Reflow and Burn-in of a Sn-20In-0.8Cu Ball Grid Array Package with a Au/Ni/Cu Pad

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The intermetallic compounds formed after reflow and burn-in testing of a Sn-20In-0.8Cu solder ball grid array (BGA) package are investigated. Along with the formation of the $Cu_6(Sn_{0.78}In_{0.22})_5$ precipitates (IM1) in the solder matrix, scallop-shaped intermetallic compounds (IM2) with a compositional mixture of $Cu_6(Sn_{0.87}In_{0.13})_5$ and $Ni_3(Sn_{0.87}In_{0.13})_4$ appear at the interfaces between the solder balls and Au/Ni/Cu pads. A significant number of intermetallic particles (IM3), with a composition of $(Au_{0.80}Cu_{0.20})(In_{0.33}Sn_{0.67})_2$, can also be found in the solder matrix. After aging at 115°C for 750 h, an additional intermetallic compound layer (IM4) with a composition of $(Ni_{0.91}Cu_{0.09})_3(Sn_{0.77}In_{0.23})_2$ is formed at the interface between IM2 and the Ni layer. The ball shear strength of the Sn-20In-0.8Cu BGA solder after reflow is 4.5 N and will rise to maximum values after aging at 75°C and 115°C for 100 h. With a further increase of the aging time at both temperatures, the joint strengths exhibit a tendency to decline linearly at about 1.7×10^{-3} N/h.

Key words: Sn-20In-0.8Cu solder, Au/Ni/Cu pads, ball grid array packages, reflow, burn-in

INTRODUCTION

The Au/Ni/Cu metallization layers have been widely applied to ball grid array (BGA) packaging.[1,2] For flip-chip assembly in advanced packaging, a Au/Ni/Cu structure has been used as the wetting layer of the under-bump metallurgy system.[3,4] However, Au normally reacts with the Sn-based solder and generates a continuous brittle $(Au,Ni)Sn_4$ phase at the solder/pad interface, and this continuous intermetallic compound can reduce the interface shear strength and lead to the embrittlement of the solder joints.[5]

Eutectic Sn-0.9Cu solder is one of the popular Pb-free solders because of its advantages of low cost, high shear strength, good creep resistance, and longer thermal fatigue life.[6,7] However, the high melting point of this alloy (227°C) in comparison with the traditional eutectic Sn-37Pb solder (183°C) impedes its applicability in electronic packaging. In Wang's study of the interfacial reactions between the Sn-0.9Cu eutectic solder and Au/Ni/Cu metallization layer in BGA packaging,[8] $(Cu,Au,Ni)_6Sn_5$ and $(Au,Ni)Sn_4$ intermetallic compounds were found in the solder matrix after reflow. After aging at a temperature of 150°C and over a longer time (>700 h), a continuous layer of the $(Cu,Au,Ni)_6Sn_5$ intermetallic compound formed at the interface, resulting in the degradation of the solder joints.[8]

The element indium has been commonly used to lower the melting temperatures of solders. Also, the addition of indium into solders has been shown to improve upon their wettability, ductility, and fatigue resistance.[9,10] Furthermore, an indium-containing solder has been found to form a Au dissolution barrier, $AuIn_2$, at the solder/pad interface, thereby preventing the formation of the brittle $AuSn_4$ phase in the solder matrix.[11] Lee reported that Au-embrittlement failure in advanced packaging could be curtailed for In-Sn solder joints because of the lower solubility of Au in the In-Sn alloy.[12] By virtue of these merits, the eutectic In-49Sn solder has also been considered as one of the candidates for Pb-free solders. However, its high indium content is notably expensive, narrowing its industrial applications down to cases where production costs are of a

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lesser concern. A compromise may be reached by consolidating the features of Sn-0.9Cu and In-49Sn alloys with the Sn-20In-0.8Cu solder instead as a promising substitute for the traditional Sn-37Pb solder. The effort of this study is, therefore, concerned with the characterization of intermetallic compounds formed at the interfaces between liquid Sn-20In-0.8Cu and Au/Ni/Cu pads during reflow and burn-in testing of the BGA packages under various conditions.

EXPERIMENTAL

The BGA packages in this study used a silicon dummy die (with a size of 4.5 mm × 4.5 mm × 0.25 mm) attached to a BT-resin substrate and encapsulated in a molding compound. Each package was fitted with 49 Cu pads electroplated with 5-μm-thick Ni and 0.5-μm-thick Au. The geometry of such BGA specimens is presented elsewhere.[13] The Sn-20In-0.8Cu (wt.%) solder balls of 0.4 mm in diameter were dipped in rosin mildly activated-type flux, placed on the Au/Ni/Cu pads, and reflowed in a hot air furnace with a capacity of five heating zones. Differential scanning calorimetry analysis showed that the Sn-20In-0.8Cu solder had solidus and liquidus temperatures at 168.3°C and 185.4°C, respectively. The reflow temperature profile for the BGA specimens was taken, as shown by Fig. 1, where the soaking temperature and peak temperature were fixed at 160°C and 226°C, respectively. Certain specimens were subjected to burn-in tests at 75°C and 115°C for durations varying from 100 h to 1,000 h.

For the metallographic study, the specimens were cross-sectioned through a row of solder balls, ground with 1,500 grit SiC paper, and polished with 0.3-μm Al_2O_3 powder. The intermetallic compounds formed after reflow and burn-in tests were examined in a scanning electron microscope (SEM), and their chemical composition was analyzed using an energy dispersive spectrometer (EDX). The bonding strengths of Sn-20In-0.8Cu solder balls on Au/Ni/Cu pads under various conditions 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). The fractography of the solder joints after ball shear tests was conducted by SEM.

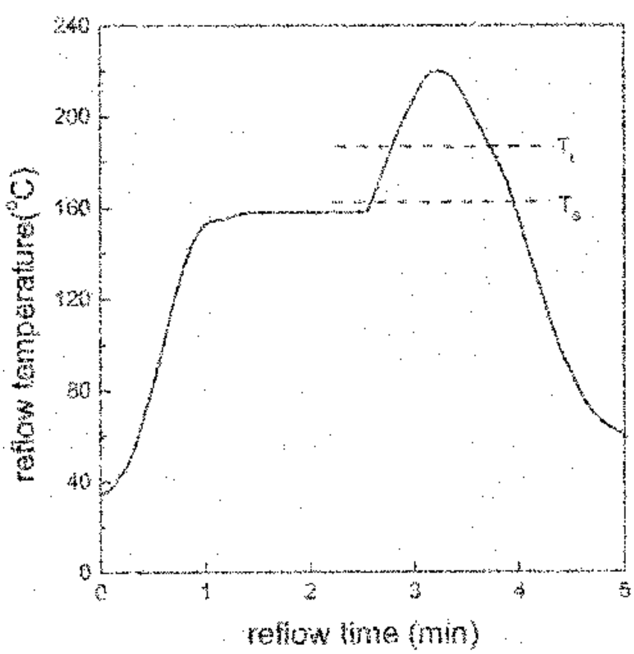

Fig. 1. Temperature profile for the reflow of Sn-20In-0.8Cu solder BGA packages used in this study (T_L: liquidus and T_S: solidus of solder).

RESULTS AND DISCUSSION

The microstructure of the Sn-20In-0.8Cu solder was found to contain island-shaped precipitates (in gray) embedded in the Sn-rich matrix, as shown in Fig. 2. The EDX analysis indicates that the composition (at.%) of these island precipitates is Cu:Sn:In = 54.25:35.47:10.28, which corresponds to the $Cu_6(Sn_{0.78}In_{0.22})_5$ phase (IM1). The formation of such $Cu_6(Sn_{0.78}In_{0.22})_5$ precipitates induces the composition (wt.%) of the solder matrix to deviate from Sn-20In-0.8Cu to Sn-21.68In-0.58Cu.

After reflow, scallop-shaped intermetallic compounds (IM2) appear at the interfaces between Sn-20In-0.8Cu solder balls and Au/Ni/Cu pads, as shown in Fig. 3. The composition (at.%) of the intermetallic compound is Cu:Ni:Sn:In = 41.86:8.41:43.04:6.69. It has been reported that the soldering reactions of liquid Sn with Cu and Ni substrates result in the formation of intermetallic compounds Cu_6Sn_5 and Ni_3Sn_4, respectively, at the $Sn_{(l)}$/Cu and $Sn_{(l)}$/Ni interfaces.[14,15] The composition of interfacial intermetallic compounds in Fig. 3 can be separated into two sets: 41.86Cu-38.52(Sn,In) + 8.41Ni-11.21(Sn,In), which corresponds exactly to a mixture of $0.83[Cu_6(Sn_{0.87}In_{0.13})_5]$ and $0.17[Ni_3(Sn_{0.87}In_{0.13})_4]$. It can also be seen in Fig. 3 that the $Cu_6(Sn_{0.78}In_{0.22})_5$ intermetallic compound (IM1) accumulates in large quantities in the vicinity of the interfacial intermetallic compound (IM2), while the IM1 precipitates in the solder matrix have been, by contrast, dwindling in number. The results indicate that the

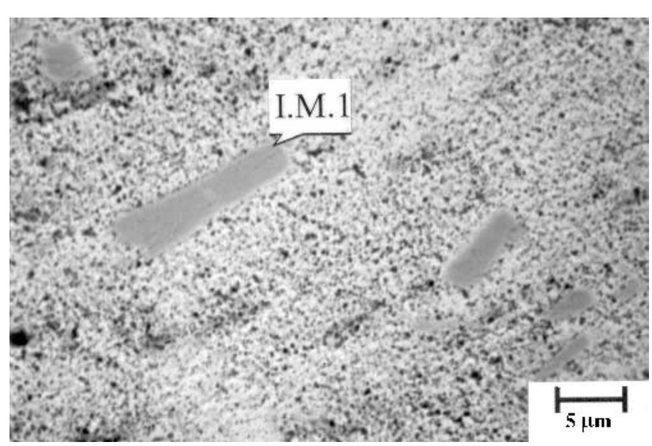

Fig. 2. Microstructure of Sn-20In-0.8Cu BGA solder specimens used in this study.

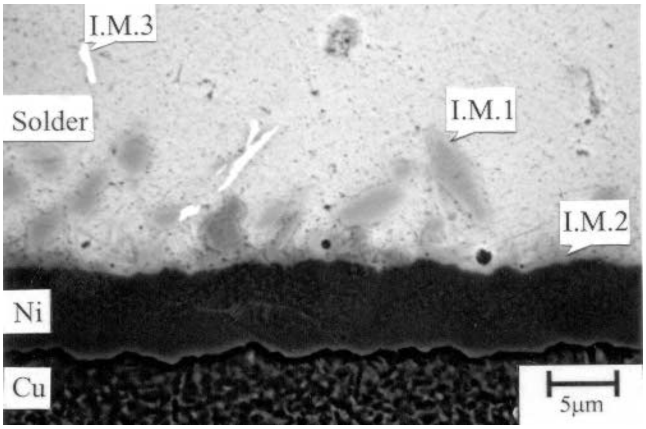

Fig. 3. Typical morphology of intermetallic compounds formed after reflowing the Sn-20In-0.8Cu solder balls on Au/Ni/Cu pads. IM1: $Cu_6(Sn_{0.78}In_{0.22})_5$ and IM2: $Cu_6(Sn_{0.87}In_{0.13})_5$ and $Ni_3(Sn_{0.87}In_{0.13})_4$.

$Cu_6(Sn_{0.78}In_{0.22})_5$ compound has been migrating from the solder matrix to the interface and participating in the soldering reaction between liquid Sn-20In-0.8Cu and Ni.

In addition to the original $Cu_6(Sn_{0.78}In_{0.22})_5$ precipitates, a large number of new intermetallic particles (white areas) can also be found in the solder ball matrix (Fig. 3). The EDX analysis shows that the composition (at.%) of these precipitates (IM3) is Au:Cu:Sn:In = 27.43:6.87:44.30:21.41, which corresponds to the $(Au_{0.80}Cu_{0.20})(In_{0.33}Sn_{0.67})_2$ phase. The appearance of such an intermetallic compound is attributed to the dissolution of the Au film and its ensuing reaction with the Sn-20In-0.8Cu solder. For the solid-state reaction between the Pb-Sn solder and the Au substrate, a $AuSn_4$ interfacial intermetallic compound was reported by Hannech and Hall.[16] In contrast, a cubic $AuIn_2$ intermetallic compound was found in our previous research[13] during the reflow of the In-49Sn solder on Au/Ni/Cu pads from 140°C to 220°C, a result similar to what Shohji et al. reported earlier in their study of the solid/solid interfacial reaction between the In-49Sn solder and the Au substrate.[17] A conclusion may be drawn from the formation of $(Au_{0.80}Cu_{0.20})(In_{0.33}Sn_{0.67})_2$ intermetallic compounds in the Sn-20In-0.8Cu solder matrix after reflow that, for the In-contained solders, it is the In/Au reaction that predominates the Sn/Au reaction.

After aging at 75°C and 115°C for 100–700 h, the scallop-shaped interfacial intermetallic compounds become thicker, as shown by Fig. 4, and grows into the solder matrix with an increase of aging temperature and time. Accompanied with the growth of the intermetallic compound (IM2) at the interface, the amount of $Cu_6(Sn_{0.78}In_{0.22})_5$ intermetallic compound (IM1) in the solder matrix decreases, as shown by Fig. 5. After aging at 115°C for 700 h, an additional thin, intermetallic compound layer (IM4) is formed at the interface between IM2 and the Ni layer (Fig. 4f). The EDX analysis identifies the composition of the newly appeared intermetallic compound as Ni:Cu:Sn:In = 53.93:5.47:31.38:9.22, which corresponds to the $(Ni_{0.91}Cu_{0.09})_3(Sn_{0.77}In_{0.23})_2$ phase. During the aging treatment, the Sn and In elements in the solder react mainly with the previously appeared intermetallic compounds (IM2). The insufficient supply of Sn and In to the IM2/Ni interface results in the composition $Ni_3(Sn_{0.87}In_{0.13})_4$ in IM2, reacting partially with the Ni layer: $(Ni,Cu)_3(Sn,In)_4 + Ni \rightarrow (Ni,Cu)_3(Sn,In)_2$.

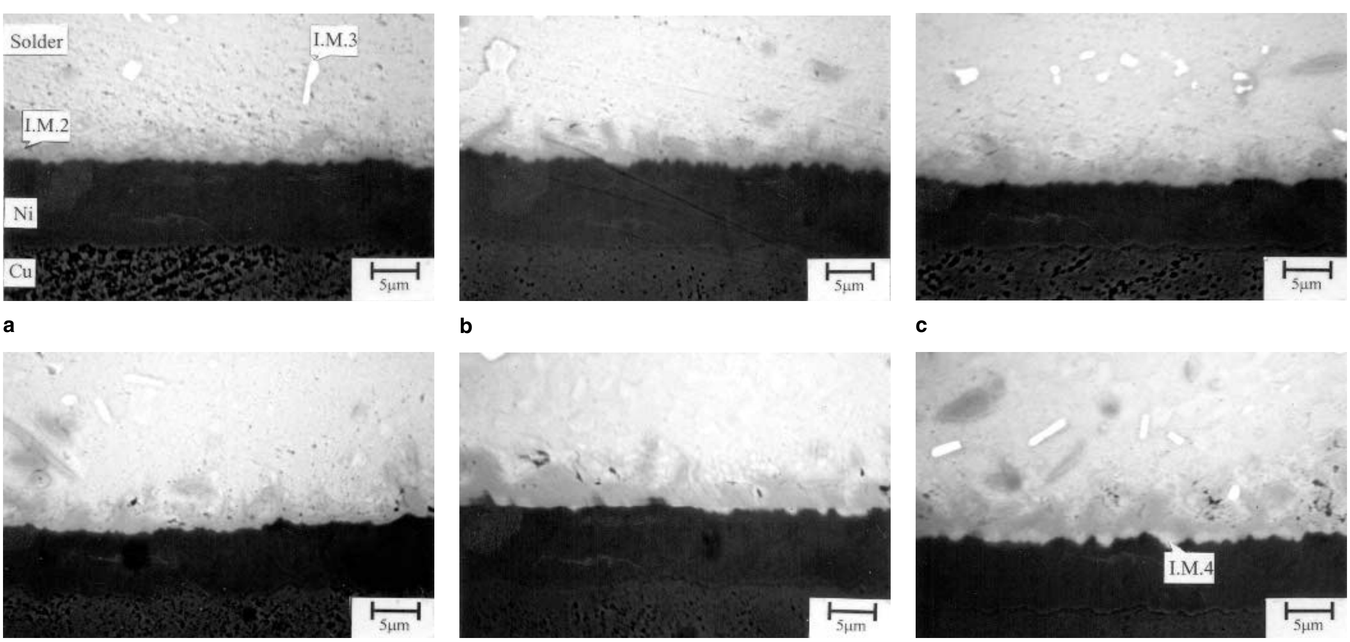

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Fig. 4. Morphology of intermetallic compounds formed after burn-in tests of the Sn-20In-0.8Cu BGA solder specimens under various aging conditions: (a) 75°C, 100 h; (b) 75°C, 300 h; (c) 75°C, 700 h; (d) 115°C, 100 h; (e) 115°C, 300 h; and (f) 115°C, 700 h. IM3: $(Au_{0.80}Cu_{0.20})(In_{0.33}Sn_{0.67})_2$.

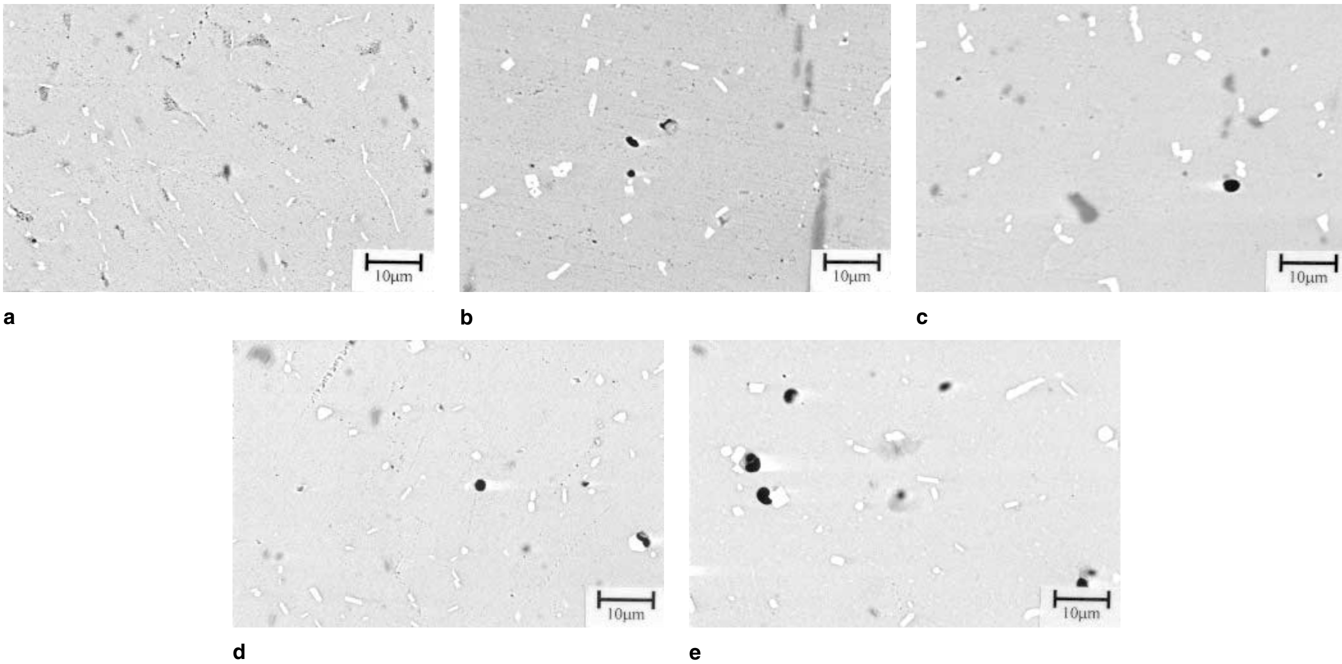

Fig. 5. Morphology of intermetallic compounds formed in the solder matrix of Sn-20In-0.8Cu BGA specimens after reflow and burn-in testing: (a) as reflowed; (b) 75°C, 100 h; (c) 75°C, 500 h; (d) 115°C, 100 h; and (e) 115°C, 500 h.

Table I and Fig. 6 provide the ball shear test results of the Sn-20In-0.8Cu BGA specimens after reflow and burn-in under various conditions. The as-reflowed solder joints possess a strength of 4.5 N, which is about 50% higher than the In-49Sn BGA solder as found in a previous study.[13] After aging at 75°C and 115°C for 100 h, the strengths rise to 5.6 N and 4.8 N, respectively. With further increasing the aging time at both burn-in temperatures, the ball shear strengths tend to decline linearly at about 1.7×10^{-3} N/h. Yet, after aging at 75°C and 115°C for 1,000 h, the strengths drop to 4.2 N and 3.2 N, respectively.

Fractography was performed on the specimens after ball shear tests, as shown in Fig. 7. The Sn-20In-0.8Cu solder BGA, having been subjected to reflow and a long aging period at 115°C, fractures along the pad regions, while the other aged specimens fracture in the solder balls. Corresponding to the fractography in Fig. 7a for the as-reflowed specimens, the composition of the fracture surface is Cu:Ni:Sn:In = 29.33:43.35:21.97:5.35, with a mixture of the compositions of the IM2 intermetallic compound and the Ni layer, i.e., $Cu_6(Sn_{0.87}In_{0.13})_5 + Ni_3(Sn_{0.87}In_{0.13})_4 + Ni$. The results indicate that the fracture of the as-reflowed Sn-20In-0.8Cu BGA specimens initiates in and propagates through the interfacial, intermetallic compound IM2. Because the intermetallic compound IM2 formed after reflow is thinner than 1 μm (Fig. 3), the Ni layer beneath is partially exposed on the fracture surface after ball shear testing. The lower strength of the as-reflowed

Table I. Ball Shear Strengths of the Sn-20In-0.8Cu BGA Packages under Various Aging Conditions

	Ball Shear Strength (N)	
Aging Time (h)	**75°C**	**115°C**
100	5.6	4.7
300	5.1	4.1
500	4.5	3.7
700	4.5	3.7
1,000	4.2	3.2

The as-reflowed strength is 4.5 N.

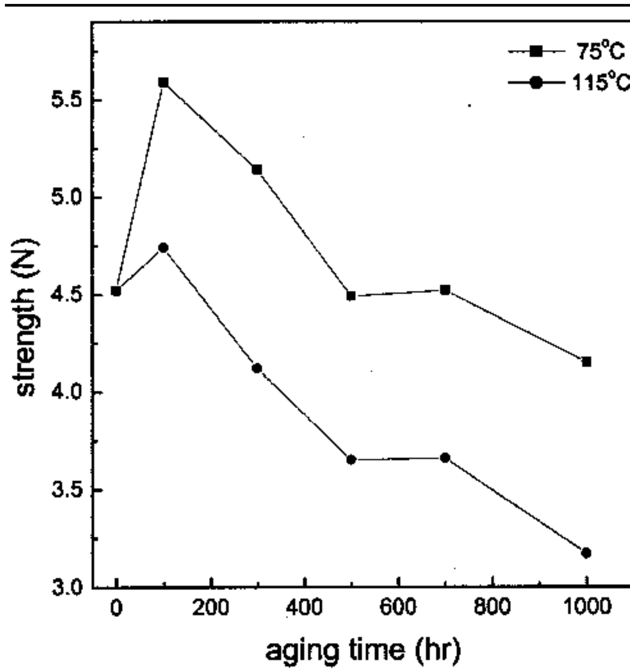

Fig. 6. Ball shear strengths of the Sn-20In-0.8Cu BGA packages under various aging conditions.

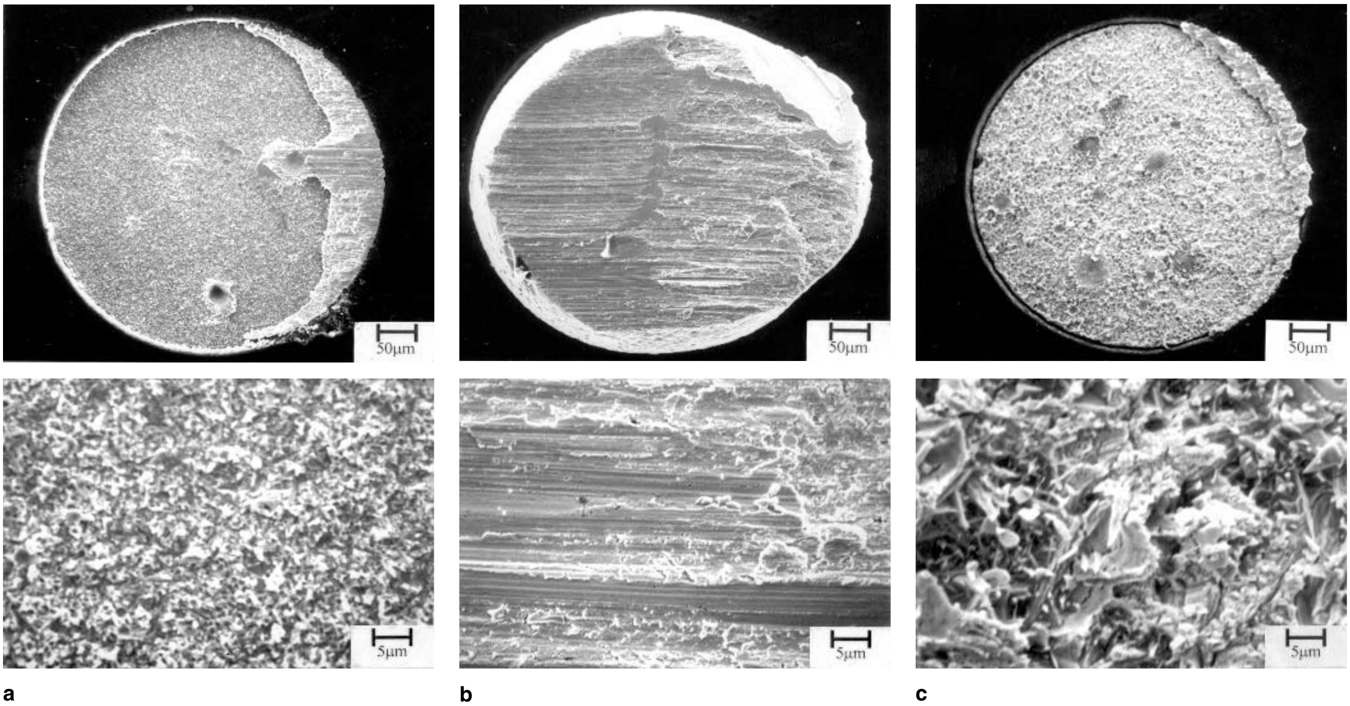

Fig. 7. Fractography of Sn-20In-0.8Cu solder joints in BGA packages used in this study after ball shear testing: (a) after reflow; (b) 75°C aging, 1,000 h; and (c) 115°C aging, 1,000 h.

specimens (Fig. 6) should be attributed to the incomplete reaction between the Sn-20In-0.8Cu solder and the Au/Ni/Cu pads.

After aging at 75°C or 115°C for durations longer than 100 h, the ball/pad interfacial strength can be counted on to increase higher than the solder strength through the formation of an adequate intermetallic layer at the interfaces between Sn-20 In-0.8Cu solders and Au/Ni/Cu pads. The location of fracture in the specimens is in the solder ball (Fig. 7b). However, as Fig. 5 indicates, accompanying the growth of the interfacial intermetallic compound (IM2), the amounts of $Cu_6(Sn_{0.78}In_{0.22})_5$ precipitates (IM1) in the solder matrix decrease with an increase of aging time, and the resultant decline of the precipitation hardening effect in the Sn-20In-0.8Cu solder ball, in turn, leads to the ebbing of the shear strength (Fig. 6). After prolonged aging at 115°C, the composition of the fracture surface as analyzed is Cu:Ni:Sn:In = 26.73:15.55:48.47:9.25, which in all likelihood is a mixture of the compositions of IM2 and IM4 intermetallic compounds, i.e., $Cu_6(Sn_{0.87}In_{0.13})_5$ + $Ni_3(Sn_{0.87}In_{0.13})_4$ + $(Ni_{0.91}Cu_{0.09})_3(Sn_{0.77}In_{0.23})_2$. The result implies that fracture occurs in the specimens where IM2 and IM4 are overlapped. The brittle nature of the $(Ni_{0.91}Cu_{0.09})_3(Sn_{0.77}In_{0.23})_2$ intermetallic compound should be responsible for the low strength given by Fig. 6.

CONCLUSIONS

During the reflow process of the Sn-20In-0.8Cu BGA packages, $Cu_6(Sn_{0.78}In_{0.22})_5$ intermetallic compounds (IM1) precipitate in the solder matrix, and interfacial reactions occur between the liquid Sn-20In-0.8Cu solder balls and the Au/Ni/Cu pads. The SEM observations and EDX analyses indicate that the scallop-shaped intermetallic compounds (IM2) formed at the interfaces have a compositional mixture of $Cu_6(Sn_{0.87}In_{0.13})_5$ and $Ni_3(Sn_{0.87}In_{0.13})_4$. Accompanying the interfacial reactions, Au dissolves into the solder matrix to form intermetallic particles (IM3) with a composition of $(Au_{0.80}Cu_{0.20})(In_{0.33}Sn_{0.67})_2$. Burn-in tests run on Sn-20In-0.8Cu BGA specimens facilitate the growth of interfacial intermetallic compounds (IM2) and the reduction of $Cu_6(Sn_{0.78}In_{0.22})_5$ precipitates (IM1) in the solder matrix. After aging at 115°C for 750 h, the interfacial intermetallic compounds (IM2) react with the Ni layer of the BGA pads to form at the IM2/Ni interface a new intermetallic layer (IM4) with a composition of $(Ni_{0.91}Cu_{0.09})_3(Sn_{0.77}In_{0.23})_2$. After reflow, a ball shear strength of 4.5 N can be obtained, which increases to the maximal values of 5.6 N and 4.7 N after aging for 100 h at 75°C and 115°C, respectively. With further increments of aging time at both temperatures, the solder joint strengths decrease because of the decline of the hardening effect of the $Cu_6(Sn_{0.78}In_{0.22})_5$ precipitates in the solder matrix.

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