National Conference on Postgraduate Studies
Universiti Malaysia PAHANG, Kuantan

Jan/2015

A Review on Effect of Nickel Doping on Solder Joint Reliability

A.M. Zetty Akhtar[a], K. Hardinna Wirda[a], and I. Siti Rabiatull Aisha[a]*

[a] Faculty of Mechanical Engineering, Universiti Malaysia Pahang, Pekan,Pahang.

* Corresponding author. Tel.: 09-4246349;
E-mail address: rabiatull@ump.edu.my

Abstract

Keywords:

Solder alloy
Nickel doping
Solder joint
Interfacial Reaction

Currently, the demands for portable electronic gadgets such as Personal Digital Assistant, tablets and smart phone have increased due to its light weight and multifunctionality. But the major drawbacks of these portable devices are prone to accidental drops and may cause internal circuit board damage. When an electronic product drops on the ground, the impact force and deformation which is transferred internally to the print circuit board (PCB) can cause brittle fracture at the solder joint interface or by impact fatigue in the solder materials. Thus, in order to further enhance the mechanical properties of the solder joints, doping an element such as such as rare earth, Bi, Sb, Fe, Co, Cr, Mn, Ti, In, Ni, and Ge as alloying addition has been selected in previous researchers as one of those solutions. This paper summarizes the effect of Ni doping element on intermetallic compound (IMC) formation, interfacial reaction and solders joint reliability. These reviews should provide an important basis of understanding the development of lead-free solders with addition of alloying elements.

Accepted: 26Dec2014
© NCON-PGR 2015. All rights reserved.

1. Introduction

The increasing awareness of health risk associated with lead (Pb) containing solder alloys has pushed the electronics industry toward lead-free solder [1-13]. Among many developed lead-free solder alloys, the Sn-Ag-Cu lead-free solder alloy is considered the best alternative to replace eutectic tin-lead solder [4, 12, 14-22]. As the density of electronic packaging improves, the solder joints are subjected to higher mechanical, electrical and thermal loads. A new type of lead-free solder with better mechanical properties is required, whose strength and plasticity should meet the needs of the electronics industry on reliability [23-26]. Recently, Sn-Ag-Cu (SAC) solders have been widely used as lead-free candidates in the microelectronic packaging industry due to its low melting temperature (range from 217°C to 222°C) and superior cyclic fatigue properties (2908

mean number of cycle to failure). Even though the SAC solders give good temperature cycling reliability which is desirable for high temperature electronic devices used in Aerospace, Military and Automotive industry, it exhibit significantly poor drop shock performance (60 drops to failure with 4% cumulative failed) for portable electronic devices [9, 27-33]. The formation of Ag_3Sn and Cu_6Sn_5 IMCs in the solder matrix also would cause heterogeneous distribution of stress and deteriorate the reliability of the solder joints [34-37]. Thus, in order to further enhance the mechanical properties in solder alloys, the alloying element such as Ni, Sb, Pd, Ce and other rare earth (RE) element are added as an alloying addition into these alloys [38-46]. Nevertheless, this paper summarizes the effect of Ni doping elements on intermetallic compound (IMC) formation, interfacial reaction and solders joint reliability.

2. Intermetallic Compound (IMC) formation

Intermetallic compounds consist of a homogenous phase of two or more materials that form prior to soldering, after soldering, and during service. This migration occurs when the solder alloy begins to liquefy or melt, and will continue rapidly as long as the temperature is above the melting point of the solder alloy. Generally, the thickness of the IMC layer at the interface between the solder and substrate is very important in determining the reliability of the whole package [47]. This is because, an excessively thick IMC layer is sensitive to stress and sometimes provides initiation sites and paths for the propagation of cracks [48, 49]. Therefore, as the growth of the IMC layer could degrade the reliability of the solder joint, it is essential to study the formation and growth of the IMC layer [12, 50-52]. Doping lead-free solders with minor additions of alloying and impurity elements such as Ni, Bi or Zn appears to have major effects on the growth of intermetallic (IMC) in solder joints during reflow soldering between the Sn-Ag-Cu lead-free solders and the surface finish metallurgy [53-56] . These doping elements either retard the growth of the IMC or refine the microstructure that lead to strengthening the solder joint further [23, 32, 57-59]. The IMC formations were investigated by Ourdijini *et al.* [60],whereby their worked focused on examine the effect of Ni on intermetallics formed during reflow soldering. From their worked, it was observed that after reflow soldering, addition of 0.05 wt% Ni to the Sn-3.0Ag-0.5Cu (SAC 305) solder was found to be very effective in reducing the thickness of Cu_6Sn_5 at the interface as can be seen in Fig 1[60]. Their result were similar to what had been reported [16, 32, 61-65].

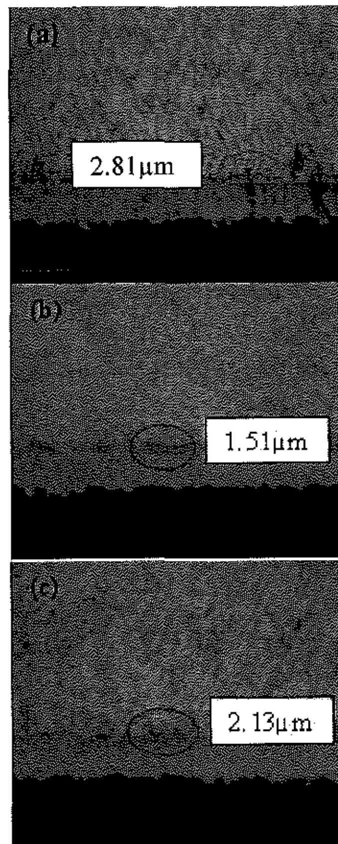

Fig.1. Morphologies of intermetallic after reflow (a) SAC (b) SAC-0.05Ni and (c) SAC-0.1Ni. [60]

Supporting the findings in previous studies is Zhao *et al.* [58]. In his research, comparison of IMC formation between Sn-1.0Ag-0.5Cu (SAC 105) and SAC 105 with addition of 0.02 Ni (SAC 105-0.02Ni); both with NiAu surface finish were observed. According to interfacial IMC EDX analysis, in the case of SAC 105, nearly all the interfacial IMC were $(Cu,Ni)_6Sn_5$ formed at the interface, but there are some particles deposited on large dimension $(Cu,Ni)_6Sn_5$ grains. But for SAC 105-0.02Ni, it is quite different in the IMC constitution, almost all interfacial IMC are $(Ni,Cu)_3Sn_4$, only a small portion interfacial IMC are $(Cu,Ni)_6Sn_5$ (the larger grain in Fig.2b). The IMC diameter of SAC 105 is 0.512μm with a length of 2.15μm, while the IMC diameter of SAC 105-0.02Ni is 0.475μm with a length of 1.62μm; that is to say, the addition of Ni in SAC solder change the phase structure of interfacial IMC. To sum up, certain amount of Ni doped reduced the grain size of intermetallic compounds probably due to adding nano-Ni particle can help the refinement of $(Ni,Cu)_3Sn_4$ [58, 66, 67].

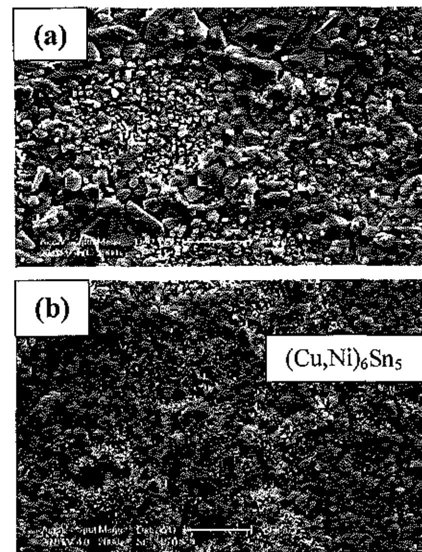

Fig.2. Top view of interface (a) SAC 105 and (b) SAC 105-0.02Ni with NiAu surface finish [58].

3. Interfacial Reaction

Aisha *et al.* [68] in their research proposed that interfacial characteristics of composite solder joints are affected significantly by the weight percentages of Ni particles and ageing time. According to the result obtained in their experiment, Ni

addition to Sn-based lead-free solder could retard the growth of Cu_3Sn intermetallic and also change the amount as well as microstructure of Cu_6Sn_5 intermetallic formed near the interface [62, 69-74]. Apart from that, Ni addition also induced the formation of a greater amount of Cu_6Sn_5 intermetallic near the solder/Cu interface and it will be produced in greater amount when Ni concentration is increase. However, the minimum Ni concentration that is effective in retarding the Cu_3Sn growth and at the same time not inducing an excessive growth of Cu_6Sn_5 has not been properly identified [68, 75-77]. Even though many previous studies proposed that 0.05 wt% is the best proportion of Ni to be added, but there are still lack of proof to conclude that theories.

Whereas, Wang *et al.* [78] in his studied focused on identifying minimum Ni concentration that is effective in retarding the Cu_3Sn growth, and at the same time does not induce an excessive Cu_6Sn_5 formation. In other words, the objective of this study was to explore the optimum Ni addition to Sn-based lead-free solders with regard to the Cu_6Sn_5 and Cu_3Sn thicknesses. In all cases, the Cu_6Sn_5 phase was the only phase observed at the interface after reflow process. The phase Cu_3Sn was not observed at this stage, but would appear after the solid-state aging [30, 79-82]. Based on their result, with 0.005 wt% Ni added, Cu_6Sn_5 exhibited a microstructure quite similar to that of SAC and described as the scallop-type microstructure. Only when the Ni concentration increased beyond 0.06 wt% did Cu_6Sn_5 become the needle-like microstructure. After aging, Cu_3Sn appeared with a layered microstructure between Cu_6Sn_5 and Cu. However, based on their observation, at any given aging time at 160 °C, shows that the addition of even the smallest amount of Ni was able to greatly reduce the Cu_3Sn thickness. To sum up, the addition of 0.01 wt.% Ni did not change the Cu_6Sn_5 microstructure too much, and also did not thicken this phase substantially. In short, 0.01 wt.% appear to be the optimal Ni addition as far as the formation and growth of the intermetallic are concerned [78]. This phenomenon happen because the dissolution rate of nickel into Sn is a lot slower than that of Cu and its act as diffusion barrier towards other element from diffusing into existing IMC [7, 83-86]. This results in a thin IMC layer in Ni doped solder after a normal soldering process.

The reason why Ni addition is effective in reducing the Cu_3Sn thickness is unclear at this moment. Several theories have been proposed, including thermodynamic arguments and kinetic arguments. It was likely that the Ni addition somehow increased the ratio of interdiffusion flux through the Cu_6Sn_5 layer and the Cu_3Sn layer. It is widely known that a phase with a higher interdiffusion

coefficient will grew faster at the expense of its neighboring phase that has a lower interdiffusion coefficient. Nevertheless, the mechanism explaining how the Ni addition can change the ratio of interdiffusion flux is still lacking [24].

4. Solder Joint Reliability

It is known that the IMC is in brittle nature and once there is crack, it can easily propagate through it and finally it will leads to failure [49]. Besides that, the rapid growth of IMC during interfacial reaction of solder whether as reflow or after aging can lead to formation of microvoids, thus decrease the solder joint strength [9, 87]. Che *et al.* [88] in his studies has compared mechanical properties between five type of solder material, including SAC 305, SAC 105, SAC 205, SAC 105-0.05Ni and SAC 105-0.02Ni. According to the result obtained from his experiment, adding Ni particle in two of SAC solder slightly improves the solder joint drop reliability because Ni dopant suppresses the IMC growth and improves the solder structure and tensile properties, similar to what been reported [89-94]. Referring to Figure 3 below, it can be seen that 0.05wt% Ni dopant in solder affects the SAC105 solder material properties significantly compared to 0.02wt% Ni dopant in solder. SAC105-0.05Ni solder has lower modulus (40GPa), ultimate tensile strength (30MPa) and yield stress (15MPa), but larger elongation (95%) compared to SAC105 and SAC105-0.02Ni. Moreover, SAC105-0.02Ni shows the similar material properties as SAC105 solder without Ni dopant [88].

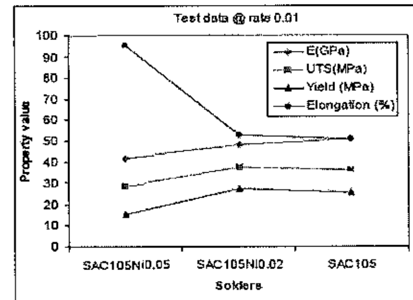

Fig.3. Ni dopant effect on solder material properties [88].

Besides that, comparison on adhesive strength between unmodified Sn-Ag solder alloys and solders with addition of Ni have been observed by Lee *et al.* [75]. Based on result obtained through his studies, show that unmodified eutectic Sn–Ag alloy exhibit the lowest tensile load after reflow; 61Mpa compared to the Ni-modified solder alloys; range from 66Mpa to 78 MPa. Thus, it is clear that Ni addition has a significant effect on the tensile behavior of the solder joint. The improvement obtained in the maximum sustainable load with increasing Ni addition can be attributed to an increase in the number of dispersed Ag_3Sn, Ni_3Sn_4, and $(Ni,Cu)_3Sn_4$ particles and a refinement of the solder microstructure [67, 95]. Figure 4 below summarize the adhesive strength results obtained for Sn-Ag, Sn-Ag-0.5Ni, Sn-Ag-1.0Ni, Sn-Ag-2.0Ni, and Sn-Ag-3.0Ni solder alloys aged for different

storage times at a temperature of 150 ◦C. In general, the adhesive strength of the as-soldered solder joint improves 4% with increasing Ni addition, result from refinement of microstructure of Ag_3Sn and Ni_3Sn_4 precipitated in the matrix [75].

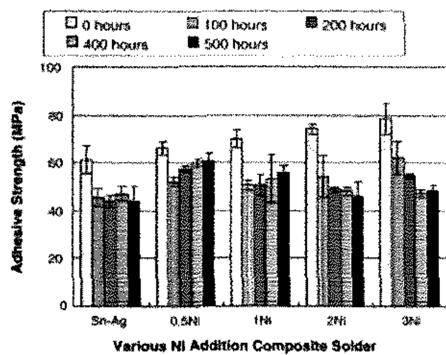

Fig.4. Variation of adhesive strength with Ni addition as function of aging time at 150˚C [75].

As mostly researchers agreed that adding some amount of Ni could ehnance the mechanical properties of the solder alloys, Cheng *et al.* [67] propose slightly different findings in their studies. Comparing between tensile properties with solder containing Ni and Co respectively and unmodified SAC 305 solder; apparently addition of alloying elements (Co and Ni) does not significantly impact the ultimate tensile strength (UTS) of SAC 305. The UTS value for SAC305-Ni range from 33MPa to 35MPa, meanwhile for the SAC 305-Co,the values is 38MPa which is close enough to UTS value of SAC 305; 40 MPa. Figure 5 below shows the UTS of solders graphically. However, the elongation ratio and reduction of area decline sharply, which indicates that the ductility of SAC305 solder becomes worse after the addition of Co or Ni [67].

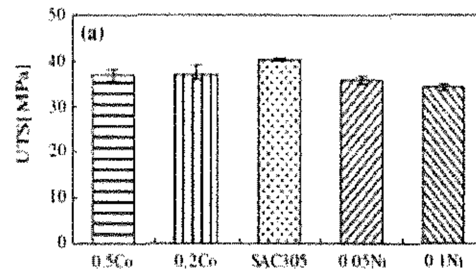

Fig.5. Ultimate tensile strength of SAC 305 alloy and addition of Co and Ni [67].

5. Conclusion

Considering the legalisation to restrict the use of environmental unfriendly materials, the use of Pb has been banned. Sn-Ag has emerged as one of the reliable solder joints in microelectronic industry to replace Sn-Pb solders. However, there is certain argument still arises such as formation of large brittle intermetallic phases and service durability of these solders. Some researchers have proven that by adding a trace amount of alloying addition to the solder, it does improve the IMC formation and mechanical properties of the joints. The results of the review can be concluded as below;

(1) Doping solders with minor additions of alloying and impurity elements such as Ni appears to have major effects on the growth

of intermetallic (IMC) in solder joints either retarding it's growth or refining the grain size.

(2) As reflow, only Cu_6Sn_5 intermetallic appear on the interface, but as solder exposed through aging, Cu_3Sn start to appear. The intermetallic layer relatively get thicker as aging time increased, but the addition of Ni can retard the growth of the intermetallic.

(3) Solder joint reliability improve with addition of Ni in the solder, as Ni enhance the mechanical properties. The yield strength, ultimate tensile strength and elongation show slightly higher value than solder without doping element.

6. References

[1] Yao, P., P. Liu, and J. Liu, Interfacial reaction and shear strength of SnAgCu–xNi/Ni solder joints during aging at 150°C. *Microelectronic Engineering*,2009. **86**(10): p. 1969-1974.

[2] Kim, D.-G. and S.-B. Jung, Interfacial reactions and growth kinetics for intermetallic compound layer between In–48Sn solder and bare Cu substrate. *Journal of Alloys and Compounds*, 2005. **386**(1–2): p. 151-156.

[3] Yao, P., P. Liu, and J. Liu, Effects of multiple reflows on intermetallic morphology and shear strength of SnAgCu–xNi composite solder joints on electrolytic Ni/Au metallized substrate. *Journal of Alloys and Compounds*, 2008. **462**(1–2): p. 73-79.

[4] Dong, W., et al., Effects of small amounts of Ni/P/Ce element additions on the microstructure and properties of Sn3.0Ag0.5Cu solder alloy. *Journal of Materials Science: Materials in Electronics*, 2009. **20**(10): p. 1008-1017.

[5] Liu, P., P. Yao, and J. Liu, Effects of multiple reflows on interfacial reaction and shear strength of SnAgCu and SnPb solder joints with different PCB surface finishes. *Journal of Alloys and Compounds*, 2009. **470**(1–2): p. 188-194.

[6] Suganuma, K., Advances in lead-free electronics soldering. *Current Opinion in Solid State and Materials Science*, 2001. **5**(1): p. 55-64.

[7] Amagai, M., et al., Mechanical characterization of Sn–Ag-based lead-free solders. *Microelectronics Reliability*, 2002. **42**(6): p. 951-966.

[8] Pecht, M., Y. Fukuda, and S. Rajagopal, The impact of lead-free legislation exemptions on the electronics industry. *Electronics Packaging Manufacturing, IEEE Transactions* on, 2004. **27**(4): p. 221-232.

[9] Wei, X.-f., et al., Microstructural evolution and shear strength of AuSn20/Ni single lap solder joints.

Microelectronics Reliability, 2013. **53**(5): p. 748-754.

[10] Wei, X.-f., et al., Microstructural evolutions of Cu(Ni)/AuSn/Ni joints during reflow. *Progress in Natural Science: Materials International*, 2011. **21**(4): p. 347-354.

[11] Vandevelde, B., et al., Thermal cycling reliability of SnAgCu and SnPb solder joints: A comparison for several IC-packages. *Microelectronics Reliability*, 2007. **47**(2–3): p. 259-265.

[12] Kang, H.-B., et al., Characterization of Interfacial Reaction Layers Formed Between Sn-3.5Ag Solder and Electroless Ni-Immersion Au-Plated Cu Substrates. *Journal of Electronic Materials*, 2008. **37**(1): p. 84-89.

[13] Yoon, J.-W. and S.-B. Jung, Reliability studies of Sn–9Zn/Cu solder joints with aging treatment. *Journal of Alloys and Compounds*, 2006. **407**(1–2): p. 141-149.

[14] Jianbiao Pan, B.J.T., Tzu-Chien Chou, Wesley J. Dee, Effect of Reflow Profile on SnPb and SnAgCu Solder Joint Shear Force. 2005.

[15] Tsao, L.C., Suppressing effect of 0.5wt.% nano-TiO2 addition into Sn–3.5Ag–0.5Cu solder alloy on the intermetallic growth with Cu substrate during isothermal aging. *Journal of Alloys and Compounds*, 2011. **509**(33): p. 8441-8448.

[16] Rizvi, M.J., et al., Effect of adding 0.3wt% Ni into the Sn–0.7;wt% Cu solder: Part II. Growth of intermetallic layer with Cu during wetting and aging. *Journal of Alloys and Compounds*, 2007. **438**(1–2): p. 122-128.

[17] Nurmi, S., et al., The effect of solder paste composition on the reliability of SnAgCu joints. *Microelectronics Reliability*, 2004. **44**(3): p. 485-494.

[18] Zhang, X.P., et al., Creep and fatigue behaviors of the lead-free Sn–Ag–Cu–Bi and Sn60Pb40 solder interconnections at elevated temperatures. *Journal of Materials Science*: Materials in Electronics, 2007. **18**(6): p. 665-670.

[19] Chen, W.M., S.K. Kang, and C.R. Kao, Effects of Ti addition to Sn–Ag and Sn–Cu solders. *Journal of Alloys and Compounds*, 2012. **520**(0): p. 244-249.

[20] Yoon, J.-W., S.-W. Kim, and S.-B. Jung, Interfacial reaction and mechanical properties of eutectic Sn–0.7Cu/Ni BGA solder joints during isothermal long-term aging. *Journal of Alloys and Compounds*, 2005. **391**(1–2): p. 82-89.

[21] Yoon, J.-W., S.-W. Kim, and S.-B. Jung, Effects of reflow and cooling conditions on interfacial reaction and

IMC morphology of Sn–Cu/Ni solder joint. *Journal of Alloys and Compounds*, 2006. **415**(1–2): p. 56-61.

[22] Yoon, J.-W. and S.-B. Jung, High temperature reliability and interfacial reaction of eutectic Sn–0.7Cu/Ni solder joints during isothermal aging. *Microelectronics Reliability*, 2006. **46**(5–6): p. 905-914.

[23] Yoon, J.-W., B.-I. Noh, and S.-B. Jung, Effects of third element and surface finish on interfacial reactions of Sn–Ag–xCu (or Ni)/(Cu or ENIG) solder joints. *Journal of Alloys and Compounds*, 2010. **506**(1): p. 331-337.

[24] Laurila, T., V. Vuorinen, and J.K. Kivilahti, Interfacial reactions between lead-free solders and common base materials. *Materials Science and Engineering*: R: Reports, 2005. **49**(1–2): p. 1-60.

[25] Dutta, I., P. Kumar, and G. Subbarayan, Microstructural coarsening in Sn-Ag-based solders and its effects on mechanical properties. *JOM*, 2009. **61**(6): p. 29-38.

[26] Lifeng, W., et al. Morphology and growth mechanisms of SAC305-xNi/pad joints intermetallic compounds. in *Electronic Packaging Technology & High Density Packaging (ICEPT-HDP), 2010 11th International Conference on*. 2010.

[27] Yong-Sung, P., et al. Effect of Sb addition in Sn-Ag-Cu solder balls on the drop test reliability of BGA packages with electroless nickel immersion gold (ENIG) surface finish. in *Electronic Materials and Packaging, 2007. EMAP 2007. International Conference on*. 2007.

[28] Shnawah, D.A., M.F.M. Sabri, and I.A. Badruddin, A review on thermal cycling and drop impact reliability of SAC solder joint in portable electronic products. *Microelectronics Reliability*, 2012. **52**(1): p. 90-99.

[29] Tay, S.L., et al., Influence of Ni nanoparticle on the morphology and growth of interfacial intermetallic compounds between Sn–3.8Ag–0.7Cu lead-free solder and copper substrate. *Intermetallics*, 2013. **33**(0): p. 8-15.

[30] Yoon, J.-W. and S.-B. Jung, Effect of surface finish on interfacial reactions of Cu/Sn–Ag–Cu/Cu(ENIG) sandwich solder joints. *Journal of Alloys and Compounds*, 2008. **448**(1–2): p. 177-184.

[31] Liu, X.D., et al., Effect of graphene nanosheets reinforcement on the performance of Sn-Ag-Cu lead-free solder. *Materials Science and Engineering: A*, 2013. **562**(0): p. 25-32.

[32] Gain, A.K. and Y.C. Chan, The influence of a small amount of Al and Ni nano-particles on the microstructure, kinetics and hardness

of Sn–Ag–Cu solder on OSP-Cu pads. *Intermetallics*, 2012. **29**(0): p. 48-55.

[33] Shnawah, D.A.-A., et al., Novel Fe-containing Sn–1Ag–0.5Cu lead-free solder alloy with further enhanced elastic compliance and plastic energy dissipation ability for mobile products. *Microelectronics Reliability*, 2012. **52**(11): p. 2701-2708.

[34] Lin, F., et al., Evolution of Ag3Sn at Sn–3.0Ag–0.3Cu–0.05Cr/Cu joint interfaces during thermal aging. *Journal of Alloys and Compounds,* 2011. **509**(23): p. 6666-6672.

[35] Luo, Z.B., et al., Revisiting mechanisms to inhibit Ag_3Sn plates in Sn–Ag–Cu solders with 1.0wt.% Zn addition. *Journal of Alloys and Compounds*, 2010. **500**(1): p. 39-45.

[36] Shnawah, D.A.-A., et al., Microstructure, mechanical, and thermal properties of the Sn–1Ag–0.5Cu solder alloy bearing Fe for electronics applications. *Materials Science and Engineering: A*, 2012. **551**(0): p. 160-168.

[37] Choi, H., et al., Improved strength of boron-doped Sn-1.0Ag-0.5Cu solder joints under aging conditions. *Intermetallics*, 2012. **20**(1): p. 155-159.

[38] Gao, L., et al., Effect of alloying elements on properties and microstructures of SnAgCu solders. *Microelectronic Engineering*, 2010. **87**(11): p. 2025-2034.

[39] Chuang, C.M., T.S. Lui, and L.H. Chen, Effect of aluminum addition on tensile properties of naturally aged Sn-9Zn eutectic solder. *Journal of Materials Science*, 2002. **37**(1): p. 191-195.

[40] Zhang, L., et al., Development of Sn–Zn lead-free solders bearing alloying elements. *Journal of Materials Science: Materials in Electronics,* 2010. **21**(1): p. 1-15.

[41] Wu, C.M.L., et al., Properties of lead-free solder alloys with rare earth element additions. *Materials Science and Engineering: R:* Reports, 2004. **44**(1): p. 1-44.

[42] Lin, H.-J. and T.-H. Chuang, Effects of Ce and La Additions on the Microstructure and Mechanical Properties of Sn-9Zn Solder Joints. *Journal of Electronic Materials*, 2010. **39**(2): p. 200-208.

[43] Lin, H.-J. and T.-H. Chuang, Effects of Ce and Zn additions on the microstructure and mechanical properties of Sn–3Ag–0.5Cu solder joints. *Journal of Alloys and Compounds*, 2010. **500**(2): p. 167-174.

[44] Lee, H.-Y. and J.-G. Duh, Influence of Ni concentration and Ni3Sn4 nanoparticles on morphology of Sn-Ag-Ni solders by mechanical alloying.

Journal of Electronic Materials, 2006. **35**(3): p. 494-503.

[45] Dudek, M.A. and N. Chawla, Effect of Rare-Earth (La, Ce, and Y) Additions on the Microstructure and Mechanical Behavior of Sn-3.9Ag-0.7Cu Solder Alloy. *Metallurgical and Materials Transactions A*, 2010. **41**(3): p. 610-620.

[46] Yu, A.M., et al. Tensile properties and drop/shock reliability of Sn-Ag-Cu-In based solder alloys. in *Electronics Packaging Technology Conference, 2009. EPTC '09. 11th.* 2009.

[47] Zeng, G., et al., A review on the interfacial intermetallic compounds between Sn–Ag–Cu based solders and substrates. *Journal of Materials Science: Materials in Electronics*, 2010. **21**(5): p. 421-440.

[48] Müller, W.H., Morphology changes in solder joints—experimental evidence and physical understanding. *Microelectronics Reliability*, 2004. **44**(12): p. 1901-1914.

[49] Bae, K.S. and S.J. Kim, Interdiffusion analysis of the soldering reactions in Sn-3.5Ag/Cu couples. *Journal of Electronic Materials*, 2001. **30**(11): p. 1452-1457.

[50] Sang-Su Ha, J.P.a.S.-B.J., Effect of Pd Addition in ENIG Surface Finish on Drop Reliability of Sn-Ag-Cu Solder Joint. 2011.

[51] Yoon, J.-W. and S.-B. Jung, Effect of isothermal aging on intermetallic compound layer growth at the interface between Sn-3.5Ag-0.75Cu solder and Cu substrate. *Journal of Materials Science*, 2004. **39**(13): p. 4211-4217.

[52] Lee, Y.G. and J.G. Duh, Characterizing the formation and growth of intermetallic compound in the solder joint. *Journal of Materials Science*, 1998. **33**(23): p. 5569-5572.

[53] Mavoori, H. and S. Jin, Dispersion strengthening for dimensional stability in low-melting-point solders. *Journal Of Material*, 2000. **52**(6): p. 30-32.

[54] Mavoori, H. and S. Jin, New, creep-resistant, low melting point solders with ultrafine oxide dispersions. *Journal of Electronic Materials*, 1998. **27**(11): p. 1216-1222.

[55] Liu, P., P. Yao, and J. Liu, Evolutions of the interface and shear strength between SnAgCu–xNi solder and Cu substrate during isothermal aging at 150°C. *Journal of Alloys and Compounds*, 2009. **486**(1–2): p. 474-479.

[56] Laurila, T., et al., Effect of Ag, Fe, Au and Ni on the growth kinetics of Sn–Cu intermetallic compound layers. *Microelectronics Reliability*, 2009. **49**(3): p. 242-247.

[57] El-Daly, A.A., et al., Microstructure, mechanical properties, and deformation behavior of Sn–1.0Ag–

0.5Cu solder after Ni and Sb additions. *Materials & Design,* 2013. **43**(0): p. 40-49.

[58] Zhenqing, Z., et al. The influence of low level doping of Ni on the microstructure and reliability of SAC solder joint. in *Electronic Packaging Technology & High Density Packaging, 2008. ICEPT-HDP 2008. International Conference on.* 2008.

[59] Yu, C.-Y., et al., Effects of Minor Ni Doping on Microstructural Variations and Interfacial Reactions in Cu/Sn-3.0Ag-0.5Cu-xNi/Au/Ni Sandwich Structures. *Journal of Electronic Materials,* 2010. **39**(12): p. 2544-2552.

[60] A. Ourdjini, I.S.R.A., Y.T. Chin, Effect of Nickel Addition into Sn-3Ag-0.5Cu on Intermetallic Compound Formation during Soldering on copper. 2012.

[61] Shi, Y., et al., Effects of small amount addition of rare earth Er on microstructure and property of SnAgCu solder. *Journal of Alloys and Compounds,* 2008. **453**(1–2): p. 180-184.

[62] Gao, F., T. Takemoto, and H. Nishikawa, Effects of Co and Ni addition on reactive diffusion between Sn–3.5Ag solder and Cu during soldering and annealing. *Materials Science and Engineering: A,* 2006. **420**(1–2): p. 39-46.

[63] Nogita, K., C.M. Gourlay, and T. Nishimura, Cracking and phase stability in reaction layers between Sn-Cu-Ni solders and Cu substrates. *Journal Of Materials,* 2009. **61**(6): p. 45-51.

[64] Wang, Y.W. and C.R. Kao. Development of lead-free solders with superior drop test reliability performance. in *Electronic Packaging Technology & High Density Packaging, 2009. ICEPT-HDP '09. International Conference on.* 2009.

[65] Vuorinen, V., et al., Solid-State Reactions between Cu(Ni) Alloys and Sn. *Journal of Electronic Materials,* 2007. **36**(10): p. 1355-1362.

[66] Tsai, J.Y., et al., A study on the reaction between Cu and Sn3.5Ag solder doped with small amounts of Ni. *Journal of Electronic Materials,* 2003. **32**(11): p. 1203-1208.

[67] Cheng, F., H. Nishikawa, and T. Takemoto, Microstructural and mechanical properties of Sn–Ag–Cu lead-free solders with minor addition of Ni and/or Co. *Journal of Materials Science,* 2008. **43**(10): p. 3643-3648.

[68] I. Siti Rabiatull Aisha, A.O., A. Astuty, O. Safoura, Effect of Nickel Doping in Sn-Ag-Cu Solders on Intermetallic Compound Formation with Immersion Silver and Bare Copper Surface Finish. 2010.

[69] Nishikawa, H., J. Piao, and T. Takemoto, Interfacial reaction between Sn-0.7Cu (-Ni) solder and Cu substrate. *Journal of Electronic Materials,* 2006. **35**(5): p. 1127-1132.

[70] Anderson, I.E. and J.L. Harringa, Suppression of void coalescence in thermal aging of tin-silver-copper-X solder joints. *Journal of Electronic Materials,* 2006. **35**(1): p. 94-106.

[71] Gao, F., et al., Microstructure and mechanical properties evolution of intermetallics between Cu and Sn-3.5Ag solder doped by Ni-Co additives. *Journal of Electronic Materials,* 2006. **35**(5): p. 905-911.

[72] Ho, C.E., S.C. Yang, and C.R. Kao, Interfacial reaction issues for lead-free electronic solders, in *Lead-Free Electronic Solders*. 2007, Springer US. p. 155-174.

[73] Gao, F., H. Nishikawa, and T. Takemoto, Additive Effect of Kirkendall Void Formation in Sn-3.5Ag Solder Joints on Common Substrates. *Journal of Electronic Materials,* 2008. **37**(1): p. 45-50.

[74] Zhu, W.H., et al. Drop reliability study of PBGA assemblies with SAC305, SAC105 and SAC105-Ni solder ball on Cu-OSP and ENIG surface finish. in *Electronic Components and Technology Conference, 2008. ECTC 2008. 58th.* 2008.

[75] Lee, H.T. and Y.H. Lee, Adhesive strength and tensile fracture of Ni particle enhanced Sn–Ag composite solder joints. *Materials Science and Engineering: A,* 2006. **419**(1–2): p. 172-180.

[76] Lee, Y.-H. and H.-T. Lee, Shear strength and interfacial microstructure of Sn–Ag–xNi/Cu single shear lap solder joints. *Materials Science and Engineering: A,* 2007. **444**(1–2): p. 75-83.

[77] Peng, L. and G. Fu. Effects of Ni particle addition on microstructure and properties of SnAg based composite solders. in *Electronics Packaging Technology Conference, 2006. EPTC '06. 8th.* 2006.

[78] Wang, Y.W., C.C. Chang, and C.R. Kao, Minimum effective Ni addition to SnAgCu solders for retarding Cu3Sn growth. *Journal of Alloys and Compounds,* 2009. **478**(1–2): p. L1-L4.

[79] Wang, C.-h. and H.-t. Shen, Effects of Ni addition on the interfacial reactions between Sn–Cu solders and Ni substrate. *Intermetallics,* 2010. **18**(4): p. 616-622.

[80] Yoon, J.-W. and S.-B. Jung, Effect of immersion Ag surface finish on interfacial reaction and mechanical reliability of Sn–3.5Ag–0.7Cu solder joint. *Journal of Alloys and Compounds,* 2008. **458**(1–2): p. 200-207.

[81] Peng, W., E. Monlevade, and M.E. Marques, Effect of thermal aging on the interfacial structure of SnAgCu solder joints on Cu. *Microelectronics Reliability*, 2007. **47**(12): p. 2161-2168.

[82] Wang, Y.W., Y.W. Lin, and C.R. Kao, Kirkendall voids formation in the reaction between Ni-doped SnAg lead-free solders and different Cu substrates. *Microelectronics Reliability*, 2009. **49**(3): p. 248-252.

[83] Wang, S.J. and C.Y. Liu, Study of interaction between Cu-Sn and Ni-Sn interfacial reactions by Ni-Sn3.5Ag-Cu sandwich structure. *Journal of Electronic Materials*, 2003. **32**(11): p. 1303-1309.

[84] Sigelko, J., et al., The effect of small additions of copper on the aging kinetics of the intermetallic layer and intermetallic particles of eutectic tin-silver solder joints. *Journal of Electronic Materials*, 2000. **29**(11): p. 1307-1311.

[85] Lee, H.-T., et al., Reliability of Sn–Ag–Sb lead-free solder joints. *Materials Science and Engineering: A*, 2005. **407**(1–2): p. 36-44.

[86] Chun, H.-S., J.-W. Yoon, and S.-B. Jung, Solid-state interfacial reactions between Sn–3.5Ag–0.7Cu solder and electroless Ni-immersion Au substrate during high temperature storage test. *Journal of Alloys and Compounds*, 2007. **439**(1–2): p. 91-96.

[87] Nai, S.M.L., J. Wei, and M. Gupta, Interfacial intermetallic growth and shear strength of lead-free composite solder joints. *Journal of Alloys and Compounds*, 2009. **473**(1–2): p. 100-106.

[88] Che, F.X., J.E. Luan, and X. Baraton. Effect of silver content and nickel dopant on mechanical properties of Sn-Ag-based solders. in *Electronic Components and Technology Conference, 2008. ECTC 2008. 58th.* 2008.

[89] Amagai, M. A study of nanoparticles in SnAg-based lead free solders for intermetallic compounds and drop test performance. in *Electronic Components and Technology Conference, 2006. Proceedings. 56th.* 2006.

[90] Kim, K.S., S.H. Huh, and K. Suganuma, Effects of fourth alloying additive on microstructures and tensile properties of Sn–Ag–Cu alloy and joints with Cu. *Microelectronics Reliability*, 2003. **43**(2): p. 259-267.

[91] Anderson, I., Development of Sn-Ag-Cu and Sn-Ag-Cu-X alloys for Pb-free electronic solder applications, in *Lead-Free Electronic Solders*. 2007, Springer US. p. 55-76.

[92] Che, F.X., et al., The study of mechanical properties of Sn–Ag–Cu

lead-free solders with different Ag contents and Ni doping under different strain rates and temperatures. *Journal of Alloys and Compounds,* 2010. **507**(1): p. 215-224.

[93] Lai, Y.-S., et al., Ball Impact Responses of Ni- or Ge-Doped Sn-Ag-Cu Solder Joints. *Journal of Electronic Materials,* 2008. **37**(2): p. 201-209.

[94] Chuang, C.-M. and K.-L. Lin, Effect of microelements addition on the interfacial reaction between Sn-Ag-Cu solders and the Cu substrate. *Journal of Electronic Materials,* 2003. **32**(12): p. 1426-1431.

[95] Chuang, C.-M., P.-C. Shih, and K.-L. Lin, Mechanical strength of Sn-3.5Ag-based solders and related bondings. *Journal of Electronic Materials,* 2004. **33**(1): p. 1-6.