

Effects of Pre-pack Thermal aging on the formation and evolution of IMC for Sn-Pb36-Ag2 and Sn-Ag3.8-Cu0.7 and it's correlation to solder joint strength

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Abstract

A quantitative analysis on the reliability and failure modes of the lead free solder alloy Sn-Ag3.8-Cu0.7 and leaded solder alloy Sn-Pb36-Ag2 on a particular test vehicle of BGA 388 (Ball Grid Array) using Electrolytic Ni-Au pads is presented regarding the formation of Inter-metallic compounds (IMC). The analysis is performed at outgoing pre-pack operations, which require thermal aging on units to remove any possible moisture trapped in the units' mold compound so as to avoid the "pop-corn" effect during reflow operations at the SMT customer's site, before packing and shipping.

Critical reliability data along with numerous test results are presented with regard to the effects of this thermal aging on the solder joint's reliability for both solder alloys. Results obtained from both shear and tensile tests were able to prove that tensile tests or CBP (cold ball pull) tests are more sensitive in detecting weak IMC joints. Fractographs depicting the types of failures from CBP and shear tests are also compared. These fractographs were able to prove the inherently better wetting characteristic of Sn-Pb36-Ag2 as compared to that of Sn-Ag3.8-Cu0.7.

The relationship of IMC layer thickness as a function of pre-pack baking hours and temperature is also studied. The IMC thickness data for both solder types showed that IMC thickness cannot be a definite factor to deem if a joint should fail or not, though it is recognized here that as IMC thickness grows, brittle failures will become more pronounced. The data shows that ball shear and ball pull strengths are still good at some level of IMC thickness, and drops at different values. Further investigation on the IMC structure with SEM (Scanning Electron Microscope) was able to showcase a flaky, layered or sometimes solidified structure for weaker joints as compared to evenly structured ones on stronger joints.

Introduction

Solder joint reliability for semiconductor manufacturers has always been an issue moreover when it involves the usage of lead-free solders. It is recognized that solder joint reliability is primarily affected by the formation of Inter-Metallic-Compounds, or IMC's [1]. As semiconductors become more and more important in applications such as aerospace and the automotive industry, the demand for more reliable and dependable solder joints are required so that there are no catastrophic failures while in the field.

Much research has been conducted primarily in assembly related operations which involve reflow, etc., to address the issues of missing balls/drop balls for BGA units due to failure on the solder joints, particularly to the lead free solder alloys types [2-7]. Studies should be done on out-

going operations in semiconductor factory sites before units leave the factory, to gauge the strength of the solder joint. It is because right here, pre-pack baking is implied to rid the unit of any trapped moisture in the mold compound, as to which how much it affects the solder joint reliability is little known. The method of thermal treatment, temperature being used and thermal duration can be accessed. It will give an indication on what quality level is being shipped to the customers after the necessary processing.

The baking of units at outgoing operations does induce some level of effect to the solderability joints of the BGA units, though the temperature is much lower than the reflow temperatures used in assembly's ball attach process. It is hoped that through this paper, a much deeper understanding of the formation of IMC's attributed to solder joint failure at pre-pack thermal aging operations can be

compared between the two solders. Figure 1 showcases the common manufacturing flow for most semiconductor fabrications, where the primary focus of this paper will be on the final operation, which includes thermal treatment.

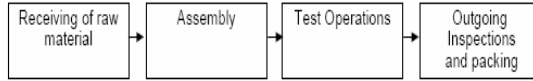


Figure 1: Common manufacturing flow for a semiconductor operation

Experiment

The package used for this study is a *Ball Grid Array* (BGA) 388 with a daisy chain formation. The solder balls/spheres have been attached via convective reflow soldering on Electrolytic Ni-Au pads. This package has a 1.0mm pitch, 0.60mm solder ball diameter and 27mm square size. It has a 0.50mm pad size and is solder mask defined (SMD). Figure 2 showcases the daisy chain formation and arrangement of solder balls/spheres on the package.

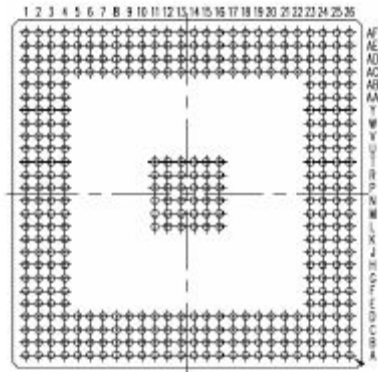


Figure 2: BGA 388 daisy formation

The common used parameter for pre-pack thermal treatment of BGA units is 8 hours at 125°C. To gauge the transition of characteristics during this process, the units underwent thermal treatment at 2, 4, 6 and 8 hours at 125°C for both solder types. A control sample without thermal treatment was also included. Each solder category was then subjected to both tensile (Cold Ball Pull) and shear tests. The table below showcases the parameters used for both these tests. Both SEM and EDX were used to study the fractographs obtained from the shear and tensile tests for each solder alloy type.

Table 1: Ball shear and tensile test parameters

Test Method	Shear test	Tensile test
Applied Load	Shear	Tensile
Loading rate	100g	500g
Shear Height	30 microns	-
Tweezer close time	-	1.0s
Clamping force	-	20psi
Test Speed	300 microns/sec	5000microns/sec



Figure 3: Dage 4000S for both ball shear and ball pull (jaw shown for CBP)

Layers of IMC were measured using an imaging microscope and special software, LeicaQWin. IMC layers were first photographed from cross-sectioned units, after detecting the thickest IMC layer from all solder spheres, and then manually traced using the software, to enable an estimate of the IMC area's thickness to be obtained. Three highest peaks were then measured from the photographed image. Three measurements were conducted for each sample to obtain an average value. The magnification used for this analysis was 100X.

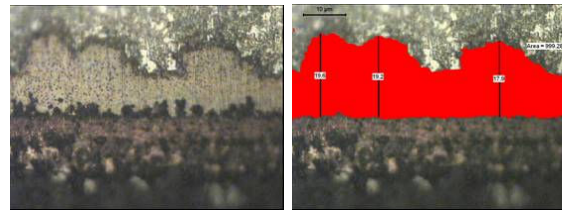


Figure 4: IMC thickness measurements

Results and Discussion

(i) Shear test analysis

Shear tests were performed on both solder types, Sn-Ag3.8-Cu0.7 and Sn-Pb36-Ag2. The average shear strength of each solder alloy was then plotted to make a comparison. Figure 5 and 6 showcase the respective plots for each solder category by hours.

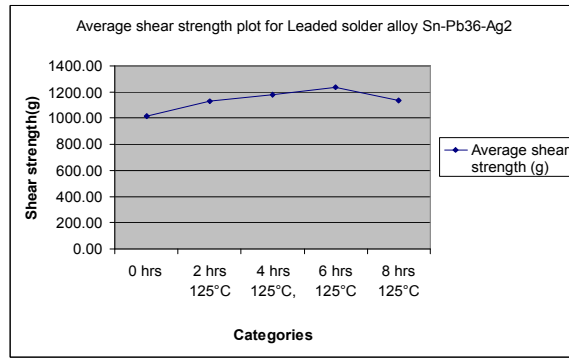


Figure 5: Average shear strength plot for Sn-Pb36-Ag2

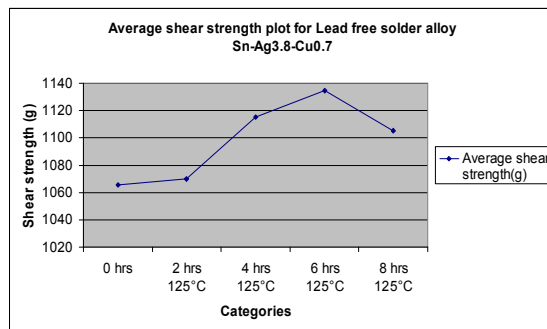


Figure 6: Average shear strength plot for Sn-Ag3.8-Cu0.7

For Sn-Pb36-Ag2, Figure 5 shows that as temperature increases, the shear strength increases also, until the 8 hour mark, where there is a significant drop in strength. The point of drop is at the current processes' parameter. For Sn-Ag3.8-Cu0.7 in Figure 6, the trend is similar, albeit rather drastic. At 4 hours, the strength increases significantly, and the point of strength drop is also similar to Sn-Pb36-Ag2, indicating longer hours do effect the solder joint strength in both solders.

Based on the findings from both solder alloys types, a comparison for shear strength was made between them for the non-thermal treated samples (0 hours), mid-table samples and end-table samples of the shear test performed. Based on the results presented above, it is noticeable that Sample 1 (0 hours baking) of the lead-free solder Sn-Ag3.8-Cu0.7 has a better shear strength when compared against Sample 1 of the leaded solder alloy Sn-Pb36-Ag2 which also did not undergo any thermal treatment.

However, when mid-table samples and end-table samples are taken, i.e. samples with thermal aging, it is seen that Sn-Pb36-Ag2 shows much superior strength. It is conclusive here that lead-free solder alloy's strength weakens against its

leaded counterpart when thermal treatment is involved, as shown by the box plots in Figures 7 to 9. We know leaded solders show contact angles of 11° whereas lead-free solders stand at 35° when it comes to wetting characteristics [8]. It can be seen here, that with the increase in temperature and baking hours, there is significant improvement in the wetting ability of leaded solders, and it is rather prominent than it's lead-free counterpart.

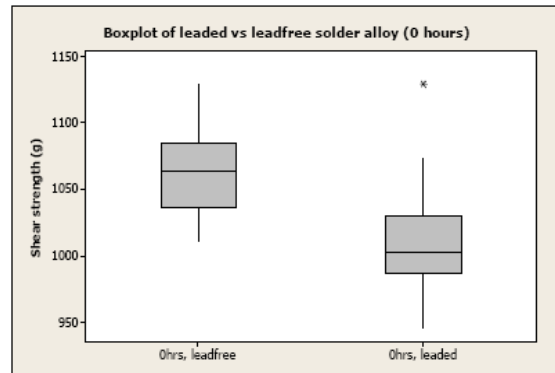


Figure 7: 0 hours sample comparison

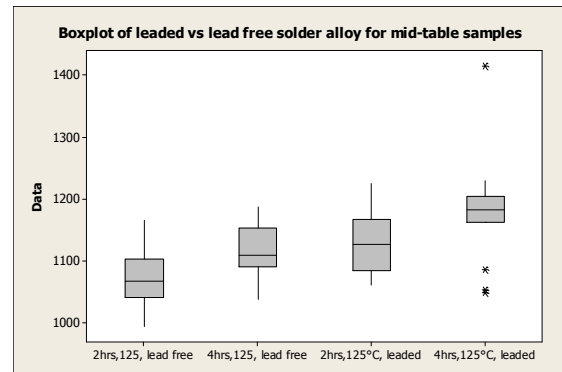


Figure 8: Mid-table sample comparison

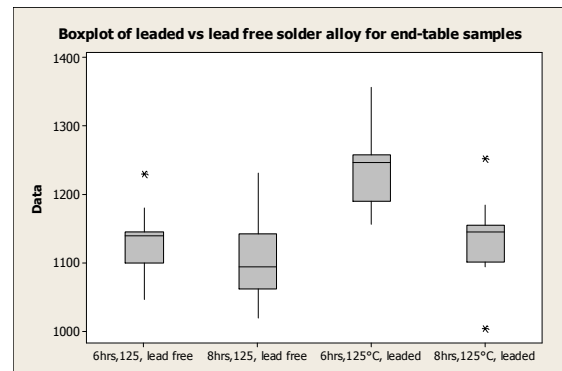


Figure 9: End-table sample comparison

(ii) Tensile test analysis

Similar to the shear tests, tensile tests were performed on the samples, followed by a box plot analysis to compare the respective tensile strengths of the samples.

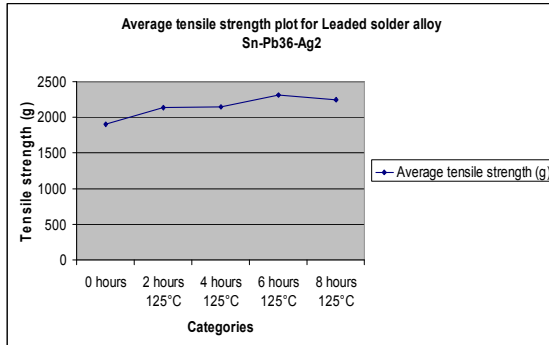


Figure 10: Tensile strength plot for Sn-Pb36-Ag2

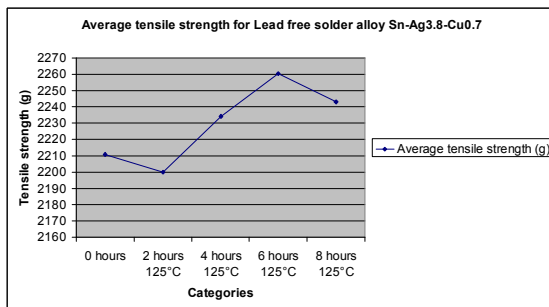


Figure 11: Tensile strength plot for Sn-Ag3.8-Cu0.7

Based on Figure 10 for Sn-Pb36-Ag2, the trend is almost similar to that of the shear results in Figure 5. There is not much fluctuation, and the tensile strength seems to increase. The drop at 8 hours is not that significant as noticed in the shear plot. For Sn-Ag3.8-Cu0.7, the fluctuations in Figure 11 are rather prominent. The drop at 2 hours is atoned by the increase to 6 hours. Once again, at 8 hours, there is a drop in tensile strength, and it is more pronounced than Sn-Pb36-Ag2. From the shear and tensile results, it is noticed that the strength generally increases, only to drop at 8 hours. This signals that at longer thermal treatment periods, the joint strength decreases.

Similarly, here we perform a comparison for 0 hours samples; mid-table and end-table between the 2 solder alloys. Based on the results, we can see that the 0 hours sample comparison after tensile tests is similar to the shear ones. However, the end and mid-table results are more closely

packed between the 2 solders, unlike previously seen in the shear test, though the slightly higher tensile strength still falls to Sn-Pb36-Ag2.

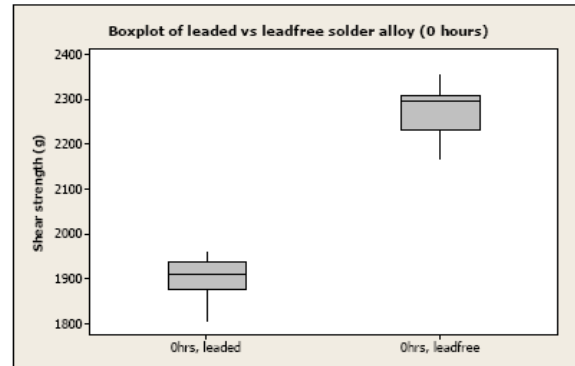


Figure 12: 0 hours sample comparison

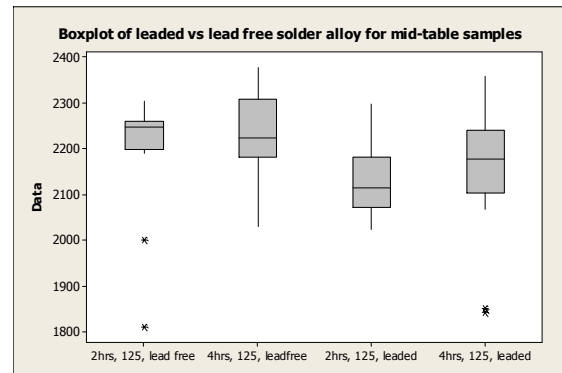


Figure 13: Mid-table sample comparison

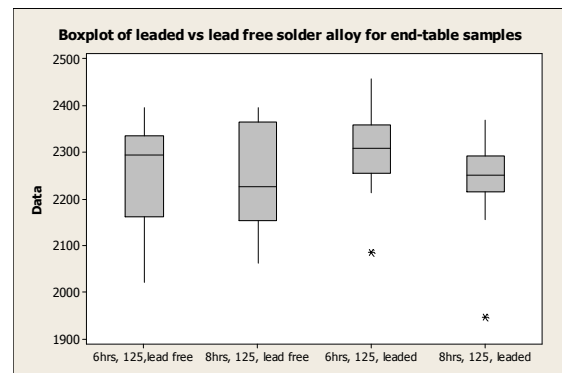


Figure 14: End-table sample comparison

(iii) Modes of fracture analysis

Based on JESD22-B117 [9], for modes of fracture, mode 1 is termed as ductile failure and is acceptable, mode 2 lifted pads and mode 4 as IMC break, which is not acceptable as it showcases brittle fracture. For shear tests, usually the most common modes of failure observed are mode 1 and mode 2, which are both acceptable.

It can be seen that the shear tests are rather insensitive in detecting IMC breaks, and may be rather misleading at times. This has been confirmed in a previous research [10], and this result only further strengthens that finding. It can also be seen that Sn-Pb36-Ag2 showcases more IMC breaks compared to Sn-Ag3.8-Cu0.7 during tensile tests. The ball shear tests only showcased ductile failures for both solder alloys.

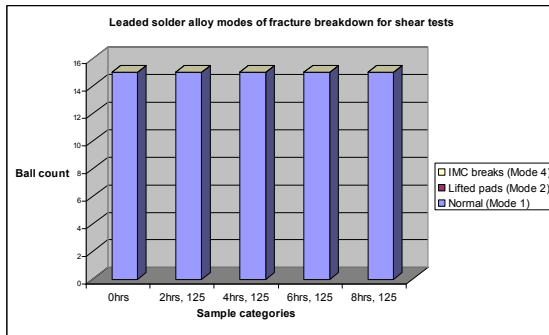


Figure 15: Modes of fracture for Sn-Pb36-Ag2 during shear tests

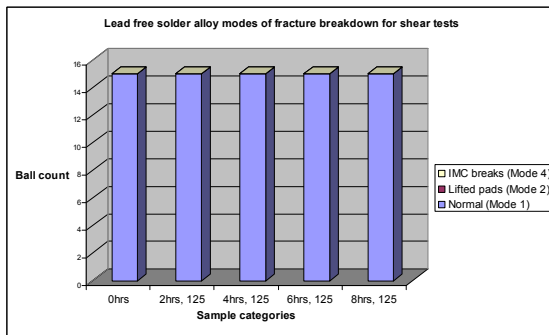


Figure 16: Modes of fracture for Sn-Ag3.8-Cu0.7 during shear tests

From Figure 17 and 18, the IMC breaks seem to increase with thermal treatment hours for Sn-Pb36-Ag2, and the lifted pad failure, which indicates good joint bonding, decreases in the same manner for Sn-Ag3.8-Cu0.7. This correlates to the pattern shown earlier through tensile and shear

tests, where strength (both tensile and shear) drops at the last sample, 8 hours thermal treatment.

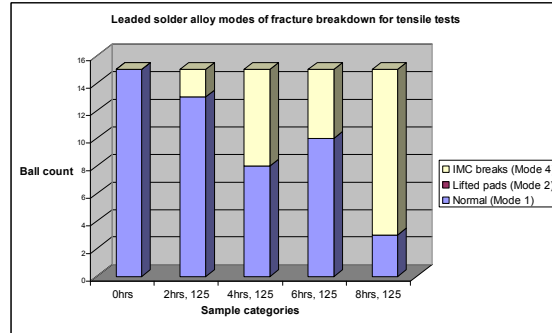


Figure 17: Modes of fracture for Sn-Pb36-Ag2 during tensile tests

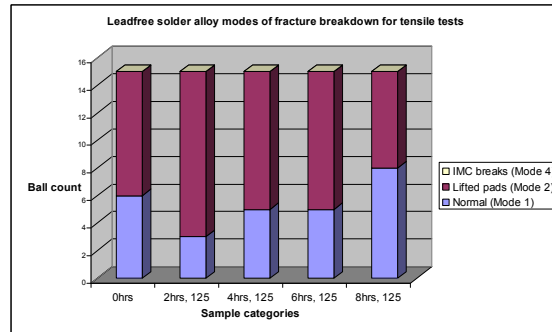


Figure 18: Modes of fracture for Sn-Ag3.8-Cu0.7 during tensile tests

The higher brittle failures in Sn-Pb36-Ag2 compared to Sn-Ag3.8-Cu0.7 can be attributed to a culmination of Gold in the IMC joint. EDX analysis on brittle failures showed a high percentage of Gold, between 15-18%. This proves that the influx on Gold into the IMC joint increases with temperature for Sn-Pb36-Ag2. Figures 19 and 20 showcase the findings.

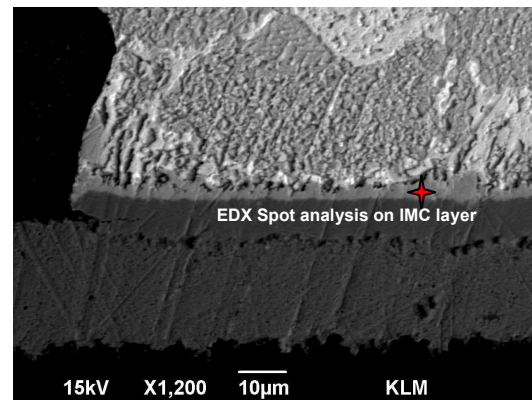


Figure 19: SEM image of Sn-Pb36-Ag2 IMC layer showing chosen EDX spot

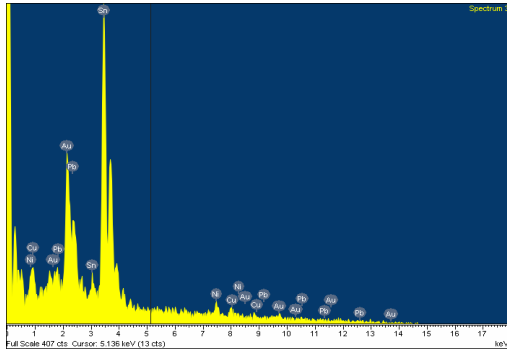


Figure 20: EDX results on Sn-Pb36-Ag2

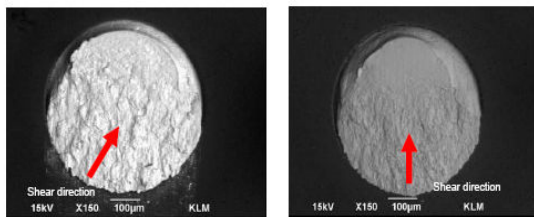


Figure 21: Shear tests ductile failure for Sn-Pb36-Ag2 (left) and Sn-Ag3.8-Cu0.7 (right)

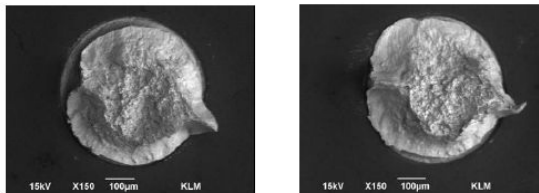


Figure 22: Tensile tests ductile failure for Sn-Pb36-Ag2 (left) and Sn-Ag3.8-Cu0.7 (right)

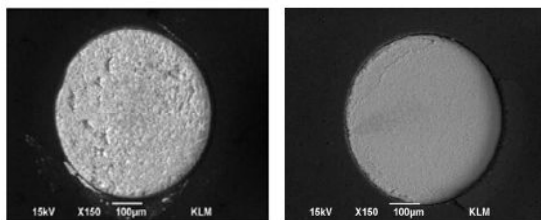


Figure 23: Tensile tests brittle failure for Sn-Pb36-Ag2 (left) and Sn-Ag3.8-Cu0.7 (right)

Based on the fractograph analysis from Figures 21 to 23, it was found that shear tests for both the leaded and lead free solders did not show much difference. But the tensile test results on the brittle failures for both solders did show some difference, surface wise. The leaded solder gave a rough, cratered surface, unlike the lead free solder which gave a smooth, un-cratered surface for the same failure. Analysis of the fracture surfaces

indicates that solder residue on the package pad is more prevalent for the leaded solder alloy compared to the lead free solder alloy, due to the better wetting qualities of leaded solders.

(iii) IMC Thickness vs. joint strength

Based on Figures 24 and 25, it can be seen that for Sn-Pb36-Ag2, as IMC thickness grows, the ball shear strength and ball pull strength drop. The drops happen at the 8 hour point, which visibly shows the thickest IMC layer growth. In Figure 26, the microstructure transition shows a change from small, evenly distributed structures to solidified ones. As grain size grows, and the number of grain boundaries is reduced, the strength required to break the bonds in the structure is also reduced. This means a weaker structure is formed.

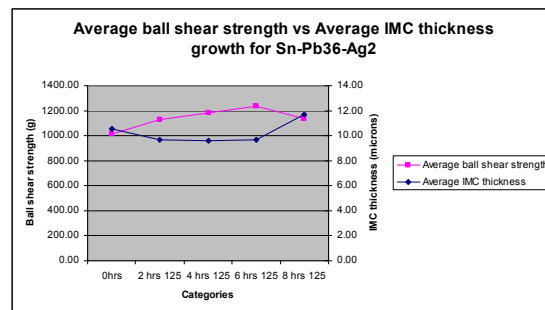


Figure 24: Average ball shear strength vs. average IMC thickness for Sn-Pb36-Ag2

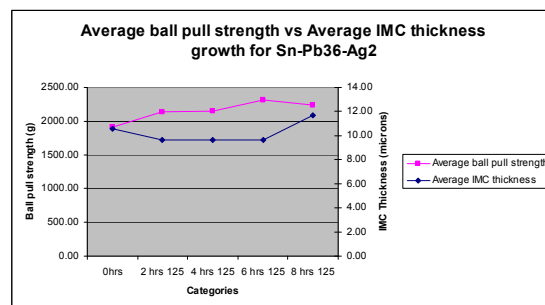


Figure 25: Average ball pull strength vs. average IMC thickness for Sn-Pb36-Ag2

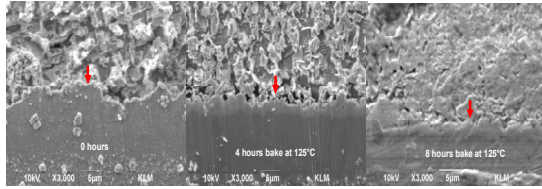


Figure 26: Microstructure transition for Sn-Pb36-Ag2

As for Sn-Ag3.8-Cu0.7, we can see that the IMC thickness at 0 hours is the highest point. With the effects of temperature and time, it reduces, only to increase slightly at 8 hours. Both ball shear and ball pull strength showcase highest points of strength at 6 hours, which is the lowest point for IMC thickness. Figure 29 shows a different behavior from that of Sn-Pb36-Ag2 earlier. The initial structure is rather flaky, meaning the strength is lower here. As the transition continues, melting and rebuilding of the structure becomes more evenly distributed, as seen in the second photo of Figure 29.

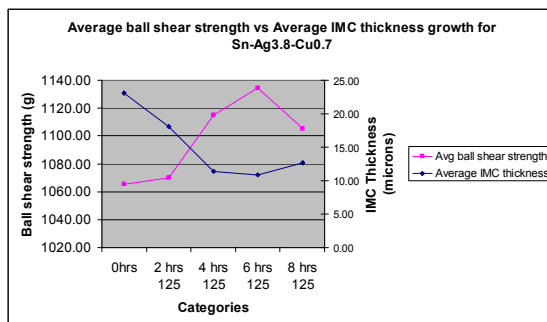


Figure 27: Average ball shear strength vs. average IMC thickness for Sn-Ag3.8-Cu0.7

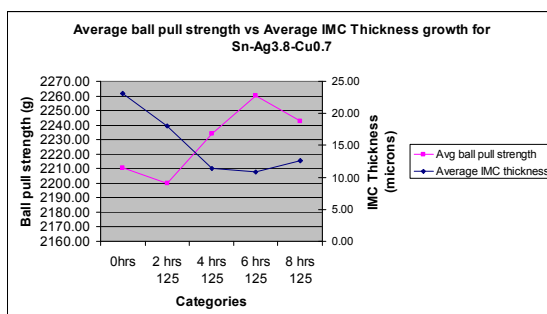


Figure 28: Average ball pull strength vs. average IMC thickness for Sn-Ag3.8-Cu0.7

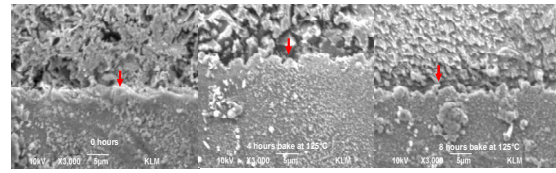


Figure 29: Microstructure transition for Sn-Ag3.8-Cu0.7

Finally, this rebuilding process reduces the number of smaller structures, giving a much solid structure, with lowered strength, as explained for Sn-Pb36-Ag2. The microstructure here shows small, solidified and conjoined lumps of IMC material, unlike previously seen on the leaded solder, whereby multiple layers have been deposited on the tips. The IMC tips are not as clear as the second photo. This indicates the material's structure has been broken, and rebuilt again.

Conclusion

From the results and data presented in this paper, it is conclusive that there are significant effects of pre-pack thermal treatment to the solder joints integrity for both solder alloys. The results prove that as time increases, IMC thickness increases also, though this behavior is different for Sn-Ag3.8-Cu0.7. It was also proven that Sn-Pb36-Ag2 much had better wetting properties through the fractograph analysis, and ball pull tests were more sensitive in detecting IMC breaks. In this study, it was also shown that Sn-Pb36-Ag2 is more prone to brittle failures compared to Sn-Ag3.8-Cu0.7 during pre-pack thermal treatment due to Gold embrittlement in the solder joint.

Acknowledgement

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