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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

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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.

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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].

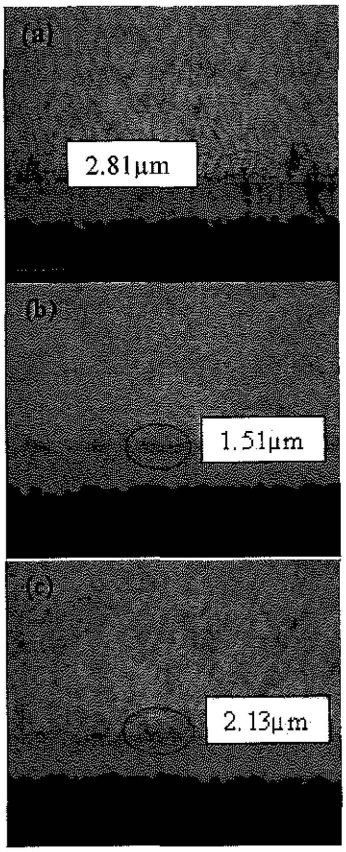

Fig.1. Morphologies of intermetallic after reflow (a) SAC (b) SAC-0.05Ni and (c) SAC-0.1Ni. [60]

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].

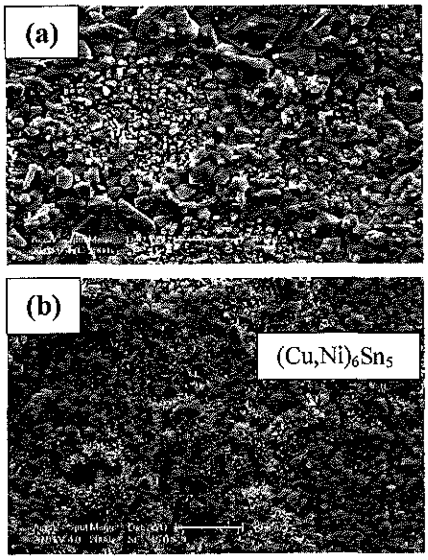

Fig.2. Top view of interface (a) SAC 105 and (b) SAC 105-0.02Ni with NiAu surface finish [58].

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].

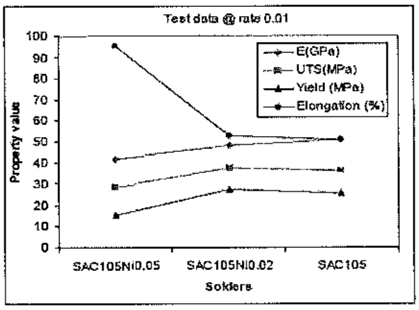

Fig.3. Ni dopant effect on solder material properties [88].

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].

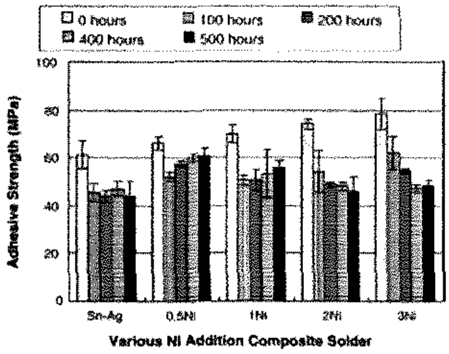

Fig.4. Variation of adhesive strength with Ni addition as function of aging time at 150°C [75].

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].

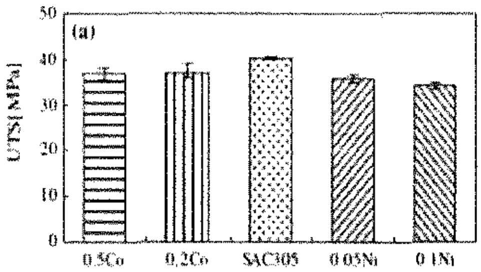

Fig.5. Ultimate tensile strength of SAC 305 alloy and addition of Co and Ni [67].

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.

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