Evaluating the Mechanical Reliability of Ball Grid Array (BGA) Flexible Surface-mount Electronics Packaging under Isothermal Ageing

Sabuj Mallik and Ahmed Z El Mehdawi

***Abstract*— Electronic systems are known to be affected by the environmental and mechanical conditions, such as humidity, temperature, thermal shocks and vibration. These adverse environmental operating conditions, with time, could degrade the mechanical efficiency of the system and might lead to catastrophic failures. The aim of this study is to investigate the mechanical integrity of lead-free ball grid array (BGA) solder joints subjected to isothermal ageing at 150°C for up to 1000 hours. Upon ageing at 150°C the Sn-3.5Ag solder alloy initially age-softened for up to 200 hours. This behaviour was linked to the coarsening of grains. When aged beyond 200 hours the shear strength was found to increase up to 400 hours. This age-hardening was correlated with precipitation of hard Ag_3Sn particles in Sn matrix. Further ageing resulted in gradual decrease in shear strength. This can be explained as the combined effect of precipitation coarsening and growth of intermetallic layer. The fractured surfaces of the broken solder balls were also investigated under a Scanning Electron Microscope. The shear failures were generally due to ductile fractures in bulk solders irrespective of the ageing time.**

***Index Terms*— Lead Free Solder Alloy, Shear Strength, Isothermal Ageing, Ductile and Brittle Fractures.**

I. Introduction

ELECTRONICS manufacturing is one of the rapid changing industries in the world. Miniaturization of electronic products is at the heart of this change. Over the last two decades, the electronic manufacturing industries have experienced tremendous pressure to meet the requirements for miniaturized products, particularly, hand-held consumer products such as mobile phones, MP3 players etc. This is coupled with the requirement of electronic products with ever-higher performance. Functionality of these products has also evolved at the same pace through packing in more and more features.

To meet the demands many area-array packages are developed, such as Ball Grid Array (BGA), Chip-Scale Package (CSP) and Flip-Chip. Among these BGAs are now widely used as high performance miniature package and offer some distinct advantages over other surface mount packages. BGAs are mounted with the substrates at its bottom surface using solder balls. As there are no leads, BGAs have reduced co-planarity issues and are easier to handle [1]. Other important benefits of BGA include self-centering of solder balls during placement, higher ball pitch than the leaded flat packages, higher heat dissipation from the package to the substrate and also better electrical performance due to low induction leads.

In most cases the failures in electronics packaging originates at the solder joints between the electronic components and substrate. In a move towards more environment friendly electronic products, the lead-based solders are now being replaced with lead-free solders. It is therefore very important to study the new lead-free solder joints under harsh environmental conditions. The tiny solder joints at the bottom of BGA serve not only to provide electrical and mechanical connections but also to dissipate heat away from the chip. With further reductions in the size of solder joints, the reliability of solder joints has become more and more critical to the long-term performance of electronic products.

Several studies have been carried out to investigate the ageing behaviors of BGA solder joints. Ageing behavior of lead-free solder alloys differs from its Sn-Pb counterpart. Xiao *et al* [2] reported that the ageing of Sn3.9Ag0.6Cu solder alloy at 180°C initially leads to age-softening due to coarsening of grains. However, ageing at 180°C beyond one day resulted in age hardening due to precipitation of hard Ag_3Sn particles. The same study also reported that the SnAgCu solder alloy offers better creep resistance than the Pb-Sn eutectic alloy. Koo and Jung [3] found that shear strength of BGA solder balls generally increased with increased test speed. Same study also demonstrated that the solder joint fractures at high shear speeds were mainly brittle fracture, with fractures occurring at the interface between the solder and pad. It was also concluded that the SnAgCu solder balls were more susceptible to interfacial brittle fractures than SnPb solder balls. In an investigation of ball shear strength of Sn-3.5Ag-0.75Cu solder balls on BGA pads with different surface finish by Lee *et al* [4] it was demonstrated that solder ball shear strength decreased with increasing ageing temperature and time. Fracture modes varied largely with pad metallization. For Cu pads, the fractures were mainly occurred at the interfacial intermetallic layer between the solder and the pad. Also for Cu pad metallization during ageing the fracture mode gradually changed from ductile fracture in the bulk solder to brittle interfacial fracture (at the intermetallic layers).

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Previous research studies in this niche area have failed to establish a clear picture of the effect of isothermal ageing on the reliability of BGA solder joints. In fact, some of the conclusions from different sources are quite contradictory. This paper aims to clarify some of those issues through evaluating the mechanical reliably of BGA solder joints under isothermal aging.

II. Materials and Methods

Table I shows the materials used in the study. The solder balls used for the BGA attachment were made of lead-free Sn-3.5Ag solder alloy with 0.75 mm diameter. For the test vehicle flexible BGA substrate was used with 304 pads with a pad opening of 0.64 mm and pad metallization of electroplated Au/Ni over an underlying Cu pad (figure 1). Commercially available rosin-based, halide free and no-clean flux was used for surface mount attachment.

TABLE I
Test Materials

Materials	Brief Details
Solder Balls	Sn-3.5Ag Solder, 0.75 mm diameter
BGA substrate	Flexible substrate with 304 pads with a pad opening of 0.64 mm
Pad metallization	Electroplated Au/Ni over an underlying Cu pad
Flux	Rosin- based, Halide free, No-Clean

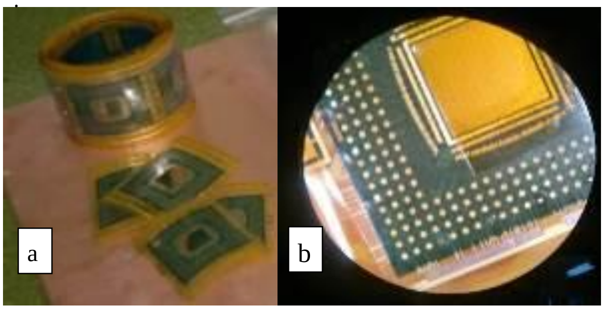

Fig. 1. (a) Flexible BGA substrate and (b) Magnified view of solder ball pads

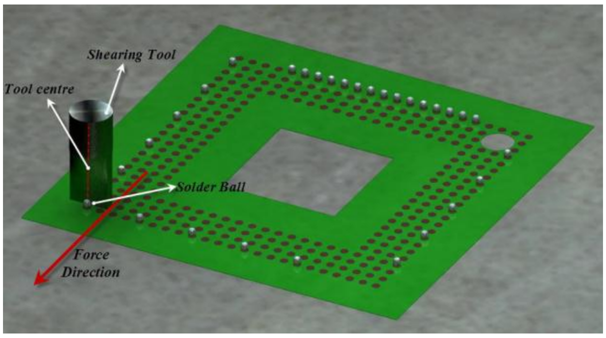

Fig. 2. Schematic of BGA substrate showing the location of mounted solder balls and positioning of shear tool during ball shear testing.

The BGA substrate was first covered with a thin layer of flux. The balls were then placed manually on to the substrate. For the ease of shear testing only limited number solder balls were placed as shown in figure 2. After placing the solder balls substrate test vehicles were then reflow soldered using a commercial scale six-zone convection reflow oven. The peak reflow temperature was maintained at around 230°C. A total of eight flexible BGA substrate were reflow soldered. One of them was used as "as-soldered" sample and rest of them were placed in a climatic chamber for thermal ageing. Samples were aged at a constant temperature of 150°C for up to 1000 hours, with samples taken out at 50, 100, 200, 400, 600, 800 and 1000 hours. Reliability of solder joints from the as-soldered and the aged samples was tested by measuring the shear strength of the joints. The ball-shear tests were carried out using a 4000 series Dage Bond Tester. The shear speed and shear height (shear tool offset) were kept at 0.7 mm/sec and 0.1 mm respectively for all the solder balls. For any particular ageing period the test sample size was 15, that is, 15 solder balls were sheared and the average was taken. The fractured solder balls were collected and fractured surfaces were investigated for brittle and ductile fractures under a scanning electron microscope (SEM).

III. Results and Discussion

The results are analyzed and discussed in two parts. First part looks at the effect of isothermal ageing on the shear strengths of solder joints and the second part studies the solder ball fractured surfaces.

A. *Effect of Isothermal Ageing on the Shear Strengths of BGA Solder Joints*

Figure 3 presents the results from ball shear tests carried out on the as-soldered and isothermally (at 150°C) aged BGA solder joints. The plot shows both the average shear force values and the variations in the collected data. The high degree of variation in shear force data could be due to uneven manual application of flux before the solder ball placement. Flux serve to facilitate solder wetting by cleaning surface oxides and preventing further oxidation during a soldering process. However, too-much or too-low quantity of flux could have an impact on solder joint integrity. In deed Painaik and Santos [5] found that the BGA solder ball shear strength affected by the flux quantity used in the BGA solder ball attachment process. Higher flux thickness and pad coverage were found to increase ball shear strength and vice-versa.

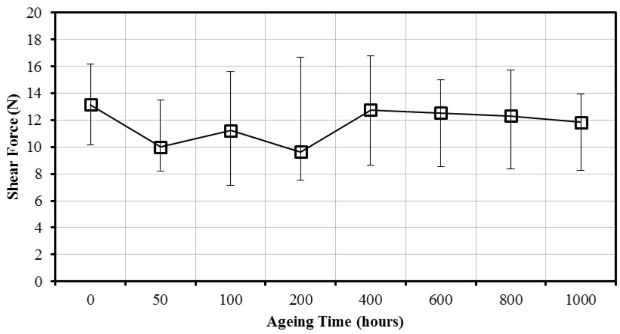

Fig. 3: Shear forces of Sn-3.5Ag BGA solder joints as a function of ageing time

A careful observation of figure 1 reveals three different patterns on how shear forces changed with increased ageing time. The shear force of Sn-3.5Ag solder joints was initially dropped till 200 hours. This was then followed by an increase in shear force till 400 hours. Ageing beyond 400 hours resulted in gradual decrease in shear force. The initial decrease in shear force can be explained as due to the

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coarsening of grains [2-3]. The coarsening of grains can be explained through a process called 'Ostwald Ripening'[6]. This natural spontaneous process occurs because larger grains are thermodynamically more stable than small grains. The whole process starts from the fact that molecules on the surface of grains are energetically less stable than the ones inside the grains. Due to lower surface to volume ratio large grains have a lower surface energy than the smaller grains. This creates a potential deference at the grain boundaries and as a result molecules from small grains diffuse through the grain boundaries and attach themselves to the larger grains. Therefore, the number of smaller grains continues to shrink, while the larger grains continue to grow. Without the application of adequate thermal or mechanical energy grain growth is very slow. The rate of grain growth increases with the application of thermal energy, because increased diffusion allows for more rapid movement of molecules. The reduced number of grain boundaries (due to grain coarsening) allows dislocations (crystal defects) to move easily through the boundaries. This results in the solder joints to deform at much lower shear loads. Xiao et al [2] also reported softening of Sn3.9Ag0.6Cu solder alloy when aged at 180°C. However the age-softening period was much shorter (24 hours compared to 200 hours) than what was observed in this study. This might be due to a lower ageing temperature of 150°C. After 200 hours of aging the solder joints shear strength was found to increase up to 400 hours. This increase in shear strength could be due to precipitation hardening. In the same study on the Sn-Ag-Cu solder joints Xiao et al [2] also observed the precipitation of hard Ag_3Sn particles after 1 day of ageing at 180°C. Ageing beyond 400 hours resulted in gradual drop in shear force. This behavior was quite expected and can be attributed due to combined effect of saturation of precipitants and further coarsening of grains and the growth of intermetallic layers. In an ageing study on Sn-Ag-Cu solder joints Lee et al [4] concluded that the Cu-Sn intermetallic layers are the major contributor of solder joint shear failures.

B. *Study of Solder Ball Shear Fractures*

The fracture behaviors of BGA solder joints are very complex in nature. For example, depending on the intensity and speed of applied load solder balls could fail through pad lift, interfacial fracture (solder /intermetallic or intermetallic/pad) and bulk solder failure [7]. Among these failures interfacial fractures are predominantly brittle and bulk solder fractures are tend to be ductile in nature. However, solder ball failure through mixed fractures are also frequently observed by various researchers [3, 7].

Figure 4 presents the fractures surfaces from ball shear tests at different ageing time. From general understanding it was expected that the BGA solder joints will fail either at the interface between solder and substrate (at the intermetallic layers) or at a region of low strength (e.g. bulk solder). It was also expected that shear fracture mode will be ductile initially and then will show a transition towards brittle fracture with increased ageing time. However, the fracture surfaces didn't show any particular trend and were found to be generally ductile in nature. Although there was no particular trend in the shear fracture, coarsening of grains is evident from 400 to 1000 hours. This finding matches very well with the finding from shear force study where the shear force was found gradually decreasing after 400 hours of ageing. The coarsening of grains on the fracture surface was also observed by Lee et al [4] for shear fracture of BGA solder joint with Au/Ni-Cu pad under isothermal ageing. The ductile nature of the shear fractures and coarsening grain structure also indicate that fractures occurred in bulk solder irrespective of the ageing time. However, the author believes that a more detail elemental analysis of the fracture surfaces is required for an in-depth understanding of fracture locations.

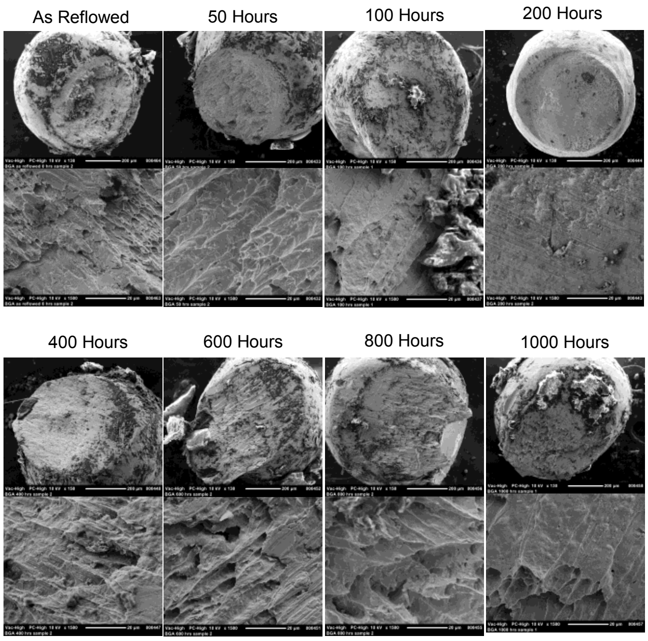

Fig. 4: Fracture surfaces of BGA joints on Au/Ni-Cu metallisation at different ageing times.

IV. Conclusions

In this study Sn-3.5Ag lead-free BGA solder joints were isothermally aged at 150°C for up to 1000 hours. The solder joint shear strengths were evaluated and solder ball fracture surfaces were investigated. Upon ageing the solder joints, shear strength initially decreased for 200 hours as a result of grain coarsening. This was then followed by increase in shear strength (till 400 hours), which was mainly due to precipitation hardening. A gradual decrease in shear strength was observed after 400 hours of ageing. Overall, it can be concluded that the lead-free BGA solder joints are able to maintain the shear strength even after 1000 hours of isothermal ageing. Investigation of shear fractures didn't show any particular trend. However, shear failures were mainly due to ductile fractures in bulk solders and therefore, the intermetallic interfacial layers were not responsible for shear failures.

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