

INTERMETALLIC REACTIONS IN A SN-51IN SOLDER BGA PACKAGE WITH IMMERSION AG SURFACE FINISH

Chao-Chi Jain, Shiuan-Sheng Wang, Hui-Min Wu and Tung-Han Chuang*

ABSTRACT

Intermetallic compounds formed in Sn-51In solder ball grid array (BGA) packages with Ag/Cu pads are investigated. After reflow, the Ag thin film dissolves quickly into the solder matrix, and scallop-shaped intermetallic layers with compositions of $(\text{Cu}_{0.89}\text{Ag}_{0.11})(\text{In}_{0.79}\text{Sn}_{0.21})_2/\eta\text{-Cu}_6(\text{Sn}_{0.54}\text{In}_{0.46})_5$ appear at the interfaces between the Sn-51In solder balls and Cu pads. Aging at 75°C and 100°C caused the $\eta\text{-Cu}_6(\text{Sn}_{0.54}\text{In}_{0.46})_5$ intermetallics to replace the $(\text{Cu}_{0.89}\text{Ag}_{0.11})(\text{In}_{0.79}\text{Sn}_{0.21})_2$ at the solder/pad interfaces. The thickness of η -intermetallic versus the square root of reaction time ($t^{1/2}$) shows a linear relation, indicating that the growth of intermetallics is diffusion-controlled. Ball shear tests show that the strength of these Sn-51In solder joints is initially 1.9 N, decreasing to 1.7 N and 1.6 N after aging at 75°C and 100°C, respectively.

Key Words: Sn-51In, immersion Ag surface finish, reflow, aging.

I. INTRODUCTION

In order to prevent oxidation and promote the wettability of a printed circuit board, many surface finishing techniques have been explored, among which the immersion Au/Ni method is popularly employed in advanced electronic packaging (Minor and Morris, 2000). However, this method is costly and in some cases can cause Au embrittlement failure (Mei and Morris, 1992). Immersion Ag (ImAg) is an alternative surface finishing agent which can provide smooth surfaces and good wettability for liquid solders on Cu pads (Lau *et al.*, 2003). In addition, the immersion Ag process takes only about 7 minutes, and the cost is close to that of traditional Sn surface finishes. An immersion Ag film is about 0.2 μm thick and dissolves quickly into the solder matrix during reflow, allowing further interfacial reaction to occur between the solder alloy and Cu pad. On the other hand, eutectic Sn-51In solder possesses the merits of greater ductility and longer fatigue life than the tra-

ditional eutectic Sn-37Pb solder (Glazer, 1995; Kang and Sarkhel, 1994; Mei and Morris, 1992; Shimizu *et al.*, 1995). Gold embrittlement failures in advanced packaging can specifically be prevented by taking advantage of the lower solubility of Au in In-based solders (Lin and Chuang, 2000). Also, the lower melting point of Sn-51In solder can be favorable in the electronic packaging hierarchy.

It is well known that the over-growth of intermetallic compounds at the interface of a solder joint can cause embrittlement and failure, significantly decreasing the reliability of electronic packaging. In our prior studies, intermetallic compounds that formed during the solder reactions of Sn-51In with Cu, Ag, and Ni substrates were analyzed (Chuang *et al.*, 2002; Huang and Chuang, 2002; Wang *et al.*, 2006). The intermetallic reactions in Sn-51In solder ball grid array (BGA) packages with Au/Ni/Cu pads have also been previously investigated (Chuang *et al.*, 2003); the results showed that a continuous double layer of $\text{Au}(\text{In},\text{Ni})_2/\text{Au}(\text{In},\text{Ni})$ intermetallic appeared at the solder/pad interface after reflowing at peak temperatures between 140°C and 170°C. In contrast, reflowing with temperature profiles above 200°C caused a number of cubic-shaped AuIn_2 intermetallic compounds to form at the interfaces and migrate toward the upper domes of the Sn-51In solder balls

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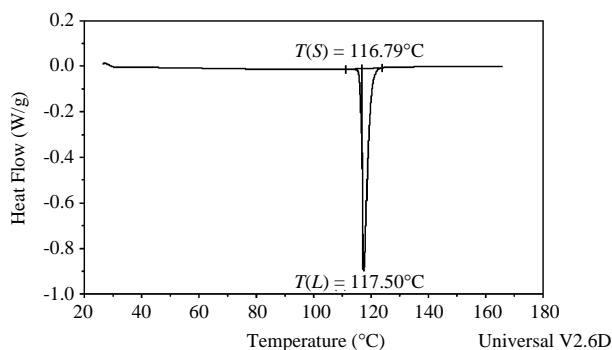


Fig. 1 DSC curve of Sn-51In solder

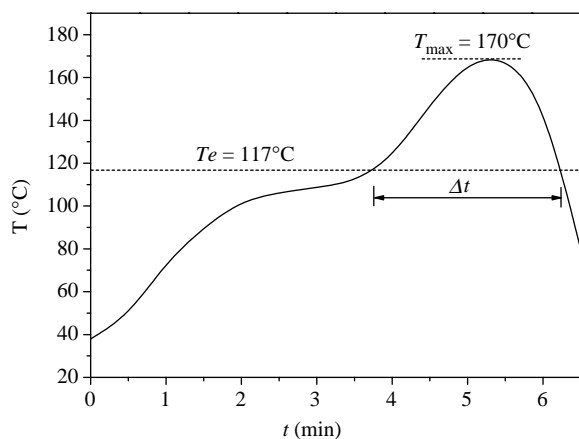


Fig. 2 Temperature profiles for the reflowing of Sn-51In solder BGA packages in this study

(Kang and Sarkhel, 1994). Although immersion Ag is commonly used for surface finishing of Cu pads in electronic packaging, the intermetallic compounds formed in such solder joints have not been extensively researched. This study focuses on the interfacial reactions and bonding strengths between Sn-51In solder balls and Ag/Cu pads in reflowed and aged BGA packages.

II. EXPERIMENTAL

The BGA packages used in this study contained 49 Cu pads set on FR-4 substrate. The Cu pads were immersion-plated with 0.2 μm thick Ag film. The Sn-51In solder balls, with diameters of 0.4 mm, were dipped in RMA type flux, placed on the immersion Ag/Cu pads of the BGA packages, and then heated in a hot-air furnace. The eutectic temperature of the Sn-51In alloy, as analyzed by DSC (see Fig. 1), was 117°C, which is consistent with the Sn-In phase diagram (Massalski, 1986). The reflow temperature profile with peak temperatures at 170°C is shown in Fig. 2. After reflow, the Sn-51In specimens were further aged at 75°C and 100°C for time durations varying from 100 hr to 1000 hr. To investigate the metallographic

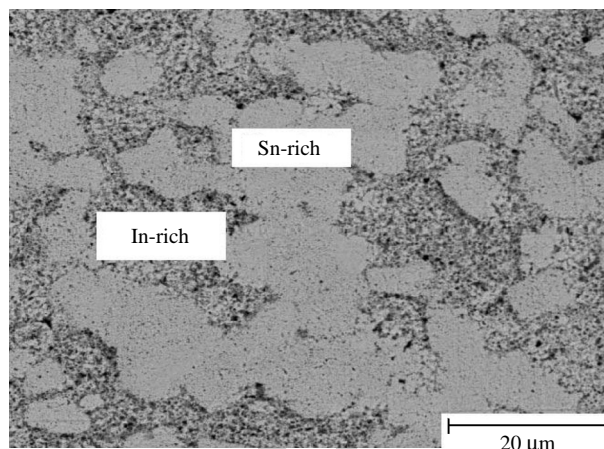


Fig. 3 Microstructure of the as-cast Sn-51In solder

microstructure, the solder joints were mounted with resin, ground with 1500 grit SiC paper, and polished with 0.3 μm Al_2O_3 powder, in that order, to obtain the cross-sections of the solder/pads interfaces. The morphology of the intermetallic compounds was examined with scanning electron microscopy (SEM). Energy dispersive X-ray (EDX) spectrometry was used to determine the chemical compositions of the intermetallic compounds.

In addition, the bonding strengths of the Sn-51In solder joints after reflow and aging were measured via ball shear testing. The measurements were taken at a shear rate of 0.1 mm/sec and a shear height of 80 μm (about 1/4 of the reflowed ball height). Fractography of the solder joints after ball shear testing was conducted by SEM.

III. RESULTS AND DISCUSSION

The typical microstructures of the as-cast Sn-51In solder in Fig. 3 show that many cluster-shaped Sn-rich phase (bright in color) with a composition (at%) of Sn : In = 74.1 : 25.9 are embedded in the matrix of In-rich phase (dark in color) with a composition (at%) of Sn : In = 28.5 : 71.5. During reflow, the Ag thin film dissolves quickly, and scallop-shaped intermetallic compounds appear at the interfaces between the Sn-51In solder balls and Cu pads, as shown in Fig. 4. In addition, an extra continuous intermetallic layer appears at the interface between these scallop-shaped intermetallics and the Cu pad. EDX analyses indicate that the composition of the continuous intermetallic layer is $\text{Cu}_6(\text{Sn}_{0.54}\text{In}_{0.46})_5$, which corresponds to the $\eta\text{-Cu}_6\text{Sn}_5$ phase in the Cu-Sn phase diagram (Massalski, 1986). The intermetallic scallops ahead of this continuous intermetallic layer possess a composition of $(\text{Cu}_{0.89}\text{Ag}_{0.11})(\text{In}_{0.79}\text{Sn}_{0.21})_2$, which is identified as CuIn_2 phase in the Cu-In phase diagram (Massalski, 1986). The formation of the $\eta\text{-Cu}_6(\text{Sn}_{0.54}\text{In}_{0.46})_5$ continuous

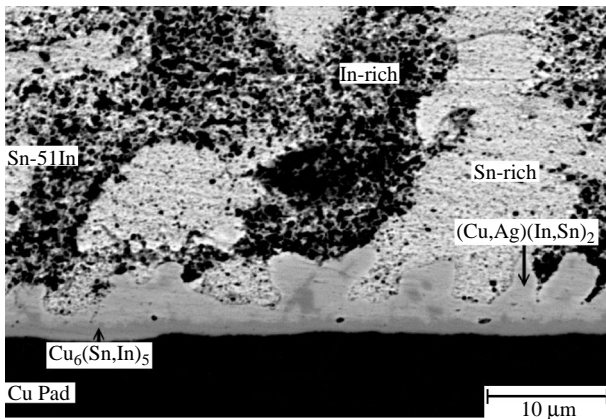


Fig.4 Morphology of the intermetallic compounds formed at the immersion Ag surface finished interfaces of reflowed Sn-51In solder BGA packages

intermetallic layer may be due to the dissolution of the Ag surface finish and the diffusion of Sn and In atoms of liquid Sn-51In solder into the Cu pad, resulting in the intermetallic reaction between Sn-51In solder and the Cu pad. On the other hand, Cu atoms diffuse from the Cu pad into the liquid Sn-51In solder, accompanying the dissolving Ag atoms in ImAg surface finish, to form the scallop-shaped $(\text{Cu}_{0.89}\text{Ag}_{0.11})(\text{In}_{0.79}\text{Sn}_{0.21})_2$ intermetallics ahead of the $\eta\text{-Cu}_6(\text{Sn}_{0.54}\text{In}_{0.46})_5$ intermetallic layer. The growth and coalescence of the $\eta\text{-Cu}_6(\text{Sn}_{0.54}\text{In}_{0.46})_5$ intermetallic scallops on the $(\text{Cu}_{0.89}\text{Ag}_{0.11})(\text{In}_{0.79}\text{Sn}_{0.21})_2$ layer results in the appearance of voids at the $\eta\text{-Cu}_6(\text{Sn}_{0.54}\text{In}_{0.46})_5/(\text{Cu}_{0.89}\text{Ag}_{0.11})(\text{In}_{0.79}\text{Sn}_{0.21})_2$ interface, as evidenced in Fig. 4.

Figure 5 shows the morphology of intermetallic compounds in Sn-51In solder BGA packages with immersion Ag pads after aging at 75°C for various times. It can be seen that the continuous $\eta\text{-Cu}_6(\text{Sn}_{0.54}\text{In}_{0.46})_5$ intermetallic layer grows toward the solder matrix with increases in aging duration. A contrast can be found in the scallop-shaped $(\text{Cu}_{0.89}\text{Ag}_{0.11})(\text{In}_{0.79}\text{Sn}_{0.21})_2$ intermetallic phase. The growth of the $\eta\text{-Cu}_6(\text{Sn}_{0.54}\text{In}_{0.46})_5$ intermetallic layer and the diminishing of $(\text{Cu}_{0.89}\text{Ag}_{0.11})(\text{In}_{0.79}\text{Sn}_{0.21})_2$ become more rapid as the aging temperature increases to 100°C, as shown in Fig. 6. It can also be observed in Figs. 5 and 6 that the voids that appear in the reflowed solder joints (Fig. 4) are left at the $\eta\text{-Cu}_6(\text{Sn}_{0.54}\text{In}_{0.46})_5/(\text{Cu}_{0.89}\text{Ag}_{0.11})(\text{In}_{0.79}\text{Sn}_{0.21})_2$ interfaces after aging at 75°C and 100°C. Accompanying the intermetallic reactions during aging of the Sn-51In solder joints, greater than 0.32 to 1.55 at% and 0.56 to 1.96 Ag elements have also dissolved into the Sn-rich and In-rich phases of the solder matrix, respectively.

For the Cu/Sn interfacial reactions, it has often been reported that an $\epsilon\text{-Cu}_3\text{Sn}$ intermetallic phase forms between the $\eta\text{-Cu}_6\text{Sn}_5$ intermetallic layer and the Cu

pad. Chi and Chuang studied the intermetallic reactions in a Sn-3.5Ag solder BGA package with Ag/Cu pads (Chi and Chuang, 2006). They found that during the aging process at 150°C, an $\epsilon\text{-Cu}_3\text{Sn}$ intermetallic layer appeared after the formation of $\eta\text{-Cu}_6\text{Sn}_5$ intermetallics. In the interior of the $\epsilon\text{-Cu}_3\text{Sn}$ layer, many Kirkendall voids were observed. The appearance of $\epsilon\text{-Cu}_3\text{Sn}$ intermetallic compounds accompanying Kirkendall voids has also been reported in immersion Ag surface finished Sn-3.5Ag-0.5Cu solder joints (Chuang *et al.*, 2006). The inhibition of the $\epsilon\text{-Cu}_3\text{Sn}$ intermetallics from the $\eta\text{-Cu}_6(\text{Sn}_{0.54}\text{In}_{0.46})_5$ phase seems to be a beneficial effect for the Sn-51In solder package with an immersion Ag surface finish.

The thicknesses (X) of the η -intermetallic compounds formed during the aging of Sn-51In solder BGA packages with Ag/Cu pads at various temperatures are plotted versus the square root of reaction time ($t^{1/2}$) in Fig. 7. For comparison, the growth thicknesses of η -intermetallic compounds in Sn-3.5Ag and Sn-20In-2.8Ag packages with Ag/Cu pads aged at 100°C and 150°C, which have been measured in prior studies (Chi and Chuang, 2006; Jain *et al.*, 2008), are also given in Fig.7. All curves exhibit linear relations, which indicates that the growth of η -intermetallics in these alloys is diffusion-controlled. Compared with the results for Sn-20In-2.8Ag and Sn-3.5Ag, Fig. 7 reveals that the η -intermetallics in Sn-51In grow more rapidly at 100°C than those in other alloys, a phenomenon which can be attributed to the lower melting point and thus smaller gap between aging and melting temperatures of Sn-51In solder in comparison to those of Sn-20In-2.8Ag and Sn-3.5Ag. It can also be seen that during aging at 100°C, the η -intermetallic in the Sn-20In-2.8Ag solder BGA package has the slowest rate of growth. However, the intermetallic growth in Sn-20In-2.8Ag solder joints accelerates drastically during aging at 150°C.

Ball shear strengths of the Sn-51In solder BGA packages after the aging process are shown in Fig. 8. For comparison, the results of ball shear tests performed on Sn-3.5Ag and Sn-20In-2.8Ag BGA packages in prior studies (Massalski, 1986; Chuang *et al.*, 2006) are also given in this figure. It is evident that the bonding strength of the as-reflowed Sn-51In solder joint (1.9 N) is much lower than those of Sn-3.5Ag (6.6 N) and Sn-20In-2.8Ag solder joints (4.4 N). After aging at 75°C and 100°C for 100 hr, the bonding strengths of Sn-51In solder joints declined to 1.7 N and 1.6 N, respectively. This decline can be attributed to the softening effect of the solder matrix, which has been confirmed by microhardness measurement. A similar tendency occurs in Sn-3.5Ag packages; their ball strengths decrease from 6.6 N to 5.8 N and 5.3 N after aging at 100°C and 150°C, respectively. In contrast, the ball shear strength of

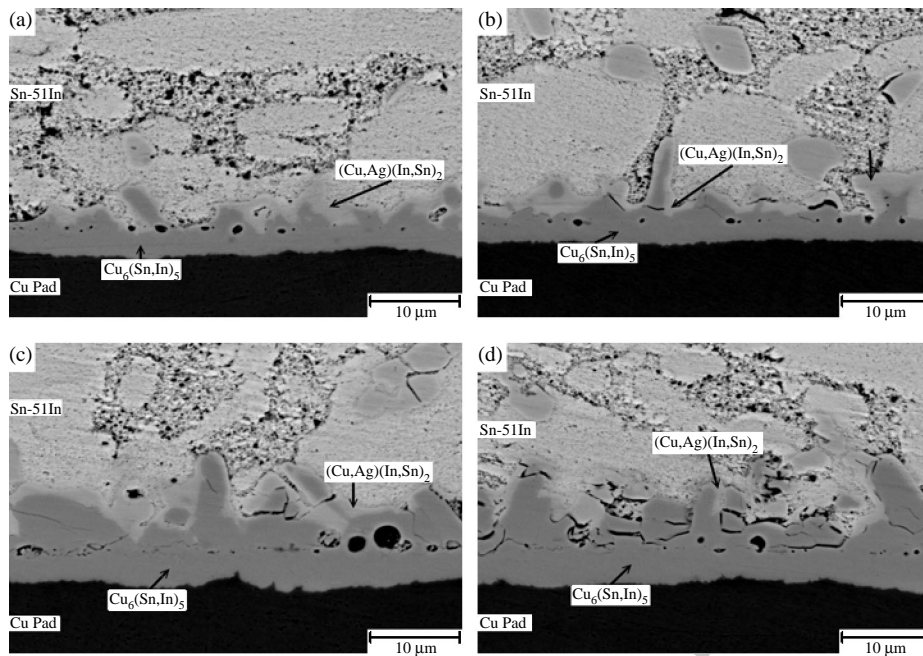


Fig.5 Morphology of intermetallic compounds formed at the interfaces between Sn-51In solder balls and Ag/Cu pads after aging at 75°C for various time periods: (a) 100 hr, (b) 500 hr, (c) 700 hr, (d) 1000 hr

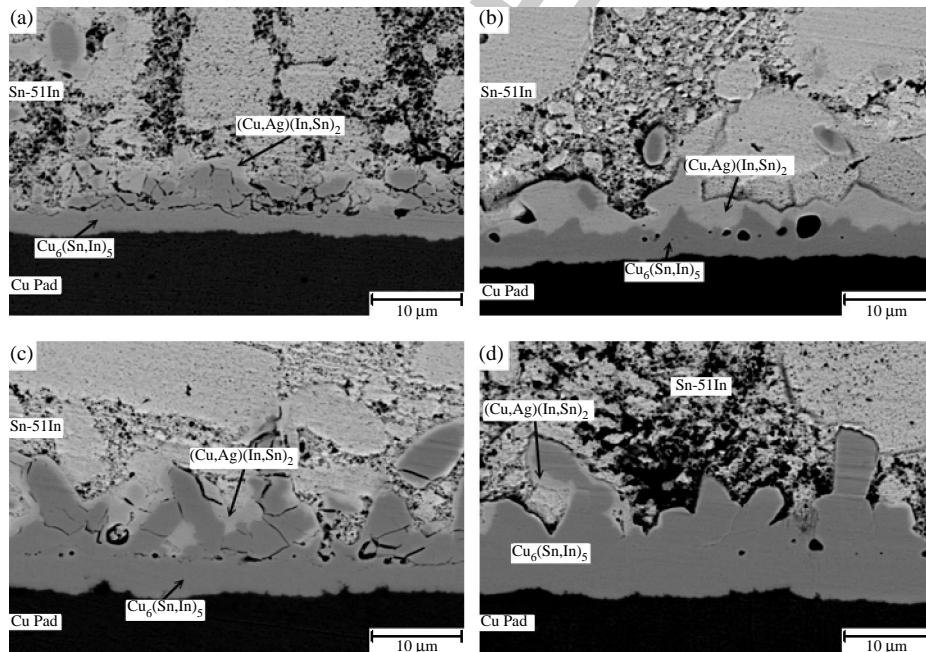


Fig.6 Morphology of intermetallic compounds formed at the interfaces between Sn-51In solder balls and Ag/Cu pads after aging at 100°C for various time periods: (a) 100 hr, (b) 500 hr, (c) 700 hr, (d) 1000 hr

Sn-20In-2.8Ag solder joints after aging at 100°C for 100 hr climbs to 5.2 N and remains almost constant with increases in aging time. Aging at 150°C for 100 hr also causes an increase of the ball shear strength to 5.1 N, while it declines slightly to 4.8 N after a longer aging time. Fig. 9 shows the typical

fractography of reflowed Sn-51In solder joints in BGA packages after ball shear tests, revealing that a ductile fracture with dimple characteristics occurs throughout the solder ball. With further aging, the Sn-51In solder joints retain ductile fracturing throughout the solder balls, as revealed in Fig. 10.

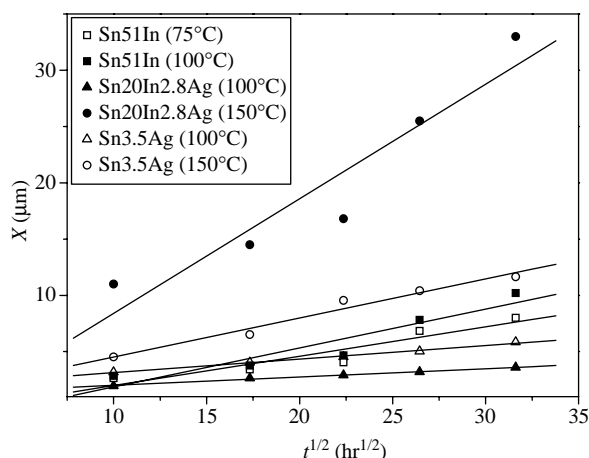


Fig. 7 Growth thickness (X) of the intermetallic compound η -IMC during the aging of the Sn-51In solder BGA packages with immersion Ag surface finish versus the square root of time ($t^{1/2}$). For comparison, the results of Sn-3.5Ag and Sn-20In-2.8Ag specimens measured in the prior studies (Chi and Chuang, 2006; Jain et al. 2008) are given

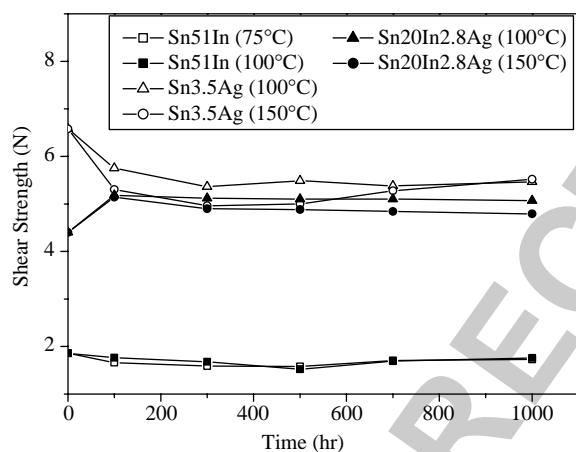


Fig. 8 The ball shear strengths of the Sn-51In solder joints with immersion Ag surface finish versus aging conditions. For comparison, the results of Sn-3.5Ag and Sn-20In-2.8Ag packages measured in prior studies (Chi and Chuang, 2006; Jain et al. 2008) are given

IV. CONCLUSIONS

After the reflow of Sn-51In solder balls with immersion Ag surface finishes in ball grid array (BGA) packages, the Ag thin film has dissolved completely and caused the formation of scallop-shaped $(\text{Cu}_{0.89}\text{Ag}_{0.11})(\text{In}_{0.79}\text{Sn}_{0.21})_2$ intermetallics ahead of a continuous η - $\text{Cu}_6(\text{Sn}_{0.54}\text{In}_{0.46})_5$ intermetallic layer at the interfaces between the solder balls and Cu pads. The occurrence of ε - Cu_3Sn phase, which is harmful to the reliability of solder joints on Cu pads, has been inhibited in this case through the use of the immersion Ag surface finish. Kinetics analyses reveal that the growth of η -intermetallic compounds in Sn-51In

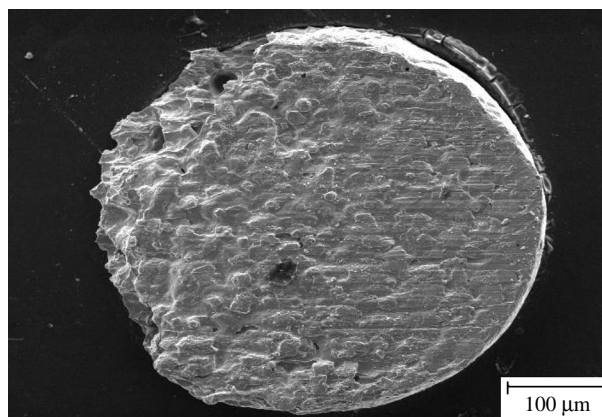


Fig. 9 Fractography of the as-reflow Sn-51In solder joints in BGA packages with immersion Ag surface finish after ball shear test

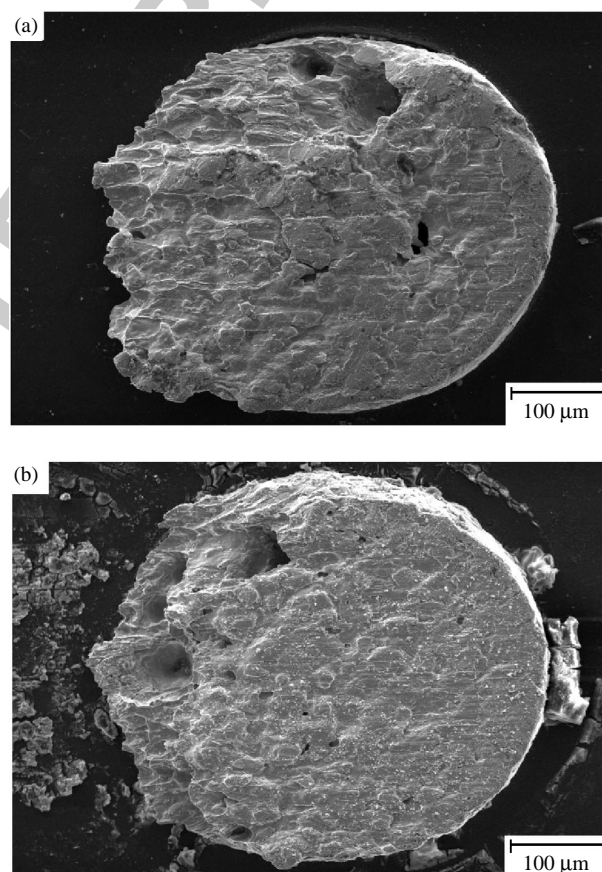


Fig. 10 Fractography of the aged Sn-51In solder joints in BGA packages with immersion Ag surface finish after ball shear tests: (a) 100°C, 100 hr, (b) 100°C, 1000 hr

packages with Ag/Cu pads follows a linear relation, indicating that the reactions are diffusion-controlled. The ball shear strengths of Sn-51In solder joints decline slightly from 1.9 N (reflowed) to 1.7 N and 1.6 N during aging at 75°C and 100°C, respectively.

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