Joint strength and interfacial microstructure between Sn–Ag–Cu and Sn–Zn–Bi solders and Cu substrate

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Joint strength and interfacial microstructure between Sn–Ag–Cu and Sn–Zn–Bi solders and Cu substrate

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Abstract

In the present research, in order to fundamentally investigate the strength and interfacial microstructure of the joints between Sn–3.5Ag–0.7Cu (SAC) and Sn–8Zn–3Bi (SZB) solders and Cu, examinations using the standardized solder joint specimen for measuring the shear strength were performed. The effects of the addition of Ag, Bi and Pb to the solders, which are the ingredients of possible lead plating materials of quad plat package, solder layer thickness and aging treatments ranging from 358 to 423 K were investigated. The SAC base solder joints, whose strength hardly degraded after aging, were more reliable than the SZB base solder joints. Since no detrimental effect of the Bi or Pb addition was recognized, the lead plating materials are found to have no significant effect on the strength of the SAC solder joints. Although the SZB base solder joints had higher strength than the SAC base solder joints in as-soldered condition, a significant degradation of the joint strength occurred after aging. In the case of thinner solder layer of 20 \( \mu \)m, the Cu$_6$Sn$_5$ layer that formed at both the solder/Cu$_5$Zn$_8$ and Cu$_5$Zn$_8$/Cu interfaces after aging caused the fracture of the solder joints and resulted in the degradation of the joint strength. In the case of thicker solder layer of 100 \( \mu \)m, the Cu$_5$Zn$_8$ interfacial layer continuously grew during aging, which caused the fracture of the solder joints and resulted in the decrease in the joint strength. As for the effect of the addition elements, while Pb addition caused a marked degradation of the joint strength, Ag addition and Bi addition had no detrimental effect on the strength of the solder joints. In particular, the joint with the Ag addition solder had the better strength in the case of thinner solder layer. Thus, as for lead plating for the SZB solder, Sn–Pb should be avoided and Sn–Bi or Sn–Ag as Pb-free plating has no detrimental effect on the joint strength. In particular, Sn–Ag plating is preferable in the viewpoint of the joint strength.

Keywords: Pb-free solders; Sn–Ag–Cu solder; Sn–Zn–Bi solder; Joint strength; Interfacial reaction; Intermetallic compound layer; Lead plating; Reflow-soldering; Aging treatment

1. Introduction

Since environmental regulations forbid the use of Pb due to the toxicity of Pb, the development of suitable Pb-free solders has been important issue for electronics assembly [1,2]. Of the Pb-free solders, Sn–Ag system and Sn–Zn system solders are promising candidates and being practically used as alternatives of near-eutectic Sn–Pb solders. In the microjoining using the Pb-free solders, the interfacial reaction under the time of soldering and use-environment has a significant influence on the strength and reliability of the joints [3–6]. Liquid state and solid state solders react to a Cu lead and Cu pad in soldering process and reliability tests, such as high-temperature exposure and thermal cycle. As for lead plating, although Sn–Pb plating is conventionally used, it has been reported that joint reliability falls remarkably in applying a Bi bearing Pb-free solder to a quad flat package (QFP) joint with a Sn–Pb plated lead [2]. Thus, the Pb-free lead plating is needed. However, systematic researches have not been fully made about the influence of lead plating materials on the interfacial reaction [3,7]. In particular, the investigation concerning the Sn–Zn–Bi base solders, which attract attention as a low-temperature solder, have been insufficient [7].

In the present research, in order to fundamentally investigate the interfacial microstructure involving growth behavior of intermetallic compounds (IMCs) resulting from the interfacial reaction between Sn–3.5Ag–0.7Cu (SAC) (when there is no mention, composition is described as a mass percent in the following) and Sn–8Zn–3Bi (SZB)
solders and Cu substrate, examinations using the standardized solder joint specimens that will be adopted as a JIS standard were performed [8]. The effects of the addition of Ag, Bi and Pb to the solders, which are the ingredients of possible lead plating materials of QFP (quad plat package), namely Sn–Ag, Sn–Bi and Sn–Pb plating, solder layer thickness and aging treatment on the shear strength and the interfacial microstructure of the solder joints were investigated.

2. Experimental procedure

The SZB solder and that mixed with 1.0Ag (SZB–Ag), 1.7Bi (SZB–Bi) or 5.7Pb (SZB–Pb), and the SAC solder and that mixed with 1.7Bi (SAC–Bi) or 5.7Pb (SAC–Pb) were used in this experiment. The melting points of the solder alloys were measured with Differential Scanning Calorimeter (DSC) using a heating rate of 5 K/min. Each solder alloy was supplied as a foil of 20 or 100 μm in thickness and 3 mm in diameter for soldering the disc type solder joint specimen.

Schematic view of the disc type solder joint specimen is shown in Fig. 1. Fig. 2 shows the dimension of the test piece. The solder foil to which flux was applied was set between the upper disc and the lower one as shown in Fig. 1 and the test piece was reflow-soldered at a peak temperature of 503 K for a holding time of 15 s. Some of the reflow-soldered specimens were subjected to high-temperature aging tests at temperatures of 358, 398 and 423 K for holding times of 500, 1000 and 1500 h. The shear strength of the disc type solder joint specimen was measured as shown in Fig. 3 using a cross-head speed of 0.083 mm/s. The shear strength of the joint for each condition was the average value of three joints. Microstructural characterization of the solder joints was performed. The solder joints were sectioned, metallographically polished and examined using a scanning electron microscope (SEM) equipped with an electron probe micro analyzer (EPMA). IMCs in the interfacial region were identified based on the quantitative composition analysis by EPMA.

3. Results and discussion

3.1. Effect of addition elements on melting temperature of solder alloys

As shown in Fig. 4, a onset temperature of melting (described as a melting start temperature, $T_s$) and an offset temperature of melting (described as a melting end temperature, $T_e$) were determined from the DSC profile for each solder. Table 1 shows the results. In the SZB solder, the Ag addition resulted in a slight fall of $T_s$ and a rise of $T_e$.

In the Bi added solder, both $T_s$ and $T_e$ fell, though it was
small. The Pb addition to the SZB solder caused a significant fall of both $T_s$ and $T_e$. Also in the SAC solder, the Pb addition brought a considerable fall of $T_s$ and $T_e$. The Bi addition to the SAC solder resulted in a slight fall of $T_s$ and $T_e$. It is found from the results that mixing of Pb to the solders from the Sn–Pb lead plating will cause the fall of the melting temperatures of the solder layers.

3.2. Evaluation of joint strength

3.2.1. After reflow-soldering

Fig. 5 shows the results of the shear test in as-soldered condition. The error bars show the maximum and minimum values of the three measured joint strengths for each solder except for the Sn–37Pb solder, of which the strength was a single measured value. The solder joints contained considerable voids, particularly in the joints using the SZB base solders. So, the area of voids in the fracture surface was measured for each solder joint, and the effective bonded area was obtained from the difference of the nominal joint area ($1.5^2 \text{mm}^2$) and the measured void area. Actual shear strength was calculated as the shear fracture load divided by the effective bonded area. Thus obtained actual joint strength is effective for comparing the strength of the solder joints including different factions of voids. Here, the absolute values of the fracture strength may be affected by the notch effect of voids as inherent defects. However, since the fracture occurred not in the solder layer but at the interface of the reaction layer after aging as mentioned in Section 3.3, in this case the above effect of voids may not be significant. Fig. 6 shows the actual shear strength for each solder joint. Although the actual shear strength was higher than the nominal strength for both the SAC base solder joints and SZB base ones, the rise of the strength in the latter was larger than that in the former. This is caused by the SZB base solder joints having more voids because of a poor wettability of the solders to the Cu substrate [9]. As a result, the strength of the SZB base solder joints was equivalent to or somewhat higher than that of the SAC base solder joints and Sn–37Pb solder joint. As for the effect of thickness of the solder layer, the joints with 20 µm solder layer had higher strength than those with 100 µm solder layer except for the SAC–Bi and Sn–37Pb solder joints. As mentioned in Section 3.3, Cu–Sn IMC layer formed at both the upper and lower solder/Cu interfaces. The effect of a plastic restraint in the solder layer by hard Cu and IMC layer is more remarkable in the thin solder layer than in the thick solder layer. This may be one possible reason that causes the higher strength of the joints with thinner solder layer thickness, although the exceptions such as the SAC–Bi and Sn–37Pb joints existed.

In the SAC base solder joints, the Pb addition solder and Bi addition solder joints had the maximum strength in the joints with 20 and 100 µm solder layers, respectively. In the SZB base solder joints, the Pb addition solder joint had a considerable lower strength than the other solder joints in the cases of both 20 and 100 µm solder layers. In the joints with 100 µm solder layer, the Bi addition solder and Ag addition solder joints had relatively higher strength. The effect of the microstructure of the solder joints on the joint strength will be mentioned in Section 3.3.

3.2.2. After aging treatment

Figs. 7–10 show the changes in the shear strength of the solder joints during the high-temperature aging for the SAC
and SZB base solder joints. All the strength values are corrected ones. In the SAC base solder joints with 20 μm solder layer (Fig. 7), the strength of each joint showed no degradation during aging at 358 and 398 K, and somewhat increased in aging time of 500 h and fell a little after longer time aging at 423 K. The solder joint with no addition element (the SAC solder joint) had a lower strength than the SAC–Bi and SAC–Pb solder joints regardless of aging temperature. In the SAC base solder joints with 100 μm solder layer (Fig. 8), no degradation in the strength of each joint was recognized after aging. Instead the strength somewhat increased after 1500 h aging at 423 K. The SAC solder joint had a lower strength than the SAC–Bi and SAC–Pb solder joints after aging.

As for the SZB base solder joints (Figs. 9 and 10), the strength considerably decreased after high-temperature aging regardless of the addition elements and exposure temperature. The reduction of the joint strength was more remarkable at higher aging temperature or after longer aging time, and more prominent in the joints with 100 μm solder layer than in 20 μm solder layer. In the joints with 20 μm solder layer, the strength of the SZB–Pb solder joint was the lowest in almost all the aging conditions. On the contrary, the Ag and the Bi addition had no detrimental effect on the joint strength. In particular, of all the solder joints, the SZB–Ag solder joint maintained relatively higher strength at aging temperature of 398 K or less and within aging time of 1000 h at 423 K. In the joints with 100 μm solder layer after aging (Fig. 10), the strength of all the joints more significantly degraded in higher aging temperature or longer holding time. The SZB–Ag and SBZ–Bi solder joints had somewhat higher strength than the SZB solder joint at aging temperature of 358 K (Fig. 10(a)). Contrastively, of all the solder joints, the SZB–Pb solder joint had the lowest strength. At aging temperature of 423 K, the strength of all the joints remarkably decreased after 500 h aging regardless of addition elements. After that time the strength was almost constant in SZB–Ag, Bi and Pb solder joints or slightly increased in the SZB solder joint.

In conclusion, the SAC base solder joints in the cases of both 20 and 100 μm solder layers, whose strength hardly degraded after high-temperature aging, were found to be more reliable than the SZB base solder joints. Since no detrimental effect of the Bi or Pb addition to the SAC solder was recognized, lead plating materials, whose ingredients mix to the solder layer, are found to have no significant effect on the joint strength.

On the other hand, although the SZB base solder joints had a higher strength than the SAC based solder joints in
as-soldered condition, a significant degradation of the joint strength occurred after the high-temperature aging. Furthermore, the addition elements had a considerable effect on the joint strength. The joints with the SZB–Bi and SZB–Ag solders had superior strength than that with the SZB–Pb solder after high-temperature aging. In particular, in aging at lower temperature or shorter time, the joint with the Ag addition had the better strength. Therefore, as lead plating for SZB base solders, the Sn–Pb plating should be avoided and Sn–Ag plating or Sn–Bi plating is desirable. Since the degradation of the joint strength is attributed to the interfacial reaction between the solders and Cu substrate, the interfacial microstructure of the solder joints and its effect on the fracture behavior of the joints will be discussed in the following sections.

3.3 Effect of interfacial microstructure on fracture of solder joints

3.3.1 Sn–3.5Ag–0.7Cu base solder joints

Fig. 11 shows the typical interfacial microstructure of the SAC base solder joints. In as-soldered condition, \( \eta (\text{Cu}_6\text{Sn}_5, \text{monoclinic: } a = 1.1033, b = 0.7294 \text{ and } c = 0.9830 \text{ nm; } \beta = 98.82^\circ) \) layer of 3–4 \( \mu \)m in thickness solely formed at the solder/Cu interface (Fig. 11(a)). While in aging at 353 K, no apparent growth of the \( \text{Cu}_6\text{Sn}_5 \) layer was recognized up to 1500 h aging, in aging at 398 and 423 K, \( \epsilon (\text{Cu}_3\text{Sn}, \text{orthorhombic: } a = 0.55521, b = 3.325 \text{ and } c = 0.4328 \text{ nm}) \) layer formed at the \( \text{Cu}_6\text{Sn}_5/\text{Cu} \) interface after 500 h aging (Fig. 11(c) and (d)) and grew in parabolic manner during subsequent aging. Addition elements and solder layer thickness had no significant effect on the growth behavior of the reaction layers. This is because even in the thinner solder layer the amount of Sn is sufficient to form the Cu–Sn IMCs during aging, and neither Bi nor Pb is included in the IMCs and affect the formation of the IMCs.

As shown in Fig. 12, fracture in the shear test mainly occurred at the solder/\( \text{Cu}_6\text{Sn}_5 \) layer interface regardless of addition elements, solder layer thickness or aging conditions. This means that formation of the \( \text{Cu}_6\text{Sn}_5 \) layer causes fracture of the solder joint and thereby have a detrimental effect on its mechanical property. However, since no further significant degradation of joint strength was recognized after high-temperature aging, growth of the IMCs layer, mainly the \( \text{Cu}_3\text{Sn} \) layer, may cause no additional deterioration of the strength at the solder/\( \text{Cu}_6\text{Sn}_5 \) layer interface. In some cases such as the joint
with 100 µm solder layer after 1500 h aging at 423 K the increment of the strength was recognized after aging (Fig. 8(c)). The reason could not be explained from the observations of the microstructure and fracture path. The thinner solder layer with the thicker IMC layer after long time aging might cause increased plastic restraint. Further investigation is necessary to reveal this phenomenon.

### 3.3.2. Sn–8Zn–3Bi base solder joints

Figs. 13 and 14 show cross-sectional microstructures of the SZB base solder joints with 20 µm solder layer in as-soldered condition and after aging at 423 K for 500 h. In as-soldered condition (Fig. 13), a thin γ(Cu5Zn8, cubic: \( a = 0.886 \) nm) layer, 0.5–1 µm in thickness, formed at the interface in all the joints. In the SZB–Ag solder joint (Fig. 13(b)), since 2–3 mol% Ag dissolved into the reaction layer, the IMC layer is estimated to be \((\text{Ag, Cu})_5\text{Zn}_8\) phase [10]. In the SZB–Pb solder joint (Fig. 13(d)), a Pb and Bi rich phase including several 10 mol% Pb and Bi segregated in front of the reaction layer. The segregation of Pb and Bi is considered to result from the very low solubility of these elements in the Cu–Zn IMC. While the bulk SZB solder includes almost pure Zn phase in Sn matrix, no Zn phase was seen in the solder layer of all the solder joints. Therefore, the Zn phase was almost completely consumed to form the Cu–Zn IMC layer during the reflow process.

During aging treatment, although the Cu5Zn8 layer hardly grew, Cu6Sn5 formed at both the solder/Cu5Zn8 and Cu5Zn8/Cu substrate interfaces after a certain aging time as shown in Fig. 14(a), (c) and (d). However, in the SZB–Ag solder joint the formation of the Cu6Sn5 layer was suppressed as shown in Fig. 14(b). This growth behavior of the reaction layers is significantly different from that in the solder-on Cu substrate specimen, in which no Zn depletion occurred after reflow-soldering and the Cu5Zn8 layer parabolically grew [11]. The growth behavior of the interfacial reaction layer for each solder joint in the case of aging at 423 K is shown in Fig. 15. Fig. 15(b) clearly shows that the formation of Cu6Sn5 is delayed and its growth is suppressed in the SZB–Ag solder joint. Sn contents in the Cu5Zn8 layer were determined from EPMA quantitative analysis. In the SZB solder joints except for the SZB–Ag solder joint, Sn content dissolved in the Cu5Zn8 layer was around 3 mol% after reflow-soldering and it increased to 6–8 mol% when the Cu6Sn5 formed. This suggests the mechanism of the Cu6Sn5 formation as follows. When Sn content dissolving in the Cu5Zn8 layer increases during aging and exceed its solubility limit, the formation of Cu6Sn5 with simultaneous decomposition of Cu5Zn8 may occur. In the SZB–Ag solder joint, the maximum Sn content dissolving in the (Ag, Cu)5Zn8 layer was over 10 mol% from EPMA quantitative analysis, which is higher than in the other solder joints. Thus, there is a possibility that the dissolution of Ag into the Cu5Zn8 extend the solubility limit of Sn in the IMC. This can cause the delay of the Cu6Sn5 formation in the SZB–Ag solder joint. Further investigation is necessary to reveal this effect. On the contrary, in the SZB–Pb solder joint, the formation and growth of Cu6Sn5 were accelerated as shown in Fig. 15(d). It has been reported that in the QFP joint with Sn–10Pb plated Cu lead using Sn–3Ag–5Bi solder the rapid growth of the Cu6Sn5 interfacial reaction layer occurred and it was attributed to...
Fig. 13. Interfacial microstructure of (a) SZB, (b) SZB–Ag, (c) SZB–Bi, and (c) SZB–Pb solder joints with 20 μm solder layer in as-soldered condition.

Fig. 14. Interfacial microstructure of (a) SZB, (b) SZB–Ag, (c) SZB–Bi, and (c) SZB–Pb solder joints with 20 μm solder layer after aging at 423 K for 500 h.

Fig. 15. Growth behaviors of interfacial reaction layers in (a) SZB, (b) SZB–Ag, (c) SZB–Bi, and (c) SZB–Pb solder joints with 20 μm solder layer during aging at 423 K.
liquation of the Bi and Pb rich phase ahead of the reaction layer [3]. Also in the present SZB–Pb joint, since the Pb and Bi rich phase segregated in front of the reaction layer (Fig. 14(d)), the same phenomena should occur and promote the growth of the Cu₆Sn₅ layer.

Figs. 16 and 17 show cross-sectional microstructures of the SZB base solder joints with 100 μm solder layer in as-soldered condition and after aging at 423 K for 500 h. The growth behavior of the reaction layer for each solder joint is shown in Fig. 18. In as-soldered condition (Fig. 16), the Cu₅Zn₈ layer of 3–4 μm in thickness, which is considerably thicker than that in the joint with 20 μm solder layer, formed at the interface and needles of Zn phase were seen in the solder layer. In the SZB–Ag solder joint, the interfacial IMC layer was (Cu, Ag)₅Zn₈ and (Ag, Cu)Zn₃ including approximately 15 mol% Ag was recognized in the solder layer near the interface.

Since Zn phase was not depleted after the reflow process, the Cu–Zn IMC layer continuously grew during aging treatment unlike the solder joints with 20 μm solder layer. Therefore, no continuous Cu₆Sn₅ layer was seen in the SZB and SZB–Ag solder joints, although island-shaped Cu₆Sn₅ locally formed (Fig. 17(a) and (b)). While the Cu₆Sn₅ layer formed in the SZB–Bi and SZB–Pb solder joints, the growth rate was significantly lower than that in the solder joints with 20 μm solder layer (Fig. 18(c) and (d)).

Above mentioned interfacial microstructures affected the fracture of the solder joints. In as-soldered condition, the fracture of the SZB base solder joints with 20 μm
solder layer initiated and propagated in the solder layer or along the solder/Cu$_5$Zn$_8$ layer interface as shown in Fig. 19. Since the SZB base solder joints had higher strength than the SAC base solder joints in as-soldered condition, the thin Cu$_5$Zn$_8$ layer had less detrimental effect on the joint strength than the Cu–Sn IMC layer in the SAC base joints. However, once the Cu$_6$Sn$_5$ layer formed after aging, the fracture occurred in the Cu$_6$Sn$_5$ layer or along the Cu$_6$Sn$_5$/Cu$_5$Zn$_8$ layer interface as shown in Fig. 20 and the joint strength decreased. Thus, coexistence of the Cu$_6$Sn$_5$ and Cu$_5$Zn$_8$ layers had the detrimental effect on the joint strength. This may be caused by insufficient strength of the Cu$_6$Sn$_5$/Cu$_5$Zn$_8$ layer interfacial and/or internal defects such as voids and microcracks in the Cu$_6$Sn$_5$ layer. In the SZB–Pb solder joint, since the Bi and Pb rich phase was seen along the crack path in as-soldered condition, it should cause the lower joint strength than the other joints (Fig. 6). After aging, the rapid growth of the Cu$_6$Sn$_5$ layer in the SZB–Pb solder joint resulted in more significant degradation of the joint strength than in the other solder joints. As for the solder joints with 100 μm solder layer, the Cu$_5$Zn$_8$ layer, which continuously grew during aging treatment, caused the fracture of the solder joint as shown in Fig. 21. Since the strength of the solder joint with 100 μm solder layer notably degraded after aging, the thicker Cu$_5$Zn$_8$ interfacial layer obviously caused the decrease in the joint strength. In some cases of joining dissimilar materials, it has been reported that although a thin interfacial reaction layer, mostly less than 1 μm in thickness, has no detrimental effect on the joint strength, increasing reaction layer thickness results in decreasing joint strength [12,13]. This is caused by increasing internal defects and/or stress in the reaction layer. Above mentioned effect of the Cu$_5$Zn$_8$ layer on the joint strength can be the same case.

In conclusion, when the SZB solder is applied to solder joints, a thin solder layer of 20 μm or less, which is the case of common QFP solder joints, is preferable and the service temperature should be below 398 K to keep a thin Cu–Zn IMC reaction layer and prevent the formation of the Cu$_6$Sn$_5$ layer. As for lead plating, Sn–Pb should be avoided and Sn–Bi or Sn–Ag as Pb-free plating has no detrimental effect on the joint strength.
effect on the joint strength. In particular, Sn–Ag plating is preferable in the viewpoint of the joint strength.

4. Conclusions

(1) The shear strength of the Sn–3.5Ag–0.7Cu base solder joints was hardly degraded after aging. Since no detrimental effect of the Bi or Pb addition was recognized, lead plating materials, whose ingredients mix to the solder layer, are found to have no significant effect on the joint strength.

(2) Although the Sn–8Zn–3Bi base solder joints had higher shear strength than the Sn–3.5Ag–0.7Cu base solder joints in as-soldered condition, a significant degradation of the joint strength occurred after aging. While Pb addition to the solder caused a marked degradation of the joint strength both before and after aging, the Ag addition and Bi addition had no detrimental effect on the strength of the solder joints. Particularly in aging at lower temperature or shorter time, the joint with the Ag addition had the better strength.

(3) In the Sn–3.5Ag–0.7Cu base solder joints, while only the Cu₆Sn₅ layer formed at the solder/Cu interface after soldering, the Cu₃Sn layer was produced between the Cu₆Sn₅/Cu interface and grew during aging. The addition elements or the solder layer thickness had no significant effect on the growth behavior of the reaction layers. Although the fracture in the shear test mainly occurred at the solder/Cu₆Sn₅ layer interface, the growth of the Cu–Sn IMC layer resulted in no further degradation of the joint strength.

(4) In the Sn–8Zn–3Bi base solder joints with 20 μm solder layer, although thin Cu₅Zn₈ layer solely formed at the solder/Cu interface in the as-soldered condition, the Cu₆Sn₅ layer formed at both the solder/Cu₅Zn₈ and Cu₅Zn₈/Cu interfaces and became thicker during aging. The formation of the Cu₆Sn₅ layer caused the fracture of the solder joints and resulted in the degradation of the joint strength. While the addition of Pb to the solder accelerated the growth of the Cu₆Sn₅ layer, the Ag addition inhibited the interfacial reaction resulting in lower growth rate of the Cu₆Sn₅ layer.

(5) In the Sn–8Zn–3Bi base solder joints with 100 μm solder layer, the Cu₅Zn₈ interfacial layer continuously grew during aging. The formation of thick Cu₅Zn₈ layer caused the fracture of the solder joints and resulted in the decrease in the joint strength.

References

[1] M. Abtew, G. Selvadurary, Mater. Sci. Engng R27 (2000) 95–141.
[2] K. Suganuma, MRS Bull. 26 (2001) 880–884.
[3] A. Hirose, T. Fujii, T. Imamura, K.F. Kobayashi, Mater. Trans. 42 (2001) 794–802.
[4] K. Uenishi, T. Saecki, Y. Kohara, K.F. Kobayashi, I. Shoji, M. Nishiura, M. Yamamoto, Mater. Trans. 42 (2001) 756–760.
[5] K. Uenishi, Y. Kohara, S. Sakatani, K.F. Kobayashi, M. Yamamoto, Mater. Trans. 43 (2002) 1833–1839.
[6] T. Hiramori, M. Ito, M. Yoshikawa, A. Hirose, K.F. Kobayashi, J. Japan Inst. Electron. Packaging 6 (2003) 503–508.
[7] H. Iwanishi, T. Imamura, A. Hirose, K. Tateyama, I. Mori, K.F. Kobayashi, J. Electron. Mater. 32 (2003) 1540–1546.
[8] Test methods for lead-free solders—Part 5: methods for tensile tests and shear tests on solder joints, JIS Z 3198–5.
[9] K. Suganuma, K. Niihara, T. Shoutoku, Y. Nakamura, J. Mater. Res. 13 (1998) 2859–2865.
[10] P. Villars, A. Prince, H. Okamoto, Handbook of Ternary Alloy Phase Diagrams, ASM International, 1995, p. 2364.
[11] H. Yanagawa, T. Imamura, E. Ide, A. Hirose, K.F. Kobayashi, J. Japan Inst. Electron. Packaging 6 (2003) 47–53.
[12] A. Hirose, Y. Matsushiro, M. Kotoh, K.F. Kobayashi, J. Soc. Mater. Sci. Japan 40 (1991) 77–88.
[13] S. Kuroda, K. Saida, K. Nishimoto, Q. J. Japan Welding Soc. 17 (1999) 484–489.