Reliability of In-48Sn Solder/Au/Ni/Cu BGA Packages during Reflow Process

JA-MYEONG KOO[1] and SEUNG-BOO JUNG[1,2]

1.—Department of Advanced Materials Engineering, Sungkyunkwan University, Suwon 440-746, Korea. 2.—E-mail: sbjung@skku.ac.kr

The interfacial reactions and shear properties of In-48wt.%Sn/Au/Ni/Cu solder joints were investigated in terms of reflow conditions, i.e., reflow temperature and duration time. The thickness of an $AuIn_2$ intermetallic compound (IMC) layer, formed at the solder/substrate interface, slightly increased with the duration time. The spalling of the $AuIn_2$ intermetallics in the solder led to the formation of a $Ni_3(Sn,In)_4$ IMC layer between the solder and exposed Ni layer. The longer duration time resulted in the spalling and grain growth of $Ni_3(Sn,In)_4$ intermetallics. The higher reflow temperature accelerated the interfacial reactions between the solder and substrate. From the ball shear test results, the formation and growth of a continuous plate-shaped $AuIn_2$ IMC layer increased the shear force of the solder joints, whereas the spalling and grain growth of cubic-shaped $AuIn_2$ intermetallics significantly decreased the shear force. The formation and spalling of cubic-shaped $Ni_3(Sn,In)_4$ intermetallics increased the shear force, whereas the spalling and grain growth of polyhedron-shaped $Ni_3(Sn,In)_4$ intermetallics decreased the shear force. The crack propagated at the Au-rich/$AuIn_2$/solder interface in the initial reflow stage, then toward the $AuIn_2$ intermetallics dispersed in the solder matrix, and finally along the $Ni_3(Sn,In)_4$ intermetallics spalling off in the solder.

Key words: In-48Sn solder, electrolytic Au/Ni/Cu, ball grid array (BGA), intermetallic compound (IMC), interfacial reactions, ball shear test

INTRODUCTION

The electronics industry is one of the most fascinating, dynamic, and important industries. One of the key technologies used to produce these products involves electronics packaging and assembly technology.[1] Eutectic and near-eutectic tin-lead (Sn-Pb) solders have been used extensively as joining materials for the interconnections between electronic components and a PCB board, due to their low-cost, good wettability, and suitable mechanical properties.[2] Recently, however, the industry is researching lead-free solders in an effort to replace Pb-containing solders for environmental reasons.[2–8] Moreover, the tremendous market potential for "green" products means that there is a strong motivation to develop Pb-free solders.[9] In these respects, the eutectic In-Sn (In-48wt.%Sn) solder alloy is considered a Pb-free solder ball material for ball-type packages due to its numerous advantages, such as its very low melting point, great ductility, long fatigue life, and good wettability on Au, Ni, and Cu substrates.[5–8,10–12] The solder alloy is particularly attractive for use in systems that require low-temperature processing, such as opto-electronic devices, and for the last step in sequential soldering operations.[6]

One of the major concerns in ball-type packages is the mechanical reliability of solder joints.[13] During the soldering process, the formation and growth of brittle intermetallic compounds (IMCs) between a solder ball and substrate is inevitable. The formation of a thin IMC layer results in a good metallurgical bond, whereas the formation and excessive growth of IMCs leads to stress concentrations and

(Received March 15, 2005; accepted August 8, 2005)

stress discontinuities at the bonded interface induced by mismatch of the elastic modulus as well as the brittleness of the IMCs, thus weakening the solder joints. Therefore, it is necessary to understand the interfacial reactions between the solder and substrate, and their effects on the mechanical reliability of the solder joints.

Electrolytic Au/Ni/Cu metallization is a popular pad structure used in ball grid array (BGA) packages, due to the excellent wettability and oxidation resistability of the Au layer and the predominant diffusion barrier property of the Ni layer between the solder and Cu substrate.[11] Shohji et al. reported that $AuIn_2$ IMC and Sn-rich γ ($InSn_4$) layers were formed at the In-48wt.%Sn/Au interface aged at 343 K to 383 K for 1000 h.[10] Huang et al. reported that a Ni_3Sn_4 IMC layer was formed at the In-48wt.%Sn/Ni interface reflowed at both 433 K and 513 K.[12] Chuang et al. investigated the interfacial reactions between the In-49wt.%Sn solder and Au/Ni/Cu BGA substrate during the reflow process, but found that the microstructural evolutions did not affect the shear properties of the solder joints.[11] However, the research into the interfacial reactions and/or mechanical reliability of In-48Sn/Au/Ni/Cu solder joints is still at the infancy stage. Therefore, this study was concerned with the interfacial reactions between In-48Sn solders and electrolytic Au/Ni/Cu substrates during the reflow process under various reflow conditions. In addition, the effects of the interfacial reactions on the shear properties of the solder joints were discussed.

EXPERIMENTAL PROCEDURES

The solder ball used in this study was an In-48Sn (in wt.%) solder sphere having a diameter of 500 μm (Indium Corporation of America). The substrate was a bismaleimide triazine (BT)–laminated BGA substrate with a thickness of 520 μm. The solder bonding pad was designed as a solder mask defined (SMD) type with a pad opening of 460 μm in diameter, a pad pitch of 1 mm in length, and a solder mask (or side wall) of 20 μm in thickness. The pads consisted of electroplated Au (0.7 μm)/Ni (7 μm) over an underlying Cu (30 μm) pad.

The BGA substrates were cleaned using an ultrasonic cleaner and then dried with hot air. The solder balls were dipped into a rosin mildly activated (RMA) flux and placed on the pads of the BGA substrates. All of the specimens were preheated at 333 K for 30 sec before heating them up to the reflow temperature in order for the superficial and internal temperatures of the reflowed specimens to be almost homogenous. The joint position was heated to reflow temperatures of 403 K, 423 K, and 443 ± 3 K and kept at those temperatures for durations of 3 sec, 10 sec, 30 sec, 60 sec, 120 sec, 300 sec, 900 sec, 1800 sec, 3600 sec, and 7200 sec using a reflow machine (SAT-5100, Rhesca Co., Japan). After the reflow process, all of the specimens were air cooled. The soldering was carried out in a nitrogen atmosphere to prevent oxidation of the specimens during the reflow process. The oxygen concentration in the reflow furnace was measured using an oxygen analyzer ($MAXO_2$, MaxtecTM) and kept below 1000 ppm during the reflow process. The specimens were cleaned using an ultrasonic cleaner with a flux remover after the reflow process.

Upon completion of the reflow process, the specimens were mounted in cold epoxy, ground using 100-, 400-, 1,200-, 1,500-, and 2,000-grit SiC papers through a row of solder balls, and polished with 0.3 μm Al_2O_3 powder. The microstructures of the specimens were observed using a scanning electron microscope (SEM) in backscattered electron imaging mode (BEI). For more accurate observation of the microstructures, solder was selectively etched with an etching solution consisting of 80vol.%H_2O, 10vol.%HF, and 10vol.%H_2O_2. The chemical compositions of each phase were analyzed using both energy dispersive spectrometer (EDS) and electron probe micro-analyzer (EPMA).

The BT-substrate without the solder mask was prepared to identify the IMCs formed at the interface. For this purpose, the solder of the reflowed specimens was removed through selective etching after mechanical polishing. The morphology and chemical composition of the IMCs were observed and analyzed using SEM and EDS, respectively. The phase analysis of the IMCs was performed using XRD (x-ray diffractometer).

The ball shear test was carried out at a displacement rate of 200 μm/s with a probe height of 50 μm using a bonding tester (PTR-1000, Rhesca Co.), within 3,600 ± 300 sec after the reflow process, in order to minimize the influence of room temperature aging on the solder alloys. The experimental procedure used for the BGA ball shear tests corresponded to the JEDEC standard.[14] Before testing, the 5 kgf load cell used in this study was calibrated using a 1 kgf standard weight. Once the shear tests were completed, the cross-sections of the fractured specimens were analyzed using both SEM and EDS.

RESULTS AND DISCUSSION

In-48Sn solders and electrolytic Au/Ni/Cu-finished BGA substrates were bonded successfully in a nitrogen atmosphere under all of the reflow conditions. The average ball diameter and height of the solder balls, after the reflow process, were 546 μm and 346 μm, respectively.

Figure 1 shows the SEM micrographs and XRD analysis result of the IMCs formed at the In-48Sn/Au/Ni/Cu interface reflowed at a reflow temperature of 443 K for a duration time of 1800 sec. Two cubic-shaped IMCs exhibiting different sizes were observed. Based on the EPMA analysis results, the chemical compositions of a coarse-grained IMC, marked as A, and a fine-grained IMC, marked as B, were In-33.4at.%Au-5.1at.% and Sn-38.4at.%Ni-19.1at.%In, respectively. The In_3Sn, $InSn_4$, $AuIn_2$, and Ni_3Sn_4 phases were found in the XRD results, as

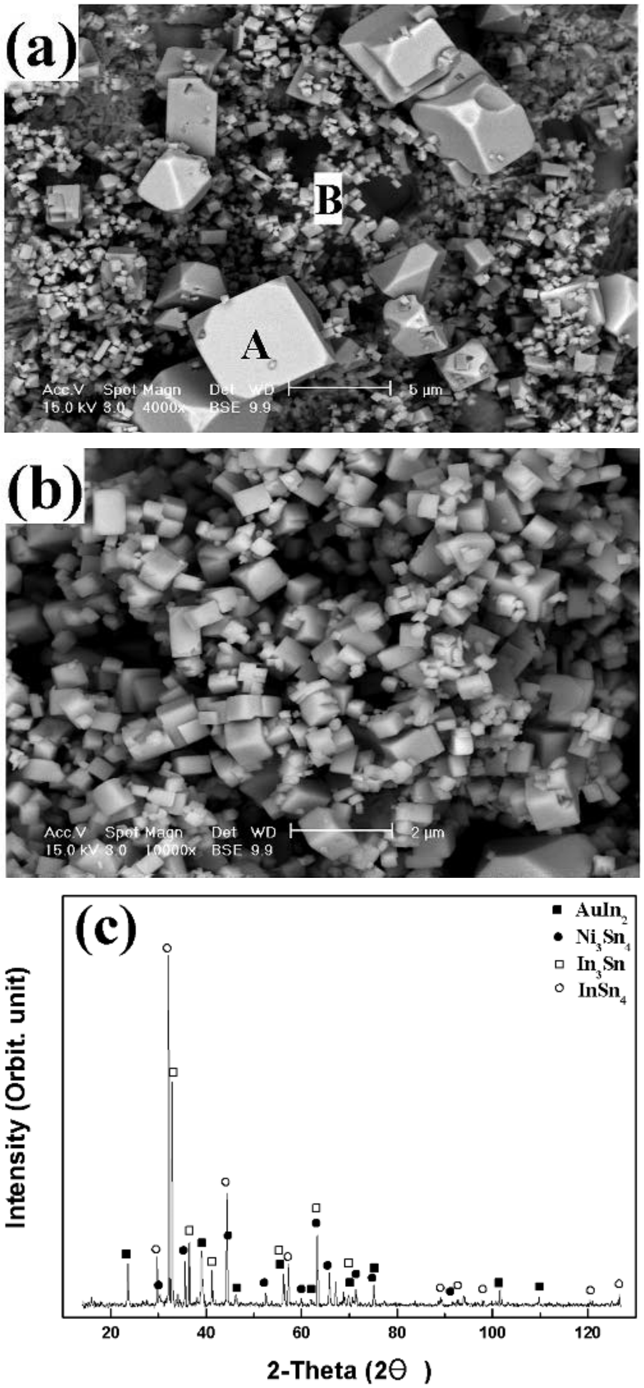

Fig. 1. SEM micrographs and XRD analysis result of the IMCs formed at the interface between the In-48Sn solder and Au/Ni/Cu substrate after being reflowed at 443 K for 1,800 sec: (b) is the magnified image of region B in (a).

shown in Fig. 1c. Based on the microstructure, EMPA, and XRD analysis results, the coarse-grained and fine-grained IMCs corresponded to the $AuIn_2$ and $Ni_3(Sn,In)_4$, respectively. These results were consistent with those in the previous studies.[10–12]

Figure 2 shows the SEM micrographs of the In-48Sn/Au/Ni/Cu interfaces reflowed at 403 K for various duration times. A continuous $AuIn_2$ IMC layer was formed at the solder/Au interface reflowed for 3 sec. As the duration time increased from 3 sec to 300 sec, most of the Au in the substrate was depleted, whereas the thickness of the $AuIn_2$ IMC layer increased from 0.57 μm to 1.33 μm. For the duration time of 900 sec, a reaction between Sn and In atoms penetrated through the boundaries among the $AuIn_2$ intermetallics and Ni layer led to the formation of $Ni_3(Sn, In)_4$ intermetallics, as shown in Fig. 2c. With the longer duration time, the $AuIn_2$ IMC layer continued to spall off of the substrate in the solder, while a continuous $Ni_3(Sn,In)_4$ IMC layer was formed between the solder and exposed Ni layer, as shown in Fig. 3d. Accordingly, the thickness of the $Ni_3(Sn,In)_4$ IMC layer was only 0.46 μm, although the reflow process was held for a duration of 7,200 sec.

The reflow temperature was further increased to evaluate the effects of reflow temperature on the interfacial reactions between the In-48Sn solder and Au/Ni/Cu substrate. Figure 3 shows the SEM micrographs of the In-48Sn/Au/Ni/Cu interfaces reflowed at 443 K for various duration times. After being reflowed for only 60 sec, the $AuIn_2$ IMC layer broke off and separated from the substrate, so that a thin $Ni_3(Sn,In)_4$ IMC layer partially formed at the interface, as shown in Fig. 3b. After the duration time of 1800 sec, fine-grained $Ni_3(Sn,In)_4$ as well as $AuIn_2$ intermetallics spalled off to the solder, as shown in Fig. 3c. With the longer duration time, more $Ni_3(Sn,In)_4$ intermetallics then spalled off above the solder/substrate interface, as shown in Fig. 3d. Accordingly, it appears that the higher reflow temperature accelerated the microstructural evolutions of the solder joints, i.e., growth and spalling of the IMCs formed at the solder/substrate interface.

The In-48Sn solder in the specimen was etched away after the reflow process to observe the morphology of the IMCs formed at the solder/substrate interface. Figure 4 shows the SEM micrographs of the IMCs retained at the interface after the reflow process at 443 K for various duration times. Only plate-shaped $AuIn_2$ intermetallics were observed at the interface after a duration time of 10 sec, as shown in Fig. 4a. The morphology of the plate-shaped intermetallics continued to change into the cubic shape as the duration time increased, as shown in Fig. 4b. Moreover, the longer duration resulted in the grain growth of cubic-shaped intermetallics, as shown in Fig. 4e. On the other hand, very fine cubic-shaped $Ni_3(Sn,In)_4$ intermetallics were observed at the solder/substrate interface after the duration time of 30 sec, as shown in Fig. 4c. The size of the fine-grained cubes remarkably increased with the duration time. Moreover, the morphology of the cubic-shaped intermetallics continued to change into polyhedron shape during the reflow processes over 3,600 sec, as shown in Fig. 4d. The amount and size of the polyhedrons were also found to increase with the duration time, as shown in Fig. 4e.

Figure 5 shows the SEM micrographs of the bulk solders reflowed at 443 K for 3 sec and 300 sec, respectively. Based on the EPMA analysis results,

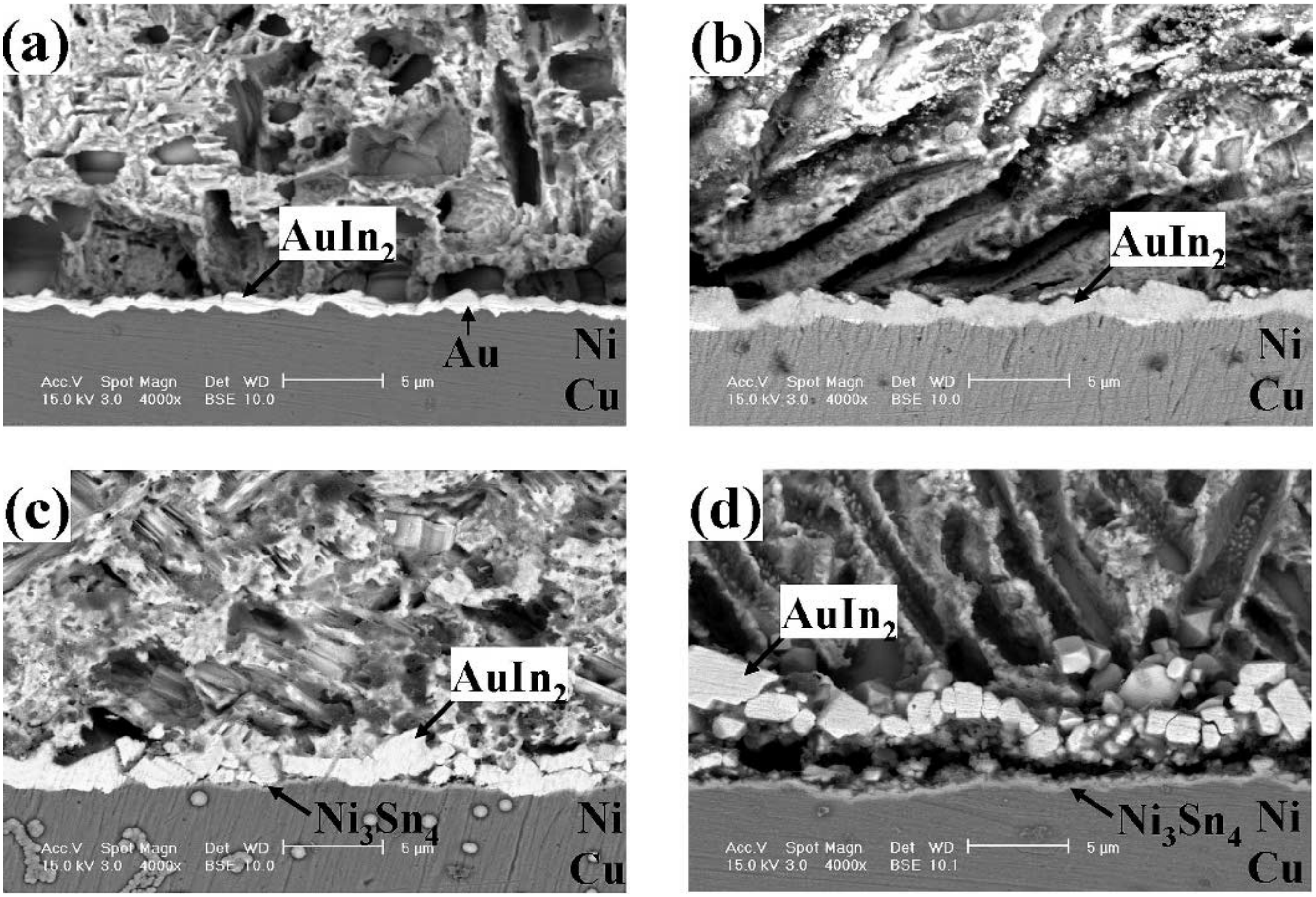

Fig. 2. SEM micrographs of the interface between the In-48Sn solder and Au/Ni/Cu substrate after the reflow process at 403 K for (a) 3 sec, (b) 300 sec, (c) 900 sec, and (d) 7,200 sec.

the bulk solder exhibited a lamellar structure consisting of β (In_3Sn) and γ ($InSn_4$) phases. The $AuIn_2$ intermetallics were observed in the bulk solder reflowed for only 3 sec, as shown in Fig. 5a, whereas coarse-grained $AuIn_2$ cubes which floated toward the top of the solder ball were observed after the reflow process over the duration time of 300 sec, as shown in Fig. 5b. These cubes might be formed by the spalling of $AuIn_2$ intermetallics from the substrate and/or the precipitating of Au dissolved in the solder during the reflow process due to the difference in the Au solubility in the solder between the reflow and room temperatures. On the other hand, no $Ni_3(Sn,In)_4$ IMC was observed in the bulk solder, whereas spalled $Ni_3(Sn,In)_4$ intermetallics were found just above the solder/substrate interface.

Figure 6 shows the shear force variations for In-48Sn/Au/Ni/Cu solder joints in terms of the reflow conditions (reflow temperature and duration time). The variations of the shear force were closely related to the reflow temperature and duration time, as shown in Fig. 6b, because the higher reflow temperature and longer duration time accelerated the microstructural evolutions of the solder joints, as stated above.

In the first reflow stage, the formation and growth of the plate-shaped $AuIn_2$ IMC layer at the solder/substrate interface increased the shear force of the solder joints with the duration time. In the second stage, however, the spalling and grain growth of the cubic-shaped $AuIn_2$ intermetallics at the interface decreased the shear force with the duration time. Moreover, the shear force indicated the minimum value when all of the $AuIn_2$ intermetallics spalled off above the solder/substrate interface and only a very thin continuous $Ni_3(Sn,In)_4$ IMC layer was formed at the interface. A reliable solder joint can be formed by a metallurgical reaction to produce stable IMCs at the molten solder/substrate interface.[15] Therefore, the breaking and spalling of the $AuIn_2$ IMC layer led to the drop in the shear force of the solder joints due to weakness of the joint interface.

In the third reflow stage, the formation and spalling of cubic-shaped $Ni_3(Sn,In)_4$ intermetallics increased the shear force, due to the dispersion hardening induced by the intermetallics spalling off in the solder. Moreover, the migration of the brittle $AuIn_2$ toward the top of the solder ball led to a decrease in the volume fraction of $AuIn_2$ just above the solder/substrate interface, increasing the shear force. In the final reflow stage, the excessive formation, spalling, and grain growth of polyhedron-shaped $Ni_3(Sn,In)_4$ intermetallics decreased the shear force.

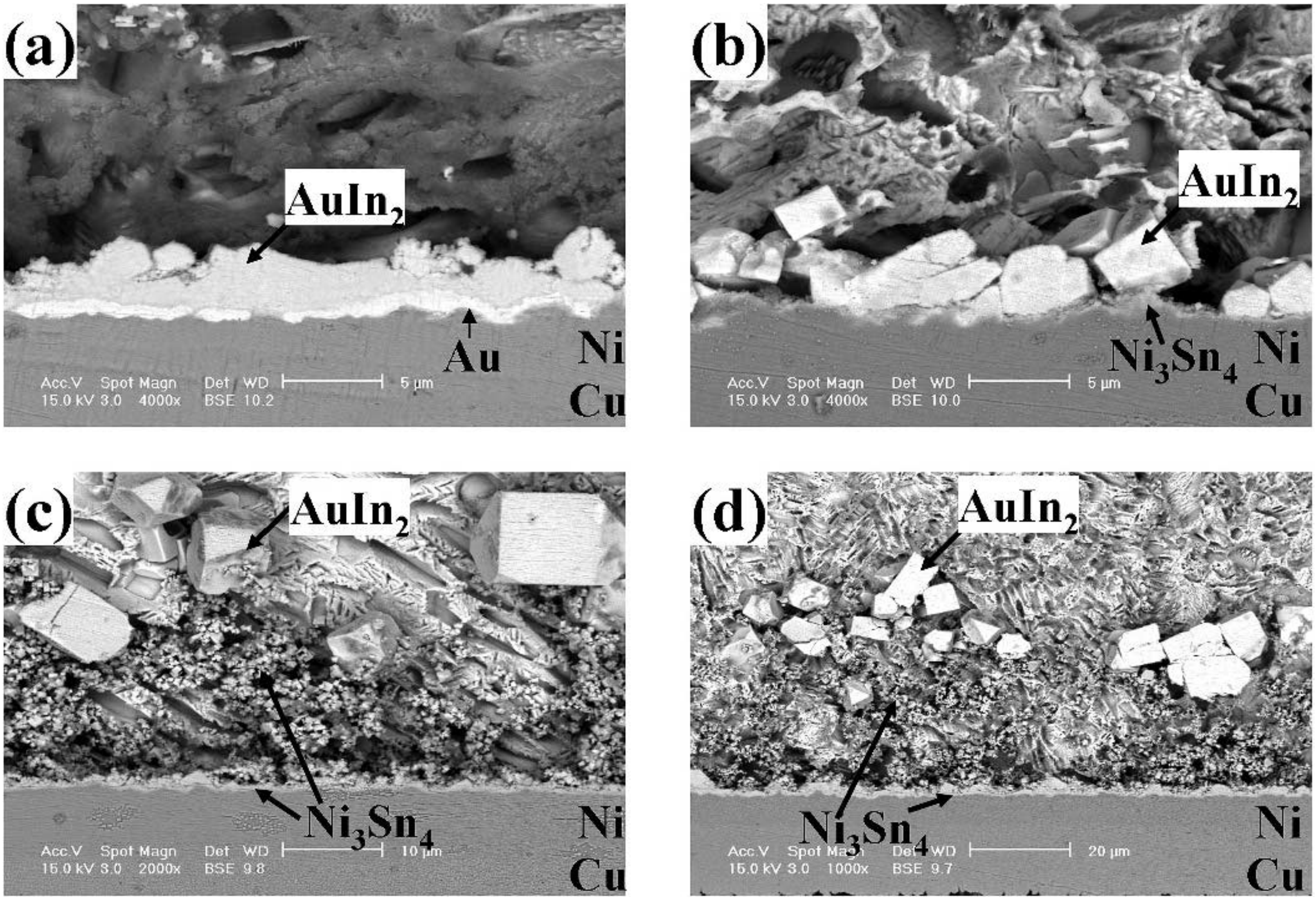

Fig. 3. SEM micrographs of the interface between the In-48Sn solder and Au/Ni/Cu substrate after the reflow process at 443 K for (a) 10 sec, (b) 60 sec, (c) 3,600 sec, and (d) 7,200 sec.

The grain growth and excessive formation of precipitates can decrease the mechanical properties of a material, because the excessive formation of reaction products generally leads to stress concentrations and stress discontinuities at the bonded interface induced by mismatch of the elastic modulus.[16] Accordingly, it is normal that the excessive formation, spalling, and transition of morphology of the $AuIn_2$ and $Ni_3(Sn,In)_4$ intermetallics played a key role in the mechanical reliabilities of the In-48Sn solder/Au/Ni/Cu BGA packages.

Figure 7 shows the cross-sectional views of the fractured specimens after the shear tests for the In-48Sn/Au/Ni/Cu solder joints in terms of the reflow conditions. The fracture of the specimen reflowed at 403 K for 3 sec, which was in the first stage in Fig. 6b, occurred at the Au/$AuIn_2$/solder interface. After the reflow process at 423 K for 1,800 sec, which was in the second stage in Fig. 6b, the fracture location shifted toward the $AuIn_2$ intermetallics dispersed in the solder matrix, not along the very thin $Ni_3(Sn,In)_4$ IMC layer. Therefore, it is reasonable that the spalled $AuIn_2$ intermetallics were obviously sensitive to external stress and provided sites of crack initiation and paths of propagation for cracks. Moreover, the side wall around the bonding pads supports the solder joints from external shear force.[17] Therefore, it is normal that the alteration of fracture locations decreased the ability to support the solder joints, decreasing the shear force. After the reflow process at 443 K for 7,200 sec, which was at the third and last stages in Fig. 6b, the fracture occurred along the $Ni_3(Sn,In)_4$ intermetallics dispersed in the solder matrix. It is normal that the alteration of the fracture locations would be significantly related to the variations of shear force for the solder joints with the reflow conditions.

CONCLUSIONS

In the present study, the interfacial reactions between the In-48Sn solders and electrolytic Au/Ni/Cu BGA substrates, and their effects on the shear properties of the solder joints, were investigated in terms of various reflow temperatures and duration times. The primary results are summarized below.

The microstructural evolutions of the solder joints were considered at four reflow stages in the reflow process. In the first stage, the growth of the plate-shaped $AuIn_2$ IMC layer, formed at the solder/substrate interface, increased the shear force of the solder joints with the duration time. The fracture occurred at the Au-rich/$AuIn_2$/solder interface.

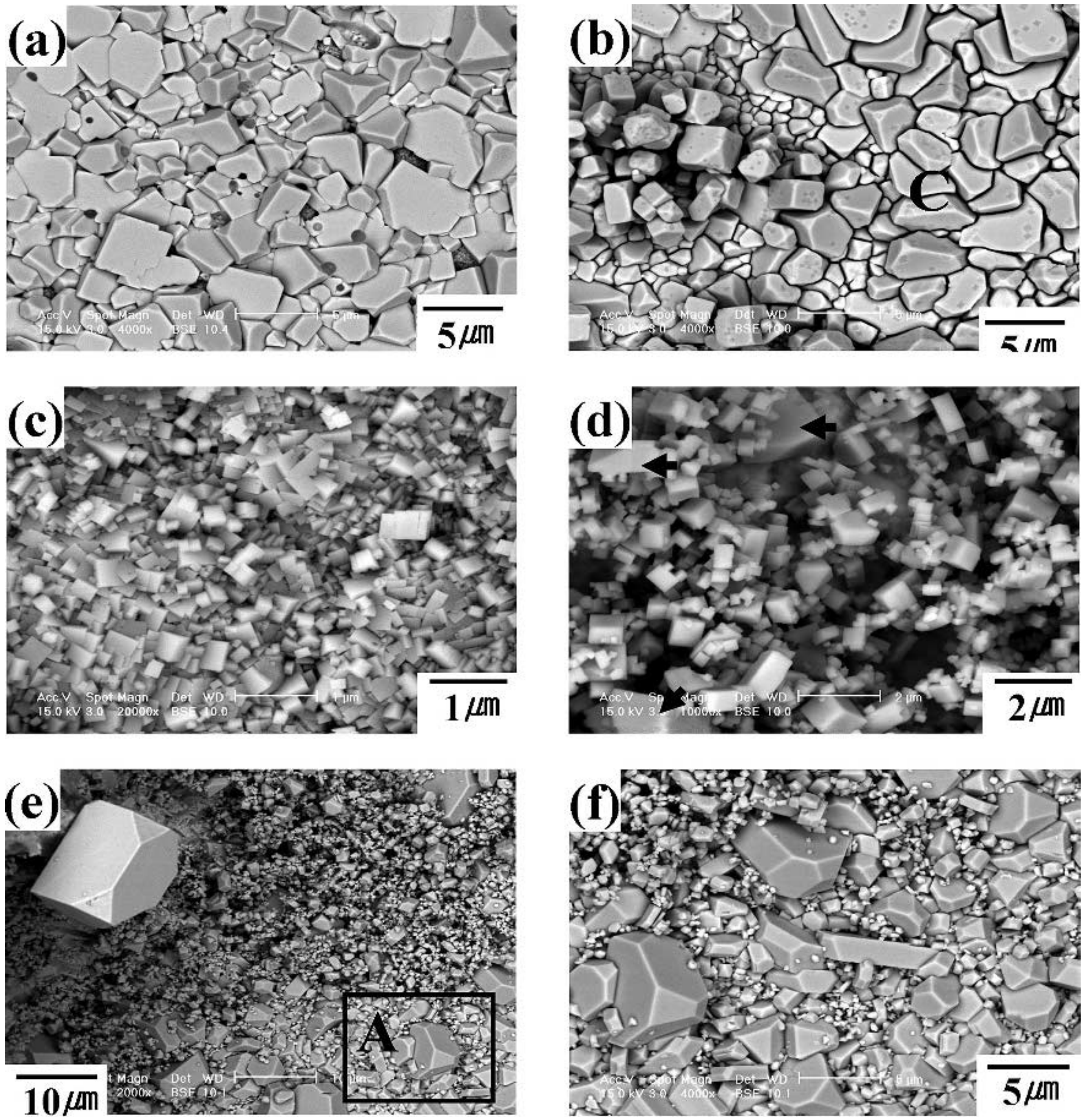

Fig. 4. Top views of the IMCs formed at the interface after being reflowed at 443 K for various duration times: (a) 10 sec, (b, c) 30 sec, (d) 3,600 sec, and (e) and (f) 7,200 sec. The arrows in (d) indicate the polyhedron-shaped $Ni_3(Sn,In)_4$ intermetallics, and (f) is the magnified image of region A in (e).

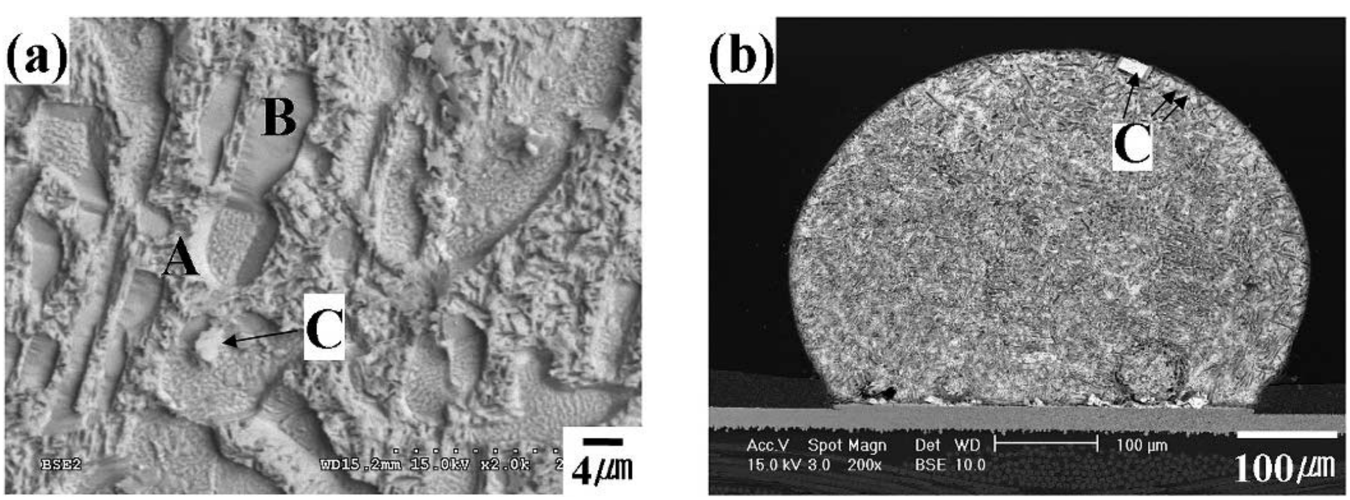

Fig. 5. The SEM micrographs of the In-48Sn solder ball after being reflowed at 443 K for (a) 3 sec and (b) 300 sec.

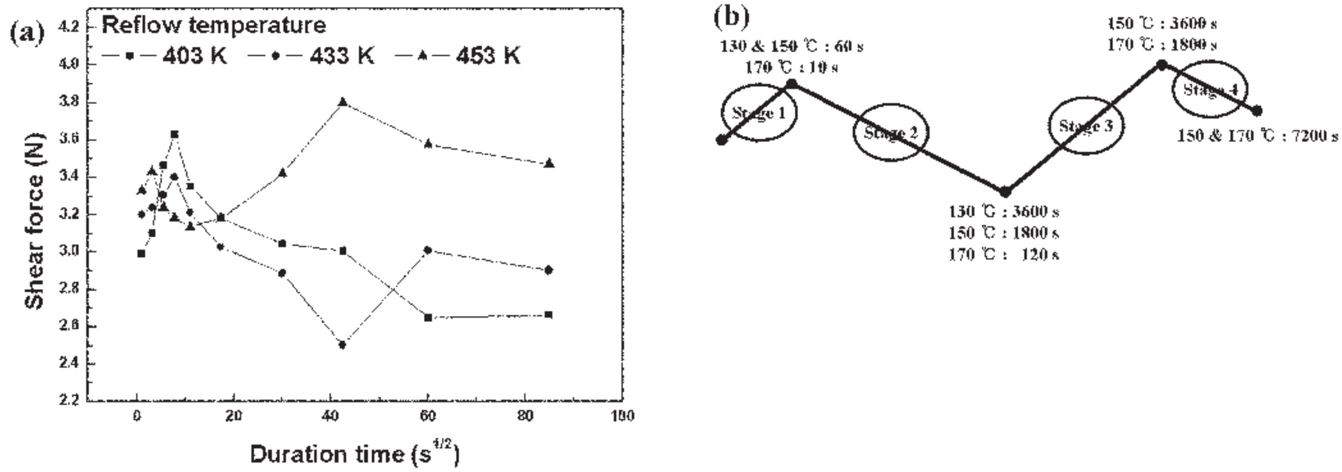

Fig. 6. Shear force variations of the In-48Sn/Au/Ni/Cu solder joints after being reflowed at various reflow temperatures for various duration times.

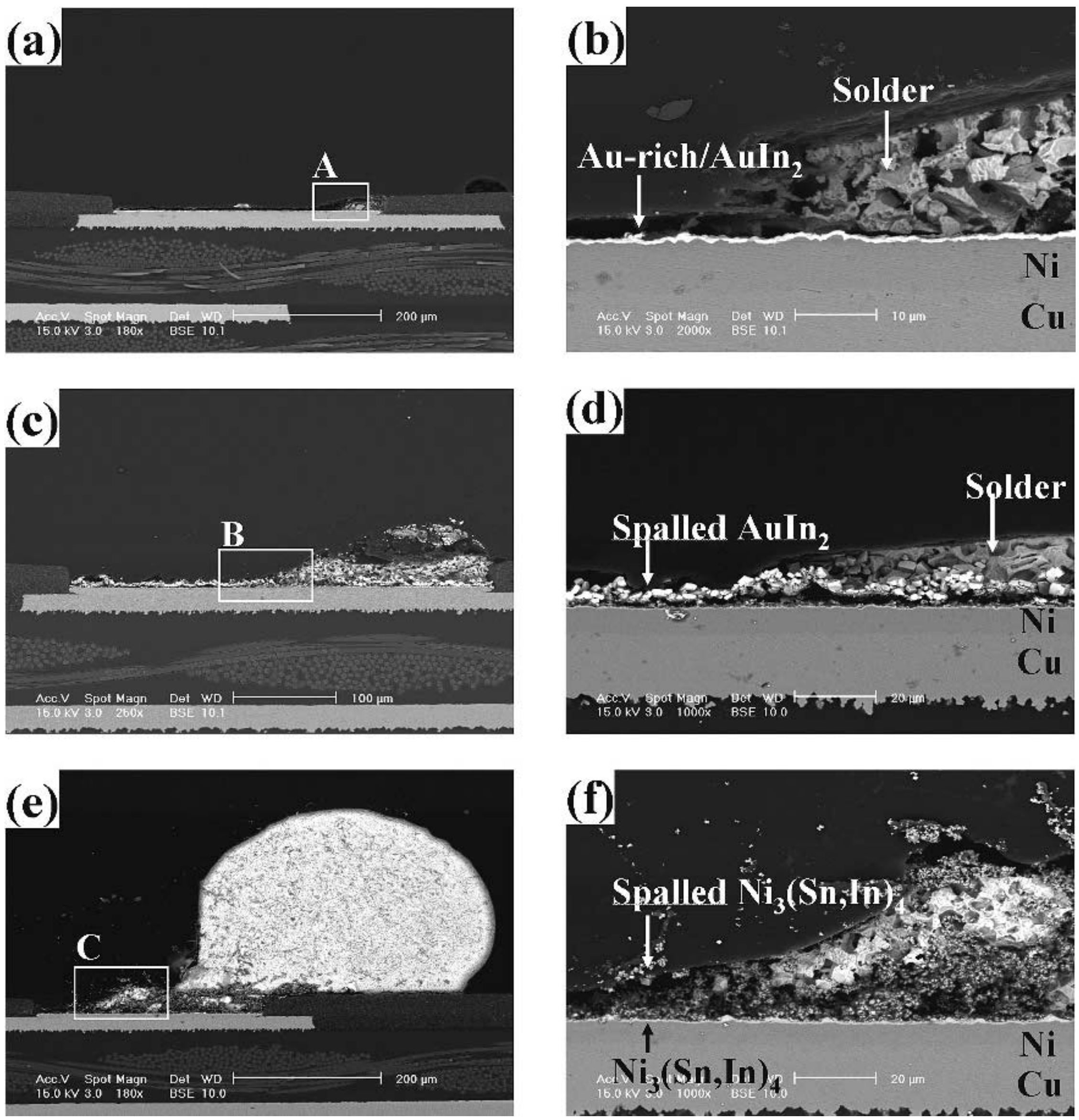

Fig. 7. Cross-sectional views of the fractured specimens after the shear tests of the solder joints reflowed (a) and (b) at 403 K for 3 sec, (c) and (d) at 423 K for 1,800 sec, and (e) and (f) at 443 K for 7,200 sec: (b), (d), and (f) are the magnified images of regions A, B, and C in (a), (c), and (e), respectively.

In the second stage, the spalling and grain growth of brittle cubic-shaped $AuIn_2$ intermetallics were observed, whereas only a very thin continuous $Ni_3(Sn,In)_4$ IMC layer was formed at the solder/substrate interface. These microstructural evolutions significantly decreased the shear force. The fracture location shifted toward the brittle $AuIn_2$ intermetallics dispersed in the solder.

The formation and spalling of very fine cubic-shaped $Ni_3(Sn,In)_4$ intermetallics increased the shear force, due to the dispersion hardening of the intermetallics in the third stage, whereas the spalling and grain growth of polyhedron-shaped $Ni_3(Sn,In)_4$ intermetallics decreased the shear force at the final reflow stage. The fracture occurred along the $Ni_3(Sn,In)_4$ intermetallics dispersed in the solder.

The higher reflow temperature accelerated the interfacial reactions between the solder and substrate. The microstructural evolutions of the solder joints during the reflow process obviously affected the mechanical reliability of the solder joints.

ACKNOWLEDGEMENT

This work was supported by grant No. RTI04-03-04 from the Regional Technology Innovation Program of the Ministry of Commerce, Industry and Energy (MOCIE).

REFERENCES

1. John H. Lau, *Ball Grid Array Technology* (New York: McGraw-Hall, Inc., 1995), p. 1.
2. M. Abtew and G. Selvaduray, *Mater. Sci. Eng.* 27, 95 (2000).
3. X. Zeng, *J. Alloys Compounds* 348, 184 (2003).
4. C.B. Lee, S.B. Jung, Y.E. Shin, and C.C. Shur, *Mater. Trans.* 42, 751 (2001).
5. N.C. Lee, *Solder. Surf. Mt. Technol.* 26, 65 (1997).
6. D.G. Kim and S.B. Jung, *J. Alloys Compounds,* 386, 151 (2005).
7. J.W. Morris, Jr., J.L. Freer Goldstein, and Z. Mei, *JOM* 45, 25 (1993).
8. J.L. Freer and J.W. Morris, Jr., *J. Electron. Mater.* 21, 647 (1992).
9. N.C. Lee, *Reflow Soldering Processes: SMT, BGA, CSP, and Flip Chip Technologies* (Boston: Newnes, 2001), pp. 239–256.
10. I. Shohji, S. Fujiwara, S. Kiyono, and K.F. Kobayashi, *Scripta Mater.* 40, 815 (1999).
11. T.H. Chuang, S.Y. Chang, L.C. Tsao, W.P. Weng, and H.M. Wu, *J. Electron. Mater.* 32, 195 (2002).
12. C.Y. Huang and S.W. Chen, *J. Electron. Mater.* 31, 152 (2002).
13. J.W. Yoon, S.W. Kim, and S.B. Jung, *J. Alloys Compounds* 385, 192 (2004).
14. JESD22-B117, JEDEC Standard (JEDEC Solid State Technology Association, 2202).
15. Y.C. Sohn, Jin Yu, S.K. Kang, D.Y. Shih, and T.Y. Lee, *J. Mater. Res.* 19, 2428 (2004).
16. J.M. Koo, W.B. Lee, M.G. Kim, D.U. Kim, Y.J. Kim, and S.B. Jung, *Mater. Trans.,* 46, 303 (2005).
17. R.J. Coyle, A.J. Serafino, and P.P. Solan, *Proc. 27th Electronic Manufacturing Technology Symp.* (Piscataway, NJ: IEEE/SEMI International, 2002), p. 200.