

Environmental Conditions Impacts on Pb-free Solder Joint Reliability

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Abstract

Understanding the sensitivity of Pb-free solder joint reliability on various environmental conditions, such as corrosive gas, low temperature, and high temperature / high humidity environment, becomes a critical topic while deploying Pb-free products in various markets and applications. In this study, several sets of test vehicles consisting of various types of packages are pretreated with corrosive gas, salt spray, low temperature storage, and humidity/temperature soak. They were then subjected to temperature cycle test to study their solder joint reliability. Test vehicles using eutectic Sn/Pb solder were also tested side-by-side with the Pb-free siblings as a reference. The results have shown, under certain conditions, these pre-treatments degrade the cycle life of Pb-free solder joints on the tested packages. In this paper, the extent of degradation, the microstructural evolutions, and dependency of the degradation on package types and solder alloys are discussed.

Key words: Pb-free solder, corrosion, solder joint reliability, environmental condition

1. Introduction

Due to the legislation and market drive toward eliminating lead (Pb) in electrical and electronic products, many lead-free solders have been studied as replacements for Sn-Pb solders. Among them, Sn-Ag-Cu series are widely accepted and used by the industry [1,2]. Electronic products and assemblies are deployed in a wide range of environments for different applications and can be subjected to various types of conditions, such as family room, outdoor environments with high humidity or wide temperature range, and factories with un-controlled atmosphere. Compared to Sn-Pb solders, Sn-Ag-Cu solders have different metallurgy and microstructure that may lead to different responses and resistance to environmental conditions. When the corrosion or phase changes present in the solder joints, it may change the microstructure and decreases the mechanical strength and reliability of solder joints.

In the past years, extensive works have been completed on solderability, mechanical properties, thermal cycling fatigue life, and reflow process characteristics, but only limited studies have been dedicated to the corrosion behavior of the alloys and the corrosion effects on Pb-free solder [3,4,5,6,7,8] and the impacts on the solder joint reliability of

electronic assemblies [9]. It is critical to investigate the sensitivity of Pb-free solder joint reliability on various environmental conditions in order to evaluate the field performance of Pb-free products. In this study, the Pb-free solder joint reliability (thermal cycle fatigue life) under the influence of the environmental factors is investigated.

2. Experimental Procedure

This study is performed based on the four selected extreme environmental conditions for two types of Pb-free solders, SAC105 (Sn-1Ag-0.5Cu) and SAC305 (Sn-3Ag-0.5Cu). The test samples are pre-treated with various conditions and then subjected to accelerated thermal cycling (ATC) test. Test vehicles using eutectic Sn/Pb solder were also tested as a control lot in order to benchmark Pb-free solder's performance.

2.1 Preparation of Test Samples

The packaging types used in the test samples are as following:

1) CABGA256: package dimension: 17 mm x 17 mm; BGA ball pitch: 1.0 mm; die size: 14.86 mm x 14.86 mm; solder ball diameter: 0.48 mm; surface finish: Electrolytic NiAu; solder ball composition: SAC105, SAC305, and eutectic solder (63Sn37Pb) respectively.
 2) TSOP54: package dimension: 10 mm x 22 mm; pitch: 0.8mm; lead frame surface: matt tin and eutectic solder coating respectively.
 3) Printed Circuit Boards (PCBs) is using 8-layer 93 mil thick high Tg material. Cu pad surface finish is high temperature OSP.

Pb-free components, either SAC105 or SAC305 BGA, were assembled on test boards using SAC305 paste only. For the Sn/Pb control samples, the eutectic solder paste was used. Each type of assembly (Pb-free and Sn/Pb) was subjected to adequate reflow profile in order to assemble the components on test board. Figure 1 illustrates the top view of the test boards.

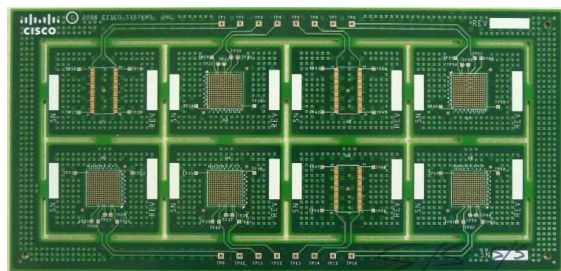


Figure 1 Top view of ATC Test Boards

2.2 Environmental Conditions Used in the Investigation

Four environmental conditions are selected to pre-treat the assembled test boards.

- 1) High temperature and humidity storage: 60°C / 86%RH for 500 hours;
- 2) Extreme low temperature storage: -40°C, 500 hours;
- 3) Corrosive gas: MFG contenting H₂S: 100 ppb, SO₂:200 ppb, Cl₂: 20 ppb, NO₂: 200 ppb, and 70% RH at 30°C for 336 hours;
- 4) Salt spray: 5 wt% of NaCl aqueous solution at 35°C for 96 hours.

An untreated leg for every package type is used as a baseline.

2.3 Experimental Process

The test vehicles are exposed to the four selected environmental conditions separately and

then subjected to accelerated thermal cycle (ATC) test. The ATC test condition is described in IPC 9701 with 0 to 100°C temperature range in a 40-minute cycle. The ramp rate of the test is 10°C/min. and the dwell time at each extreme is 10 minutes. Datalogger is employed to monitor the continuity of each daisy chain package during test. Figure 2 illustrate the flow chart of the test.

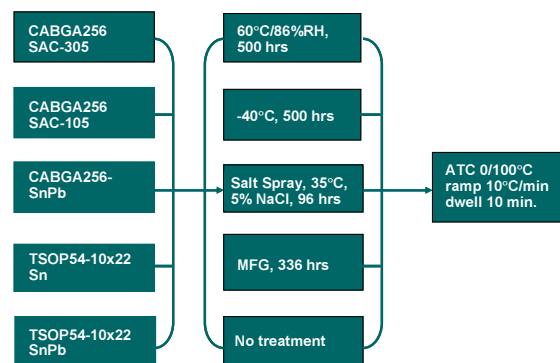


Figure 2 Flow chart of the environmental conditions and reliability tests

3. Results and Discussions

3.1 CABGA256 with SAC305 BGA Solder Joints Reliability

The results of accelerated thermal cycling after the treatments at 60°C / 86%RH and -40°C for 500 hours separately for CABGA256 with SAC305 solder balls are presented in the Weibull plots as show in Figure 3. It is observed that these two conditions change the slope of the failure rate in Weibull while comparing to the non-treated samples. It can be noted as having lower fatigue life cycle number at cumulative 1% of failure rate and no significant differences on the characteristic life (cycle number at 63.2% cumulative failure rate).

The results of thermal cycling after the treatments with MFG (336 hrs) and salt spray (96 hrs) are presented in Weibull plots as show in Figure 4. From the results in Figure 4, it is also observed that the slopes of the Weibull plots from MFG and salt-spray treated samples are changed while comparing to un-treated samples. It is noted that the characteristic life of the salt spray samples is lower when comparing to untreated samples. However, for the samples treated with MFG, just like the -40C and 60°C / 86%RH treated samples, the characteristic life is comparable with the characteristic life of untreated samples.

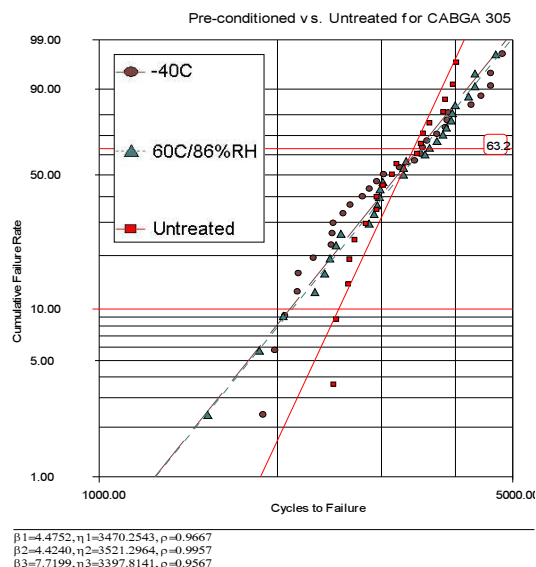


Figure 3 Weibull plots of ATC test results of CABGA SAC305 treated at 60°C / 86%RH and -40°C for 500 hours respectively vs. untreated

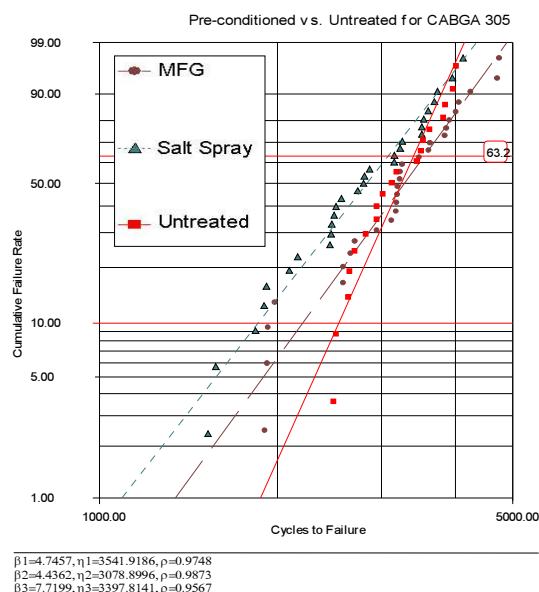


Fig. 4 Weibull plots of ATC test results of CABGA SAC305 treated with MFG (336 hrs) and salt spray (96 hrs) respectively vs. untreated

The slopes of the failure rates of test samples with different pre-treatments and their corresponding characteristic lives are summarized in Table 1.

In order to have an easy comparison methodology among all samples, Table 2 summarizes the relative solder joint reliability cycle life degradation of CABGA256 with SAC305 solder

balls for 1% cumulative failure rate and characteristic life at different environmental conditions. The data showed that, all the pre-treatments have reduced 1% of failure rate cycle life in the range of 30% to 40%, however, the pre-treatments do not have significant impacts on the characteristic life. Only salt spray treatment has more impact on the solder joint fatigue cycle life at both 1% failure rate and characteristic life compared with the rest treatments.

Table 1 Slope of Failure Rate and Characteristic Life of CABGA SAC305 with Different Pre-treatment

Pre-treatment	Slope of Failure Rate, β	Characteristic Life, η
60C/86%RH	5.42	3521
Minus 40 °C	4.48	3470
MFG	4.75	3541
Salt Spray	4.44	3078
Untreated	7.72	3397

Table 2 CABGA256 SAC305 Solder Joint Reliability De-rating at Different Pre-Conditions

Pre-treatment Condition	SAC 305, 1% Failure Rate, Cycles	1% Failure Rate Cycle Change	SAC 305, Characteristic Life, Cycles	SAC 305, Characteristic Life Change
60C/86%RH	1245	-33%	3521	4%
Minus 40 C	1240	-34%	3470	2%
MFG	1340	-28%	3541	4%
Salt Spray	1090	-42%	3078	-9%
Untreated	1870		3397	

Figure 5 (a) and (b) show the SEM Images of SAC305 solder joint treated with mixed flowing gas for 2 weeks. It failed at ATC at 1500 cycles. At the corner of substrate pad and the solder ball, there is corrosive residue and the cracks initiated at the corner of the ball and propagated cross the solder joint. Except the indication of oxide layer at the surface of the ball and along the crack, the failure mode is consistent with normal fatigue failures.

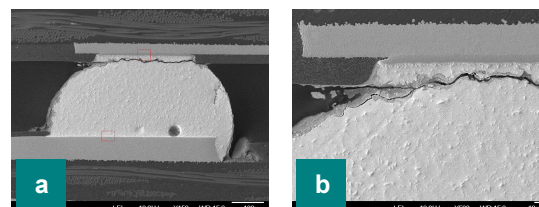


Figure 5 SEM images of SAC305 solder joint treated with MFG and failed at 1500 cycle of ATC

3.2 CABGA256 with SAC105 BGA Solder Joints Reliability

The results of ATC test after the treatments at 60°C / 86%RH and -40°C for 500 hours separately for CABGA256 with SAC105 solder balls are presented in the Weibull plots as show in Figure 6. It is observed that the condition of 60°C / 86%RH changes the slope of the failure rate in Weibull plot while comparing to the non-treated samples. It can be recorded as having lower cycle number at 1% of failure rate, however, the change on the characteristic life is minimal (cycle number at 63.2% cumulative failure rate). It is also observed that the condition of -40°C reduces the characteristic life in Weibull, however, the slope of the failure rate remain comparable with that of untreated samples.

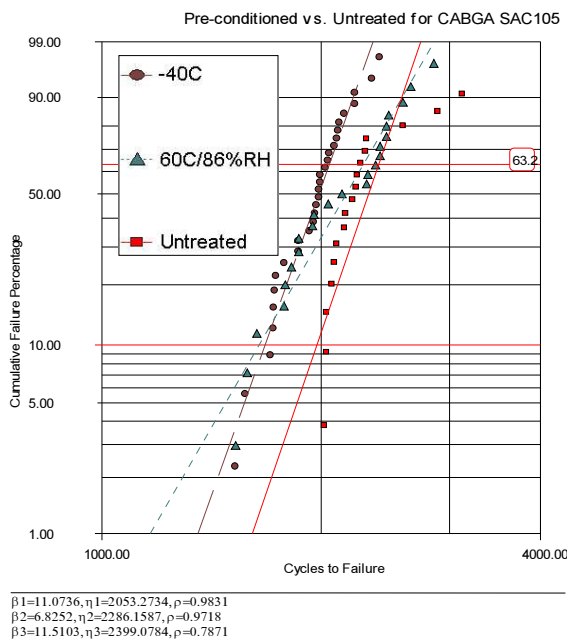


Figure 6. Weibull plots of accelerated thermal cycling test results of CABGA SAC105 treated at 60°C / 86% RH for 500 hours and -40°C, 500 hours respectively vs. untreated

The results of thermal cycling after the treatments with MFG (336 hrs) and salt spray (96 hrs) are presented in terms of Weibull plots as show in Figure 8. From the results in Figure 7, it is noted that the characteristic lives of Weibull plots from both MFG and salt spray samples are much lower than untreated samples. It is also observed that the slope of the Weibull plots of the samples treated with MFG are increased slightly comparing to untreated samples. However, the slope of the samples treated with salt-

spray stays at the same range as the un-treated samples.

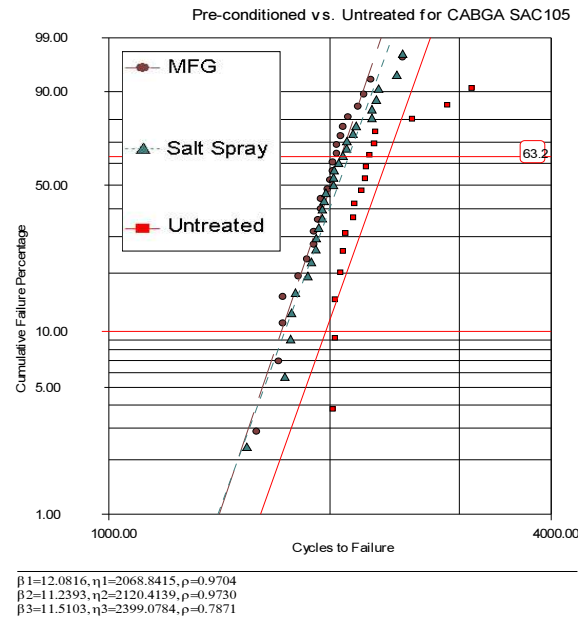


Figure 7. Weibull plots of accelerated thermal cycling test results of CABGA SAC105 treated with MFG (336 hrs) and salt spray (96 hrs) respectively vs. untreated

The slopes of the failure rates of test samples with different pre-treatment conditions and their corresponding characteristic lives are summarized in Table 3. The slope variation and characteristics life degradation are different among SAC305 and SAC105 on the CABGA package while examining the data in Table 1 and Table 3.

Table 3. Slope of Failure Rate and Characteristic Life of CABGA SAC105 with Different Pre-treatment

Pre-treatment	Slope of Failure Rate, β	Characteristic Life, η
60C/86%RH	6.82	2286
Minus 40 C	11.07	2053
MFG	12.08	2068
Salt Spray	11.24	2120
Untreated	11.51	2399

To have an easy comparison methodology among all samples with SAC105 BGA, the solder joint reliability degradation of 1% cumulative failure rate and characteristic life of the test samples treated at different environmental conditions is summarized

in Table 4. The data showed that, all the treatments have reduced 1% of failure rate cycle life between 10% to 25% range, and characteristic life reduction in the range of 5% to 14%.

Table 4. SAC105 BGA Solder Joint Reliability De-rating at Different Conditions

Pre-treatment Condition	SAC 105, 1% Failure Rate, Cycles	1% Failure Rate Cycle Change	SAC 105, Characteristic Life, Cycles	SAC 105, Characteristic Life Change
60C/86%RH	1165	-28%	2286	-5%
Minus 40 C	1355	-16%	2053	-14%
MFG	1415	-12%	2068	-14%
Salt Spray	1405	-13%	2120	-12%
Untreated	1608		2399	

Figure 8 (a) and (b) show the SEM images of SAC105 solder joint soaked in 60°C/86%RH condition for 500 hrs. The picture was taken from a sample failed at around 1500 cycles. The crack is initiated at the corner of substrate pad and the solder ball, and propagated cross the solder joint, which is representing a typical fatigue failure.

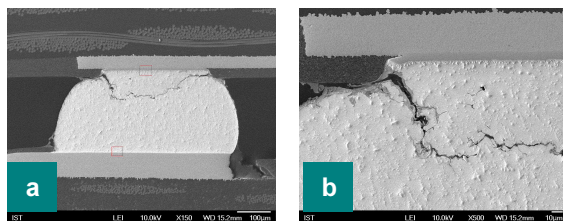


Figure 8. SEM images of SAC105 solder joint soaked in 60°C/86%RH for 500 hrs and failed ATC before 1500 cycle

In order to understand the reason behind the different trend on the degradation of cycle life among SAC305 and SAC105 BGA on CABGA packages, stand-alone packages without mounting on PCB were treated with the same pre-treatment as all ATC test samples. A series of SEM images and EDAX analysis were taken on treated samples in order to find out the difference among these samples. One common phenomenon has been noticed that oxide layer is form on those treated samples. However, the salt spray treatment seems to have strong interaction with SAC305 alloy but not on SAC105 alloy.

Fig. 9 (a) and (b) show the SEM Images of SAC305 solder ball treated with salt spray for 96 hrs. The solder ball mass is severely corroded. Different microstructures and voids are developed within the solder ball. Through EDAX analysis, the dark region in SEM, in addition to the presence of tin, seems to

have oxygen and chlorine. It might imply certain forms of oxide or chloride has formed due to salt spray on SAC305.

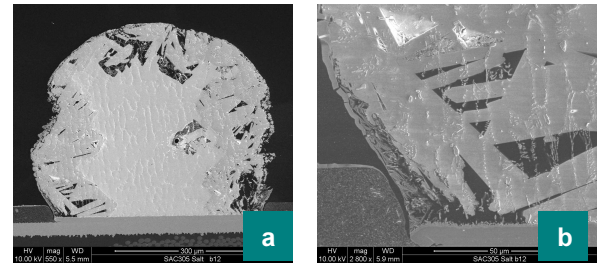


Figure 9. SEM images of SAC305 solder ball treated with Salt Spray, 5% wt% at 35°C for 96 hrs.

Figure. 10 (a) and (b) show the SEM Images of SAC105 solder ball treated with salt spray for 96 hrs. The extent of corrosion of solder ball seems not as severe as the SAC305. The composition of the dark region at surface is also a compound of tin, oxygen and chloride.

Further investigations are undertaken in order to understand whether the formation of the chloride/oxide contribute to the different behavior (degradation on characteristic life) of failure rate in Weibull among 4 pre-treatment conditions under ATC for SAC305 alloy.

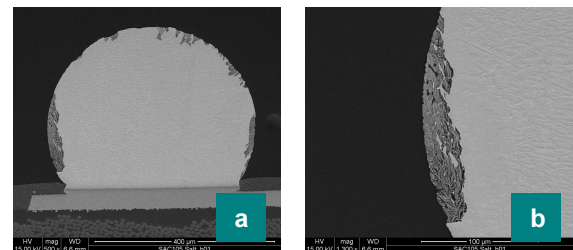


Figure 10. SEM images of SAC105 solder ball treated with Salt Spray, 5% wt% at 35°C for 96 hrs.

3.3 TSOP Solder Joint Reliability

The results of accelerated thermal cycling after all the treatments are presented in terms of Weibull plots as show in Figure 11 for the samples assembled with SAC305 solder paste and Figure 12 for the samples assembled with SnPb eutectic solder paste. From the results of Figure 11 and 12, it is observed that there are no significant impacts on the slope of the failure rate and solder joint reliability in terms of the fatigue cycle life for both SAC305 solder

joints and SnPb solder joints. The difference on the slopes of the failure rate and their characteristic life are very minimal. It seems that the pre-treatment condition are not making significant impacts on the TSOP solder joint fatigue cycle life. However, for BGA packages, as described in previous section, the pre-treatment conditions introduced sizable degradation on the cycle life under certain conditions.

Although there is no obvious changes on the results of Weibull analysis between the treated and untreated solder joints within each type of solder joints (SAC305 and SnPb), when comparing the SEM images of solder joint cross section treated with salt spray in Figure 13 (a) and (b), it can be noted that there is difference on the surface conditions between the SAC305 and SnPb solder joints. The SAC305 solder joint surface becomes rough, however, the SnPb solder joint surface remains smooth after salt spray treatment.

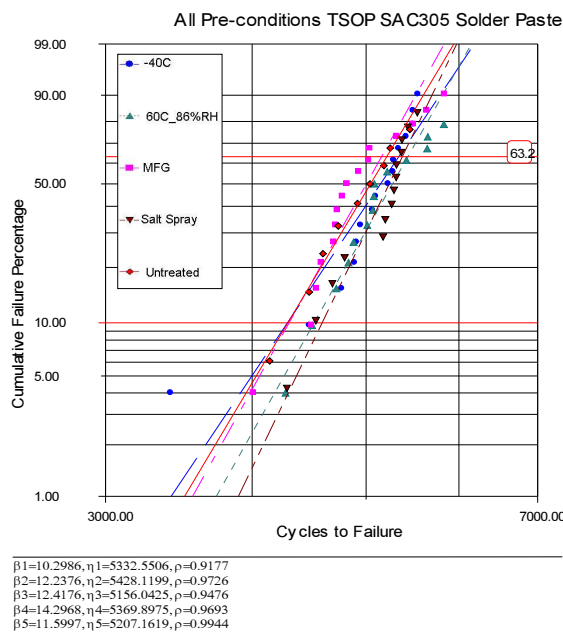


Figure 11. Weibull plots of accelerated thermal cycling test results of TSOP54 assembled with SAC305 solder paste

4. Conclusion

The impacts of environmental conditions on the Pb-free solder joint reliability were investigated by using a set of test vehicles consisting of 17mm x 17 mm CABGA package and 10mm x 22 mm TSOP packages. Among the four pretreatment conditions (corrosive gas, salt spray, low temperature storage, and humidity/temperature soak), and the different

solder alloys (SAC305, SAC105, and Sn/Pb), we can derive the following observations.

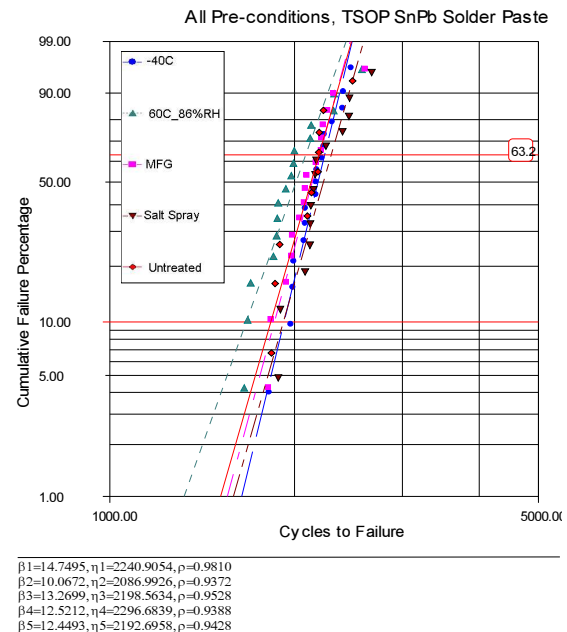


Figure 12. Weibull plots of accelerated thermal cycling test results of TSOP54 assembled with SnPb solder paste

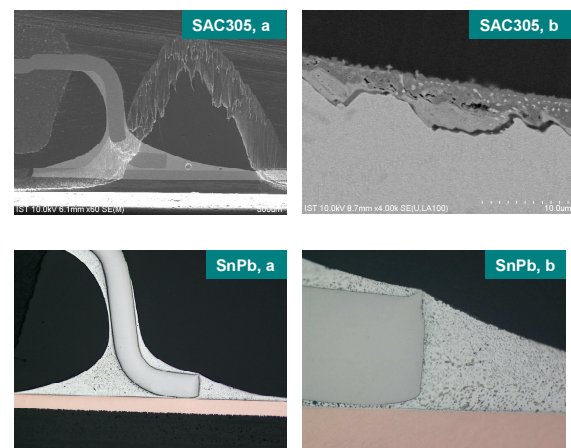


Figure 13. Comparison of SEM images of cross sections of TSOP solder joints with SAC305 and SnPb paste

1) For BGA package, the pretreatments introduce certain amount of degradation on cycle life. For packages using SAC305 BGA balls, the salt spray treatment not only degraded the 1% cumulated life but also the characteristics life. However, the other three treatments only lower the 1% cumulated life because of the slope change. For packages using

SAC105 BGA balls, the way of degradation is not the same as SAC 305. The salt spray treatment did not introduce as severe reactions on alloy as SAC105.

2) TSOP packages: All pre-treatment conditions did not result in the significant degradation of cycle life as the BGA packages. The inherent differences on strain rate and stress distribution between TSOP package and BGA package seem to play a role on the level of impact from the four treatments.

Since the package types might be a factor on the level of impact of the treatment on cycle life, further work should be taken to study the other type of packages, such as flip-chip package and large plastic BGA. In addition, the correlation between the amounts of corrosion on solder joint from various treatments to the solder joint's fatigue cycle life will need further systematic investigations in order to understand it quantitatively.

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