

Intermetallic Reactions in Sn-8Zn-20In Solder Ball Grid Array Packages with Au/Ni/Cu and Ag/Cu Pads

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During the reflow process of Sn-8Zn-20In solder joints in the ball grid array (BGA) packages with Au/Ni/Cu and Ag/Cu pads, the Au and Ag thin films react with liquid solder to form γ_3 -AuZn₄/ γ -Au₇Zn₁₈ and ϵ -AgZn₆ intermetallics, respectively. The γ_3/γ intermetallic layer is prone to floating away from the solder/Ni interface, and the appearance of any interfacial intermetallics cannot be observed in the Au/Ni surface finished Sn-8Zn-20In packages during further aging treatments at 75°C and 115°C. In contrast, ϵ -CuZn₅/ γ -Cu₅Zn₈ intermetallics are formed at the aged Sn-8Zn-20In/Cu interface of the immersion Ag BGA packages. Bonding strengths of 3.8N and 4.0N are found in the reflowed Sn-8Zn-20In solder joints with Au/Ni/Cu and Ag/Cu pads, respectively. Aging at 75°C and 115°C gives slight increases of ball shear strength for both cases.

Key words: Sn-8Zn-20In solder, intermetallic compounds, Au/Ni/Cu pad, Ag/Cu pad, ball shear strength

INTRODUCTION

Au/Ni metallization has been widely used for surface finishing of printed circuit boards.¹ The Au thin film can protect Cu pads from oxidation and promote the wettability of liquid solder during the reflow process. However, the Au/Ni surface finishing process is quite costly and complex. In addition, the Au film is apt to react with Sn-based solders to form AuSn₄ intermetallic compounds, leading to the embrittlement of the solder joints. Immersion silver is a viable alternative for the surface finishing of Cu pads. It cannot only provide immunity against Au embrittlement but also provide the advantages of lower cost and simpler operation.

Among a number of Pb-free solders, the Sn-Zn system possesses the merits of adequate melting temperature, low cost, high strength, and longer fatigue life.² However, the eutectic Sn-9Zn solder exhibits insufficient wettability and oxidation resistance. The addition of indium into solder alloys can improve the wettability and lower the melting point as well. The solidus temperatures of Sn9Zn10In and Sn9Zn50In alloys, as reported by McCormack and

Jin, are 178°C and 188°C, respectively, both lower than the melting points of eutectic Sn9Zn (199°C).^{3,4} Further investigations on the phase equilibria and thermodynamics properties of Sn-Zn-In and Sn-Zn-In-Bi have been conducted by Cui et al.⁵ and Yoon et al.⁶ This present study is concerned with the interfacial reactions of a Sn-8Zn-20In solder with Au/Ni/Cu and Ag/Cu pads in ball grid array (BGA) packages.

During the soldering reaction, the formation of intermetallic compounds that takes place at the interface allows for sound wetting and bonding. However, an overgrowth of interfacial intermetallics will cause embrittlement and cracking in the solder joints. During the reflow process of Sn-8Zn-20In solder BGA packages with Au/Ni and Ag surface finishes, the Au and Ag thin films dissolve rapidly into the molten solder matrix, resulting in interfacial reactions of liquid Sn-8Zn-20In with solid Ni and Cu in the Au/Ni/Cu and Ag/Cu pad structures, respectively. As indicated in published research, the intermetallic compounds formed during the Sn9Zn/Ni and Sn9Zn/Cu soldering reactions are Ni_{19.0}Zn_{80.0}Sn_{1.0} and Cu_{33.4}Zn_{66.5}Sn_{1.0}, respectively.⁷ Yoon et al. showed that a Cu₅Zn₈ intermetallic phase appeared at the interfaces between liquid Sn-

Zn-In-Bi solders and Cu substrates at the heating temperature of 240°C,⁶ while Shiue et al. aged a Sn9Zn15In solder joint on a Au/Ni-P deposited Cu substrate at 90°C for 168 h and reported an intermetallic compound of Zn-rich γ phase (NiZn_3) at the interface.⁸ In the present study, a Cu_5Zn_8 intermetallic compound appears in the immersion Ag surface-finished Sn-8Zn-20In BGA package. However, no trace of the NiZn_3 intermetallic, as reported by Shiue et al., is found in the Sn-8Zn-20In solder joints of BGA packages with Au/Ni/Cu pads.

EXPERIMENTAL PROCEDURES

For this study of interfacial reactions, Sn-8Zn-20In (wt.%) solder balls of 0.4-mm diameter were dipped in rosin mildly activated (RMA) flux, placed on the Au/Ni/Cu and Ag/Cu pads of various BGA packages, and reflowed in a hot-air furnace equipped with five heating zones. The reflow temperature profile is shown in Fig. 1; the soaking temperature and peak temperature were fixed at 169°C and 210°C, respectively. After reflow, a separate set of these specimens was further aged at 75°C and 115°C for durations varying from 100 to 1000 h.

The reflowed and aged specimens were cross-sectioned through a row of solder balls, ground with 1500 grit SiC paper, and polished with 0.3- μm Al_2O_3 powder. The morphology of intermetallic compounds formed in the solder joints was observed using a scanning electron microscope (SEM), and their chemical compositions were analyzed with energy-dispersive x-ray spectrometry (EDX). The bonding strengths of the Sn-8Zn-20In solder joints under various conditions were measured via ball shear testing. The measurements were taken at a shear rate of 0.1 mm/s 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 examined by SEM.

RESULTS AND DISCUSSION

The microstructure of the as-cast Sn-8Zn-20In solder is shown in Fig. 2. A large amount of needle-shape Zn-rich precipitates (shown in black) are seen embedded in the β -Sn matrix (shown in gray). The

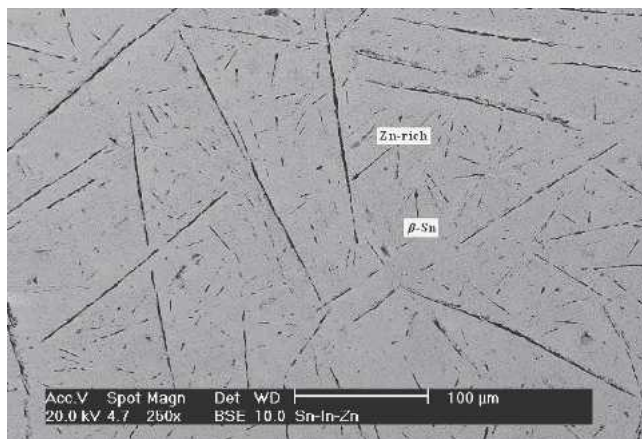


Fig. 1. Microstructure of the as-cast Sn-8Zn-20In solder.

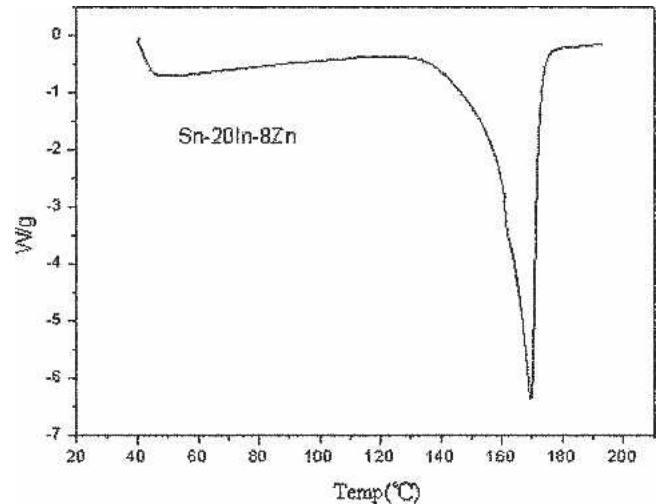


Fig. 2. DSC curve of the Sn-8Zn-20In solder.

element indium is found to have dissolved in the β -Sn solder matrix. The DSC analysis shows that the Sn-8Zn-20In solder possesses solidus and liquidus temperatures (T_S , T_L) of 156.2 and 171.2, respectively, as shown in Fig. 3.

After reflow, a planar double layer of intermetallic compounds can be observed to have formed at the interface between the Sn-8Zn-20In solder and the Au/Ni/Cu pad (Fig. 4). It can also be seen in Fig. 4 that part of the intermetallic layer has floated away from the interface. The EDX analysis shows that the composition (at.%) of the outer intermetallic layer (shown in dark) is Au:Zn = 19.2:80.8, which corresponds to the γ_3 phase (AuZn_4) in the Au-Zn equilibrium diagram. The inner layer (in gray) of the interfacial intermetallics has the composition Au:Zn = 28.4:71.5, which corresponds to the γ phase ($\text{Au}_7\text{Zn}_{18}$). Although the Au thin film has dissolved and reacted with the liquid Sn-8Zn-20In solder in contact with the Ni/Cu pad, no Ni-Zn intermetallic compound can be found in Fig. 4.

In the case of the Sn-8Zn-20In BGA solder joints with Ag/Cu pads, the interfacial intermetallics ap-

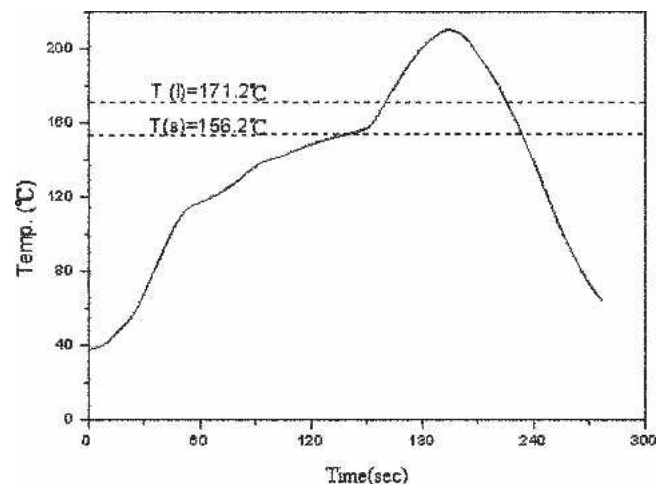


Fig. 3. Temperature profile for the reflow operation of Sn-8Zn-20In solder BGA packages in this study.

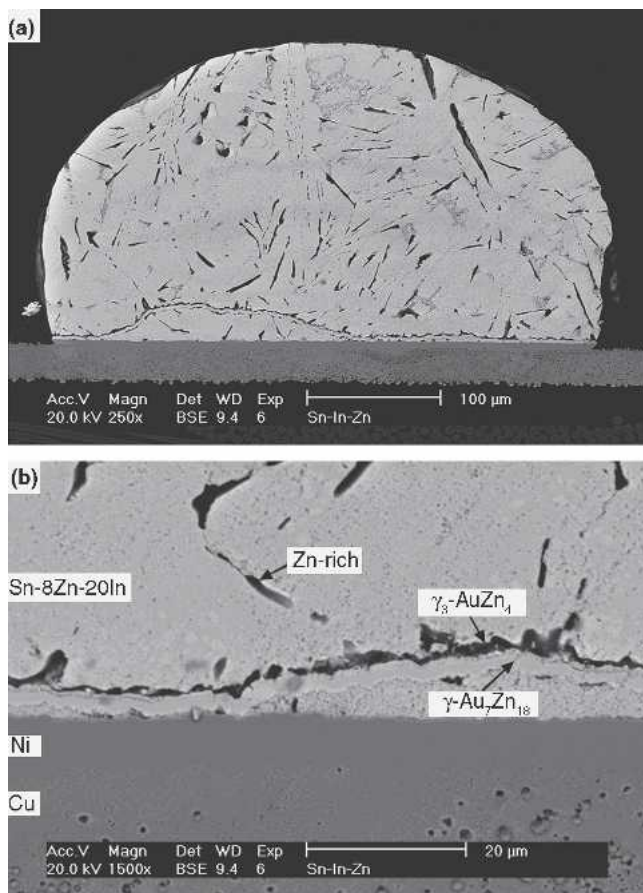


Fig. 4. Morphology of intermetallic compounds formed after the reflow of Sn-8Zn-20In solder BGA package with Au/Ni/Cu pads.

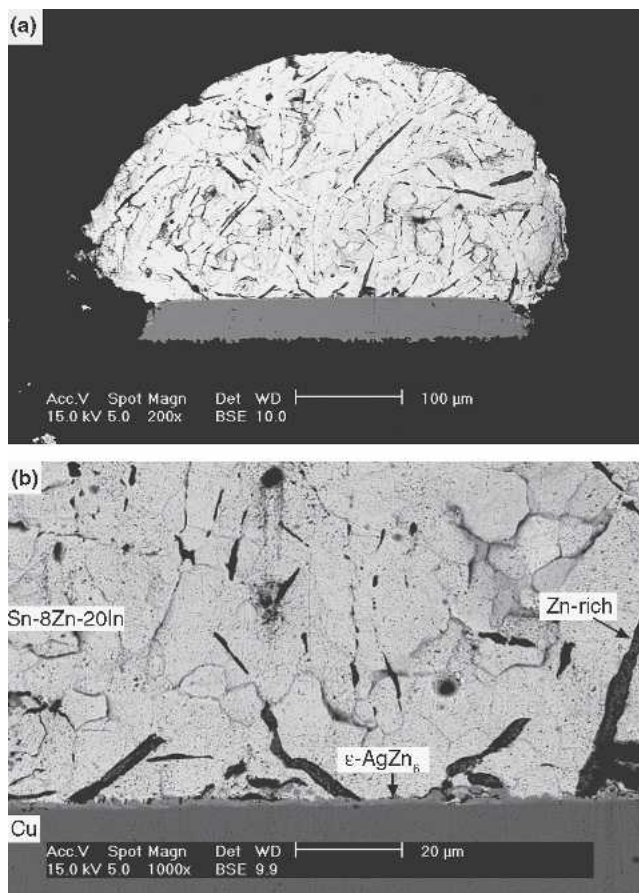


Fig. 5. Morphology of intermetallic compounds formed after the reflow of Sn-8Zn-20In solder BGA package with Ag/Cu pads.

pear as a thin layer of scallops. The composition (at.%), as analyzed by EDX, is Ag:Zn = 14.4:85.6, which corresponds to the ϵ phase (AgZn_6) in the Ag-Zn equilibrium diagram. Similar to the case of the Au/Ni surface finish, the liquid Sn-8Zn-20In solder does not react further with the Cu pads after the exhaustion of the Ag thin film. When Fig. 4a and Fig. 5a are compared, it can be found that the reflowed ball height for the case of the Ag/Cu pad is greater than that for the Au/Ni/Cu pad. The more vigorous collapse of the solder balls on the Au/Ni/Cu pads may be attributed to the rapid formation and migration of the γ_3/γ intermetallic layer.

Figure 6 shows the morphology of intermetallic compounds in Sn-8Zn-20In solder joints with Au/Ni/Cu pads after aging at 75°C for various time periods. It can be seen that the thickness of $\gamma\text{-Au}_7\text{Zn}_{18}$ intermetallics (gray, inner layer) decreases slightly, while the outer $\gamma_3\text{-AuZn}_4$ intermetallic layer (dark) grows noticeably with the increase of aging time. Accompanied by the growth of $\gamma_3\text{-AuZn}_4$, the γ_3/γ intermetallic double layer migrates toward the solder matrix. As evidenced by Fig. 6b, the needle-shaped Zn-rich precipitates in the Sn-8Zn-20In solder matrix join with the γ_3/γ intermetallic layer, resulting in the growth of the $\gamma_3\text{-AuZn}_4$ phase. Figure 6 also reveals that the swept region of the solder matrix behind the migrated γ_3/γ intermetallic layer

has been swept cleaned of Zn-rich precipitates. The remaining $\beta\text{-Sn}$ matrix contains only small amounts of Zn atoms, which might also react with the Ni/Cu pad to form Ni-Zn intermetallic compounds ($\text{Ni}_4\text{Zn}_{21}$ phase) at the solder/Ni interface, as reported, in a Sn-9Zn solder BGA packages with Au/Ni surface finish after aging at 150°C.⁹ However, the Zn content in the remaining $\beta\text{-Sn}$ matrix of the present Sn-8Zn-20In solder packages and the aging temperature are too low to result in an intermetallic thickness to be observed at the interface. In that case of Sn-9Zn packages,⁹ the interfacial Ni-Zn intermetallics were also absent at the low aging temperature of 100°C. For Sn-8Zn-20In solder joints with Au/Ni/Cu pads, aging at 115°C results in a much more rapid growth of the $\gamma_3\text{-AuZn}_4$ phase, as shown in Fig. 7. With the increase of aging time at 115°C, breakage occurs at certain locations in the inner $\gamma\text{-Au}_7\text{Zn}_{18}$ layer, which causes the γ_3 phase to grow across the γ phase to the inner side of the intermetallic layer. Similar to the case with 75°C aging, the Ni-In intermetallic compounds cannot be observed at the $\beta\text{-Sn}$ solder/Ni interface after aging at 115°C.

In the case of the Sn-8Zn-20In BGA specimens with Ag/Cu pads, their intermetallic reaction after aging is quite different from what is shown in Figs. 6 and 7 for the solder joints with Au/Ni/Cu pads. Figure 8 indicates that the thin layer of $\epsilon\text{-AgZn}_6$

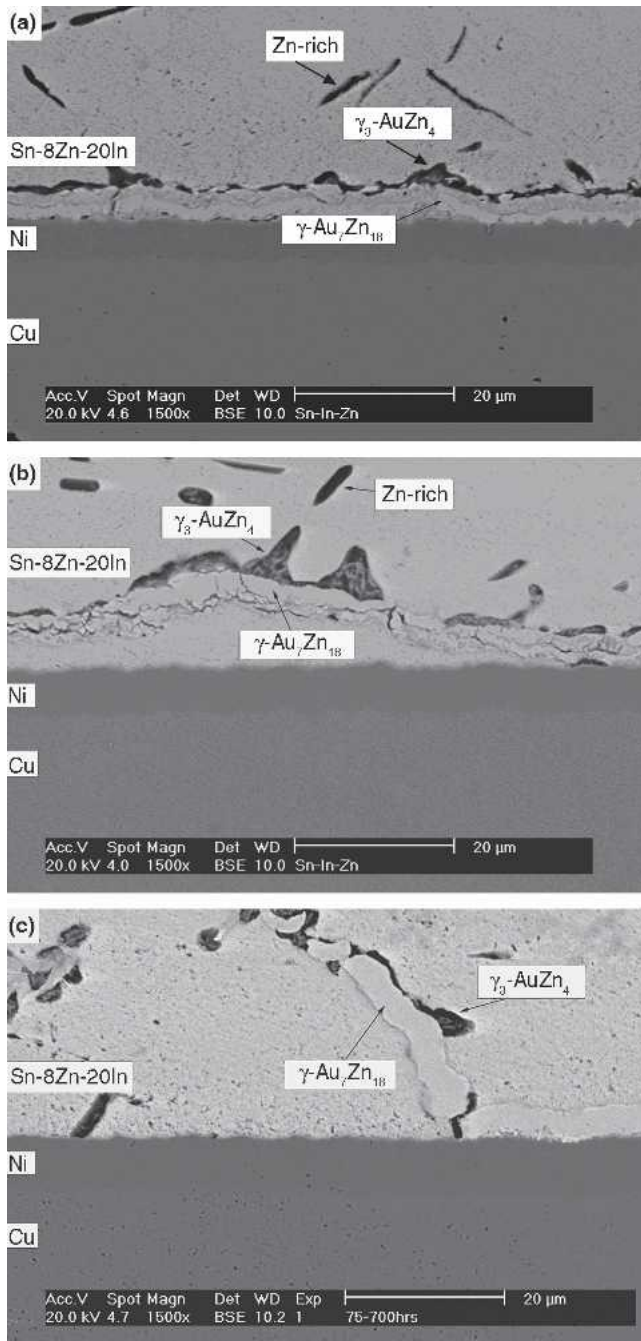


Fig. 6. Morphology of intermetallic compounds formed in Sn-8Zn-20In solder BGA packages with Au/Ni/Cu pads after aging at 75°C for various times: (a) 100 h, (b) 300 h, and (c) 1000 h.

intermetallic scallops formed at the as-reflowed interface vanishes after aging at 75°C for time periods longer than 300 h. Accompanied with the disappearance of ϵ -AgZn₆ intermetallics at the interface, formation of an intermetallic double layer takes place as the Sn-8Zn-20In solder reacts with the Cu pad. The thicker inner layer, as analyzed by EDX, has a composition (at.%) of Cu:Zn = 37.7:62.3, which corresponds to the γ -Cu₅Zn₈ phase in the Cu-Zn equilibrium diagram. In addition, a thin layer of intermetallic scallops can be observed ahead of the γ -Cu₅Zn₈ phase. The EDX analysis indicates that the compo-

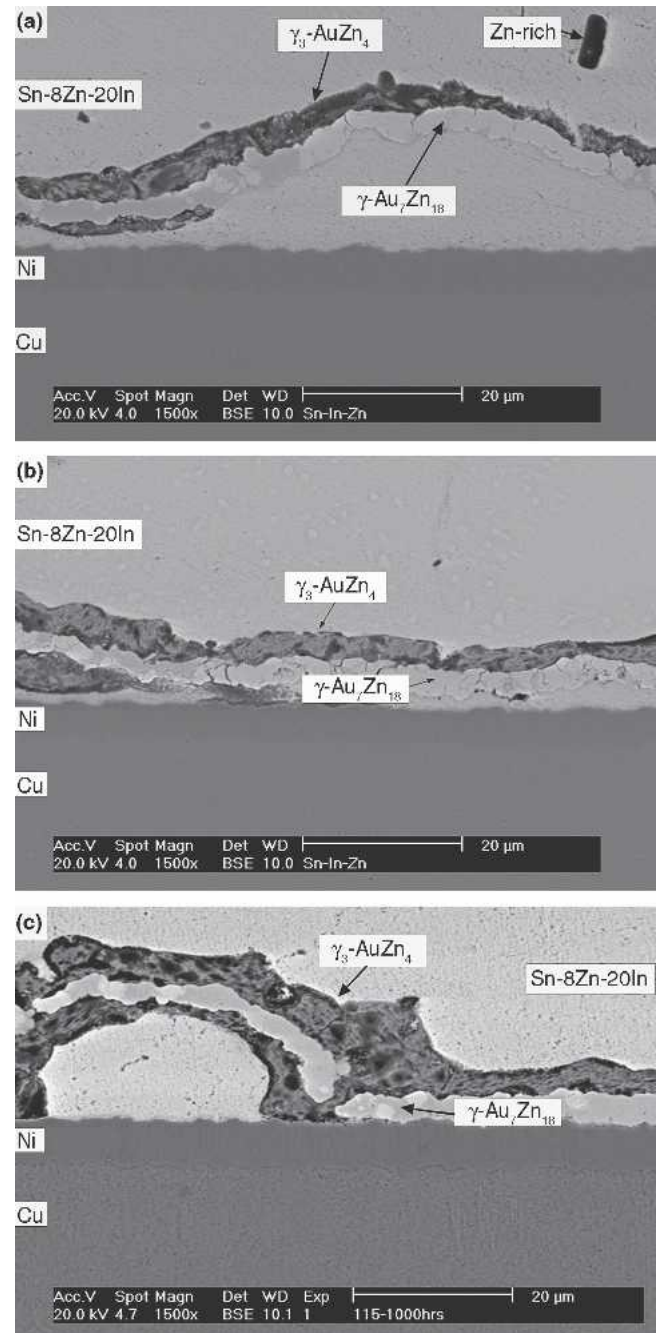


Fig. 7. Morphology of intermetallic compounds formed in Sn-8Zn-20In solder BGA packages with Au/Ni/Cu pads after aging at 115°C for various times: (a) 100 h, (b) 300 h, and (c) 1000 h.

sition of the scallop-shaped intermetallic thin layer is Cu:Zn = 19.1:80.9, which corresponds to the ϵ -CuZn₄ phase in the Cu-Zn equilibrium diagram. From Figs. 8 and 9, it can also be seen that the ϵ -CuZn₄ intermetallic scallops are replaced by the γ -Cu₅Zn₈ thick layer with the increase of aging time and temperature. The γ -Cu₅Zn₈ intermetallic layer grows even further as the time is increased. Along with the growth of γ -Cu₅Zn₈ intermetallic compounds at the interface, the needle-shaped Zn-rich precipitates in the Sn-8Zn-20In solder matrix decrease in quantity, as shown in Figs. 8 and 9.

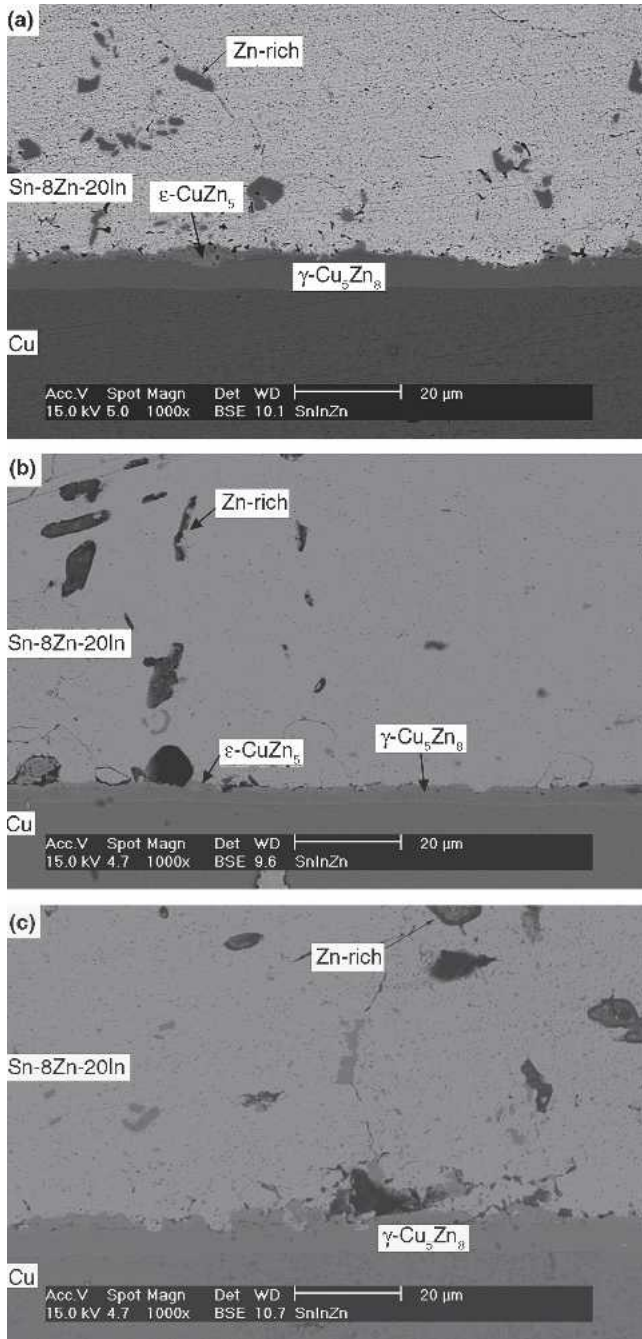


Fig. 8. Morphology of intermetallic compounds formed in Sn-8Zn-20In solder BGA packages with Ag/Cu pads after aging at 75°C for various times: (a) 100 h, (b) 300 h, and (c) 1000 h.

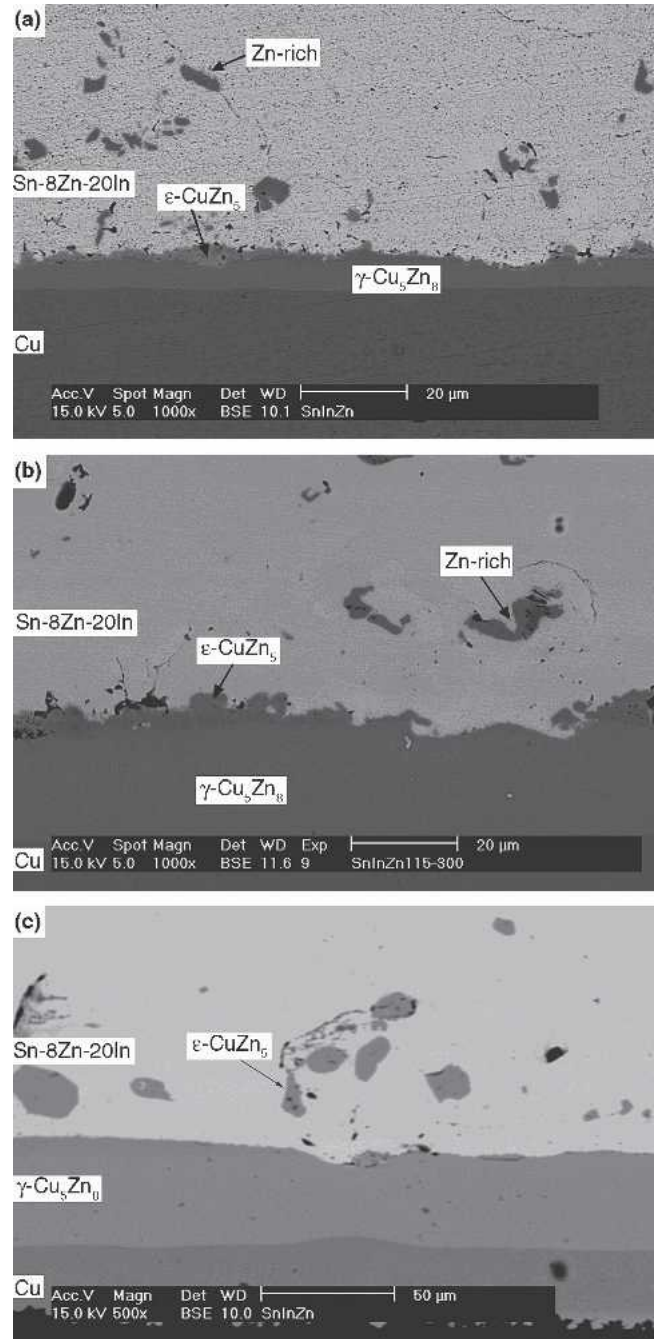


Fig. 9. Morphology of intermetallic compounds formed in Sn-8Zn-20In solder BGA packages with Ag/Cu pads after aging at 115°C for various times: (a) 100 h, (b) 300 h, and (c) 1000 h.

Ball shear tests for the as-reflowed Sn-8Zn-20In solder joints with Au/Ni/Cu pads show a bonding strength of 3.8 N, which increases slightly to about 4.5 N after aging at 75°C for various time periods (Table I and Fig. 10). At the aging temperature of 115°C, their ball shear strengths increase to about 4.0 N for the time periods of 100 h to 700 h and then drop to 3.5 N after a prolonged aging time of 1000 h. After ball shear tests, the as-reflowed and aged solder joints reveal ductile fractures across the solder balls, as shown in Fig. 11. It is evidenced that the

material strength of Sn-8Zn-20In solder is lower than the solder/pad interfacial strength.

The as-reflowed Sn-8Zn-20In solder joints with Ag/Cu pads possess the ball shear strength of 4.0 N, which increases to about 5.2 N after aging at 75°C for 300 h and 500 h and then decreases to 4.4 N for aging times longer than 700 h, as shown in Fig. 12 and Table I. Aging at 115°C shows a tendency of ball shear strength similar to that for 75°C aging. The fractography of solder joints after ball shear tests also reveals ductile characteristics, as shown in

Table I. Ball Shear Strengths of the Sn-8Zn-20In Solder BGA Packages with Au/Ni/Cu and Ag/Cu Pads after Various Aging Treatments

Aging Time (h)	Au/Ni/Cu Pads		Ag/Cu Pads	
	75°C	115°C	75°C	115°C
0 (as reflowed)	3.8	3.8	4.0	4.0
100	4.2	3.9	4.2	4.9
300	4.6	4.0	5.1	5.2
500	4.3	4.1	5.4	5.0
700	4.5	4.1	4.3	4.4
1000	4.9	3.5	4.4	4.5

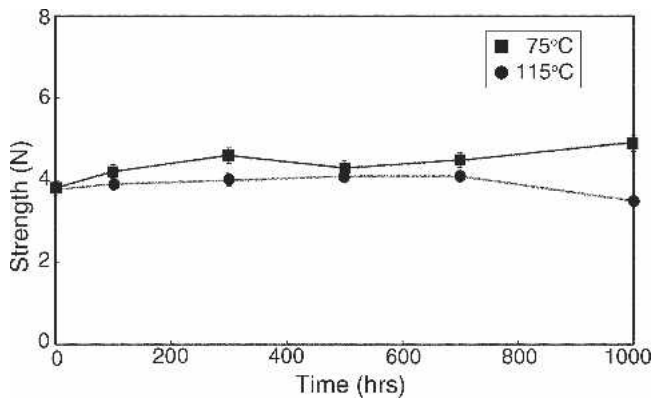


Fig. 10. Ball shear strengths of the Sn-8Zn-20In BGA packages with Au/Ni/Cu pads.

Fig. 11. In comparison with the immersion Ag solder joints, the relatively lower strength of the Sn-8Zn-20In solder joints with Au/Ni/Cu pads may be correlated with the inhomogeneous microstructure of the latter due to migration of the γ_3/γ intermetallic layer into the solder matrix. The interfacial ε -CuZn₅/ γ -CuZn₈ intermetallics in the immersion Ag solder joints have induced no effect on the ball shear strengths due to the weaker Sn-8Zn-20In solder matrix. For most Sn-based solders, the element Ag is the dissolver that can aid in the formation of Ag₃Sn particles in the solder, which will certainly strengthen the solder matrix. Yet, such a strengthening effect does not occur in Sn-8Zn-20In solder joints with the immersion Ag surface finish, as the formation of scallop-type ε -AgZn₆ intermetallics at the solder/pad interface predominates over the dispersion of Ag₃Sn precipitates in the solder matrix.

CONCLUSIONS

The intermetallic reactions of Sn-8Zn-20In solder BGA packages with Au/Cu/Ni and Ag/Cu pads are investigated. After reflow, the Au thin film on the Au/Ni surface finish reacts rapidly with the Sn-8Zn-20In solder to form a γ_3 -AuZn₄/ γ -Au₇Zn₁₈ intermetallic double layer. The γ_3/γ intermetallic layer tends to float away from the solder/pad interface. During aging at 75°C and 115°C, the γ_3 phase grows rapidly with the dissolution of Zn-rich precipitates in the solder matrix. However, the interfacial Ni-Zn intermetallics reported in the Au/Ni surface finished Sn-9Zn packages after aging at 150°C might be too

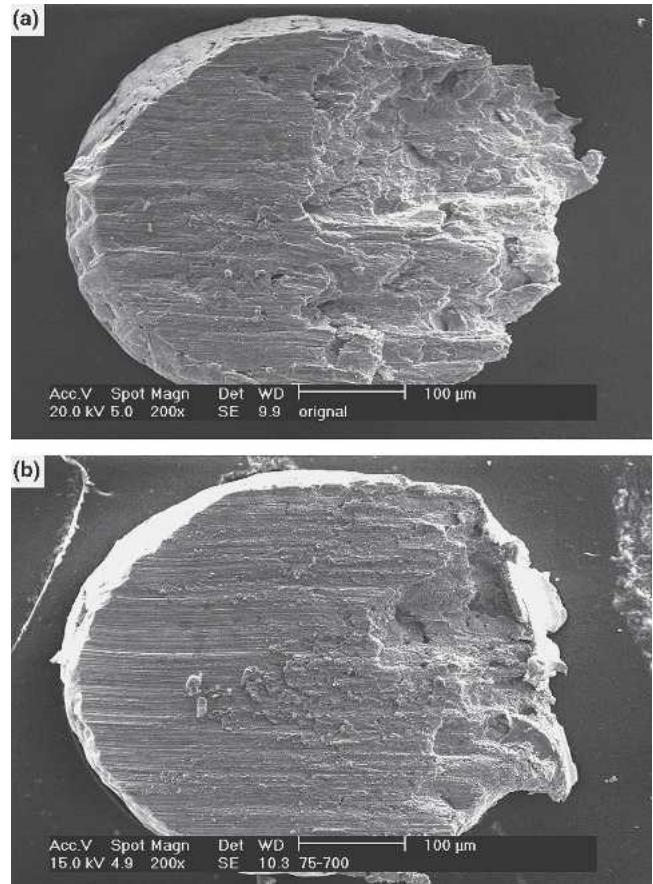


Fig. 11. Typical fractography of solder joints in Sn-8Zn-20In packages with Au/Ni/Cu pads after ball shear tests: (a) as-reflowed and (b) aging at 75°C for 700 h.

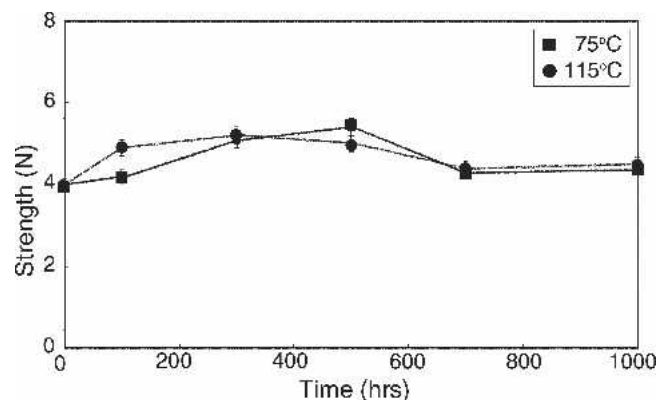


Fig. 12. Ball shear strengths of the Sn-8Zn-20In BGA packages with Ag/Cu pads.

thin to be observed in the present Sn-8Zn-20In solder joints aged at 75°C and 115°C. In the case of the immersion Ag surface-finished Sn-8Zn-20In solder joints, a thin layer of ε -AgZn₆ intermetallic scallops is formed at the interface after reflow. With further aging at 75°C and 115°C, the ε -AgZn₆ intermetallics disappear, and a ε -CuZn₅/ γ -Cu₅Zn₈ double layer is formed at the solder/Cu interface. Increase of aging time causes γ -Cu₅Zn₈ to grow. The inhomogeneous microstructure in the Au/Ni surface-finished Sn-8Zn-20In solder joints results in lower strengths af-

ter reflow and aging as compared to those of the immersion Ag solder joints.

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