cu solder alloys.

Qualitative examination of the SEM micrographs showed differences in the morphology and spatial distribution of Ag₃Sn particles between the investigated conditions. The reference sample exhibited a relatively homogeneous distribution of fine Ag₃Sn particles within the β -Sn matrix, whereas the thermally aged samples showed greater local variation in particle size and distribution. The vibration and thermal-cycling-plus-vibration samples also exhibited variations in Ag₃Sn morphology, but these changes were not interpreted solely from the ImageJ measurements because the thresholding procedure did not capture all visible particles. The field-retained sample showed a visibly different and more heterogeneous particle distribution compared with the laboratory-aged samples. These qualitative observations, together with the ImageJ results, indicate that the Ag₃Sn morphology was affected by the different ageing conditions, although the extent of particle evolution cannot be quantified reliably from a single ROI alone.

The differences observed between the loading conditions should be interpreted in terms of both thermal and mechanical effects. Thermal cycling promotes atomic diffusion within the solder matrix and provides the conditions for Ag₃Sn particle evolution through diffusion-controlled processes such as Ostwald ripening. Mechanical vibration introduces cyclic deformation and local stresses that may influence the redistribution and deformation of the solder microstructure. Therefore, both thermal and mechanical loading may contribute to the observed microstructural evolution, although the present study does not provide sufficient evidence to separate their individual contributions to Ag₃Sn evolution. The observed differences in particle morphology and distribution between the thermal, vibration and combined loading conditions should consequently be considered as the result of their respective loading histories rather than being attributed to a single mechanism.

Changes in Ag₃Sn particle morphology are important because they influence the local mechanical behaviour of the solder matrix. Coarser or more heterogeneous particle distributions may reduce the effectiveness of particle strengthening and promote localized deformation during cyclic loading. Although no fatigue cracks were observed within the investigated samples, the measured microstructural evolution suggests that the solder joints were undergoing thermal ageing and that continued service exposure or additional thermal cycles could eventually contribute to fatigue crack initiation.

5.3 Intermetallic Compound (IMC) Growth and Interfacial Evolution

Intermetallic compounds (IMCs) play a critical role in determining the mechanical integrity and long-term reliability of solder joints. A thin and continuous IMC layer is necessary to provide metallurgical bonding between the solder and substrate. However, continued thermal exposure promotes interfacial diffusion, leading to IMC growth. Excessive IMC thickening may reduce the ductility of the solder joint and increase its susceptibility to fatigue crack initiation under cyclic thermal and mechanical loading.

SEM analysis demonstrated that continuous IMC layers were present at both the package and PCB interfaces in all samples investigated. The reference sample exhibited the thinnest IMC layer, while the thermally aged specimens generally showed thicker IMC layers, indicating progressive interfacial reactions during thermal shock testing. No interfacial cracks or delamination were observed after either 1000 or 2000 thermal cycles, suggesting that the solder joints remained metallurgically intact despite measurable microstructural evolution. The vibration-only and thermal-cycling-plus-vibration samples also exhibited continuous IMC layers at both the package and PCB interfaces. The measured PCB-side IMC thicknesses were approximately $5.4\ \mu\text{m}$ for the vibration-only sample and $5.51\ \mu\text{m}$ for the thermal-cycling-plus-vibration sample. The corresponding package-side IMC thickness was approximately $2.53\ \mu\text{m}$ for both conditions. These observations indicate that interfacial reactions also occurred in the vibration-tested samples. However, since the vibration-only condition was not subjected to the same thermal exposure as the thermal shock samples, the present results do not allow the specific contribution of mechanical vibration to IMC growth to be separated quantitatively.

The PCB-side IMC was consistently thicker than the package-side IMC. This difference can be explained by the different metallization systems at the two interfaces. The PCB interface provides direct contact between the SAC305 solder and the copper pad, promoting continuous diffusion of copper atoms into the solder and the formation and growth of copper-containing intermetallic compounds. Consequently, greater IMC growth was observed on the PCB side during thermal ageing.

In contrast, EDS elemental mapping and line scan analysis identified a continuous Ni-rich layer at the package interface. This nickel-containing layer acts as a diffusion barrier by reducing the transport of copper atoms from the underlying substrate into the solder. As a result, interfacial reactions at the package side proceed more slowly, producing a thinner IMC layer than that observed on the PCB side. The presence of the Ni-containing phase was further supported by the XRD phase identification.

Although the Ni diffusion barrier reduces the rate of IMC growth, interfacial reactions continue during thermal exposure. Progressive IMC thickening increases the stiffness and brittleness of the interface, reducing its ability to accommodate thermally induced deformation. Under prolonged service conditions, this may increase local stress concentrations and contribute to fatigue crack initiation, particularly at the solder-IMC interface where thermal mismatch stresses are highest.

SEM observations demonstrated that Ag_3Sn particles were present throughout the $\beta\text{-Sn}$ solder matrix in all investigated samples. Differences between the investigated conditions were observed in the morphology and distribution of the Ag_3Sn particles, including variations in particle size and spacing within the analysed regions. These differences were supported by the ImageJ measurements of particle count, mean particle area and mean Feret diameter, although the thresholding procedure did not capture all visible particles. In addition to the Ag_3Sn particle characteristics, differences were observed in the thickness of the interfacial IMC layers. The PCB-side IMC was generally thicker than the package-side IMC, with the measured thickness varying between the reference, laboratory-aged, vibration and field samples. Thus, the observed microstructural differences involved both changes in Ag_3Sn particle morphology and variations in interfacial IMC thickness.

5.4 Correlation between SEM, ImageJ, EDS and XRD Results

The combined use of SEM, ImageJ, EDS and XRD provided complementary information regarding the microstructural evolution of the SAC305 solder joints. SEM was used to examine the solder microstructure and interfacial morphology, ImageJ provided quantitative information on Ag_3Sn particle characteristics, EDS identified the elemental distribution within the solder joint, and XRD confirmed the crystalline phases present in the solder alloy. The combined interpretation of these techniques provides a more comprehensive understanding of the microstructural changes occurring during laboratory ageing and field service.

SEM observations demonstrated that Ag_3Sn particles were present throughout the β -Sn solder matrix in all investigated samples. Although qualitative differences in particle morphology were observed after thermal ageing, ImageJ analysis enabled these changes to be evaluated quantitatively through measurements of particle count, mean particle area and mean Feret diameter. The combination of qualitative SEM observations and quantitative ImageJ measurements provided greater confidence in assessing changes in Ag_3Sn particle morphology than either technique alone.

The microstructural features observed in the SEM images were further verified using EDS elemental mapping and point analysis. Ag-rich particles identified within the solder matrix corresponded to the Ag_3Sn particles observed in the SEM micrographs, while Cu-rich regions were associated with interfacial reaction products. EDS mapping also confirmed the presence of a continuous Ni-rich layer at the package interface, supporting the observed differences in IMC thickness between the package and PCB sides.

XRD analysis complemented the EDS results by confirming the crystalline phases present within the solder alloy. The dominant β -Sn phase identified by XRD is consistent with the β -Sn matrix observed in the SEM images. Similarly, the Ag-containing phase detected by XRD supports the identification of Ag_3Sn particles within the solder matrix. The Ni-containing phase identified by XRD is also consistent with the Ni-rich interfacial layer observed during EDS analysis, indicating good agreement between the structural and chemical characterization techniques.

Comparison of the laboratory-aged and field-retained samples demonstrates that accelerated thermal shock testing reproduced several of the microstructural characteristics observed in the field component, including the presence of β -Sn, Ag-containing intermetallics and continuous interfacial IMC layers. However, differences in Ag_3Sn particle morphology and interfacial characteristics indicate that field ageing cannot be completely reproduced through thermal shock testing alone. The field component was subjected to simultaneous thermal, mechanical and environmental loading throughout service, whereas the laboratory specimens experienced controlled thermal cycling under well-defined conditions.

Overall, the combined characterization techniques demonstrate that thermal shock primarily influences the microstructure through gradual IMC growth and modifications to Ag_3Sn particle morphology rather than through immediate crack formation. The absence of visible cracking after 1000 and 2000 thermal cycles suggests that the ageing conditions investigated represent an intermediate stage of solder degradation.

Continued thermal exposure or additional mechanical loading would be expected to promote further microstructural evolution and eventually increase the likelihood of fatigue crack initiation.

5.5 Microstructural Evolution and Its Influence on Solder Joint Reliability

In the present study, SEM and ImageJ analyses demonstrated changes in Ag_3Sn particle morphology after thermal shock testing. Variations in particle size, particle count and mean Feret diameter indicate that the solder microstructure evolved during thermal exposure. Such changes are consistent with the initial coarsening stage described in the literature, where fine precipitates gradually grow through diffusion-controlled processes.

Recrystallization could not be directly evaluated because EBSD analysis was not performed. Nevertheless, thermal cycling introduces repeated plastic deformation and creep within the solder joint, both of which are recognized as driving forces for recrystallization in Sn-based solder alloys. Consequently, recrystallization may occur after prolonged thermal exposure, although it could not be confirmed experimentally in the present work.

No fatigue cracks or interfacial delamination were observed in the solder joints analyzed after 1000 or 2000 thermal cycles. This suggests that the samples investigated have not yet reached the final stage of fatigue degradation. Instead, the observed microstructural evolution represents an intermediate stage preceding crack initiation and propagation. The laboratory-aged samples primarily exhibited the early stages of solder degradation associated with thermal exposure. The field-retained sample exhibited continuous IMC layers at both interfaces and a visibly heterogeneous Ag_3Sn particle distribution within the β -Sn matrix. However, the field sample did not exhibit exactly the same Ag_3Sn particle morphology as the laboratory-aged samples. These differences should be interpreted cautiously, since the field component experienced an uncontrolled service history involving thermal cycling, mechanical vibration and environmental exposure, whereas the laboratory samples were subjected to controlled thermal cycling. The microstructural observations therefore indicate that the field sample cannot be directly compared with the laboratory-aged samples based solely on particle statistics.

Qualitatively, differences were observed in the morphology and spatial distribution of Ag_3Sn particles between the field-retained and laboratory-aged samples. The field sample showed a heterogeneous particle distribution that differed from the laboratory-aged specimens. In addition, the field sample exhibited continuous IMC layers at both interfaces, with measured thicknesses of approximately $5.517\text{ }\mu\text{m}$ on the PCB side and $2.9\text{ }\mu\text{m}$ on the package side. These observations indicate that the field sample had undergone interfacial and solder-matrix evolution, although the individual contributions from thermal, mechanical and environmental loading cannot be separated from the available data.

Overall, the results indicate that the investigated SAC305 solder joints were undergoing progressive microstructural evolution rather than catastrophic failure. The

observed Ag_3Sn particle evolution, IMC growth and elemental redistribution are consistent with the early stages of fatigue degradation reported in the literature and provide insight into the mechanisms governing long-term solder joint reliability.

5.6 Limitations of the Present Study

The present study provides insight into the microstructural evolution of SAC305 BGA solder joints during laboratory thermal shock testing and field service. However, several limitations should be considered when interpreting the results.

ImageJ particle analysis was performed using manually selected thresholds because image contrast varied between SEM micrographs. Although care was taken to identify Ag_3Sn particles consistently, slight variations in threshold selection may have influenced the measured particle count, mean particle area and Feret diameter. A single region of interest (ROI) was analyzed for each SEM image. While the selected ROI was chosen to be representative of the solder microstructure, analyzing multiple ROIs for each sample would provide a more statistically robust assessment of particle morphology and distribution. recrystallization could not be evaluated directly because EBSD analysis was not performed. Consequently, conclusions regarding recrystallization are based on microstructural observations and published literature rather than direct crystallographic measurements.

In addition, XRD analysis was performed only for phase confirmation and was not conducted on all samples investigated. Therefore, XRD results were used to support the phase identification obtained from SEM and EDS rather than to compare phase evolution between different ageing conditions.

The laboratory thermal shock tests were limited to 1000 and 2000 thermal cycles. Although measurable microstructural evolution was observed, no fatigue cracks or interfacial delamination were detected. Additional thermal cycling or combined thermo-mechanical testing would provide further understanding of the transition from microstructural evolution to fatigue crack initiation and propagation.

Another limitation of the present study is that the microstructural analysis was performed on a corner solder ball. The corner ball was selected because its longer distance from the neutral point (DNP) is expected to result in a higher shear stress during thermomechanical loading. However, Sn-based solder is anisotropic, and the crystallographic orientation can vary between individual solder balls within a BGA package. Consequently, the fatigue response and microstructural evolution may also vary between solder balls. Analysis of a larger number of solder balls would provide a more statistically representative assessment, while EBSD analysis of individual solder balls could provide additional information about the influence of crystallographic orientation and recrystallization on the observed damage.

6

Conclusions

The major conclusions drawn from the study are listed below:

1. Laboratory thermal shock testing successfully produced measurable microstructural evolution in SAC305 BGA solder joints without causing visible fatigue cracks or interfacial delamination after 1000 and 2000 thermal cycles. This indicates that the investigated ageing conditions represent the early stages of solder degradation.
2. SEM and Image analysis demonstrated changes in the morphology and distribution of Ag_3Sn particles after thermal ageing. Variations in particle count, mean particle area and mean Feret diameter indicate that thermal exposure influenced the solder microstructure through diffusion-controlled processes.
3. Interfacial IMC growth was observed on both the PCB and package sides of the solder joints. The PCB side generally exhibited a thicker IMC layer, while the package side showed slower IMC growth due to the presence of a Ni-containing diffusion barrier, as confirmed by EDS analysis.
4. EDS elemental mapping, point analysis and line scan confirmed the elemental distribution within the solder joints, while XRD verified the presence of the major crystalline phases, including β -Sn and Ag-containing phases. The combined use of SEM, Image Analysis, EDS and XRD provided complementary information for understanding the microstructural evolution of the SAC305 solder alloy.
5. Comparison of the investigated conditions showed differences in Ag_3Sn morphology and interfacial IMC thickness compared with the reference sample. However, the present characterization methods could not clearly separate the individual effects of thermal and mechanical loading. The methods were therefore useful for comparing overall microstructural evolution, but not for quantifying the contribution of each loading condition to fatigue damage.
6. Overall, the present study improves the understanding of the microstructural evolution of SAC305 solder joints used in heavy-duty truck electronic control units. The findings demonstrate that combining laboratory ageing with complementary microstructural characterization techniques provides an effective approach for evaluating solder joint reliability and understanding degradation mechanisms under both controlled laboratory and field operating conditions.

7

Future Scope

Based on the findings of the present study, the following recommendations are proposed for future work:

1. Investigate the effect of underfill materials on SAC305 BGA solder joints to evaluate their influence on reducing thermomechanical stresses, suppressing solder joint deformation, and improving long-term reliability under thermal and vibration loading.
2. Perform Electron Backscatter Diffraction (EBSD) analysis to investigate grain orientation, recrystallization, and grain boundary evolution, providing a more comprehensive understanding of the microstructural changes during thermal ageing.
3. Conduct extended thermal shock testing using longer dwell times and a higher number of thermal cycles to promote crack initiation and propagation, thereby more closely replicating the degradation mechanisms observed in field-retained components.
4. Develop finite element simulations (FEA) of PCB assemblies with and without underfill to evaluate stress distribution, strain localization, and the effectiveness of underfill in improving solder joint reliability.
5. Integrate the experimental observations with fatigue life prediction models, such as Coffin–Manson or Engelmaier, to estimate solder joint lifetime and establish a stronger correlation between laboratory ageing, numerical simulations, and field performance.
6. Analyze field-retained solder joints from vehicles at or near the end of their expected service lifetime. Such samples would provide a better representation of advanced field-induced microstructural degradation and allow more direct comparison with laboratory-aged samples at later stages of damage evolution.

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