

EFFECT OF MULTIPLE REFLOW CYCLES ON SOLDER JOINT FORMATION AND RELIABILITY

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ABSTRACT

In a typical electronic assembly, many of the solder joints undergo multiple reflow cycles during the course of a complete manufacturing process from wafer bumping to the board level assembly. Effect of these reflows on the solder joint formation and its evolution during these cycles was investigated. In the first part of the study, small size BGA's were assembled with 12mil spheres of a number of low-silver lead-free solder alloys. Substrate surface finish used was Cu-OSP. Components were subjected to up to six Pb-free reflow cycles. After reflows, joints were cross sectioned and the thickness of the IMC layers formed was measured. Also, SEM images of the cross sections were recorded to see any change in the interfacial IMC morphology as well any change in the bulk alloy microstructure. The mechanical integrity of the solder joints was evaluated using high-speed ball pull test. In the second part of study solder joints were formed using Pb-free solder pastes and reflowed two times under three different reflow profiles. The main measure of solder joints used was the voids formed in the joints. Effect of the reflows on the short term and long term solder reliability is discussed.

INTRODUCTION

Reflow soldering is the most common technique used in the formation of solder interconnects in electronics at the component and board level assemblies. The increasing complexity of the components such as stacked Package-on-Package (POP) or System-in-Package (SiP) and circuit board assembly (e.g., stacked, double sided boards, etc.) makes it impossible to form all the solder joints in a single reflow. More often than not, there will be some interconnects that will be forced to go through more than one reflow cycle. Following the first reflow, sometimes the subsequent reflow profiles are the same as the first while in other circumstances a hierarchy of reflows with decreasing temperatures is necessary. Solder joints formed in the first reflow further evolve during the subsequent reflows. Therefore, it is important to understand the impact of multiple reflows on solder joint reliability.

Similar to the complexity of the electronic components, PWB assembly has become more complicated. It is common these days to have double sided boards. That means the solder joints on the first assembled side undergo

one additional reflow cycle. Therefore, even for SMT assembly, it is important to understand the effect of multiple reflows on the solder joint formation, growth and reliability.

Solder joint formation is basically a reaction between the solder and the pad material. In the process a fraction of the pad material is dissolved into the solder and forms an intermetallic layer at the interface. A thin uniform layer is an essential requirement for the solder joints. However, a thicker IMC layer is undesirable because of the brittle nature of the IMC's. A thick IMC layer is associated with early failure in mechanical shock tests. Growth of intermetallic layers during aging at high temperature was studied by Zribi et. al [1]. In this study, Sn4.7Ag1.7Cu and Sn3.5Ag1.0Cu alloys were used on Cu and NiAu substrates. It appears that the presence of Cu and Ni together alters the nature of interfacial IMCs. Zhang et al [2] reported the effect of different substrate metallization under multiple reflows soldered with Sn3.5Ag1.0Cu. Effect of different substrate metallization used in soldering to Sn3.5Ag and subjected to multiple reflow was also reported by Koo and Jung[3]. It was demonstrated that the solder bumps with Electroless Nickel Immersion Gold (ENIG) finish showed a dramatic decrease in the shear force after 4-5 reflows. Change in shear force was negligible for Cu and Electrolytic Nickel Gold (NiAu) pad metallizations. However, a recent study by Zhang et al [4] on ENIG finish showed that solder joints formed with Sn3.0Ag0.5Cu8.0In, Sn3.0Ag0.5Cu and SnPb alloys do not show any decrease in the shear force up to 12 reflows. Rather the results presented in this paper show a small increase in the shear force during the initial first few reflows. The effect of multiple reflows on Sn4.0Ag0.5Cu spheres soldered to immersion Sn coated pads was reported by Lai et al [5]. A change in the morphology of the interfacial IMC layer during multiple reflows has been reported. This report also shows results of the "Ball Impact Test", which appears to be just another name for high-speed ball shear test. The results show a degradation of solder joints undergoing multiple reflows.

In SMT assembly, usually a solder paste is used to attach the BGA, QFP, LGA etc. type of components to the PWB using a solder paste. Solder paste consists of a solder alloy in the powder form mixed with a flux that has a solvent, a thickener, an activator package and a tackifier as some of

the major ingredients. During reflow, usually the solvent and/or one or more of the other ingredients evaporates. Most of the time there is an overlap in the time/temperature of the solvent evaporations and solder powder melting. A molten solder is a liquid medium with high surface tension. The evaporating materials in the vapor form try to evaporate resulting in an unstable equilibrium. This equilibrium is disturbed by a bubble of vapors escaping the solder volume. Any remaining vapors, unable to escape, form voids inside the solder joint. These voids in the solder joints are one of major concerns for the electronic industry, especially the PWB assemblies using solder paste in a SMT process. Bruno et. al [6] presented a comparative study of different types of reflow profiles on BGA voiding. Effect of multiple reflows on voiding in pb-free paste and their impact on solder joint reliability was reported by Nurmi et. al [7].

Current paper reports two studies on the effect of multiple reflows on solder joint reliability. The first part of the study consists of 12 mil (0.3mm) solder spheres of four low-Ag alloys soldered to Cu-OSP pads and subjected to up to six reflows. The measures of the solder joint quality are the thickness of the interfacial IMC layer and its growth during multiple reflows. The mechanical integrity of the solder joints is assessed by a high-speed ball pull test. In previous studies, we have reported that high-speed ball pull test can be used to predict the solder joint performance in a drop shock test [8,9]. Low-Ag alloys were selected because industry is moving to low-Ag allows for applications where drop-shock reliability is important.

In the second part of this study we evaluated BGA components assembled on a PWB using four different lead-free pastes. All the pastes used SAC305 type 3 powder and different types of fluxes. Since the formation of the voids in a solder paste is also dependent on the type of reflow profile used, three different reflow profiles were used in this study. These reflow profiles cover most of the common process windows used in SMT assemblies using standard SAC type lead-free solder pastes. Since in the SMT assembly it is very unlikely that a solder joint would encounter more than two reflow profiles, our study was restricted to only two reflows. The measure of the quality of the solder joints was the average fraction of the voids in the solder joints observed.

EXPERIMENTAL DETAILS

The first set of experiments was performed on CABGA228 substrates with Cu-OSP pad finish. BGA components were assembled with 12 mil solder spheres using a water soluble flux (Alpha WSX) that was stencil printed on the substrates. Spheres were placed using a simple manual alignment assembly setup and reflowed in air, in a seven-zone convection reflow oven. After the first pass through the reflow oven, the components were washed with hot water and subjected to five more reflows. The components were built with four low-silver SnAgCu base alloys (SAC105: Sn1.0Ag0.5Cu, SAC105Ni: Sn1.0Ag0.5Cu0.05Ni, SACX: Sn0.3Ag0.7Cu0.1Bi and SACX-Plus: Sn0.3Ag0.7Cu0.1Bi

0.05Ni). Mechanical integrity of the solder joints was evaluated using Dage 4000HS Ball Pull and Ball Shear system. The Dage 4000HS can do the ball pull test up to 1000 mm/sec. Failed solder joints were categorized by failure mode, as shown in Figure 1 for ball pull test.

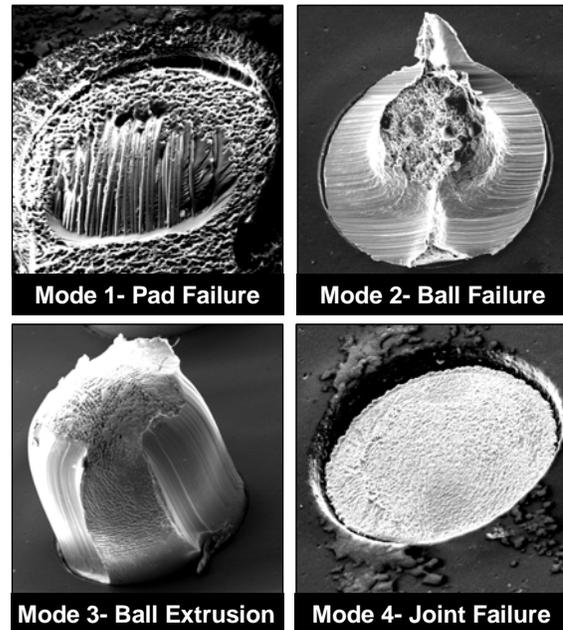


Figure 1. SEM pictures of ball pull failure modes

Mode 1 – Pad failure: The whole pad comes off the substrate indicative of a board or substrate quality problem.

Mode 2 – Ball Failure / Neck Break: Failure occurs in the bulk of the solder material indicative of a ductile failure. This is the preferred failure mode.

Mode 3 – Ball Extrusion: This occurs because of improper placement of the pull tool or a solder that is too soft.

Mode 4 – Joint failure /IMC failure: Failure occurs at the solder pad interface. This failure may have a larger peak force but total breaking energy will be lower and is predominantly a brittle failure.

Our system cannot measure the breaking energy and peak breaking force measure and was not reliable at high speeds. Therefore, it was decided to make a comparative study on the fraction of brittle failure to estimate the mechanical reliability of the solder joints for various alloys.

In the second part of this study, the effect of multiple reflows was studied on the formation of voids in a typical lead-free surface mount electronics assembly process. For paste reflow, the voids formed during first pass through the reflow oven and its growth during subsequent reflows is a major concern for the electronics manufacturers. Also, the probability of void formation is dependent on the type of reflow profile, so three different profiles were selected in this study with different peak temperatures of 230, 235 and 240 degree Celsius. The profiles (shown in the Figures 2-4) selected in this study were the most commonly used profiles in lead-free electronics manufacturing processes. BGA 256

components were used in studying the effect of number of reflows and the reflow profiles on the paste voids formation with four different solder paste compositions.

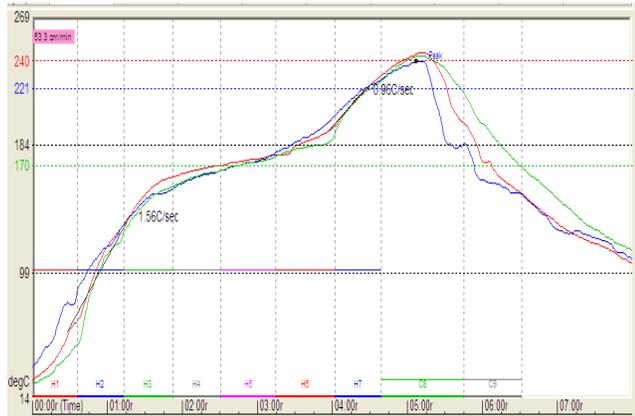


Figure 2. Profile 1: 175°C/60s Soak 240°C Peak 60s TAL

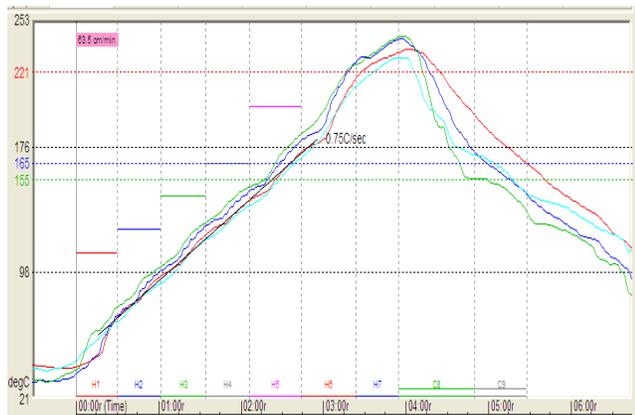


Figure 3. Profile 2: Straight Ramp 0.7°C/s 235°C Peak 60s TAL



Figure 4. Profile 3: Straight Ramp 1.35°C/s 230°C Peak 45s TAL

After reflow the BGA256 components were inspected using x-ray.

RESULTS AND DISCUSSION

Prior to the characterization of the ball pull strength, the components assembled with the different alloys and with the

different reflow passes were cross-sectioned, polished and examined with a scanning electron microscope to characterize the intermetallic formation and thickness of the layer. The SEM images of the cross-sections of the solder joints after single and six reflows for the different alloys used in this study were shown in the Figures 5 – 8. In all the samples not only the IMC thickness increases from the first to the sixth reflow, but also the IMC layer shows different morphology after six reflows as compared to the samples reflowed only once.

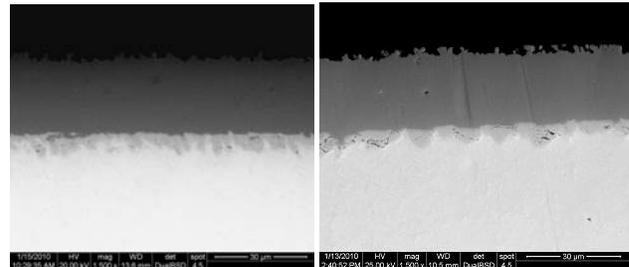


Figure 5. Cross section of SACX sample after the first reflow (left) and after sixth reflow (right).

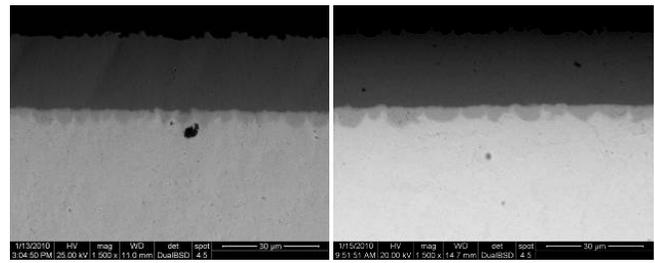


Figure 6. Cross section of SACX-Plus sample after the first reflow (left) and after the sixth reflow (right).

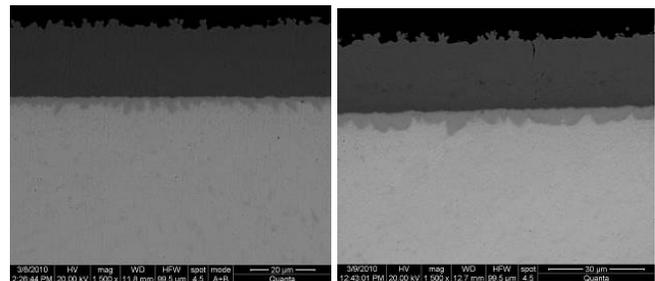


Figure 7. Cross section of SAC105 after the first reflow (left) and after the sixth reflow (right).

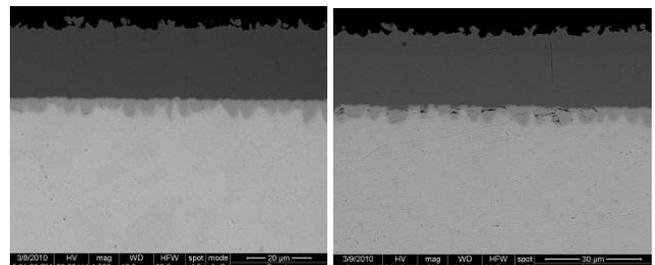


Figure 8. Cross section of SAC105+Ni after the first reflow (left) and after the sixth reflow (reflow).

Figure 9 shows the total thickness of the interfacial intermetallic layer ($\text{Cu}_3\text{Sn} + \text{Cu}_6\text{Sn}_5$) for SACX and SACX-Plus after one reflow and after six reflows. SACX-Plus shows a relatively thinner IMC layer after first reflow and a slower growth during the subsequent five reflows. This is probably due to the fact that presence of Ni in SACX-Plus alters the nature of the intermetallic layer and alters the diffusion through the interfacial layer. Cu_6Sn_5 is more likely to be $(\text{CuNi})_6\text{Sn}_5$ or $(\text{CuNi})_3\text{Sn}_4$. Therefore, one would expect SACX-Plus joints to perform better than SACX and to have smaller effects in multiple reflows.

Similarly, the thickness of the total intermetallic layer for SAC105 and SAC105+Ni is shown in figure 10. SAC105+Ni shows thinner initial IMC layer but growth is not less than SAC105. After six reflows, the IMC layer thickness for SAC105+Ni is still thinner than that for SAC105. Therefore, one would expect better mechanical integrity for the SAC105+Ni solder joints.

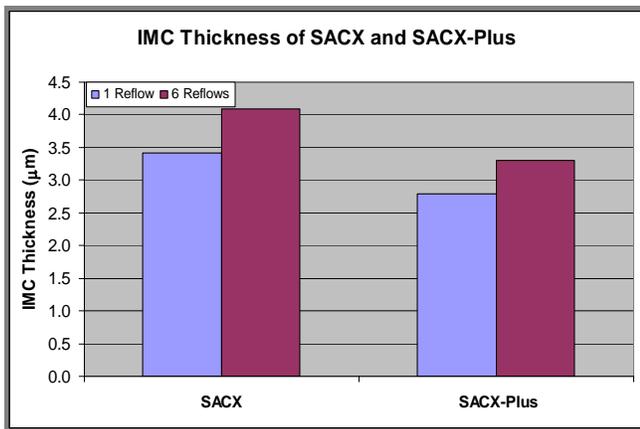


Figure 9. SACX and SACX IMC growth during six reflows.

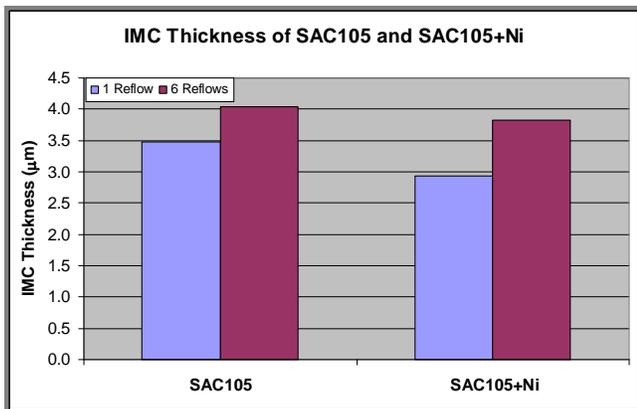


Figure 10. SAC105 and SAC105+Ni IMC growth during 6 reflows.

Figure 11 shows a summary of the ball pull results. Data shows the fraction of mode 4 failures (interfacial fractures) for all the four alloys and for the samples that have undergone one to six reflows. SAC105 shows the highest percentage of brittle failures. Addition of Ni to SAC105 reduces the probability of interfacial failures. This result is,

as one would expect, from the thickness of the interfacial IMC layer shown in figures 9 and 10 above. Usually a thicker IMC layer results in more mode 4 failures. SACX and SACX-Plus show slightly lower Mode 4 failures. SACX-Plus shows practically no change in the fraction of brittle failures after multiple reflows. It appears that in both the cases, the addition of Ni has an effect in improving the solder joint reliability. This is probably due to change in the nature of the second intermetallic that has the probability to change from pure Cu_6Sn_5 to mixed $(\text{CuNi})_6\text{Sn}_5$. Net result of Ni doping is also to reduce the interfacial IMC thickness due to reduced diffusion of Cu through $(\text{CuNi})_6\text{Sn}_5$ intermetallic layer.

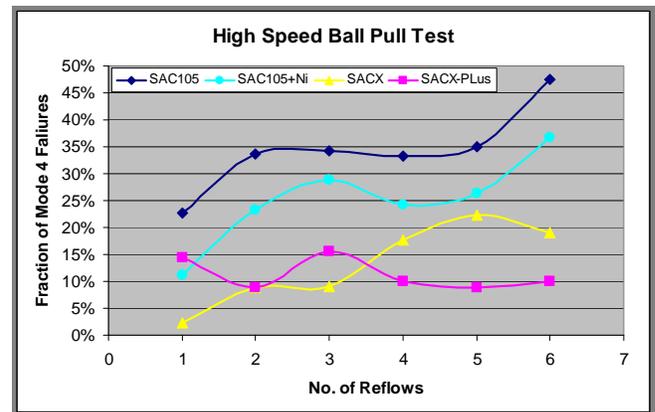


Figure 11. High speed ball pull test

In the second part of the study, the effect of multiple reflows on void formation in BGA's assembled on the circuit boards using four solder pastes was evaluated. Evaluating different pastes was not the objective of this study. Four different pastes were selected to get a distribution so that in the end any paste-specific effects can be ruled out. Similarly, to rule out the effect of a particular reflow profile, three different reflow profiles were selected. Figure 12 shows two of the x-ray images of several BGA's inspected. The picture on the left is paste 2 after the first reflow and that on the right is after two reflows. The images have been enhanced with artificial coloring to estimate the area of each void. The void data is presented as the average area of the void as a fraction of the BGA cross sectional area.

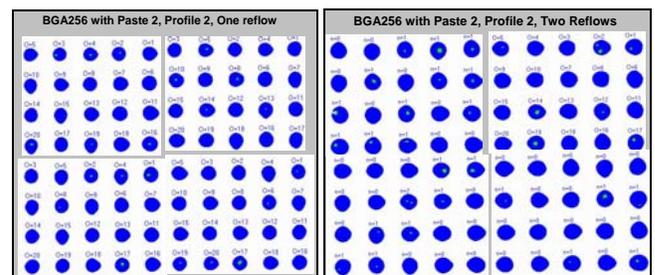


Figure 12. Typical enhanced X-ray images of the BGA256 components assembled with paste 2 showing the voids after one reflow and after two reflows.

Figures 13 to 16 show the voids in paste 1, paste 2, paste 3 and paste 4 respectively. Data shown is for each of the three

reflow profiles and on the samples after one reflow and after two reflows. In all the cases, voids show an increase during the second reflow. All the data indicate that Profile 2, which is a slower ramp profile with medium peak temperature, shows slightly more voids than the other two profiles.

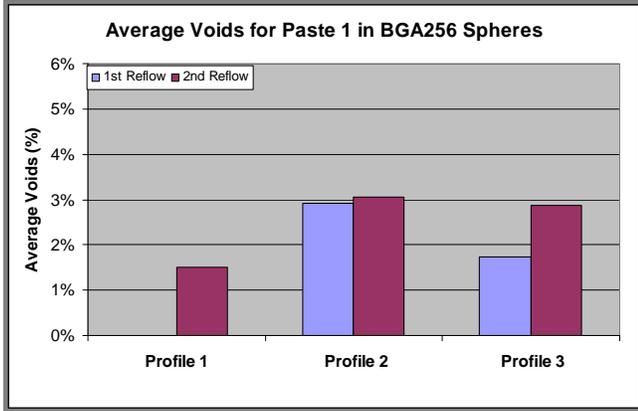


Figure 13. Voids after the first and the second reflow for paste 1.

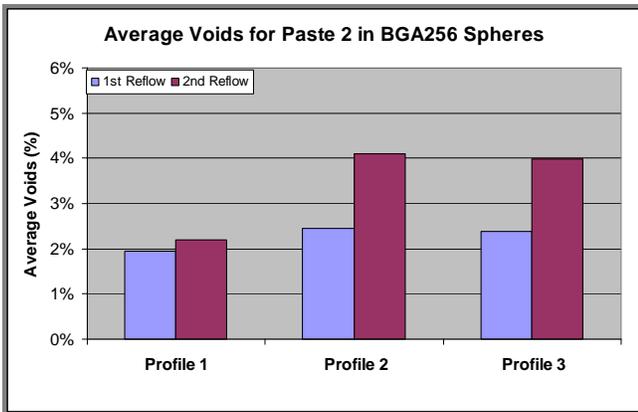


Figure 14. Voids after the first and the second reflow for paste 2.

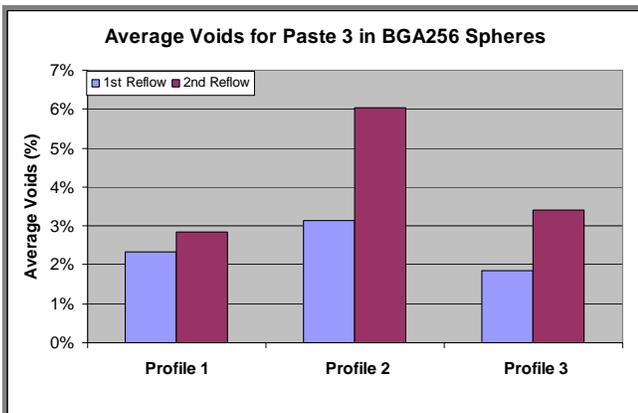


Figure 15. Voids after the first and the second reflow for paste 3.

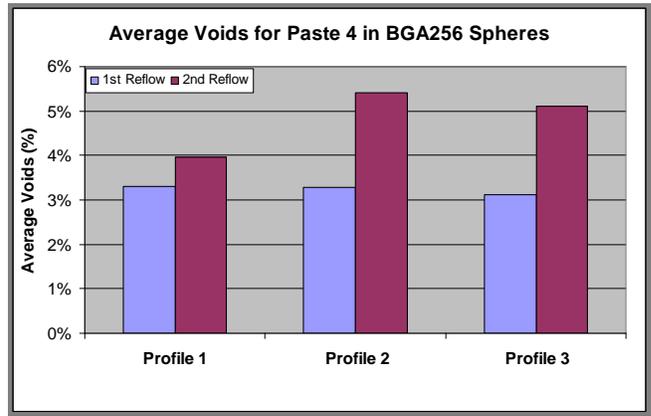


Figure 16. Voids after the first and the second reflow for paste 4.

Figure 17. shows a summary of all void data. An average fraction of void areas of all the samples assembled using the three reflow profiles is shown. The results show that irrespective of the paste and irrespective of the profile, multiple reflows always increase the voids. It is difficult to understand the reason for this increase in voids. There appear to be two possibilities. One of them is that there are undetected micro-voids after the first reflow which coalesce to form bigger voids that are detected after the second reflow. Second possibility is that some volatile material is still entrapped inside the voids, which expands again during the second reflow. In the cooling phase of the second reflow, solder freezes before the gaseous phase inside the voids has chance to shrink back to its original size.

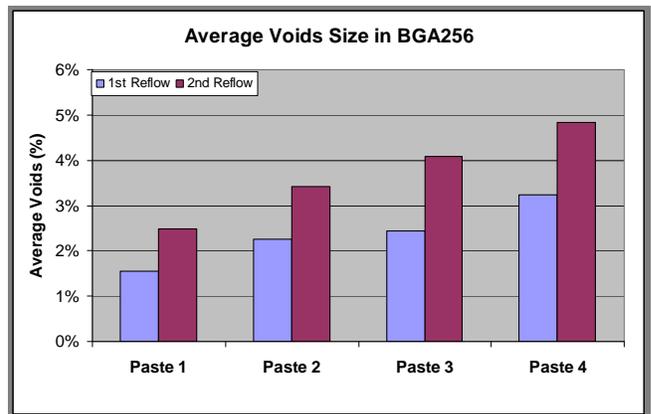


Figure 17. Voids shown as average of all the three reflow profiles.

CONCLUSIONS

Effect of multiple reflows has been studied on BGA solder joints on the component side as well as on the board side. Solder joints on the component side were subjected to up to six reflows. Growth of the interfacial IMC layer and its impact on mechanical integrity of the solder joints has been demonstrated. It appears that low-Ag SnAgCu alloys with a small amount to Ni doping show thinner IMC layers and slower growth during multiple reflows as compared to their counter parts without any Ni. The thinner IMC is correlated with better solder joint integrity as measured by the high-

speed ball pull test. On the board side the effect of multiple reflows on void formation in BGA components has been studied using three different reflow profiles and four different solder pastes. Results show an increase in void sizes during the second reflow.

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