ABSTRACT

Title of Document: SOLDER JOINT RELIABILITY OF SN AND SNBI FINISHED AND REFINISHED SN (SAC/SNPB) SMT PACKAGES UNDER TEMPERATURE CYCLING TEST

Weiqiang Wang, M.S., Mechanical Engineering, 2009

Directed By: Prof. Michael G. Pecht, Chair Professor, Mechanical Engineering

Solder dip may be used as a peripheral leaded terminal refinishing process to replace the original pure tin finish with eutectic tin-lead finish to mitigate tin-whisker risk. Tin-silver-copper is an option of lead-free terminal finish. Solder dip is the way to obtain tin-silver-copper finish. However, the reliability of solder joints formed with these refinished terminals may be affected by the refinishing process. The solder joint reliability of refinished components under temperature cycling conditions need to be determined to study the effects of refinishing on the solder joint reliability. Tin-bismuth terminal finish is another tin-whisker mitigation strategy. The reliability of solder joints under temperature cycling conditions formed with tin-bismuth finished terminals also needs to be determined before the implementation.

The microstructure and strength of solder joints formed with refinished terminals were evaluated by comparing with those of solder joints formed with original pure tin finished terminals. The reliability of solder joints formed with original pure tin finished terminals, refinished terminals and original tin-bismuth finished terminals were tested under temperature cycling.

Under temperature cycling test, solder joints formed with Sn3.0Ag0.5Cu solder dipped terminals have shorter characteristic life for thin-small-outline-packages but longer characteristic life for 2512 resistors than those formed with the original pure tin finished terminals in both eutectic SnPb and Sn3.0Ag0.5Cu solder assembly. Solder joints formed with eutectic SnPb dipped terminals have equal characteristic life for thin-small-outline-packages, but longer characteristic life for 2512 resistors than those formed with the original pure tin finished terminals when reflowed with eutectic SnPb solder. Solder joints formed with tin-bismuth finished terminals have shorter characteristic life than original pure tin finished terminals for thin-small-outline-packages for both eutectic SnPb and Sn3.0Ag0.5Cu solder assembly.

If a 20% decrease in characteristic life of solder joints under temperature cycling conditions is acceptable, then the SAC solder dip process can be a potential choice for refinishing purpose. SnPb solder dip process is a good choice of refinish process without causing degradation to characteristic life under temperature cycling conditions. If a 25% decrease in characteristic life of solder joints under temperature cycling conditions can be accepted, then SnBi finish can be an alternative finish to tin finish.

SOLDER JOINT RELIABILITY OF SN AND SNBI FINISHED AND REFINISHED SN (SAC/SNPB) SMT PACKAGES UNDER TEMPERATURE CYCLING TEST

By

Weiqiang Wang.

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Advisory Committee:
Dr. Michael Pecht, Chair, Professor of Mechanical Engineering
Dr. Donald Barker, Professor of Mechanical Engineering
Dr. Patrick McCluskey, Associate Professor of Mechanical Engineering
Dr. Michael Osterman, Senior Research Scientist of Mechanical Engineering

Dedication

To my parents, my brother and sister for their support, and also to my friends who stood by me.

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Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

The electronics industry has transitioned to lead-free electronics both to comply with government legislations and to be compatible with supply-chain infrastructure [1]. Component termination finish transitioned from tin-lead (SnPb) finish to lead-free finish. Pure tin finish has been the most popular finish in lead-free electronics. However, the growth of tin whisker on pure tin finish has caused electronics to fail and resulted in substantial loss [2] [3]. The use of electronic parts with pure tin has been forbidden in most military and aerospace electronics [4] [5]. Tin finished terminals are typically required to contain a minimum of 3% lead by weight in these applications [5]. However, the conversion to lead-free electronics by commercial and consumer electronics dramatically reduced the availability of electronic components with lead-containing finished terminals [6].

To overcome the difficulty of getting SnPb finished components, the military and aerospace communities may seek help from a third party other than the original component manufacturer to refinish the component terminations. Solder dip is a refinishing process that is being used to modify some commercial off-the-shelf components in order to convert pure tin finish to tin-lead finish that is more resistant to tin-whiskering or other non-pure tin lead-free finishes which may be also more resistant to tin-whiskering. Sn-Ag-Cu solder has been one of the most promising lead-free solder alloys. Although whiskers have been observed on solder joints formed with Sn-Ag-Cu solder paste [7], there are still much less reporting on whisker growth on Sn-Ag-Cu solder than on pure tin finish in the literature. Solder finish formed by melting of the solder is also believed to decrease the tin-whiskering propensity [8].

1.1 *Refinishing of component terminations*

By refinishing the component terminations, the original pure tin finish was replaced by another finish. During the refinishing process, the components will experience handling, heating, dipping, cooling and rinsing. These processes may cause problems to the quality of the components and thus the reliability of solder joints assembled with these components.

1.1.1 Overview of solder dip process

Solder dip is the process of dipping component terminals in molten solder to coat the terminals with solder. It is used to finally finish the terminals or to replace the original finish [6]. Solder dip may be performed manually or by automatic robotic process. A robotic hot solder dip process consists of six steps, as shown in Figure 1. Flux is applied to the component terminals. It can be applied before and/or after preheat. The flux process removes oxide from the solder as well as the component terminals. Flux displaces the oxygen from the solder, thereby preventing re-oxidation of the surfaces [9]. To avoid damage to components caused by thermal shock or differential heating during the solder dip process, components are preheated to a certain temperature at a relatively low rate. Preheating can also activate the fluxes, since they become active at an elevated temperature, but they must not be heated above 150°C since this will cause most fluxes to break down prematurely and prevent from functioning properly during the solder dip process. There are several types of preheating methods; the most common ones are forced hot air convection and infrared. Forced hot air convection is usually preferred, since it can heat all of the surfaces evenly.

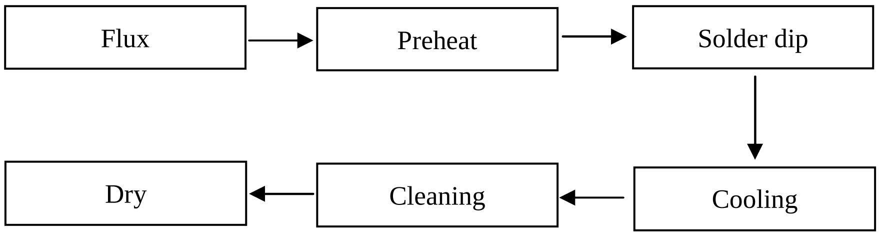


Figure 1: Procedure of solder dip process

In the solder dip step, the terminations of the components are submerged in a molten solder bath to replace the original finish. The terminations should be dipped to the edge of the component body to ensure the complete removal of the noncompliant finish. The dipping dwell time should fall within a certain range. The time at submergence or dwell time is important. If the dwell time is too short, wetting and complete removal of the original finish may not be achieved. If the dwell time is too long, the component may be overheated and terminals may corrode. The temperature of the molten solder bath is also important. If it is too low there can be non-wetting or artifacts. If it is too high, components may be damaged. The solder bath may be dynamic or static. In a dynamic solder bath, an oxide-free standing wave is produced by using a solder pump. In a static solder bath, some provision is made to remove the solder dross. After the solder dip, the component cool down temperature needs to controlled to minimize thermal shock. The cooling can be realized either by natural convection, forced air convection, or a combination of the two. As a last step, the components are cleaned to remove flux residues that may cause corrosion. Hot de-ionized water is used as cleaning solution. After cleaning, the components are dried to lower the moisture level.

1.1.2 Risks associated with solder dip process

During the solder dip process, thermal-mechanical damages may be caused to the components due to thermal shock. Sengupta, et al., [10] found that the ratio of die area to package thickness could be used to evaluate the propensity of thermo-mechanical damage of a package type during solder dip process. For the same package type, a component with a larger ratio of die area to package thickness was at higher risk of suffering thermo-mechanical damage from solder dip than a component with a smaller ratio of die area to package thickness. In addition, package types with larger ratio of die area to package thickness, such as TQPF and TSSOP, are more vulnerable to thermo-mechanical damage during solder dip.

Solder dip process may also cause non-uniformity in the finish thickness [11]. The finish formed by solder dip process was found to have larger thickness in the concave sections and to have smaller thickness at the convex sections of the leads, as that observed by Sengupta [11]. The non-uniformity in the finish thickness on the bottom surface of the termination may result in conformity problem to the component terminations.

1.1.3 Solder joint assembly

The quality and reliability of solder joints formed with solder dipped components may be affected by the solder dip process. The changes in finish composition, the non-uniformity in finish thickness and the conformity of the component terminations may affect the solder joint composition, microstructure and strength. Subbarayan, et al., studied the interfacial intermetallic growth and strength of solder joints formed with solder dipped components [12]. In their study, components with pure tin finish were converted to SnPb and lead-free finishes (Sn-3.0Ag-0.5Cu and Sn-3.6Ag) and components with SnPb finish were converted to lead-free finish (Sn-3.0Ag-0.5Cu). Both original components and solder dipped components were assembled with eutectic SnPb solder paste and lead-free solder paste (Sn-3.0Ag-0.5Cu) on printed circuit boards with different surface finishes (Organic solderability preservative (OSP), Immersion Ag (ImAg) and Eletroless Ni Immersion Au (ENIG)). For the solder joints assembled on boards with OSP finish, the IMC layer thickness was found to be around 2-3 μm at the component/solder interface and the solder/board interface. The pull strength of the solder joints was found to be not significantly affected by the solder dip process.

The mixed solder assembly is another issue when a SnPb finished component is assembled with a lead free solder paste or when a lead-free solder finished component is assembled with a SnPb solder paste. Many studies have been conducted on the mixed solder, microstructure and reliability [13] [14] [15] [16] [17] [18] [19]. Zbrzezny, et al., [14] and Grossmann, et al., [16] found that if the reflow peak temperature or dwell time was not high enough during the reflow process, the lead-free solder ball and SnPb solder paste did not completely mix. Choubey, et al., [19] observed that the Pb coarsening did not occur in solder joints formed with lead-free BGA and SnPb solder paste. Choi, et al., [17] confirmed the formation of a ternary eutectic phase Sn36.15Pb1.35Ag with a lower melting point of 178^{o}C than eutectic SnPb solder when SnPb solder and SnAg solder or SnAgCu solder were mixed.

1.2 *Goal of the study*

Although studies have been conducted on the effects of the solder dip process on component quality, no studies have been conducted on the effect of solder dip process on the reliability of solder joints formed with solder dipped components. To determine whether the solder dip process is suitable for converting component termination finishes, the reliability of solder joints formed with solder dipped components should be determined under temperature cycling test conditions. After the solder dip process, the original pure tin finish was replaced by SnPb finish or lead-free finish. Both the finish composition and distribution on the component terminations were changed. The component termination conformity might also have been changed due to non-uniformity in finish thickness. These changes would result in changes in the solder joints formed with solder dipped components, such as solder joint composition, microstructure and strength. A solder joint's reliability is affected by its composition, microstructure and strength. So the effect of solder dip process on the microstructure and strength of the solder joints formed with solder dipped components should be studied.

SnBi termination finish is also being considered as an option for mitigating tin whisker risk, as SnBi finish has been found to be resistant to tin-whiskering

[20] [21] [22] [23]. To determine the suitability of SnBi finish as a tin whisker mitigation strategy, the reliability of solder joints formed with SnBi finished terminal is also examined and compared to solder joints formed with original pure tin finished components.

Chapter 2: Component refinishing and assembly

2.1 *Refinishing of TSOPs*

Thin small outline packages (TSOPs) were refinished by dipping them into molten solder to replace the original pure tin finish with SnPb solder or SAC solder. Before and after the solder dip process, a portion of the components were inspected to study the effect of solder dip process on the quality of the components.

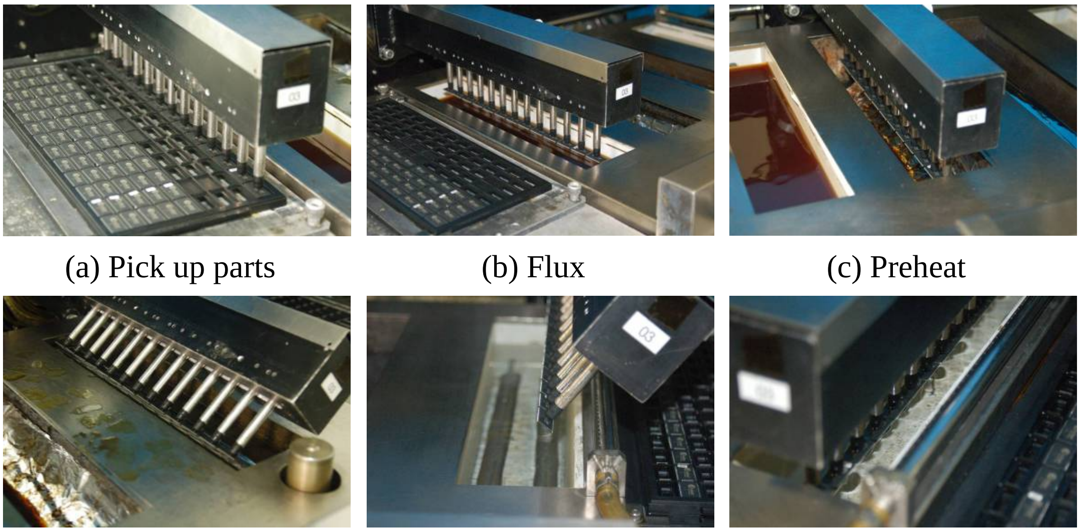
2.1.1 Components

Thin small outline packages (TSOPs) manufactured by Amkor Technology were used in this study. Each component has 50 leads. The pitch size is 0.8 mm. The part body dimension is 20.95×10.36×1.00 mm. From X-ray images, it is measured that the die size is 3.70 × 3.00 × 0.14 mm. The lead-frame material was Alloy-42 (42%NiFe). The leads were electro-plated with pure tin finish or Sn(2.0-4.0 wt.%)Bi finish.

2512 Resistors were also used in this study. The size of the resistors is 6.35×3.05 mm^2 (0.25×0.12 in^2). The terminations of the resistors were made of nickel with pure tin finish electroplated.

2.1.2 Solder dip process

In our study, the solder dip process was performed according to the procedure introduced in chapter 1 section 1.1.1. The components were preheated to 125±25°C before the solder dip. The preheating rate was lower than 5°C/s while the temperature was above 60°C to reduce the thermal stress caused by differential heating. During the solder dip, the dwell time of the component terminations on one side of the TSOP in the molten solder was controlled to be at least 2 s, to ensure wetting and complete removal of the original Sn finish. The total dwell time for both sides of one component was controlled to be less than 10 s to avoid possible damage to components caused by excessive heat. During the process, only one solder bath was used to dip the component terminations and the solder bath was dynamic. For SnPb solder dip, the solder bath used molten solder of eutectic Sn37Pb solder with a temperature of 250 °C. For the SAC solder dip, the solder bath used molten solder of Sn3.0Ag0.5Cu with a temperature of 250°C. After the solder dipping, the components were cooled down then rinsed with water. The cooling rate was controlled to be less than 5°C/s, while the temperature was above 60°C. The process is shown in Figure 2



(a) Pick up parts (b) Flux (c) Preheat

(d) Solder dip (e) Cool down (f) Clean

Figure 2: Pictures of solder dip process

The temperature profile of the solder dip process was measured by attaching a thermocouple onto one component that went through the whole process. The thermocouple was embedded into the molding compound by drilling a hole close to the silicon die in the component, as shown in Figure 3. Thus the measurement of temperature profile reflects the temperature experienced by the silicon chip as closely as possible.

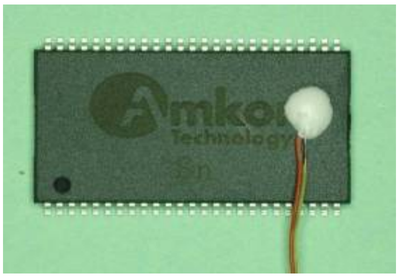


Figure 3: A TSOP component attached with a thermocouple

The measured SnPb solder dip temperature profile is shown in Figure 4. The component was preheated to 149.8°C with a rate of 2.6°C/s for 40 s. The peak temperature experienced by the component was 170.3°C, as shown in Table 1. The SAC solder dip temperature profile was almost the same as the SnPb solder dip temperature profile.

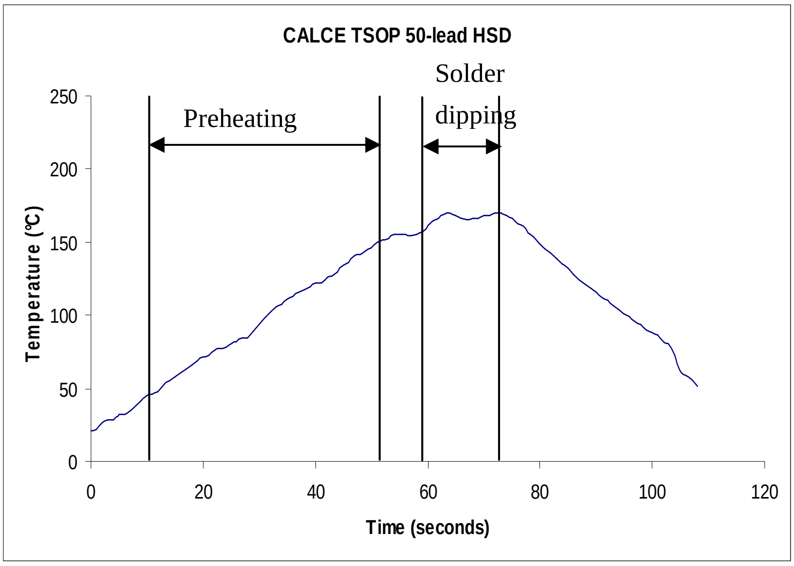


Figure 4: Temperature profile of the SnPb solder dip process measured by a thermocouple

Table 1: Temperature profile parameters of the SnPb solder dip process

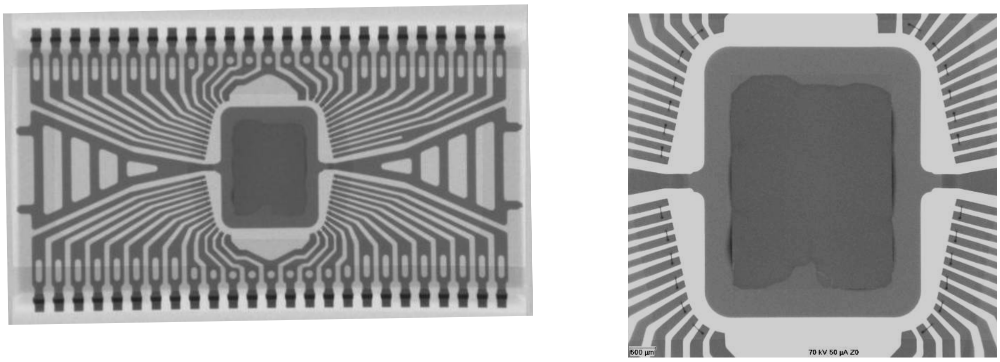
Profile Data	**Value**
Preheat Temperature (°C)	149.8
Preheat Time (sec)	40
Preheat Rate (°C/sec)	2.6
Peak Temperature (°C)	170.3
Cooling Rate (°C/sec)	3.5

2.1.3 Effect of solder dip process on the quality of components

Since the solder dip process may cause thermo-mechanical damage to the dipped components, part of the components were inspected before and after solder dipping to investigate the effect of solder dip process on the quality of the components.

X-ray inspection was conducted on 20 TSOP components to detect cracks, voids or open circuit in the components before solder dip. No cracks, voids or open circuits were found from the X-ray images of the components, as shown in Figure 5.

The wire-bonds were all correctly bonded to adjacent lead-frames. 10 of these 20 components were processed with SnPb solder dip, while the other 10 were processed with SAC solder dip. After the solder dip process, X-ray inspection was conducted again on these 20 components. No cracks, voids or open circuits were found on any of the components.



(a) Full view (b) Die

Figure 5: X-ray images of TSOP component before solder dip

Scanning acoustic microscope (SAM) inspection was also conducted on the above mentioned 20 components, which experienced X-ray inspection. Before and after solder dip process, SAM inspection was performed on those components to detect delaminations at the interfaces. Two interfaces were scanned: the interface between die top surface and molding compound and the interface between die bottom surface and die attach.

No delamination was found on all the 20 components before solder dip process. After solder dip process, some of the components were suspected to have delaminations from the C-SAM images. However, after cross-section analysis of these suspected components, no delamination was confirmed.

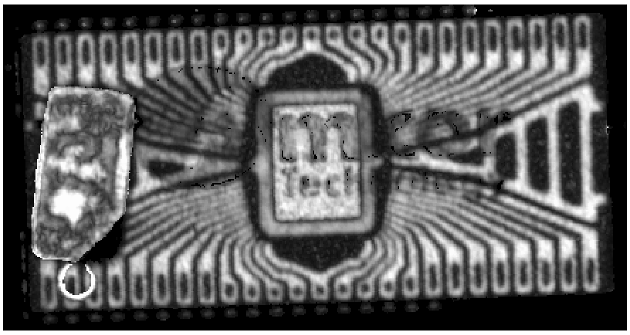
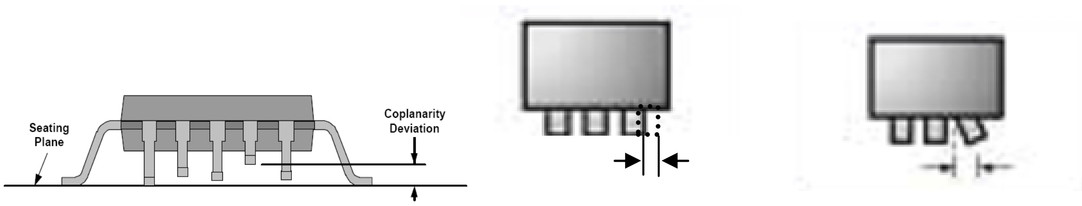


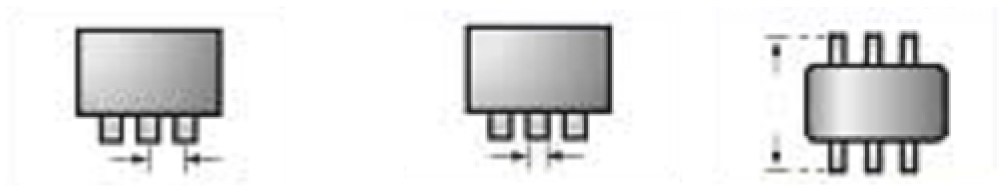
Figure 6: C-SAM image of the interface between die surface and molding compound with 75Hz transducer

From X-ray and SAM inspection, it can be concluded that the solder dip process did not cause any detectable damage to the components. No cracks, voids, open circuits, or delaminations at the interfaces were induced to the sample components by the solder dip process.

Conformity measurement was performed before and after solder dip on part of the processed components. The measured conformity terms include coplanarity, offset, skewness, lead pitch, lead width and terminal dimension, whose definitions are provided as diagrams, as shown in Figure 7. 234 TSOP components, 2 trays, were measured to determine the conformity. All components met the required specifications, as shown in Table 2. Half of the measured components were processed with SAC solder dip, while the other half were processed with SnPb solder dip. After solder dip, all these components passed the conformity test again. So the effect of solder dip process on the conformity of components was still within the defined tolerance.



(a) Coplanarity (b) Offset (c) Skewness



(d) Lead pitch (e) Lead width (f) Termination dimension

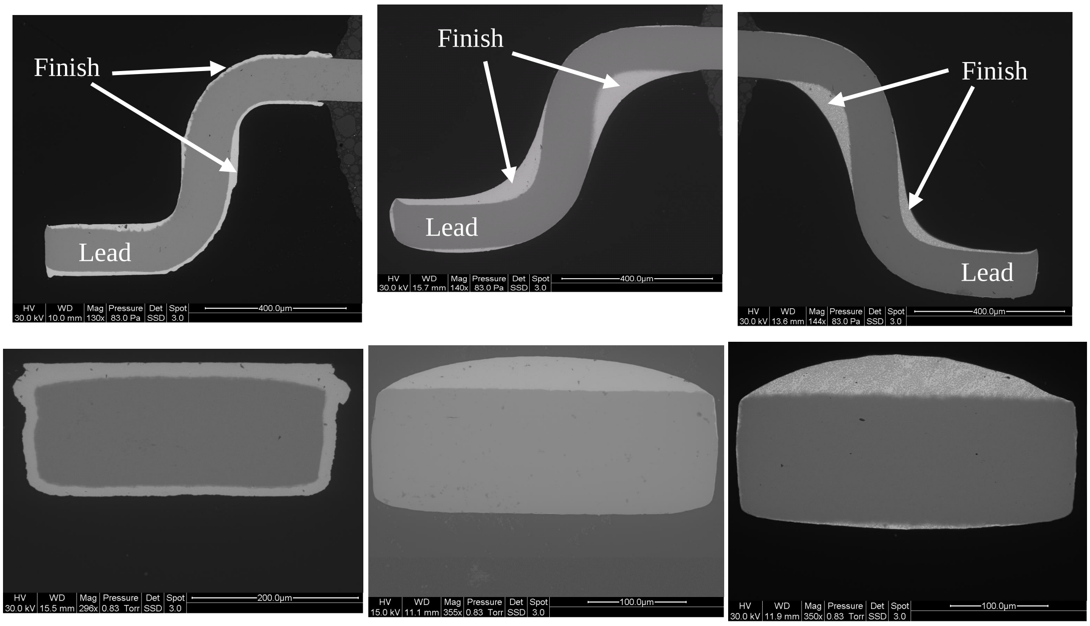
Figure 7: Diagrams of definitions of measured conformity terms

Table 2: Conformity specifications for TSOP 50 components

	Coplanarity	**Offset**	**Skewness**	**Lead pitch**	**Lead width**	**Terminal Dimension**
Tolerance (µm)	+100 0	+75 -75	+65 -65	+75 -75	+80 -80	+200 -200

2.1.4 Lead finish characterization

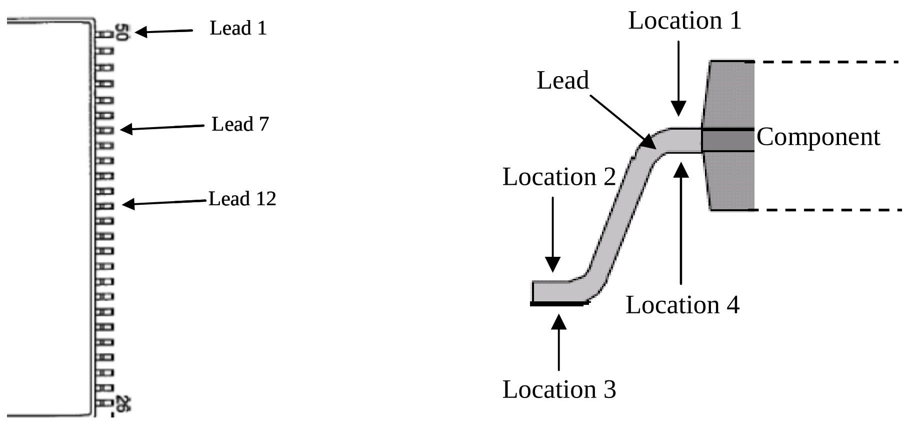
After the solder dip, the volume of the solder finish on the lead changed since the original pure tin finish was replaced by SAC solder or SnPb solder. From pictures taken under an environmental scanning electron microscope (ESEM), as shown in **Figure 8**, it was found that after the solder dip, the lead finish lost its uniformity both around and along the leads. The SAC or SnPb solder accumulated at the corner of the heels and knees of the leads. The solder finish thickness at these locations was sometimes over 30 µm. Since the solder finish volume and composition changed after the solder dip, the mixing of lead finish with the solder paste produced different compositions in the solder joints that were formed.



(a) Original Sn finished lead (b) SAC dipped lead (c) SnPb dipped lead

Figure 8: Lead finish before and after solder dip.

X-ray fluorescence (XRF) was applied to measure the finish composition and thickness at different positions of the leads. The collimator used on the XRF was 0.1mm. The acquisition time for each reading was set at 60s. One TSOP component of each type was measured. Three leads on each component and 4 locations on each lead were measured by XRF, as shown in **Figure 23**. At each location, 3 readings were obtained to calculate the mean value. The measurement results for solder finish composition are shown in Table 3. The lead finish composition is not the same as the solder bath composition. The solder bath composition for SnPb solder was eutectic 63%Sn37%Pb and for SAC solder it was Sn3.0%Ag0.5Cu. Composition differences exist for both kinds of solder dip lead finishes. The percentage of Sn was higher than expected. This was because the original Sn finish and the solder from the solder bath mixed and therefore increased the Sn percentage. The dissolution of Sn might have caused a local concentration of Sn element around the leads, which then formed the new finish composition on the leads.



(a) Definition of measured leads (b) Definition of measured locations

Figure 9: XRF measurement sites on a TSOP component.

Table 3: TSOP lead finish composition

Solder	**Element**	**Composition (wt%) ± Standard deviation (wt%)**
Sn (original)	Sn	100
SAC305 (dipped)	Sn	97.2±1.0
	Ag	1.6±0.4
	Cu	1.2±0.6
Sn37Pb (dipped)	Sn	71.5±8.2
	Pb	28.5±8.3
Sn(2.0-4.0)Bi (original)	Sn	97.2 ± 0.5
	Bi	2.8 ± 0.5

2.2 *Printed circuit board assembly*

The original pure tin finished TSOPs and the solder-dipped TSOPs were assembled onto PCBs using the solder reflow process. The test board design was for temperature cycling test purposes, as shown in Figure 10. The board material was FR4 with organic solderability preservative (OSP) finish applied. The glass transition temperature (T_g) of the board material was 153°C.

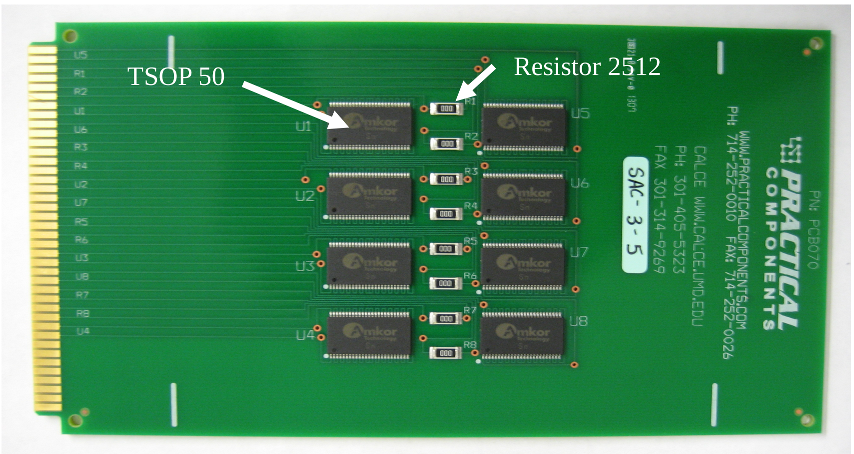


Figure 10: Optical picture of test board

2.2.1 Assembly matrix

There were nine assembly combinations with different component terminal finishes, solder pastes and reflow profiles, as shown in Table 4.

Table 4: Assembly matrix and reflow conditions

Part Lead Finish	**Solder Paste**	**Reflow Profile**	**Board Assembly ID** (Termination finish - Solder paste - Reflow peak temperature)
Pure Sn	Eutectic SnPb	I	Sn finish - SnPb solder - 215C
	Sn3.0Ag0.5Cu	II	Sn finish - SAC solder - 240C
Eutectic SnPb dipped (original pure Sn finish)	Eutectic SnPb	I	SnPb dip - SnPb solder - 215C
Sn3.0Ag0.5Cu dipped (original pure Sn finish)	Eutectic SnPb	III	SAC dip - SnPb solder - 205C
	Eutectic SnPb	I	SAC dip - SnPb solder - 215C
	Eutectic SnPb	IV	SAC dip - SnPb solder - 225C
	Sn3.0Ag0.5Cu	II	SAC dip - SnPb solder - 240C
SnBi	Eutectic SnPb	I	SnBi finish - SnPb solder - 215C
	Sn3.0Ag0.5Cu	II	SnBi finish - SAC solder - 240C

2.2.2 Reflow process

No-clean flux was used on the board during the reflow process. The four different reflow profiles were as follows:

I. SnPb solder profile: 70~80 seconds above 183°C, the peak temperature was 215°C, as shown in Figure 11;

II. SAC solder profile: 50~60 seconds above 217°C, the peak temperature was 240°C;

III. 205 peak solder profile: 70~80 seconds above 183°C, the peak temperature was 205°C;

IV. 225 peak solder profile: 70~80 seconds above 183°C, the peak temperature was 225°C.

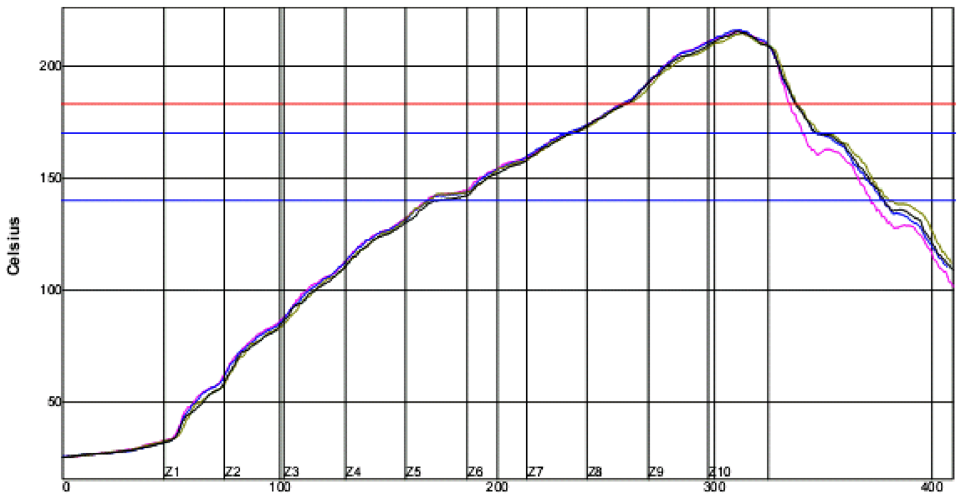
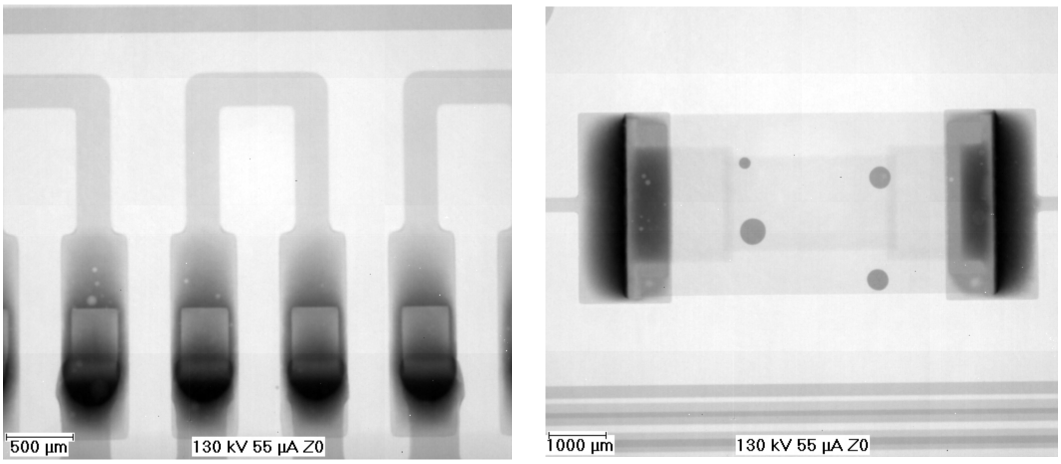


Figure 11: Temperature profiles of reflow processes

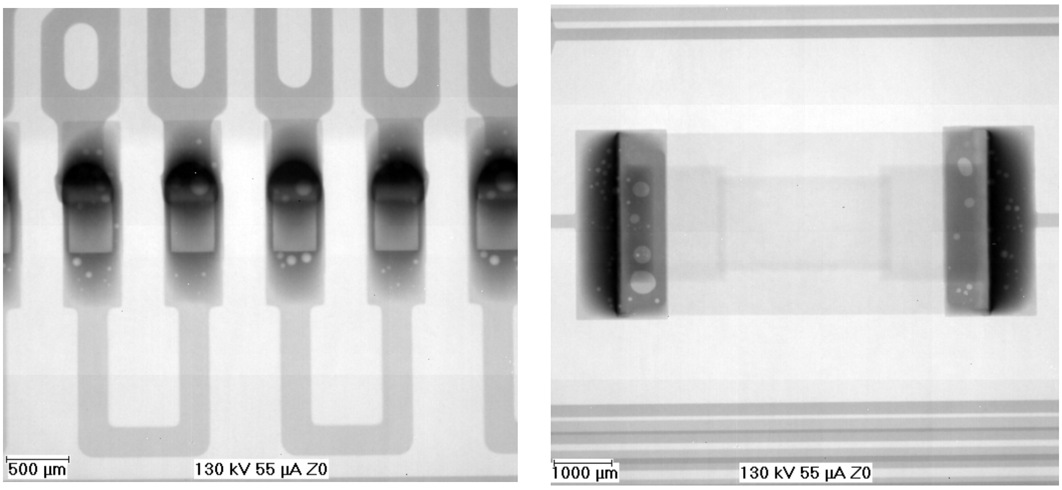
2.2.3 Voids in solder joints

After assembly, one board of each type of assembly was inspected under X-ray to detect cracks or voids formed in the assemblies during assembly process. No detectable cracks have been found. Voids were found in all nine boards with different levels, as shown in Figure 12 and Figure 13. There is difference in void levels between the solder joints formed with SnPb solder paste and SAC solder paste. Solder joints formed with SnPb solder paste have lower level of voids than that formed with SAC solder paste.



(a) TSOP solder joints (b) 2512 resistor solder joints

Figure 12: X-ray pictures of TSOP solder joints and resistor solder joints: SAC dip – SnPb solder – 215C



(a) TSOP solder joints (b) 2512 resistor solder joints

Figure 13: X-ray pictures of TSOP solder joints and resistor solder joints: SAC dip – SAC solder – 240C

2.3 *Conclusion*

From inspection of the components before and after the solder dip process it can be concluded that the solder dip process did not cause any thermomechanical damage to the components. No wirebond liftoffs, cracks or delamination in the components were caused to the components by the solder dip process.

The original pure tin finish was uniform around the leads. The lead finish composition and distribution changed after the solder dip process. The lead finish thickness was not uniform along the lead after dipping. The thickness in the corners of the heels and knees of the leads was larger than other positions. After solder assembly, the solder joints reflowed with SAC solder had a higher density of voids than the solder joints reflowed with SnPb solder.

Chapter 3: Microstructure of solder joints

After solder dipping, the original pure tin finish is replaced by the Sn-Pb solder finish or Sn-Ag-Cu solder finish. The resulting changes in terminal finish composition and distribution, however, may cause changes in solder joints when these solder-dipped components are assembled with Sn-Pb solder paste or lead-free solder paste. Mixed solder assembling is an issue when assembling a lead-free component with Sn-Pb solder paste, which may pose concerns to the reliability of solder joints [13] [14] [15]. Reflow profiles affect the extent of mixing between lead-free solder and Sn-Pb solder during reflow process [14] [16]. The mixing of Sn-Ag-Cu solder and Sn-Pb may produce solder joints that have different microstructure and mechanical properties from pure lead-free solder joints or pure SnPb solder joints. The addition of Pb into Sn-Ag-Cu solder may produce a eutectic ternary phase of Sn-Ag-Pb with a lower melting temperature of 178^{o}C than that of eutectic Sn-Pb solder [17] [18]. It is important to evaluate the solder joint microstructure that can affect its function and reliability [24]. In our current study, microstructure of solder joints formed with refinished components were compared with solder joints formed with original pure tin finished components in order to understand the effects of the solder dip process on the solder joints.

3.1 *Sample preparation*

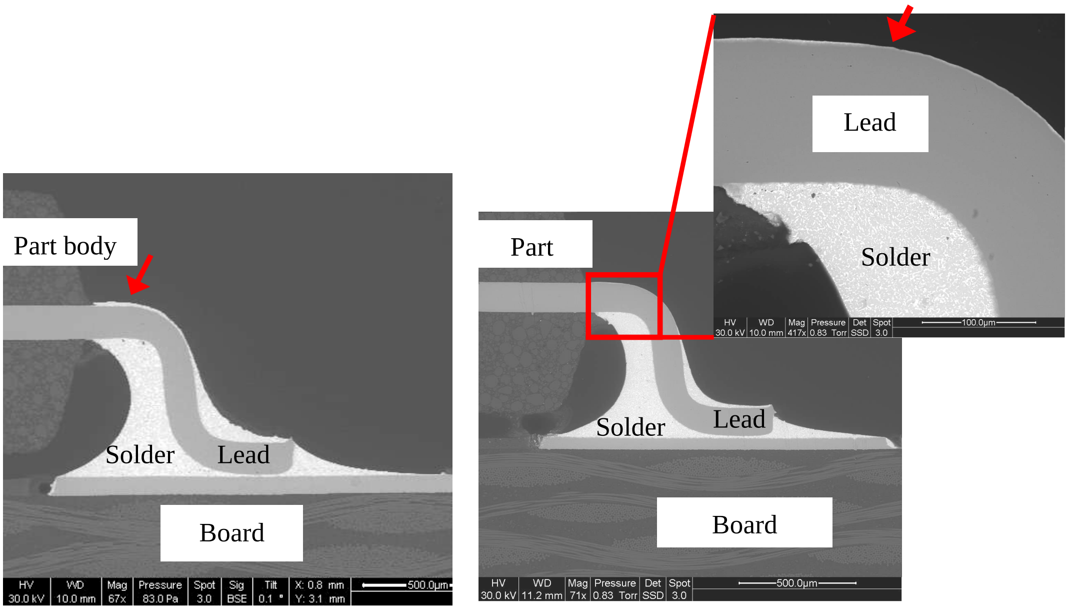
Board segments containing the assembled TSOPs were cut out as samples from the board for micro-structural analysis of the solder joints. The samples were mounted in epoxy and cross-sectioned. After being polished with Al_2O_3 powder, the solder joint surfaces were etched with a mixed acid solution containing 5% acid (HNO_3:HCl=2:1) and 95% ethanol for 7 seconds. The solder joints were investigated under an environmental scanning electron microscope (ESEM) to characterize the microstructure.

3.2 *Solder coverage on leads after assembly*

After reflow assembly, solder joints formed with refinished TSOPs had thinner solder coverage on leads close to component body edges than those formed with original pure tin finished TSOPs, as shown in **Figure 14**. This was observed on all 10 cross-sectioned solder joints formed with refinished TSOPs, including both SAC dipped and SnPb dipped TSOPs. These 10 solder joints were from 5 assembly combinations, 2 solder joints on the same part from each assembly combination. They were compared with 4 cross-sectioned solder joints formed with original pure tin finished TSOPs, including 2 assembly combinations.

The thin solder coverage on refinished TSOPs was partly due to the thin solder coverage at these locations after the solder dip process, as seen in **Figure 8** (b) and (c), compared with that of an original pure tin finished TSOP in **Figure 8** (a). Also, during reflow assembly, not much molten solder climbed up to the locations and solidified there to make up for the loss of solder during the solder dip process. Both of these reasons resulted in thinner solder coverage at those locations on the refinished TSOPs compared with the original pure tin finished TSOPs.

If the pure tin layer on the lead was not completely replaced from the lead at these above mentioned locations, the residual pure tin layer may cause tin whisker risk in future service life because of the thin coverage of solder after assembly. However, in our current study, the solder compositions at these locations were not pure tin, as confirmed by XRF analysis. A SnPb dipped TSOP contained much higher Pb elements than 3% by weight, which is generally accepted to be the minimum standard for lead-content to mitigate tin whisker risk [25] [26].

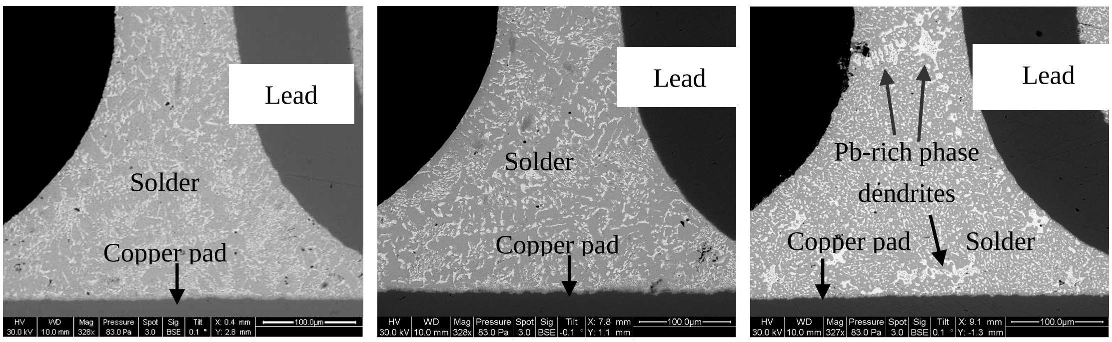


(a) Sn finish – SnPb solder – 215C (b) SAC dip – SnPb solder – 215C

Figure 14: Solder coverage on leads of TSOPs.

3.3 *Pb-rich phase distribution*

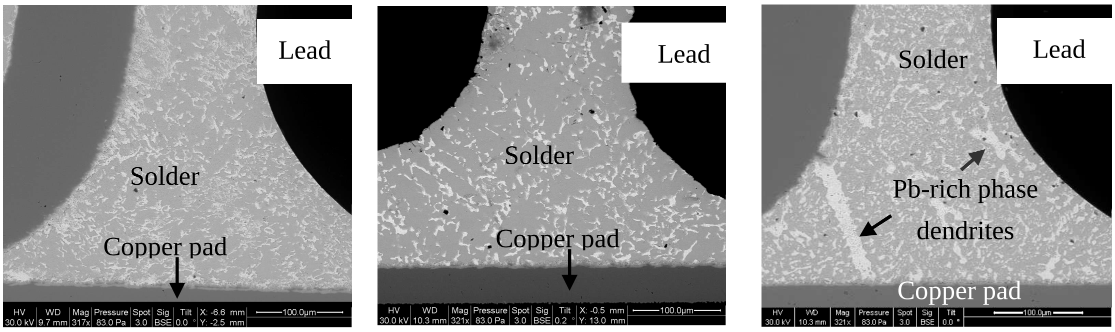
In SnPb solder paste assembled solder joints, Pb-rich phase particles are distributed in a Sn-rich matrix. No clear boundary has been observed between the lead-finish layer and the SnPb solder, as shown in **Figure 15** (a) and (b). However, it has been reported in the literature [14] [16] that when a BGA component with lead-free solder balls (SAC solder) was reflowed with an eutectic SnPb solder paste in order to achieve complete mixing of lead-free solder balls and SnPb solder paste, the reflow peak temperature had to be above a certain temperature range that was around the solidus temperature of SAC solder alloy. Also the dwell time above the melting temperature of eutectic SnPb solder had to be long enough. Otherwise, clear boundaries were observed between the lead-free solder alloy and the SnPb solder alloy in the solder joints, or Pb-rich phase particles were distributed in the solder balls unevenly. In our current study, 3 assembly combinations were reflowed with reflow peak temperatures of 215^{o}C and 205^{o}C, including Sn finish-SnPb solder-215C, SAC dip-SnPb solder-205C, and SAC dip-SnPb solder-215C. Although the reflow peak temperature was lower than the melting temperature of the SAC solder finish (217^{o}C) and Sn finish (232^{o}C), the solder finish material and solder paste material were mixed during assembly, and no clear boundaries were observed between them. This was different from the situation of BGA components reported in the literature [14] [16].



(a) Pure tin finished TSOP - SnPb paste – 215^{o}C (b) SAC dipped TSOP - SnPb paste – 215^{o}C (c) SnPb dipped TSOP - SnPb paste – 215^{o}C

Figure 15: Microstructure of solder joints assembled with SnPb solder paste.

The microstructure of solder joints formed with SnPb dipped TSOPs is different from the microstructure of solder joints formed with original pure tin finished TSOPs and SAC dipped TSOPs when assembled with the same SnPb solder paste. Solder joints formed with SnPb dipped TSOPs have large-size Pb-rich phase dendrites inside, as shown in **Figure 15** (c), while other SnPb solder paste assembled solder joints do not have such large-size Pb-rich phase dendrites. After aging at 125 ^{o}C for 350 hours, such a situation still existed. Large-size Pb-rich phase dendrites were observed in solder joints formed with SnPb dipped TSOPs, while they were not observed in solder joints formed with the original Sn finished TSOPs or SAC dipped TSOPs, as shown in **Figure 16**.



(a) Pure tin finished TSOP - SnPb paste – 215^{o}C (b) SAC dipped TSOP - SnPb paste – 215^{o}C (c) SnPb dipped TSOP - SnPb paste – 215^{o}C

Figure 16: Microstructure of solder joints assembled with SnPb solder paste after aging at 125^{o}C for 350 hours.

It was suspected that the solder joints formed with SnPb dipped TSOPs had a greater ratio of Pb element than the other solder joints. However, through EDS analysis it was determined that they have the same ratio of Pb element in the corresponding area of the solder joints, as shown in **Figure 15**, and in **Figure 17**. So Pb concentration can not explain the difference in large-sized Pb-rich phase. Solder reaction is another possible reason for the difference. For SnPb dipped TSOPs, during the reflow soldering the solder finish and solder paste were both melted and the reaction propagated fairly completely, since the melting temperature of eutectic

SnPb solder (183^{o}C) was relatively lower than the reflow peak temperature (215^{o}C). The Pb-rich phase precipitated to form dendritic structure. However for original pure tin finished TSOPs and SAC dipped TSOPs, the Pb content in the SnPb solder paste was diluted by the lead finish materials. Also more energy from heating was needed to heat the lead finish materials than with the SnPb dipped TSOPs because of the relatively higher melting temperatures (232^{o}C for Sn and 217^{o}C for SAC) to help the reaction with the solder paste than the situation in SnPb dipped TSOPs.

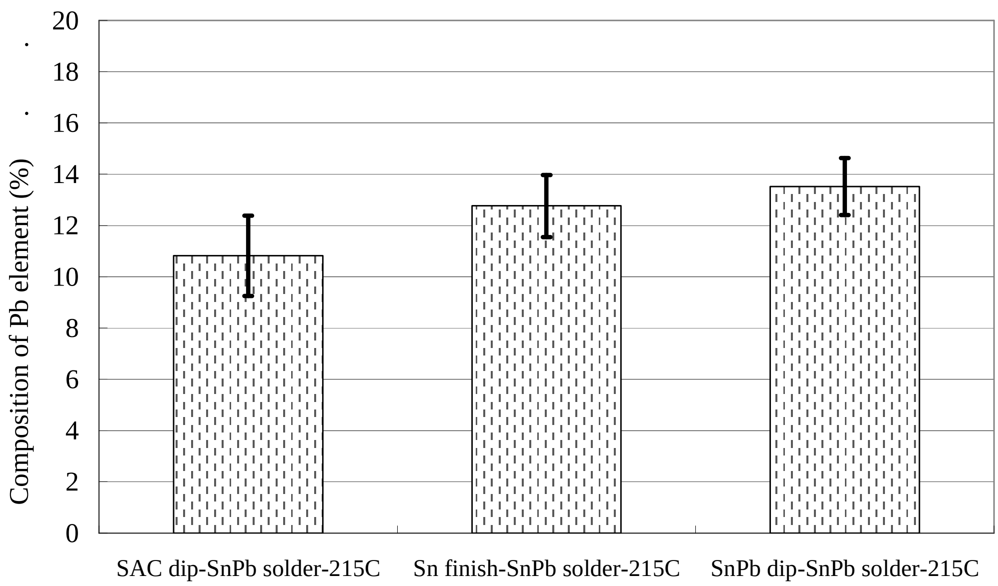


Figure 17: Concentration of Pb element in TSOP solder joints assembled with SnPb solder paste.

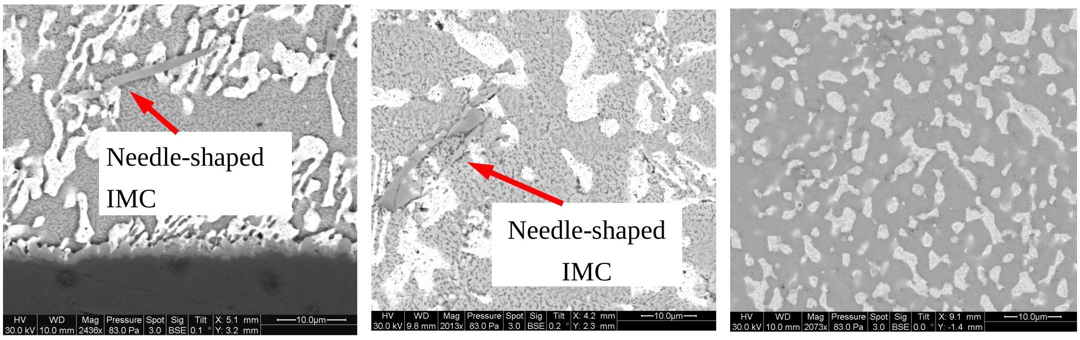
The Pb-rich phase is softer than the Sn-rich matrix after aging and much softer than the IMCs, Ag_3Sn and Cu_6Sn_5. Pb-rich pahse provides ductility in SnPb solder alloy [24]. However, large-sized Pb-rich phase dendrites may degrade the reliability of solder joints. They may serve as crack propagation paths during thermo-mechanical stress loading and cause the failure of the solder joint [14].

3.4 *Intermetallic growth*

A typical TSOP solder joint was formed by soldering a TSOP lead and copper pad together. An IMC layer was formed separately on the copper pad side and the lead side. IMC particles were also observed in the bulk solder of the solder joints. Ag_3Sn particles were dispersed in the bulk solder around Sn-rich matrix grain boundaries [27] in the solder joints formed with SAC dipped TSOPs and solder joints reflowed with SAC solder paste. During thermal aging, the microstructure of the solder joints evolved. IMCs at the interface and in the bulk solder both grew along with thermal aging. The thickness of the IMC layer at the copper pad side was measured. IMCs of large size were investigated.

3.4.1 Large sized IMC growth

IMCs of large size in the bulk solder of solder joints are important to the mechanical properties and reliability of solder joints [27] [28]. On one hand, IMCs can increase the strength of solder joints. On the other hand, under mechanical loading conditions, especially mechanical shock loading conditions, high local stress concentration can occur at the boundaries of IMCs and the Sn-rich matrix due to the different mechanical properties of these two phases. Micro-cracks can be formed in the local stress concentration area and propagate through the solder joint and result in failures.



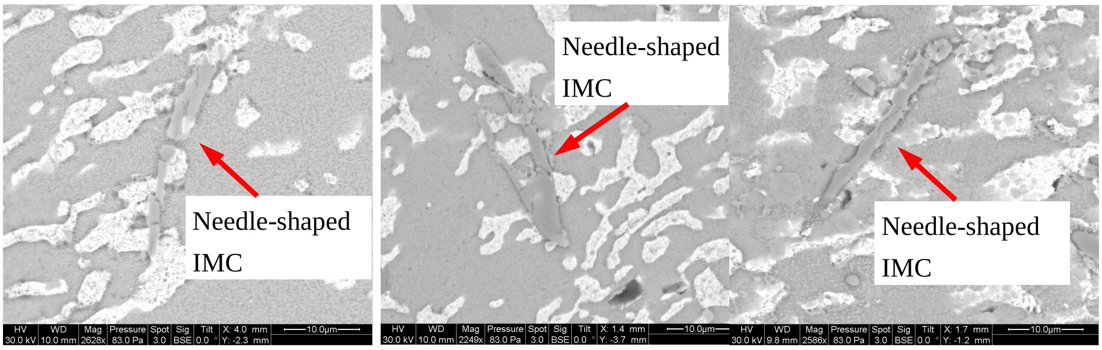
(a) Pure tin finished TSOP - SnPb paste – 215°C

(b) SAC dipped TSOP - SnPb paste – 215°C

(c) SnPb dipped TSOP - SnPb paste – 215°C

Figure 18: Microstructure of solder joints assembled with SnPb solder paste.

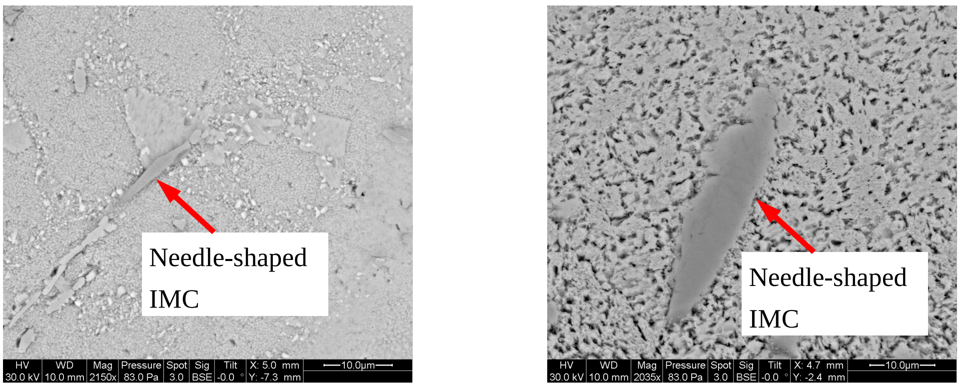
In solder joints assembled with SnPb solder pastes, IMCs with lengths up to about 20 μm were observed in the bulk solder for solder joints formed with original pure tin finished TSOPs and SAC dipped TSOPs, as shown in **Figure 18**. However, no such large IMCs were observed in the bulk solder of solder joints formed with SnPb dipped TSOPs. After aging at 125°C for 350 hours, IMCs with lengths up to around 20 μm were observed in all SnPb solder paste assembled solder joints, including original pure tin finished TSOPs, SAC dipped TSOPs, and SnPb dipped TSOPs, as shown in **Figure 19**. Based on EDS analysis and phase diagram, it was determined that these Needle-shaped IMCs were Cu_6Sn_5 [27] [29]. Some Cu_6Sn_5 may have a small percentage of Ni dissolved into it to form $(Cu, Ni)_6Sn_5$.



(a) Pure tin finished TSOP - SnPb paste – 215^{o}C
(b) SAC dipped TSOP - SnPb paste – 215^{o}C
(c) SnPb dipped TSOP - SnPb paste – 215^{o}C

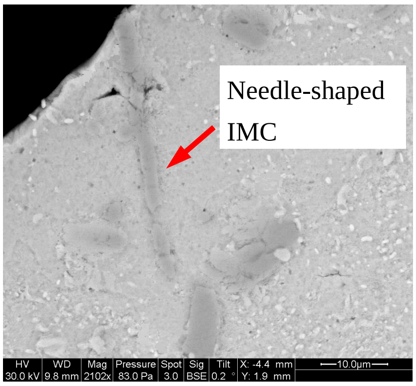
Figure 19: Microstructure of solder joints assembled with SnPb solder paste after aging at 125^{o}C for 350 hours.

In solder joints assembled with SAC solder paste, needle-shaped IMCs with lengths up to around 20 μm were also observed in the bulk solder, as shown in **Figure 20**. After aging at 125^{o}C for 350 hours, similarly sized IMCs were also observed in the bulk solder, as shown in **Figure 21**. It was also determined that these IMCs were Cu_6Sn_5.

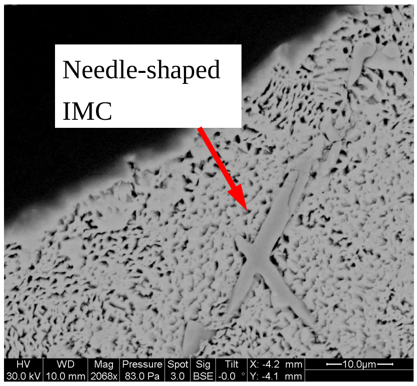


(a) Pure tin finished TSOP - SAC paste – 240^{o}C
(b) SAC dipped TSOP - SAC paste – 240^{o}C

Figure 20: Microstructure of solder joints assembled with SAC solder paste.



(a) Pure tin finished TSOP - SAC paste – 240°C



(b) SAC dipped TSOP - SAC paste – 240°C

Figure 21: Microstructure of solder joints assembled with SAC solder paste after aging at 125°C for 350 hours.

From the above investigation, it can be seen that no large Ag_3Sn dendrites were observed at the interface or in the bulk solder of solder joints formed either with SAC dipped TSOPs or assembled with SAC solder paste. After thermal aging, the dispersed Ag_3Sn particles did not grow to be large dendrites. So in the assemblies of SAC dipped TSOPs with SnPb solder, the addition of Ag from SAC solder finish into the solder joints did not cause the occurrence of Ag_3Sn dendrites, which may pose reliability concern to the solder joints under mechanical loading conditions [28] [30] [31].

Fe and Ni elements from the Alloy-42 leads were detected by EDS in the solder joints. At the interface between the solder and the lead, a layer of IMC was observed in solder joints formed with original pure tin finished TSOPs and solder-dipped TSOPs. However, it was too thin to be analyzed by EDS. It was reported in the literature that Alloy-42 can react with pure Sn or Sn-Ag-Bi solder alloy to form $FeSn_2$ IMC containing less than 10 at.% Ni as impurities at the interface after reaction at 250°C for 5 minutes [32] [33] while Ni_3Sn_4 was not detected at the interface, but in the β-Sn matrix of the solder.

At the interface between the solder and the copper pad on the board side, a layer of IMC was observed on all the 7 assembly combinations. Based on the element ratios obtained from EDS analysis and the phase diagram, it was determined that the IMC layers on the copper pad on the board side were Cu_6Sn_5 for the 7 assembly combinations studied here [27] [29].

3.4.2 IMC thickness measurement

The thickness of the IMC layer on the board side of the solder joints was measured by dividing the area of the IMC layer by its length along the interface. Six measurements were made at 3 different positions, as shown in **Figure 22**. The average, maximum and minimum values were plotted to compare the IMC thickness between the solder joints formed with refinished TSOPs and original pure tin finished TSOPs, as shown in **Figure 23**.

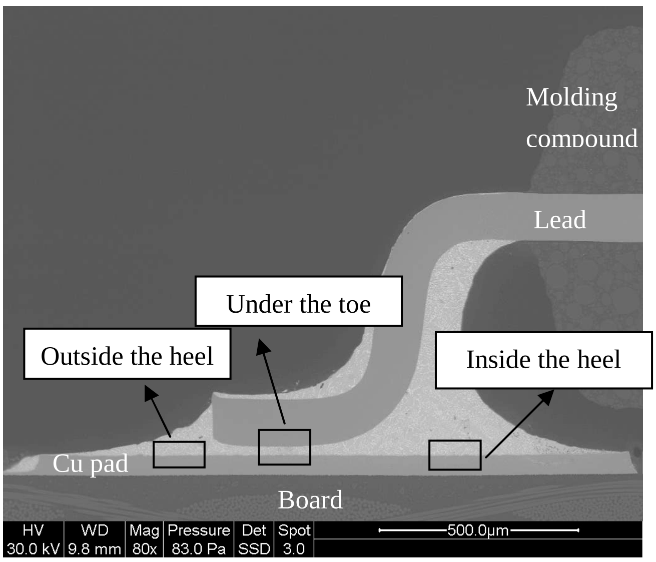


Figure 22: Locations investigated for IMC thickness in a solder joint.

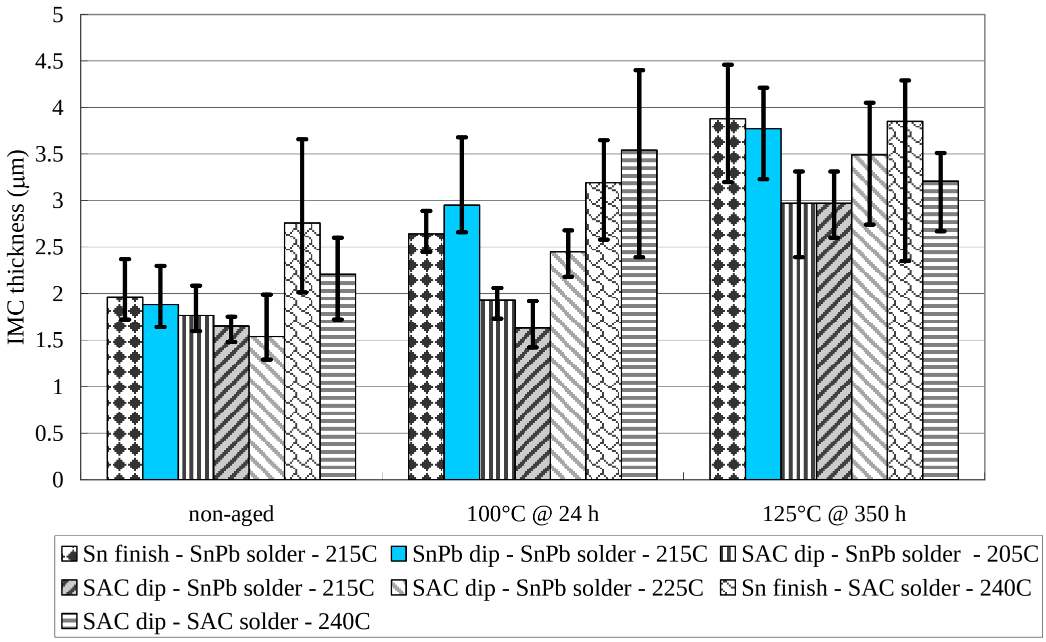


Figure 23: IMC layer thickness at the interface between the solder and the board copper pad in solder joints formed with Sn finished, SAC dipped and SnPb dipped TSOPs.

In solder joints formed with SnPb solder paste, there was no difference in IMC thickness between the original pure tin finished TSOP and solder-dipped TSOPs (either SAC or SnPb dipping). In solder joints formed with SAC solder paste, there was also no difference in IMC thickness between original pure tin finished TSOPs and SAC dipped TSOPs. After aging at 100°C for 24 hours and 125°C for 350 hours, for solder joints formed with SnPb solder paste the IMC layers in the original pure tin finished TSOPs and SnPb dipped TSOPs were thicker than those in the SAC dipped TSOPs. The interfacial IMC layers showed slower growth in the solder joints formed with SAC dipped TSOPs assembled with SnPb solder paste than that in original pure tin finished TSOPs assembled with SnPb solder paste. For solder joints formed with SAC solder paste, the thickness of the IMC layers in the two assembly combinations were still in the same range.

The thickness of the interfacial IMC layer was also measured on the board side of the solder joints formed with SnBi finished TSOPs, as shown in **Figure 24**. From the results, it can be seen that the thickness of the interfacial IMC layer is the same for the solder joints formed with SnBi finished TSOPs and pure tin finished TSOPs for both eutectic SnPb solder assembly and SAC solder assemblies.

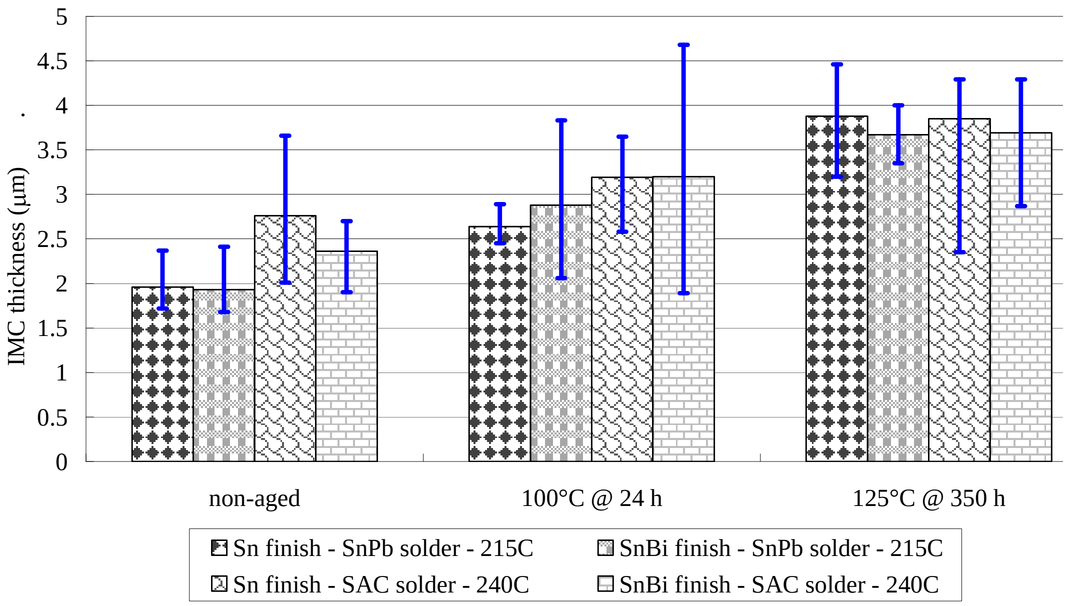


Figure 24: IMC layer thickness at the interface between the solder and the board copper pad in solder joints formed with Sn finished and SnBi finished TSOPs.

3.5 *Discussion*

After SAC dipping of the TSOPs, the pure tin solder finish was replaced by the SAC finish. The Ag and Cu elements were introduced into the solder finish. They were dispersed in the solder by forming IMCs with Sn [27] [35]. During reflow with

SnPb solder paste, the SAC solder finish made contact with molten SnPb solder paste. From the microstructural analysis of solder joints it can be seen that even though the reflow peak temperature was lower than the melting temperature of the SAC solder, the SAC solder finish still mixed with the SnPb solder paste. This was confirmed by the distribution of the Pb-rich phase and the absence of boundaries between the SAC solder finish and the SnPb solder paste. Although the SAC solder finish could not be melted, it was able to dissolve into the molten solder to get mixed in with the SnPb solder. This is different from the mixed assembly of BGA components, where clear boundaries were observed between the SAC solder ball and the SnPb solder paste in the final solder joints [14] [16]. This difference may be because of the relative amount of SAC solder compared to the SnPb solder paste in those situations. Since the ratio of SAC solder finish to SnPb solder paste was smaller than that of the SAC solder ball to the SnPb solder paste, the SAC finish was able to dissolve into the molten SnPb solder within the reflow process.

Although the Ag element was introduced into the solder joints by the SAC solder finish, it did not form large Ag_3Sn IMC flakes with Sn in the solder joints, which might cause reliability risk to the solder joints, especially under shock loading conditions [30] [31]. Large Ag_3Sn flakes may change the failure mode of a solder joint to cause brittle fracture. It can act as a crack initiation site as well as a crack propagation path [28]. The concentration of Ag element in the solder joints studied here is not high enough to form large Ag_3Sn flakes, as shown in **Figure 25**, as it was reported that a minimum of 3.2 wt.% Ag was needed to form large Ag_3Sn

flakes in the Sn-Ag-Cu solder [28]. Even after aging, the dispersed Ag_3Sn IMC particles didn't grow to be large flakes. The reason was that the Ag concentration was relatively low so that there was not enough material to form the large structures. The Ag_3Sn particles were dispersed along the tin rich phase grain boundaries, which increased the creep resistance of the solder joints [36]. Needle-shaped Cu_6Sn_5 IMCs with lengths up to around 20 μm were observed in all solder joints assembled with SAC dipped TSOPs as in the solder joints assembled with the original pure tin finished TSOPs. So in terms of large-size IMCs, the SAC dipping of the TSOPs did not make a difference to the solder joints.

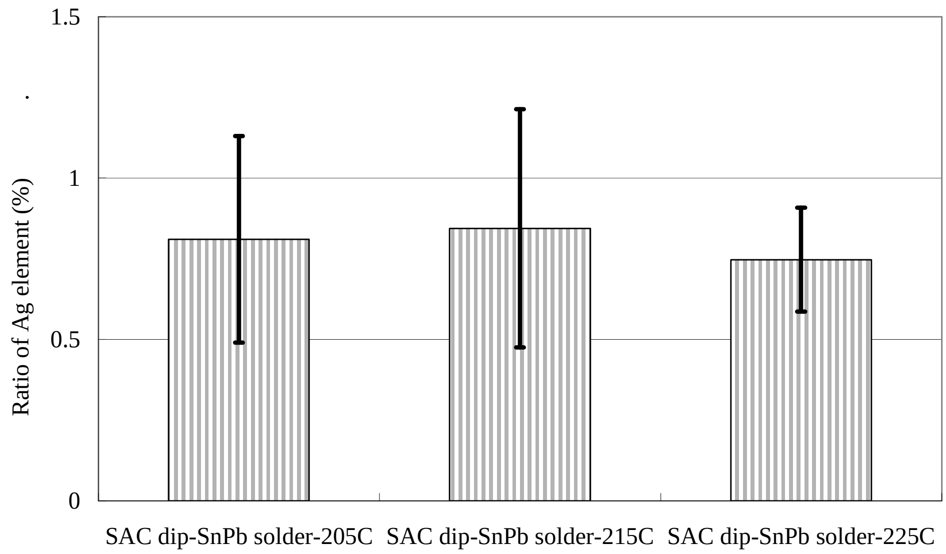


Figure 25: The ratio of Ag element in the solder joints formed with SAC dipped TSOPs assembled with SnPb solder paste (Non-aged)

After SnPb dipping, the original Sn finish was replaced by the SnPb solder finish. During the process of reflowing with SnPb solder paste, the SnPb solder finish was melted and mixed with the SnPb solder paste. IMCs of large size were not observed in the solder joints formed with SnPb dipped TSOPs as they were in original pure tin finished TSOPs. The IMC growth on the interface was the same for the SnPb dipped TSOPs and original pure tin finished TSOPs.

When the TSOPs were assembled with SnPb solder paste, the interfacial IMC thickness was the same for all five of the assembly combinations. However, after aging, the interfacial IMCs in solder joints formed with SAC dipped TSOPs were thinner than those in solder joints formed with original pure tin finished TSOPs and SnPb dipped TSOPs. This IMC growth difference can be partly attributed to the Cu concentration in the solder joints introduced by the SAC solder finish. During the liquid state in reflow process, the reaction between the molten solder and copper pad is about 4 orders of magnitude higher than that during solid state aging [37]. Although the addition of Cu element into the solder slowed the dissolution of the Cu pad into the molten solder, the reaction between the solder and Cu pad seemed to be not affected by the dissolution difference since the IMC growth was not dissolution controlled [38]. However, during solid state reaction in the aging process, the dissolution rate of Cu pad into the solder slowed down. The growth of IMCs was controlled by the dissolution of Cu pad. Thus, the IMC growth in solder joints formed with SAC dipped TSOPs was slower than that in solder joints formed with original pure tin finished TSOPs.

3.6 *Conclusion*

Solder joints formed with solder-dipped TSOPs showed thinner solder coverage close to the component body edges than those formed with original pure tin finished TOPs. In the mixed solder assembly of SAC dipped TSOPs with SnPb solder paste, the solders were mixed and no boundaries between the SAC solder finish and the SnPb solder were observed in the formed solder joints.

Solder joints formed with SAC dipped TSOPs did not show larger IMC size in the bulk solder of the solder joints than the original pure tin finished TSOPs. However, the interfacial IMC layer on the board side showed a slower growth and smaller thickness than the original pure tin finished TSOPs after aging at 100^{o}C for 24 hours or at 125^{o}C for 350 hours, when the solder joints were reflowed with SnPb solder paste.

Solder joints formed with SnPb dipped TSOPs reflowed with SnPb solder paste had large Pb-rich phase dendrites, while other assembly combinations did not have them. Solder joints formed with SnPb dipped TSOPs did not show a difference in large-size IMC growth in bulk solder and interfacial IMC growth from solder joints formed with original pure tin finished TSOPs.

Solder joints formed with SnBi finished TSOPs and pure tin finished TSOPs had the same thickness for interfacial IMC layers both before and after aging for both eutectic SnPb and SAC solder assemblies.

Chapter 4: Solder joint strength evaluation

Solder joint strength is an important metric for evaluating the quality and reliability of a solder joint. A solder joint should have enough strength to ensure reliable bonding of the component and the PCB. A shear test was implemented to evaluate solder joint strength.

4.1 *Test setup*

The shear test was conducted on a DAGE 2400 Bond-tester, as shown in **Figure 26**. One part per assembly combination per condition was cut out of the board for the shear test. Shear force was applied onto the lead using the shear tool. The standoff height of the shear tool head is the distance from the copper pad on the board to the lower edge of shear tool head, as shown in **Figure 27**. It was maintained at 30 μm, which was higher than the solder joint height between the lead and the copper pad to ensure that the shear force was applied to the solder joint through the lead during the test. A gap between the vertical part of the lead and the shear tool head was maintained to minimize the impact of the lead-frame's strength on the test results of solder joint strength. The shear test was displacement-controlled with a constant shearing speed of 200 μm/s, in consideration of the recommendations for the ball grid array (BGA) shear test in JEDEC Standard JESD22-B117A [34]. The test was stopped when the lead was sheared off of the solder joint. The maximum shear force during the test was recorded as the shear force for the solder joint. After the shear test, the fracture surface area of the solder joint was measured. The solder joint strength was calculated by dividing the shear force by the fracture surface area.

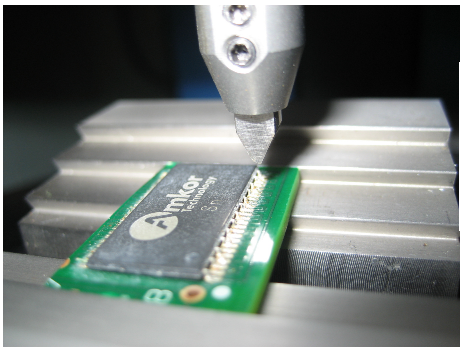


Figure 26: Picture of shear test setup on DAGE 2400 Bondtester.

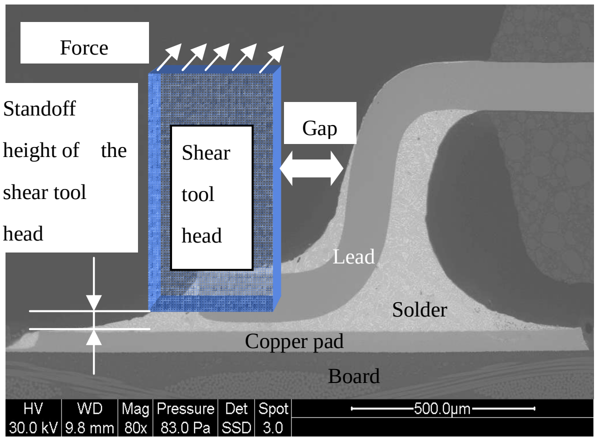


Figure 27: Diagram of shear test setup.

4.2 *Shear strength of solder joints formed with solder dipped TSOPs*

Fourteen solder joints on each part were sheared. Average values and standard deviations were calculated. Solder joints reflowed with SnPb solder paste had the same strength, as shown in **Figure 28**. For solder joints formed with SnPb solder paste, there was no difference in solder joint strength between different assembly combinations both before and after thermal aging, including original pure tin finished, SAC dipped, and SnPb dipped TSOPs. For solder joints assembled with SAC solder paste, the strength of solder joints formed with SAC dipped TSOPs was higher than the original pure tin finished TSOPs. Even after thermal aging at 125^{o}C for 350 hours, from analysis of variance (ANOVA) it can be determined that the strength of solder joints formed with SAC dipped TSOPs was still higher than that of original pure tin finished TSOPs. Even with aging, the strength of solder joints formed with SnPb solder paste did not change. However, the strength of solder joints formed with SAC solder paste decreased.

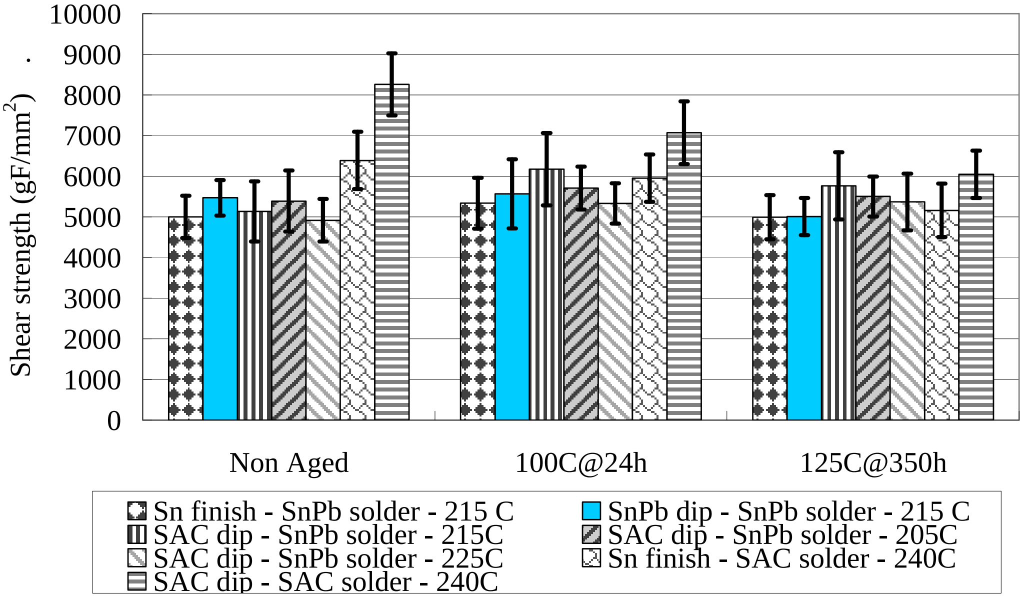


Figure 28: Strength of solder joints reflowed with SnPb solder paste.

4.3 *Shear strength of solder joints formed with SnBi finished TSOPs*

When assembled with SnPb solder paste, the shear strength of solder joints formed with SnBi finished TSOPs was a little bit higher than that of solder joints formed with pure tin finished TSOPs before aging based on ANOVA analysis. However, after aging at 100°C for 24 hours, they became the same. After aging at 125°C for 350 hours, the shear strength of solder joints formed with SnBi finished TSOPs was higher than that of solder joints formed with pure tin finished TSOPs, based on ANOVA analysis.

When assembled with SAC solder paste, the shear strength of solder joints formed with SnBi finished TSOPs was higher than that of solder joints formed with pure tin finished TSOPs before aging. However, after aging at 100°C for 24 hours, they became the same. After aging at 125°C for 350 hours, the shear strength of solder joints formed with SnBi finished TSOPs became higher again.

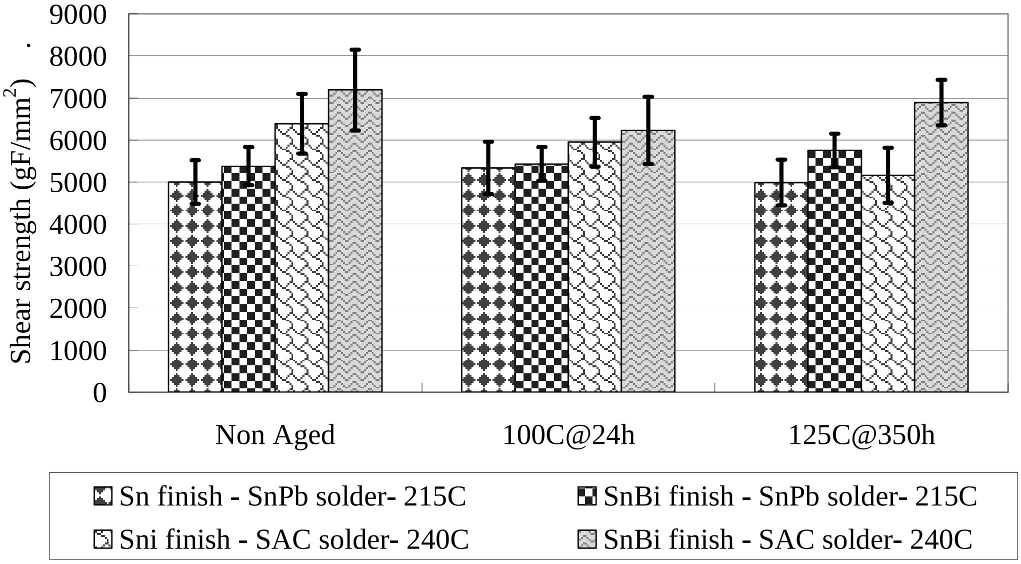


Figure 29: Shear strength of solder joints formed with SnBi finished TSOPs and pure tin finished TSOPs.

From the results, it can be seen that before aging, the shear strength of solder joints formed with SnBi finished TSOPs was higher than that of solder joints formed with pure tin finished TSOPs in both eutectic SnPb solder assembly and SAC solder assembly. After aging at 100°C for 24 hours, they became the same. After aging at 125°C for 350 hours, the shear strength of solder joints formed with SnBi finished TSOPs became higher again.

4.4 *Discussion*

When the TSOPs were assembled with SnPb solder paste, different assembly combinations had the same solder joint strength. Although the Ag element was added into the solder joint by the SAC finish from SAC dipped TSOPs, these solder joints did not show higher strength than the solder joints formed with original pure tin finished TSOPs and SnPb dipped TSOPs. This was probably because after the reflowing process, the microstructure of the solder joints did not reach a state of equilibrium state because of the incomplete mixing of solders and fast cooling. Although silver and copper from the SAC finish can form dispersed IMC particles that can strengthen the solder joints by increasing the stiffness of the solder joints [39], such effects may not be revealed in the non-aged solder joints because of the uneven dispersion of IMC particles and the non-equilibrium state of the materials. However, after aging at 125^{o}C for 350 hours, the solder joint materials were annealed to help the materials reach a state of equilibrium. The IMC particles also grew, became more evenly dispersed through diffusion, and were embedded in the matrix with better adherence [40]. So the strengthening effect of the IMC particles was manifested by the shear strength of the solder joints. Thus, the solder joints formed with SAC dipped TSOPs had higher shear strength than the solder joints formed with original pure tin finished TSOPs and SnPb dipped TSOPs when they were reflowed with eutectic SnPb solder paste.

Along with aging, there were also microstructure coarsening and an increase in the volume fraction of IMCs in the solder joints. These can increase the embrittlement of the solder joints and cause faster crack propagation. So the shear strength of the solder joints decreased for original pure tin finished TSOPs and SAC dipped TSOPs reflowed with SAC solder paste after thermal aging.

4.5 *Conclusion*

When assembled with SnPb solder paste, solder joints formed with solder dipped TSOPs had the same shear strength as the original pure tin finished TSOPs. When assembled with SAC solder paste, solder joints formed with SAC dipped TSOPs showed higher shear strength than the original pure tin finished TSOPs.

Solder joints formed with SnBi finished TSOPs have higher shear strength than those formed with pure tin finished TSOPs before aging and after aging at 125^{o}C for 350 hours in both the eutectic SnPb assembly and the SAC solder assembly.

Chapter 5: Solder joint reliability under temperature cycling test

Temperature cycling tests were conducted to determine the reliability of solder joints formed with refinished components by comparing with solder joints formed with original pure tin finished components. Assemblies with TSOPs and 2512 resistors were tested to obtain the time-to-failure of solder joints under temperature cycling.

5.1 *Temperature cycling test*

Three boards of each assembly combination were tested. Before the temperature cycling test, the test boards were preconditioned by storing them in chambers at 100^{o}C for 24 hours. The purpose of preconditioning was to anneal the test boards. The annealing released the residual stress induced during the assembly process and helped the microstructure of the solder joints to reach equilibrium.

The temperature profile was from -55^{o}C to 125^{o}C with a 15 minute dwell at each temperature extreme and 1 hour per cycle, as shown in **Figure 30**. The resistance of daisy chains (components) was electrically monitored in-situ by event detectors. The failure criterion was defined according to IPC standard 9701: the first interruption of electrical continuity (>300Ω) that is confirmed by 9 additional interruptions within an additional 10% of the cyclic life [41].

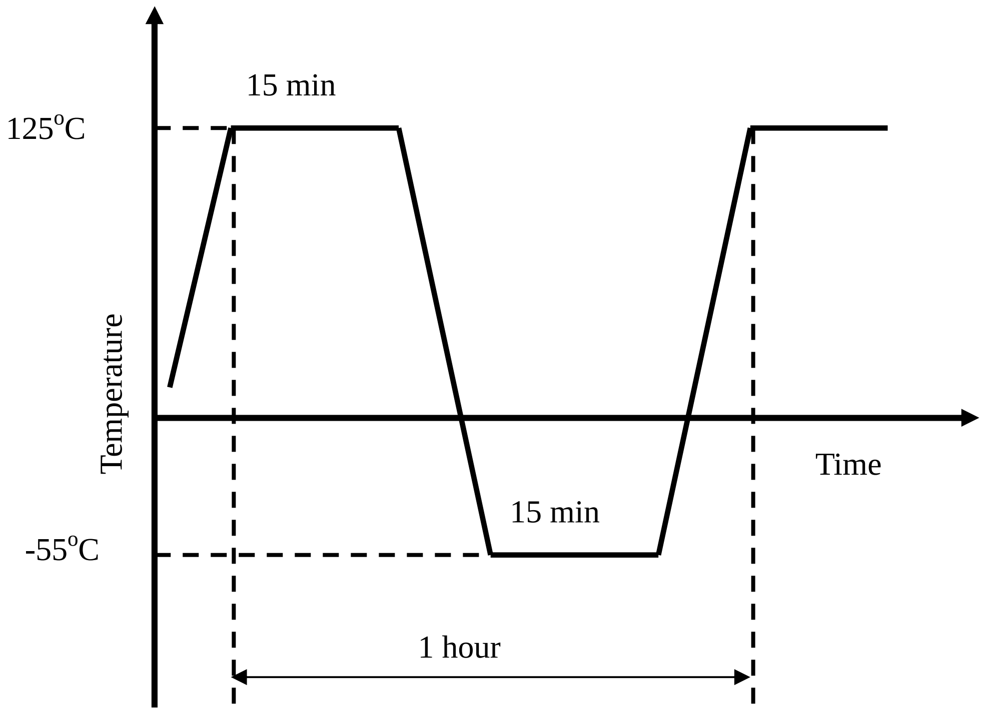


Figure 30: Temperature profile of temperature cycling test

5.2 *Effect of solder dip on solder joint reliability*

The failure data was obtained as time-to-failure. The time-to-failure data was plotted using Weibull ++ software. The time-to-failure distribution was assumed to follow the Weibull distribution. All the data was plotted using the 2-parameter Weibull distribution.

5.2.1 SnPb solder assembly

Original pure tin finished components, SAC dipped components and SnPb dipped components were assembled with SnPb solder paste. The failure probability following the 2-parameter Weibull distribution is plotted in **Figure 31**. The assembly combinations plotted here were all reflowed with a peak temperature of

215^{o}C. The dwell time above the melting temperature of eutectic SnPb solder was 70-80 seconds. It took 95 seconds to cool to 100^{o}C.

The characteristic life of SAC dipped TSOPs is 2052 cycles, as shown in **Figure 31**. It is 13% shorter than the characteristic life of original pure tin finished TSOPs, which is 2353 cycles. The characteristic life of SnPb dipped TSOPs is 2213 cycles, which is very close to the characteristic life of original pure tin finished TSOPs. In addition, SnPb dipped TSOPs and original pure tin finished TSOPs have very close Weibull plot slopes, 9.4 versus 9.1. If the 90% confidence intervals are considered and analysis of variance (ANOVA) is applied to these two distributions, they are the same distribution. This means that SnPb dipped TSOPs have the same reliability as original pure tin finished TSOPs under the temperature cycling test in our current study.

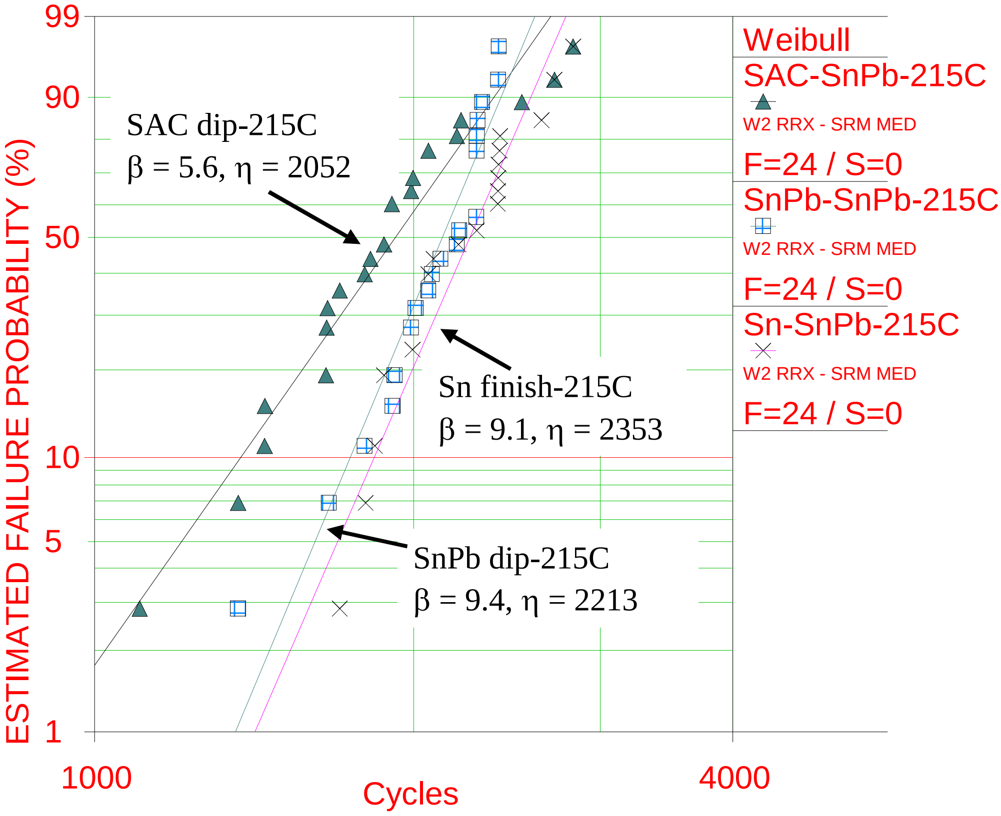


Figure 31: Failure probability of TSOP solder joints reflowed with SnPb solder paste under temperature cycling test

Most of the 2512 resistors reflowed with eutectic SnPb solder paste had failed after 5146 cycles, as shown in **Figure 32**. 47 out of 48 of the original pure tin finished resistors failed. 20 out of 24 of the SAC dipped resistors reflowed with a peak temperature of 215°C failed. 23 of 24 of the SnPb dipped resistors failed. The characteristic life is 3763 cycles for the SAC dipped resistors reflowed with a peak temperature of 215°C. It is 77% longer than the characteristic life of original pure tin finished resistors, which is 2126 cycles. The characteristic life of the SnPb dipped resistors is 3107 cycles, which is 46% longer than the characteristic life of the original pure tin finished resistors. If the 90% confidence intervals are considered and ANOVA analysis is performed, it can be seen that the SAC dipped resistors and SnPb dipped resistors have the same characteristic life when they are reflowed with a peak temperature of 215°C.

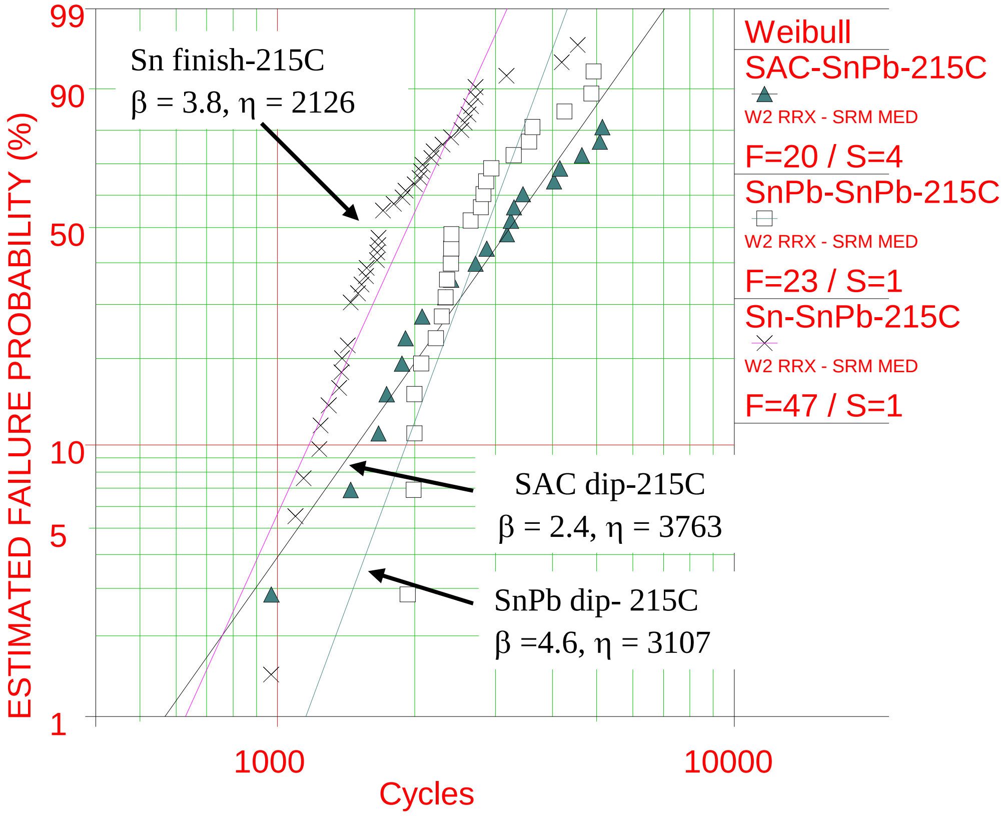


Figure 32: Failure probability of 2512 Resistor solder joints reflowed with SnPb solder paste under temperature cycling test

From the above results, it can be seen that when the components were reflowed with eutectic SnPb solder paste, the characteristic life of TSOP solder joints under the temperature cycling test was decreased by SAC solder dipping , but was un-changed by SnPb solder dipping. For the 2512 resistor components, the characteristic life of solder joints under the temperature cycling test was increased by both SAC solder dipping and SnPb solder dipping, based on the current data.

5.2.2 SAC solder assembly

Original pure tin finished components and SAC dipped components were assembled with SAC solder paste. The reflow profile had a peak temperature of 240°C. The dwell time above the solidus temperature of the SAC solder was 50-60 seconds. It took 110 seconds to cool to 100°C.

The characteristic life of SAC dipped TSOPs was 2430 cycles, as shown in **Figure 33**. This is 20% shorter than the characteristic life of the original pure tin finished TSOPs, which is 2941 cycles. Even if the 90% confidence intervals are considered, they have very little overlap. Thus, they are two different distributions. From the plots, it can be seen that they have similar slopes, 6.9 and 7.5.

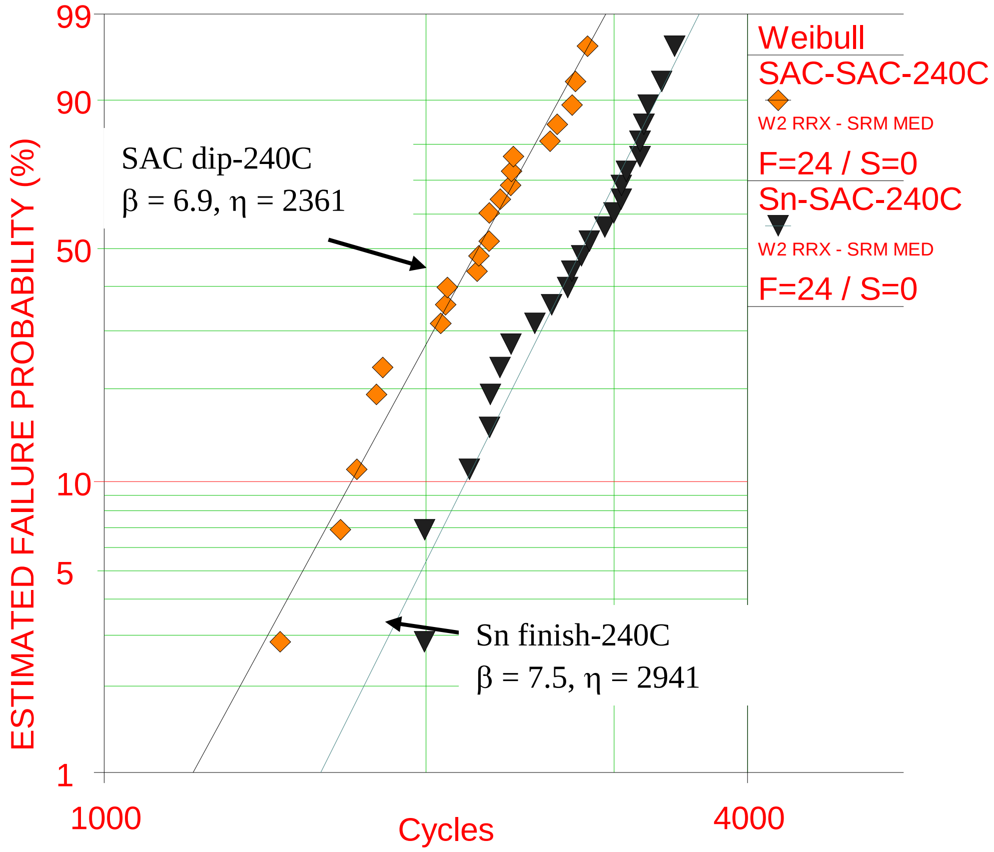


Figure 33: Failure probability of TSOP solder joints reflowed with SAC solder paste under temperature cycling test

16 out of 48 of the original pure tin finished 2512 resistors reflowed with SAC solder paste have failed after 5146 cycles, as shown in **Figure 34**. Only 2 out of 24 of the SAC dipped resistors reflowed with SAC solder paste had failed after 5146 cycles. The characteristic life of the original pure tin finished resistors was 7164 cycles based on the current data. It is obvious that the SAC dipped resistors were more reliable than the original pure tin finished resistors based on the current data.

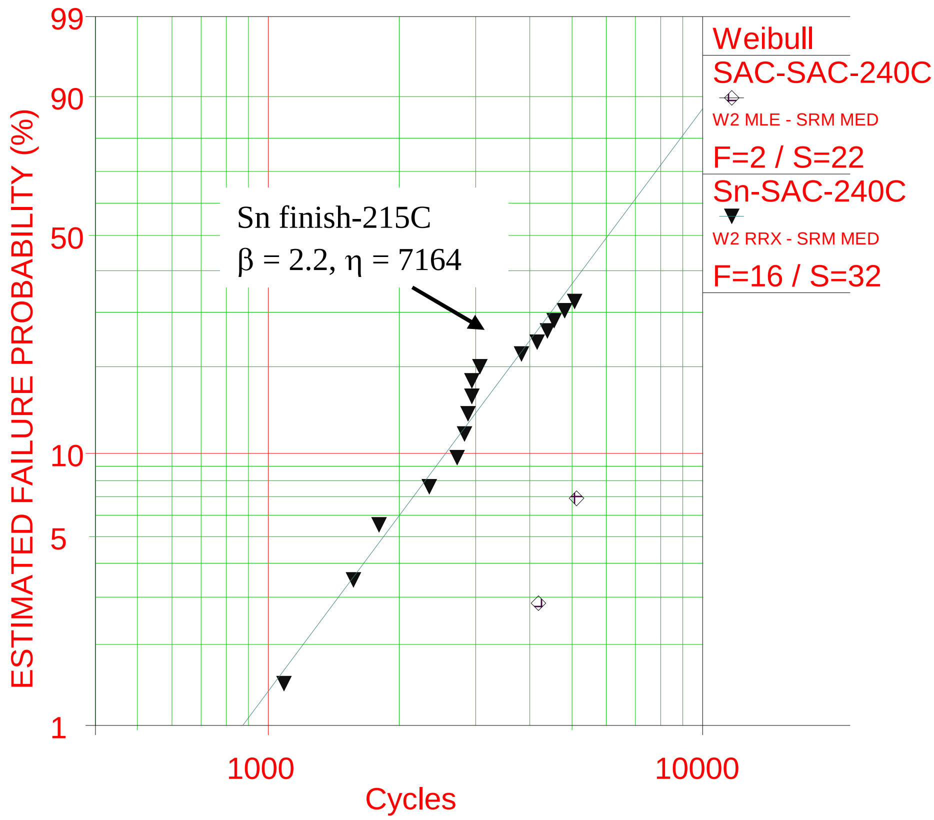


Figure 34: Failure probability of solder joints of 2512 Resistor reflowed with SAC solder paste under temperature cycling test

From the above results, it can be seen that when the components were assembled with SAC solder paste, the characteristic life of the TSOP solder joints under temperature cycling test were decreased by the SAC solder dipping. For resistor solder joints, the characteristic life of solder joints under the temperature cycling test was increased by the solder dipping.

5.3 *Effect of reflow profile on solder joint reliability*

For SAC dipped components, there were three different reflow profiles when they were assembled with eutectic SnPb solder paste. The major difference among these three different reflow profiles was that they had different reflow peak temperatures, 205°C, 215°C and 225°C. The solidus temperature of SAC solder finish is 217°C. One of the reflow peak temperatures is lower (205°C) than the solidus temperature of SAC solder finish. Another one of them is close (215°C) to the solidus temperature. The last one is higher (225°C) than the solidus temperature. It was expected that the difference in reflow profiles might cause a difference in the reliability of solder joints under the temperature cycling test.

However, from the test results as shown in **Figure 35**, it can be seen that the difference in reflow profiles did not cause much difference in the reliability of solder joints under the temperature cycling test for SAC dipped TSOPs. The solder joints reflowed with a peak temperature of 215°C and 225°C have very similar Weibull plots. Their characteristic lives are close to each other, 2052 cycles and 1956 cycles. Their slopes are also similar, 5.6 and 6.0. However, although the Weibull plot of the solder joints reflowed with a peak temperature of 205°C has a similar characteristic life which is 1920 cycles, it has a much larger slope (8.9). From ANOVA analysis, it can be concluded that these three different assembly combinations have the same characteristic life. The characteristic lives of all the assembly combinations formed with SAC dipped TSOPs are longer than the characteristic life of the solder joints formed with original pure tin finished TSOPs when reflowed with eutectic SnPb solder paste.

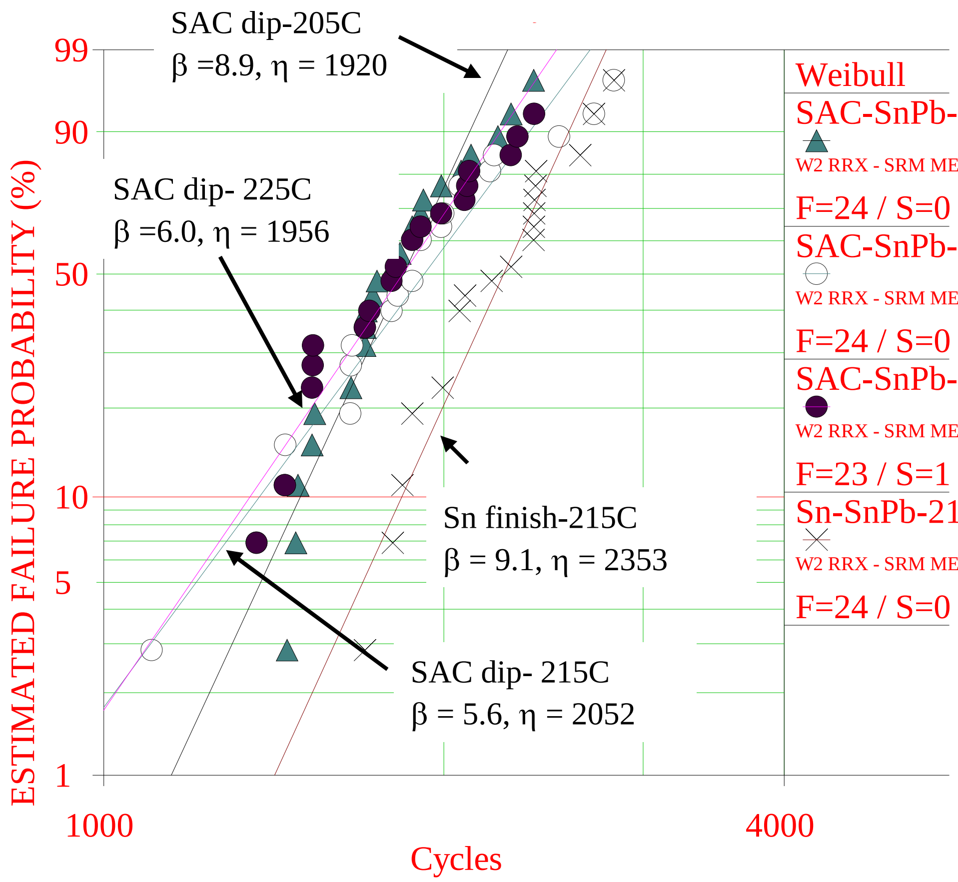


Figure 35: Failure probability of TSOP solder joints formed with SAC dipped TSOPs reflowed with SnPb solder paste under temperature cycling test

Opposite to the test results of TSOP solder joints, the solder joints of SAC dipped resistors all have longer characteristic lives than those of original pure tin finished resistors. From ANOVA analysis, it can be concluded that the SAC dipped resistors reflowed with different reflow profiles have the same characteristic life when assembled with eutectic SnPb solder paste. However, SAC dipped resistors reflowed with a peak temperature of 225°C have a bigger slope of the Weibull plot than the other two.

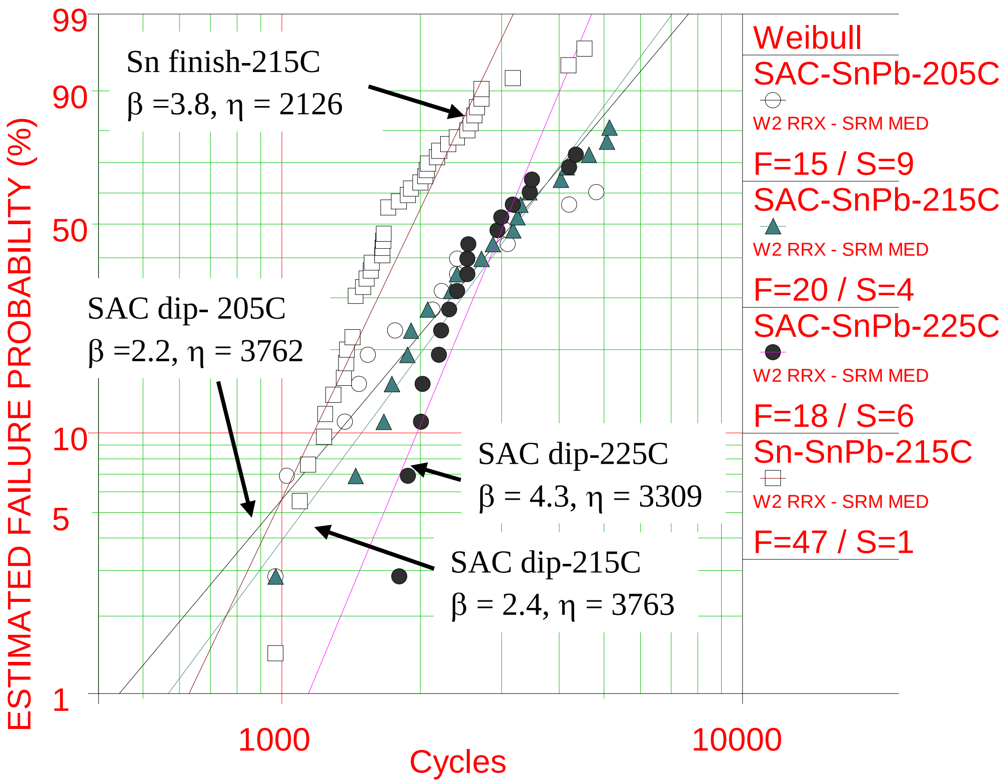


Figure 36: Failure probability of solder joints formed with SAC dipped 2512 Resistor reflowed with eutectic SnPb paste under temperature cycling test

From the above results, it can be seen that different reflow profiles did not cause differences in the characteristic lives for SAC dipped TSOPs and 2512 resistors when they were assembled with SnPb solder paste. However, SAC dipped TSOPs reflowed with the lowest peak temperature had the larger slope in the Weibull plot than the other two. SAC dipped 2512 resistors reflowed with the highest peak temperature have the largest slope of Weibull plot.

5.4 *Reliability of SnBi finished TSOPs*

Original SnBi finished TSOPs were assembled with eutectic SnPb solder and Sn3.0Ag0.5Cu solder as were the original pure tin finished TSOPs. The reliability under the temperature cycling test was compared side by side between the original SnBi finished TSOPs and the original pure tin finished TSOPs.

When assembled with eutectic SnPb solder paste, the characteristic life of SnBi finished TSOPs is 1771 cycles. It is 25% shorter than the characteristic life of pure tin finished TSOPs, which is 2353 cycles. When assembled with SAC solder paste, the characteristic life of SnBi finished TSOPs is 2544 cycles. It is 12% shorter than the characteristic life of pure tin finished TSOPs, which is 2941 cycles.

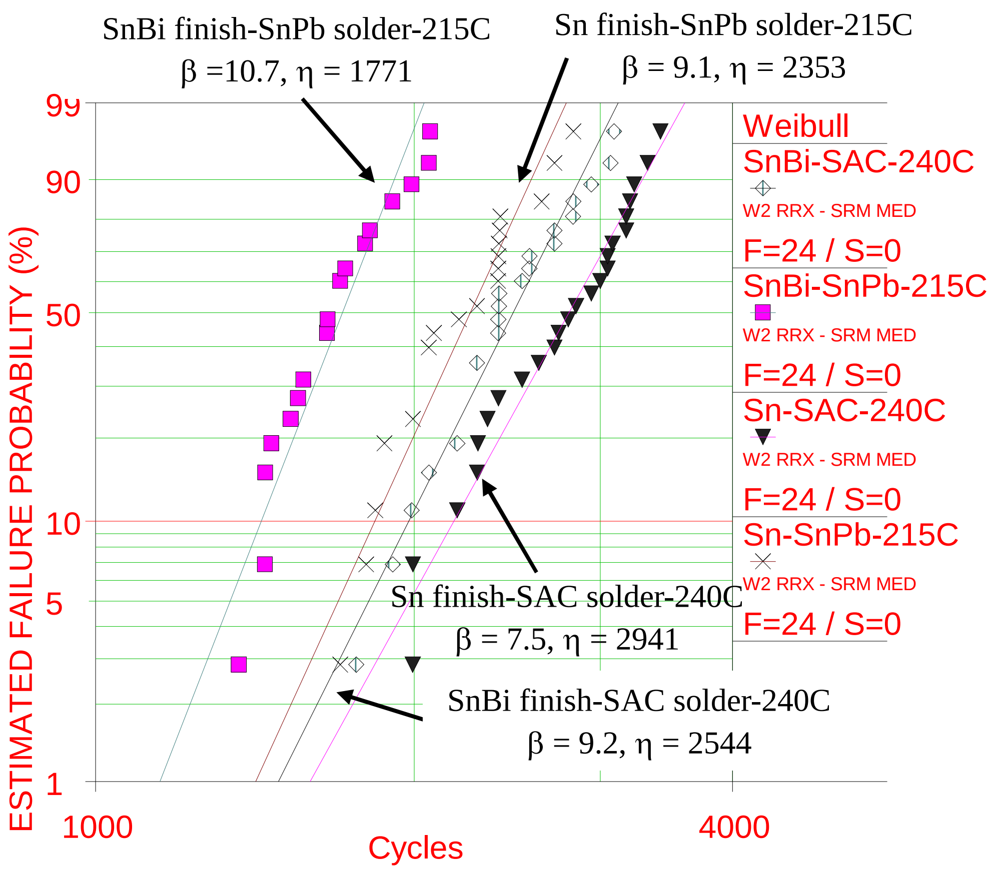


Figure 37: Failure probability of solder joints formed with original pure tin finished and original SnBi finished TSOPs under temperature cycling test

From the above results, it can be seen that the solder joint reliability of SnBi finished TSOPs is lower than that of pure tin finished TSOPs under temperature cycling test for both the eutectic SnPb and the SAC solder assembly. Especially when assembled with SnPb solder paste, the characteristic life of the solder joints formed with SnBi finished TSOPs was much lower than that of pure tin finished TSOPs.

5.5 *Failure analysis of solder joints*

After temperature cycling, electrical continuity test was conducted to confirm the failure of each daisy chain with multi-meter. The electrical test results were consistent with the monitoring results from the temperature cycling test. X-ray analysis was also used to inspect the possible failure of wirebonds in the daisy chains. No wirebond failure including lifeoff and break was observed. There was also no copper trace break failure observed on the board. So the above test confirmed that the daisy chain failures were due to the failure of solder joints.

The earliest TSOP failure of each assembly combination was picked out for failure analysis. The last TSOP failure and the first and last resistor failure on the same board were also picked out for failure analysis. These board sessions with failed components were cut out from the board with band-saw. To protect the solder joints from further damage from the mechanical shock and vibration during the cutting process, the board surface with components was applied with a thin layer of epoxy. After the epoxy solidified, the cutting was performed. Then board session with failure components were then mounted with epoxy for cross-sectioning and polishing. Cracks with solder joints were searched for during the cross-sectioning and polishing process. Pictures of the cracks and microstructure around the cracks were taken under ESEM.

5.5.1 Cracks within solder joints of SnPb solder assemblies

SAC refinished, SnPb refinished and original Sn finished TSOPs and resistors were analyzed in this section. It was found that the earliest failure and the last failure on the same board had almost the same crack propagation path. Different SnPb solder assembly combinations also had the almost the same crack propagation path in the corner solder joints. The crack propagation path for TSOPs was shown in **Figure 38**. This is the typical form of cracks in the corner solder joints of different SnPb solder assembly combinations. The crack propagated at the interface between the bulk solder and the alloy 42 leads and through part of the bulk solder. However, it was not clear that where the crack was initiated.

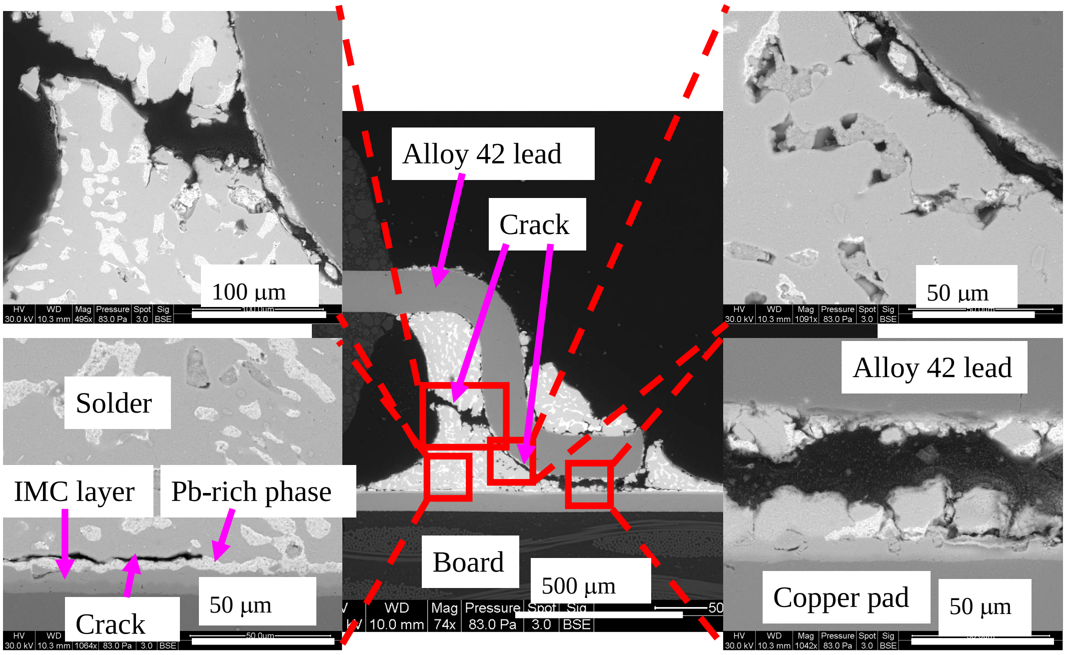


Figure 38: Crack in TSOP solder joints: SAC dip-SnPb solder-215°C-failed at 2216 cycles (corner solder joint)

Further cross-sectioning was performed to approach to the middle the TSOP component. Cracks with a slight different path were observed in some of the non-corner solder joints, as shown in **Figure 39**. The crack propagated totally at the interface between the bulk solder and the leads. Although this didn't give us complete proof of the crack initiation site, it reminded us that the crack might be initiated somewhere at the interface between the bulk solder and the leads. The crack initiation site might have the highest stress concentration at the interface. A void in the stress concentrated area would benefit the crack initiation and propagation. There was residual Pb-rich phase around the crack path. This was clearer in the solder joints formed with SnPb solder refinished TSOPs, as shown in **Figure 40**. There was a layer of residual Pb-rich phase layer on the lead side. This layer of Pb-rich phase was accumulated because of the consumption of Sn to form IMC at the lead interface. During temperature cycling test, the Sn from SnPb solder reacted with metal elements (such as Ni or Cu) to form IMC. Thus, the Pb-rich phase was precipitated at the interface to accumulate. Under stress loading conditions, the adhesion between the Pb-rich phase layer and the bulk solder seemed to be weaker. So the crack propagated through the interface between the Pb-rich phase and the bulk solder. This mechanism was more clearly illustrated on the board side of the solder joints as shown in the bottom left picture of **Figure 38**. There was a layer of Pb-rich phase at the interface. The crack separation was between the Pb-rich phase layer and the bulk solder.

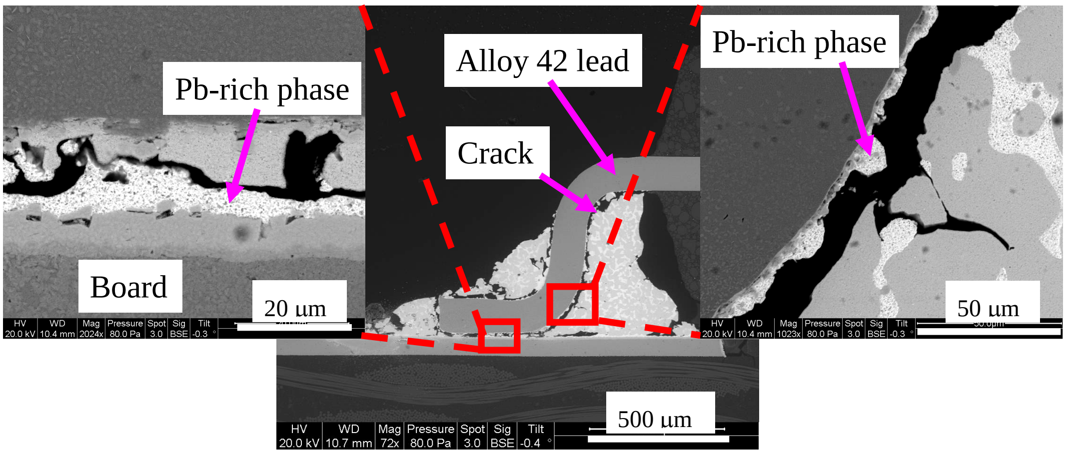


Figure 39: Crack in TSOP solder joints: SAC dip-SnPb solder-215°C-failed at 1136 cycles (non-corner solder joint)

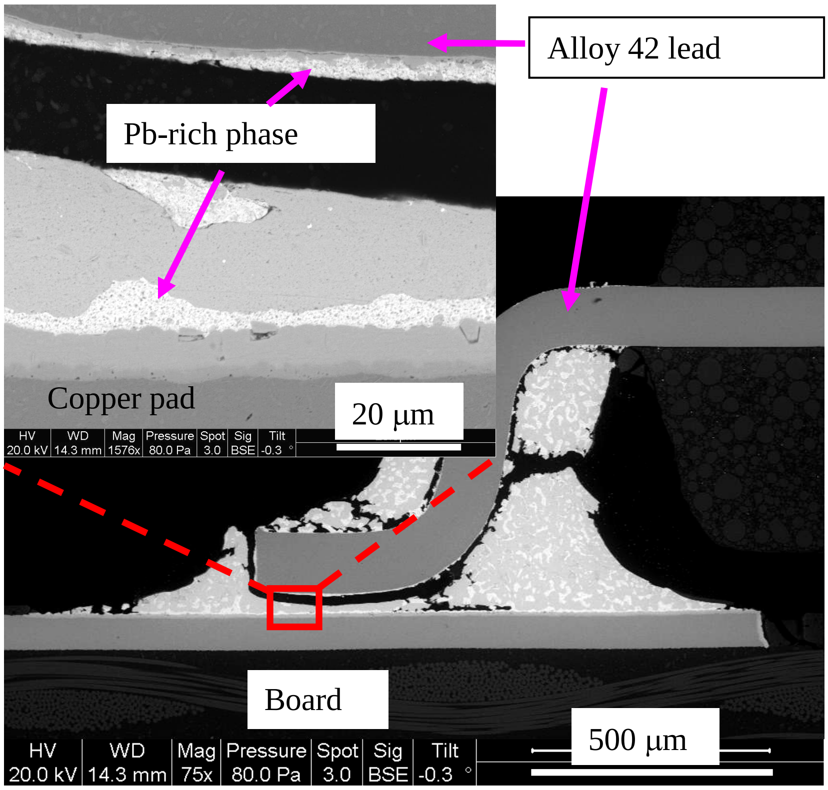


Figure 40: Crack in TSOP solder joints: SnPb dip-SnPb solder-215°C-failed at 1366 cycles (corner solder joint)

The cracks in resistor solder joints for different SnPb assembly combinations were also the same. As shown in **Figure 41**, the crack propagated at the interface between the nickel termination and the bulk solder. A layer of Pb-rich phase was observed at the interface on the nickel termination side. The crack separation was between the Pb-rich phase and the bulk solder.

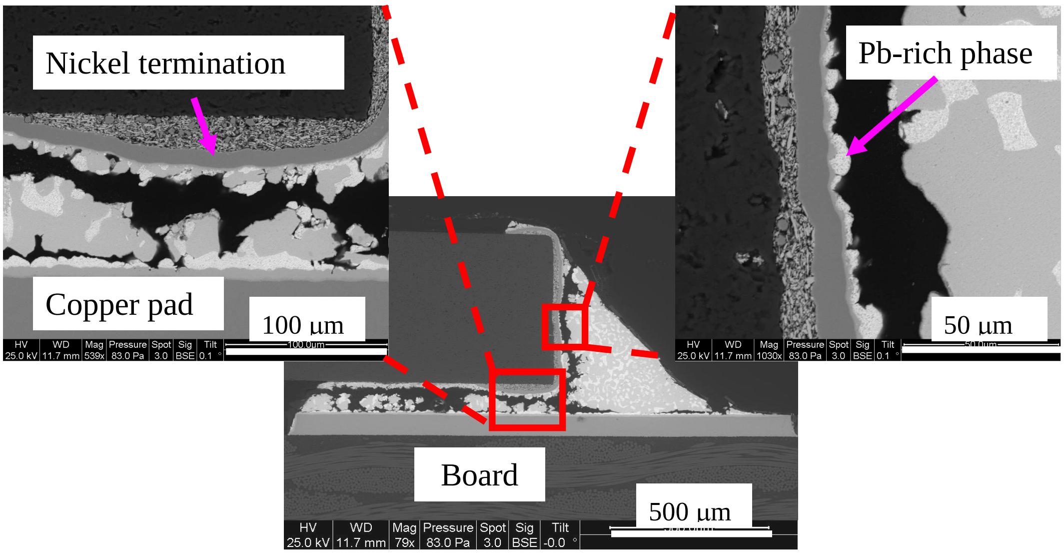


Figure 41: Crack in resistor solder joints: SAC dip-SnPb solder-215°C-failed at 1655 cycles

5.5.2 Cracks within solder joints of SAC solder assemblies

The cracks in SAC solder assemblies were basically the same as those in SnPb solder assemblies. In TSOP solder joints, the cracks propagated at the interface between the lead and the bulk solder and through part of the bulk solder. The difference was that there was no Pb-rich phase in SAC solder joints. Particles of Ag_3Sn and Cu_6Sn_5 with much larger size than before temperature cycling were observed in the bulk solder. However, there was not any observed preference of crack propagation path to these IMC regions.

The cracks in resistor solder joints with SAC solder were also the same as that in SnPb solder assemblies. The crack propagated at the interface between the bulk solder and the nickel termination, as shown in **Figure 43**. Since there were also survived resistor solder joints, cross-sectioning analysis was also performed on some of the survivors. Partial cracks were observed in the survived resistor solder joints, as shown in **Figure 44**. It shows that the cracks could be initiated at multiple sites, for example somewhere in the middle of the interface or at the edge of the interface. These sites should have high local stress concentration in order for crack initiation. The initiated cracks propagated through the interface and finally linked to each other to cause a failure.

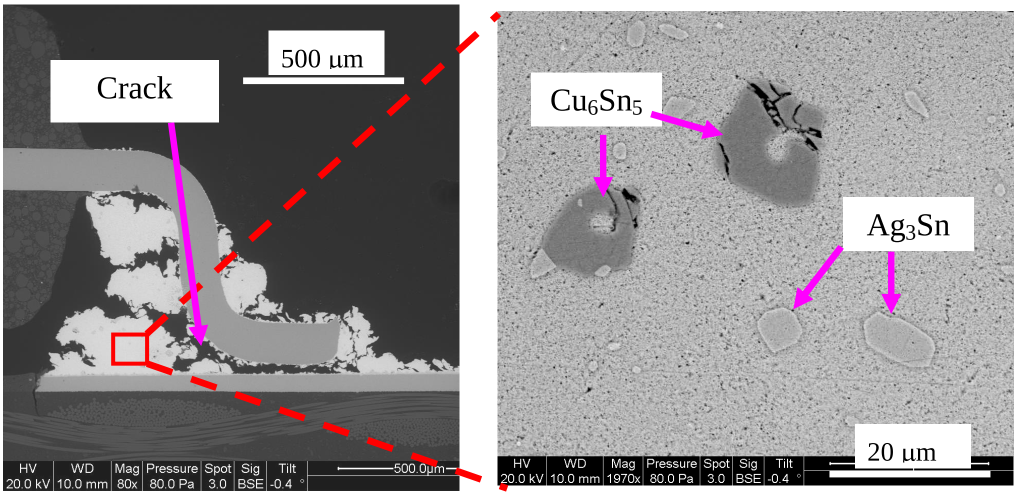


Figure 42: Cracks in TSOP solder joints: SAC dip-SAC solder-240oC-1461 cycles

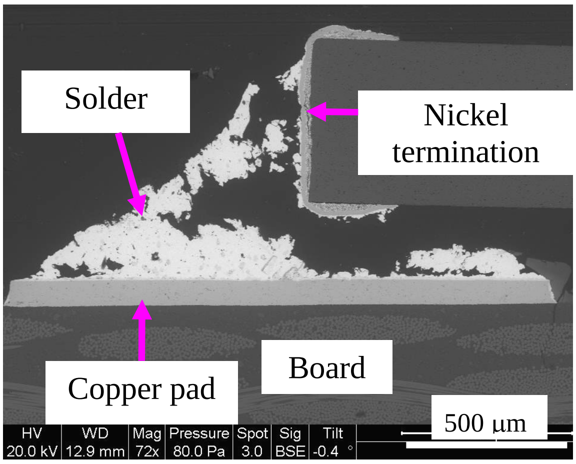


Figure 43: Cracks in resistor solder joints: SAC dip-SAC solder-240°C-4182 cycles

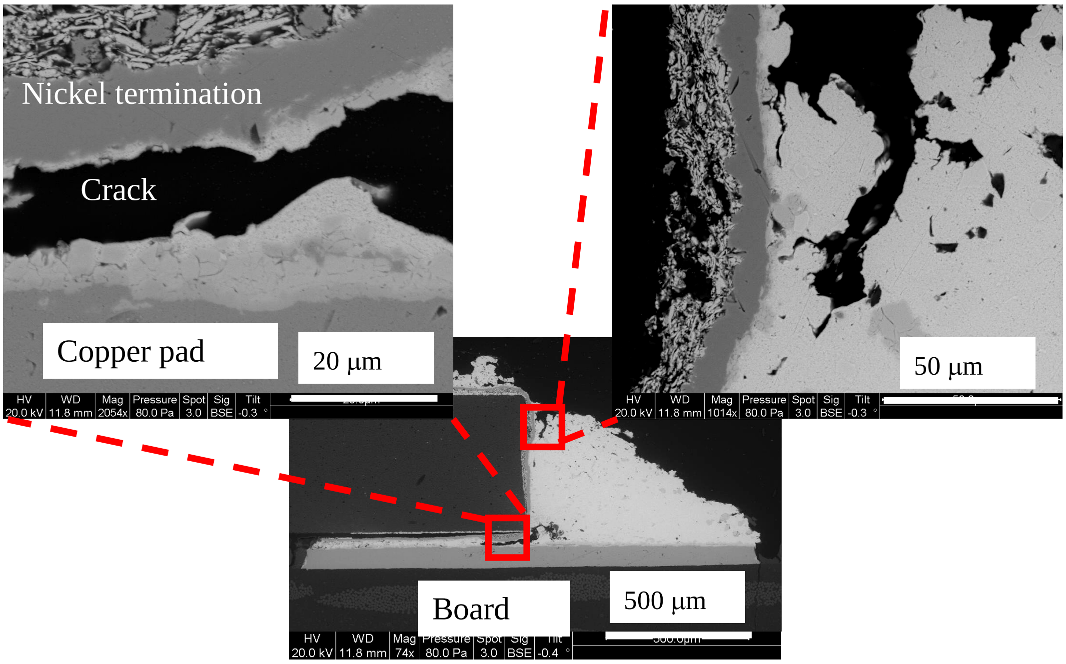


Figure 44: Partial crack in resistor solder joint: SAC dip-SAC solder-240°C

5.6 *Discussion*

The Weibull parameters of the failure data of different assembly combinations can be summarized in the following **Table 5**.

Table 5: Summary of Weibull parameters and number of failures under temperature cycling test

Assembly combination (Termination finish – Solder paste)	Reflow peak temperature	TSOP 50 (Alloy 42)			2512 Resistor		
		Weibull parameters		Sample size (failures/total)	Weibull parameter		Sample size (failures/total)
		η	β		η	β	
Sn finish – SnPb solder	215°C	2353	9.1	24/24	2126	3.8	47/48
Sn finish – SAC solder	240°C	2941	7.6	24/24	7275	2.2	17/48
SnPb dip – SnPb solder	215°C	2200	9.5	23/23	3164	4.6	24/24
SAC dip – SnPb solder	205°C	1920	8.9	24/24	3762	2.2	15/24
	215°C	2052	5.6	24/24	3763	2.4	20/24
	225oC	1924	6.3	23/23	3450	3.9	19/24
SAC dip – SAC solder	240°C	2430	6.4	24/24	NA	NA	2/24
SnBi finish –SnPb solder	215°C	1771	10.7	24/24			
SnBi finish – SAC solder	240°C	2594	8.3	24/24			

The comparison between different assembly combinations can be summarized as in the following **Table 6**.

Table 6: Comparison of characteristic life with tin finished components

	SAC Dip Refinishing		**SnPb Dip Refinishing**	**SnBi Finish**	
Solder Paste	Eutectic SnPb Solder	Sn3.0Ag0.5Cu Solder	Eutectic SnPb Solder	Eutectic SnPb Solder	Sn3.0Ag0.5Cu Solder
TSOP 50	13% decrease	20% decrease	Equal	25% decrease	12% decrease
2512 Resistor	77% increase	Increase	48% increase		

The characteristic life with 90% confidence intervals is plotted as in **Figure 45**. It shows that the fatigue life decrease of TSOPs after refinishing was small and the increase in fatigue life of 2512 resistors was large. If 20% maximum decrease in characteristic life can be accepted, then the solder dip is a good potential choice for refinishing of tin finished components.

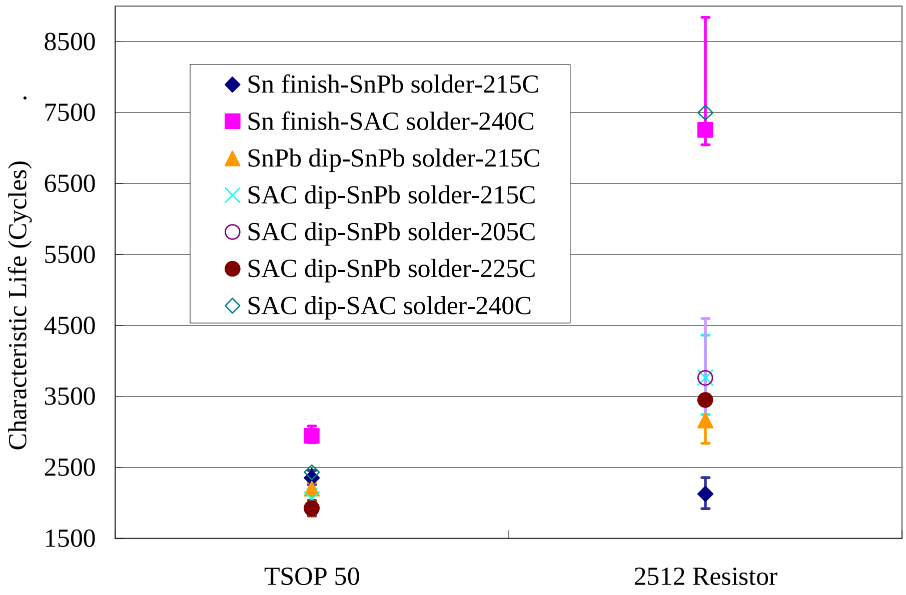


Figure 45: Characteristic life of solder joints with 90% confidence intervals

During the temperature cycling test, the change in temperature caused stress between the component, the solder joints and the PCB due to their mismatch of coefficients of thermal expansion (CTEs). The stress caused damage to the solder joints from cycle to cycle and finally caused failure. For a component that has multiple solder joints on it, the solder joints at the corners of the component tend to fail early because of the highest stress or strain level. The shear strain range of the solder joints, $\Delta\gamma$, can be defined as

$$\Delta\gamma = \frac{L(\alpha_c - \alpha_b)\Delta T}{h} \qquad (1)$$

Where L is the distance between the neutral point and the outermost joints; h is the nominal height of solder joint, α_c and α_b are CTEs for the component and the PCB, respectively; and ΔT is the temperature range during the temperature cycling test.

During the dwell at the high temperature extreme, stress relaxation happened within the solder joints because of the creep properties of the solder materials, including SnPb solder and SAC solder.

Yoon, et al., [42] studied the effects of the highest temperature, the dwell time at the highest temperature and the component size on the fatigue life of SnPb and lead-free solder joints formed with leadless ceramic chip carriers (LCCCs) during a temperature cycling test. They found that the highest temperature in the temperature cycling profile affected the stress relaxation in the solder joints. When the highest temperature was changed from 75^{o}C to 125^{o}C, the fatigue life of solder joints decreased for eutectic SnPb, Sn3.9Ag0.7Cu and Sn3.5Ag solder due to a higher rate of stress relaxation. Also when the highest temperature was 125^{o}C, increasing the dwell time from 15 minutes to 75 minutes did not help the stress relaxation more and the fatigue life of eutectic SnPb solder was close to the two lead-free solders, or even longer. However, when the highest temperature was 75^{o}C, the fatigue life of eutectic SnPb solder was much shorter than those of the two lead-free solders due to the much lower rate of stress relaxation in the lead-free solder joints. The results of our current study showed that under the condition used in the current temperature cycling test, the lead-free solder SAC performed better than the eutectic SnPb solder. The characteristic life of the SAC solder was 25% longer than the eutectic SnPb solder for solder joints formed with original pure tin finished TSOPs. This means that due to the creep resistance of SAC solder, the stress relaxation in the SAC solder has not reach the maximum rate, perhaps due to the much smaller size of the TSOP than the LCCCs, which may have caused a lower strain level in the solder joints. The characteristic life of the SAC solder was three times as long as the eutectic SnPb solder due to the much smaller size of the 2512 resistors than the TSOPs.

When a SAC dipped TSOP was assembled with SnPb solder, the mixing between the SnPb solder and SAC solder could form a new eutectic phase within the solder, which was Sn-36.15Pb-1.35Ag with a melting point of 178^{o}C that was lower than the melting point of eutectic SnPb [17] [18]. The formation of this eutectic phase with a low melting point may degrade the performance of TSOP solder joints. After solder dipping, the solder finish on the bottom of the lead toe seemed thinner than the original pure tin finish. After assembly, the height of the solder joints formed by the SAC dipped TSOPs may have been higher than those formed by original pure tin finished TSOPs. The decrease in solder joint height increased the strain in the solder joints during temperature cycling as defined by Equation (1). Thus the fatigue life of the solder joints decreased as the strain increased. Although the formation of small Ag_3Sn particles can increase the creep resistance of the solder joints, the limited amount of SAC finish may not have significant impact on the fatigue life of the solder joints. When the SAC dipped TSOPs were assembled with SAC solder, the reason for the decrease in fatigue life was the same as that with the SnPb solder.

From the failure analysis, it can be seen that the IMCs in the bulk solder and on the board side did not have direct effects on the crack initiation and propagation.

The crack propagation path did not show any preference to these IMC concentrated regions. However, it doesn't mean that the IMCs are not important for solder joint reliability. The IMCs as a harder second phase in the solder matrix strengthened the solder material. Reliability of solder joints under mechanical shock conditions is more sensitive to IMCs. Under mechanical shock conditions, the strain rate is very high. The solder alloy behaves as a strong material due to strain-rate hardening effect. The IMCs are brittle and have lower fracture toughness. The stress concentrated in the IMCs and brittle fracture is very prone to happen within the IMCs [27][43].

5.7 *Conclusion*

The effects of the solder dip process on the reliability of solder joints formed with solder dipped components are opposite for TSOPs and 2512 resistors under temperature cycling test. The SAC solder dip process decreased the characteristic life of TSOP solder joints for both the eutectic SnPb solder assembly (13% shorter) and SAC solder assembly (20% shorter). However, the SAC dip process increased the characteristic life of solder joints of 2512 resistors for both the eutectic SnPb solder assembly (77% longer) and SAC solder assembly (unknown) based on current available data. The SnPb solder dip process did not change the characteristic life of TSOP solder joints assembled with eutectic SnPb solder paste. However, the SnPb solder dip process increased the characteristic life of 2512 resistor solder joints assembled with eutectic SnPb solder paste (46% longer).

Different reflow profiles did not change the characteristic lives of the solder joints formed with SAC dipped TSOPs and 2512 resistors reflowed with SnPb solder paste.

The solder joint reliability of SnBi finished TSOPs was lower than that of pure tin finished TSOPs for both the eutectic SnPb solder assembly and the SAC solder assembly under temperature cycling test. The characteristic life of solder joints of SnBi finished TSOPs was 25% shorter when assembled with eutectic SnPb solder paste and 12% shorter when assembled with SAC solder paste than that of pure tin finished TSOPs.

If about 20% fatigue life decrease is accepted, then the solder dip can be an acceptable choice of solder refinishing process and SnBi can also be an acceptable alternative finish to tin finish.

Contributions

1. Evaluated the solder dip (SAC/SnPb) refinishing process in terms of its effects on solder joint strength, solder joint reliability under temperature cycling test and microstructure of solder joints.
   (1) Refinished TSOPs (alloy 42 leads) had the same solder joint strength as original tin finished TSOPs.
   (2) Refinished TSOPs (alloy 42 leads) had slight shorter (<20%) fatigue life than original tin finished TSOPs. Refinished 2512 resistors (nickel termination) had much longer (>48%) fatigue life than original tin finished resistors.
   (3) Refinishing did not increase the reliability risk of TSOP (alloy 42 leads) solder joint under mechanical shock conditions in terms of IMCs in bulk solder and at the interface on the board side.
2. Proved that different reflow peak temperature (205oC, 215oC and 225oC) didn't cause difference in microstructure, solder joint strength and reliability under temperature cycling test when SAC refinished TSOPs with alloy 42 leads were assembled with eutectic SnPb solder paste.

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