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SOLDER JOINT STRENGTH ON COPPER SUBSTRATE UNDER THERMAL AGING CONDITION

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ABSTRACT

Failure of solder joints has been a serious reliability problem in microelectronic packages. This phenomenon is more prevail in die-attach industry, particularly in power semiconductor whereby the electronic components is often exposed to high operating temperature. The formation and growth of the intermetallic compound (IMC) layer between the solder and the substrate tends to change accordingly to the operating temperature of the solder joint. A thick IMC layer containing coarse intermetallic compounds may adversely affect the mechanical properties and performance of the solder joint. It is often reasoned that the mechanical integrity of the solder joint is degraded by the inherent brittleness of the IMC layer since cracking can readily occur when the joint is mechanically or thermally stressed. In present work, the shear strength of Pb-2.5Ag-2Sn and Sn-25Ag-10Sb solder joints on copper (Cu) substrate, a widely used material as bond pad in electronic packaging industry is studied. The two types of solder used are of lead-based and lead-free solder that are commonly used in automotive application. The use of shear testing is included in the study to evaluate accelerated thermo-cycling as a method that has commonly been used for reliability assessment and lifetime prediction. Thermal aging accelerates the development of cracks and structural changes that will eventually weaken a solder joint.

Keywords: intermetallic compounds, shear strength, lead-based solder, lead-free solder, thermal aging.

INTRODUCTION

Solder material plays a crucial part to provide the necessary electrical and mechanical interconnection in an electronic assembly (K.-I. Chen *et al*, 2006). During the soldering process, metallurgical reaction between liquid solder and copper pad forms a layer of intermetallic compound (IMC) at the solder/metallization interface. The formation of interfacial IMCs is one of the mechanisms for establishing the connection between the solder and the substrate. It is desirable that there is good metallurgical bond between the solder and substrate. The reliability of solder joint are directly influenced by IMC formation (T. Laurila *et al*, 2005). In IMC formation, Sn reacts with Cu that is a conventional on substrate, Cu6Sn5 and Cu3Sn IMCs form (D. Yang *et al*, 2015). The variation of thickness of Cu6Sn5 and Cu3Sn IMCs will influence the solder joint (Chawla, 2003).

However, due to the brittle nature of the intermetallic layer and the mismatches of the physical properties (like elastic modulus and coefficient of thermal expansion), excessive intermetallics growth degrades interfacial integrity. This would hence result in deleterious effect on the solder joint reliability. Kirkendall voids usually form at the interface between Cu3Sn and Cu, which reduce the fracture toughness of solder joints and cause the joint failure (K. Zeng *et al,* 2005)

In the automotive industry, more and more circuits are being placed in the engine compartment in order to reduce the quantity of cables and, therefore, reduce cost. With the desire for device miniaturization and increase in higher input/output (I/O) connections in packing, IC devices with high density substrates generate higher heat during service. The heat is dissipated through the solder joints and this could result in a temperature increase in the joints. These under the hood conditions often see temperatures in excess of 150°C (Anderson, I.E and Harringa, J.L, 2004). A leading automobile manufacturer has even measured temperatures as high as 170 °C on a hybrid circuit. The high thermal stresses imposed on the solder joints at these temperatures has led automotive manufacturers to research Pb-free alternatives with high thermal fatigue resistance, because it is observed that Sn-37Pb has poor thermal fatigue properties even at 125 °C. Higher temperatures dramatically reduce the strength of the solder joint during thermal cycling, due to greater plastic deformation of the solder as well as diffusion, recrystallization and grain growth inside the solder. As this is major concern for the mechanical and microstructural stability of the solder joint, it is important to study the solder joint strength under thermal aging.

Lead-based solders have been used extensively in the assembly of modern electronic circuits due to its ease of handling, melting temperatures, good workability, ductility, and excellent wetting on Cu and its alloys (Philip Adamson, 2002). However, increasing environmental and health concerns about the toxicity of lead, as well as the possibility legislation (as described in the WEEE proposal) limiting the usage of lead-bearing solders, have stimulated substantial research and development efforts to discover substitute, lead-free solder alloys for electronic applications. In short, the toxicity of the lead present in Sn-Pb solders will pollute the environment and harm to human health, thus the new lead-free solder alloy is introduced to replace the lead solder alloy.

This study will provide useful data and information of the influence of the soldering temperatures and under thermal aging effect on the Pb-2.5Ag-2Sn and Sn-25Ag-10Sb solder joint. It is vital to know the behaviour of the solder joint in terms of shear strength when varying the thermal aging test. Furthermore, these

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selected solders are commonly used in die-attach industry, particularly in power semiconductor whereby the main application is used in automotive industry. Thermal aging study is performed on solder joint to investigate the reliability of the solder joint strength as solder joints used in automotive application are usually exposed to high operating temperature. The result of this study can provide the information to produce an effective and durable electronic product as the solder joint provides a better physical connection between the electronic component and its supporting printed circuit board.

EXPERIMENTAL PROCEDURE

The shear strength of the disc type solder joints were investigated between lead-based solder, Pb-2.5Ag-2Sn and lead-free solder, Sn-25Ag-10Sb onto copper substrate. Schematic view of the disc type solder joint specimen is shown in Figure-1 (Akio Hirose *et al,* 2004).

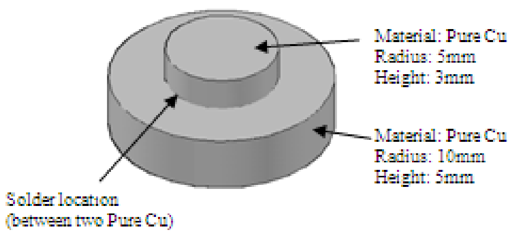

Figure-1. Schematic view of disc type solder joint specimen.

A special jig is needed to hold the position of the two different diameter disc shape coppers and at the same time to fix the thickness of the solder joint during the soldering process. Aluminium is chosen as the material to fabricate the jig mainly because it is corrosion resistant and it has high thermal conductivity which is also an important factor that will affect to the soldering process. There are four steps of specimen cleaning process needed to be carried out. The disc shape coppers are cleaned with acetone at ultrasonic cleaning bath for 6 minutes and to be dried at ambient temperature. acetone is one of the best cleaning fluid to wash away unwanted materials that stick on the surface of the copper, such as paint or ink. The acetone is replaced with 50 ml 4% sulphuric acid (H_2SO_4) and the specimens are cleaned for 2 minutes. H_2SO_4 is used to remove the oxidation layer of the coppers. The specimens are then immersed in distilled water and to be cleaned for 2 minutes to remove the residual solutions.

The specimens are then cleaned with acetone again for another 6 minutes. The soldering process is done on the hotplate and the temperature is set to the desired value. Thermocouple thermometer is used to double confirm the temperature on the hotplate for the entire soldering process. The coppers are set up into the jig while waiting for the hotplate to reach the required temperature. The 0.3mm thickness round copper plate (this thickness is equal to the thickness of solder joint) is first placed into the jig, followed by the 10mm diameter copper into the jig. The jig is turned over and the 5mm diameter copper is inserted into the small hole. The copper from top is pressed to ensure that the three components contact with each other closely. The position of the copper is fixed by tightening the screw. The set up is turned over again and the 10mm diameter copper and the thin copper plate are removed from the jig. A small amount of flux paste is applied to the coiled solder wire before being placed on top of the 5mm diameter copper and then is covered with 10mm diameter copper. Finally, the set up is turned over again and being placed on to the side of the hotplate for preheating. Figure-2 shows the illustration of setting up the coppers into the jig.

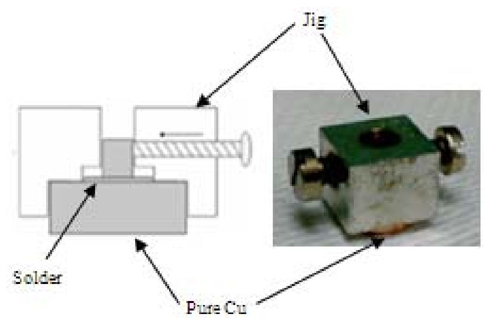

Figure-2. Copper setup process by using a jig.

The specimen is pre-heated at 100 °C for 5 minutes. Then, the specimen is pushed to the middle of the hotplate where it is the highest temperature area of the hotplate. The specimen is heated to the first parameter for 8 minutes. The temperature was set such that the melting temperature of the solder alloy added with 40°C. Therefore, the temperatures for experiment were set to be 335˚C for solder alloy Pb-2.5Ag-2Sn and 435˚C for Sn-25Ag-10Sb. The specimen is then cooled down at ambient temperature and is unloaded from the jig. The flux around the solder joint is cleaned using ethanol. The fillet formed around the solder joint need to be removed using hand grinder as it will affect the shear strength of the solder joint during shear testing. The procedures described are repeated three times for each parameter for better accuracy. Later, the specimens are being put into the heat treatment furnace where they are being heated to 200°C for the thermal aging purposes for 1 day, 3 days and 5 days.

The shear strength of the disc type solder joint specimen was measured as shown in Figure-3 using Instron model 4469 universal testing machine, with cross-head speed of 1 mm/min. The shear strength of the joint for each condition was the average value of three joints. The specimen before shear testing and after shear testing will be gone through with the cold mounting process. The purpose is to mount the specimen into epoxy so that it is easier for cross-sectioning the specimen and observing under the light optical microscope. The observation of lead-based and lead-free solder joint under light optical microscope needs to be carried out for both before and after shear testing specimens. For after shear testing specimen, thing to be determined is position of the cracks

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or breaks at the solder joint. The data to be collected from the experiment is the maximum load that the solder joint of lead and lead-free solder alloy can be supported when varying the temperature of soldering process and aging time. The shear strength of lead-based and lead-free solder joints are compared and to be analysed.

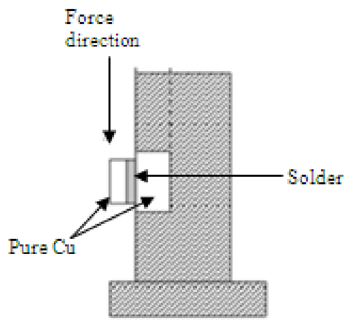

Figure-3. Force direction during shear strength test.

RESULT AND DISCUSSIONS

According to the results shown in Figure-4, the shear strength of the Sn-25Ag-10Sb solder joint is higher than the Pb-2.5Ag-2Sn solder joints under the same experimental parameter. In other words, the maximum load that can be withstood by the Sn-25Ag-10Sb solder joint is higher than the Pb-2.5Ag-2Sn solder joints. However, in the tested range of temperatures, the shear strength of both solder joints is decreasing when the temperature of soldering is increasing under all thermal aging condition fixed in the experiment.

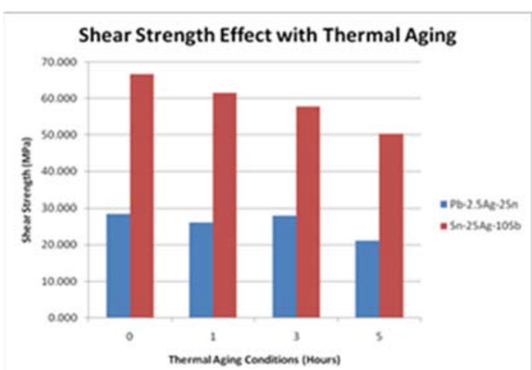

Figure-4. Shear strength with thermal aging condition.

Surface fracture

Voiding in a solder joint occurs during the solder reflow process. Voiding can form in the attachment from melting anomalies associated with oxides or organic films on the bonding surfaces, trapped air in the attachment, local non-wetting, outgassing and attachment shrinkage during solidification. There are many causes to the void formation in a solder joint. Among of the causes is the indication that it is due to the difficulty in releasing out gassing flux material entrapped during reflow process (W. B. Hance and N.-C. Lee, 1993). Some of the factors influencing the incidence and amount of voiding such as flux material used in soldering, reflow profile used, solderability of the pad, component and solder paste, surface oxide for the solder paste particles, reflow atmosphere used

From the experiments, it is noticed that the void formation fracture surface of the Pb-2.5Ag-2Sn solder joint tends to increase with the increasing aging time condition. This clarifies the decrease in shear strength of solder joint across increasing aging time condition.

On the other hand, the fracture surface of the Sn-25Ag-10Sb solder joint contains less significant void formation when compared to the Pb-2.5Ag-2Sn specimen. The void formation of the Sn-25Ag-10Sb solder joint (shown in Figures 5 and 6) fracture surface shows increasing trend towards rising aging time condition. These surfaces for the solder/Cu joints provided more insight into the deformation mechanisms. Fracture surface smearing is a common phenomenon because the loading direction is parallel to the fracture surface. Some incidence of intermetallic exposure was observed. It is interesting to note that the dimple size in the fracture surface increased significantly with thermal aging time due to the coarsening of the solder particles. Generally, spherical voids are simply shaped by surface tension of molten solder whereas the irregular voids are not only affected by surface tension, but also interfered by the sluggish flow of solders with large quantity of intermetallics.

In this study, the voiding is caused by flux outgassing and aggravated by poor wetting and large joint coverage area (Bradley and Edwin, 2007). From the observation, the solder joint soldered at higher temperature contains more voiding as with an increased tendency to have more oxidized surfaces on the solder particles. This is thought to be due to the fact that increased soldering temperatures and times tend to dry out the volatile flux solvent more readily than cooler soldering temperature. This will leave a more viscous flux remnant that will be more difficult to expel from the molten solder. In brief, solder alloys with a lower surface tension is expected to spread easier, thus promising a lower voiding.

The incidence of voiding can give rise to a reduction in mechanical integrity of a solder joint. Large voids or a collection of smaller voids at the board or component interface can be problematic. In general, solder joint failure occur at the component side, where there can be a stress concentration which induces a crack. In contrast, voiding may actually enhance the reliability of a solder joint because it acts to reduce the crack propagation energy, in effect as a crack blunter.

Figure-5 and Figure-6 present the fracture surfaces of Sn-25Ag-10Sb solder joint soldered at temperature of 435 °C with no thermal aging condition and with 5 days thermal aging condition correspondingly. Under aging treatment, the fracture mode changes from a mixture of ductile and brittle fracture in the solder to a brittle interfacial fracture. The interfacial-fracture mode implies poor solder joint shear strength. The growth of the IMC layer will increase the potential for the brittle interfacial-fracture mode and further reduce the strength of the solder joint attachment. Consequently, the degradation of the solder joint shear strength during aging must be attributed to the formation and growth of the intermetallic compounds.

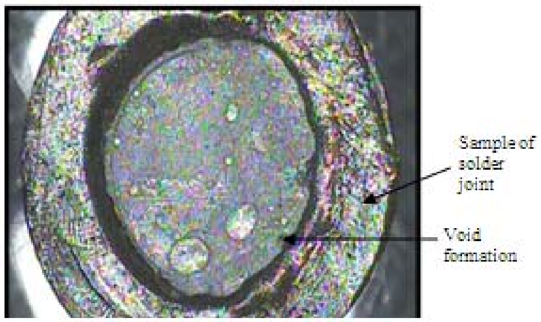

Figure-5. Surface fracture of Sn-25Ag-10Sb solder joint soldered at temperature of 435 °C with no thermal aging treatment.

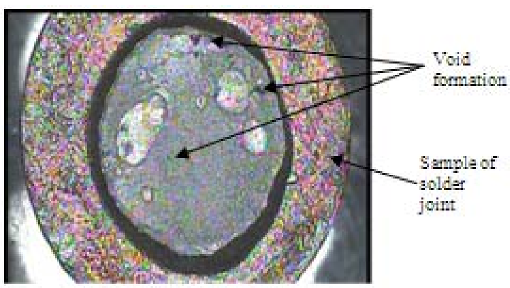

Figure-6. Surface fracture of Sn-25Ag-10Sb solder joint soldered at temperature of 435 °C under 5 days thermal aging treatment.

Intermetallic compounds (IMC)

There are three important items in a solder joint namely, the solder, the Cu substrate, and the intermetallic compound (IMC) layer between the solder alloy and the Cu substrate, and two interfaces -the solder/IMC interface and the IMC/Cu interface Thus the mechanical behavior of the solder joint is closely related with the mechanical behavior of these constituents (Tong An and Fei Qin, 2014). During the aging process, the microstructure of solder joint will evolves continuously (D. Ma, W.D. Wang and S.K. Lahiri, 2002) and J.C. Gong, C.Q. Liu, P.P. Conway and V.V. Silberschmidt, 2008). This will cause the changing properties of solder joint and produce a new layer namely as intermetallic compound (IMC).

In general, solders bond strongly to the metallized substrate by forming a thin, continuous, and uniform IMC layers between the solder and metallized substrate. In this study, the copper is used as the metallized substrate. The formation and evolution of IMCs between solder and Cu substrate will strongly influence the reliability of joints. Unfortunately, the excessive growth of IMCs layer at the solder/Cu substrate interface may degrade the reliability of the solder joints due to their inherent brittle nature and the tendency to generate structural defects. Thus, they can become sources of mechanical weakness in the solder joint.

The formation of the Cu6Sn5 layer caused the fracture of the solder joints and resulted in the degradation of the joint strength. The larger the width of reaction layer in the solder joint, the brittle the microstructure of the solder joint and will results in lower shear strength of solder joint. The Cu6Sn5 layers will grow during the soldering operation according to increasing thermal aging time. The width of the both layers becomes larger when the temperature of soldering is increasing and also subjected to increasing aging time. This will results in the brittle the microstructure of the solder joint. Thus, in the tested range of temperature, the shear strength of both Pb-2.5Ag-2Sn solder joint and Sn-25Ag-10Sb solder joint is decreased when the temperature of soldering operation is increased and also with increasing aging time.

CONCLUSIONS

The study has determined the influence of the temperature of soldering operation and also the influence of the aging time and soldering operation temperature on the shear strength of both Pb-2.5Ag-2Sn solder joint and Sn-25Ag-10Sb solder joint. Besides, this study also has compared the shear strength of both solder joints. The soldering temperature and thermal aging time are significant factors that will influence the shear strength of solder joint. With increasing soldering temperature and thermal aging time, the shear strength of both Pb-2.5Ag-2Sn solder joint and Sn-25Ag-10Sb solder joint decrease. The Sn-25Ag-10Sb solder joint has higher strength than of Pb-2.5Ag-2Sn solder joint for all the corresponding parameters set in this study.

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