Influence of Thermal Aging on Lead-Free Solder Joints Reliability: A Review

Chang May Shin¹, Mohd Arif Anuar Mohd Salleh¹ and Dewi Suriyani Che Halin¹

¹Centre of Excellence Geopolymer and Green Technology, School of Materials Engineering, Universiti Malaysia Perlis (UniMAP), Taman Muhibbah 02600, Jejawi, Arau, Perlis, Malaysia.

E-mail: cmshin@ymail.com

Abstract. The handheld electronic products currently turning to high density, high performances, and multifunctionality, which sets higher demands on the solder joints reliability in electronic packaging. Because of environmental conscious towards Pb-containing solders, Pb-free solder get attracted wide attention in the electronic industry. Challenges of the Pb-free solders in the microelectronics device are the microstructural evolution influence the mechanical behavior of the solder reliability. This paper analyses a short overview on the progress of the study on the relationship between structure and property, and possible concerns regarding reliability of Pb-free solders joints. Furthermore, the measures to enhance the solder joint reliability are evaluated which contribute to a further theoretical foundation for the research on the solder joints reliability of electronic devices in service life.

1. Introduction

With the advancing in the Pb-free electronics field, electronic packaging technology are progressively moving towards miniaturization, multifunctionality and high integration. As the miniaturization electrical and electronic products trend continues, the decreasing of the solder joints size becomes a most prominent problems in solder joint reliability generate by assembling materials constituents and method varies. Generally, the electronic interconnect of the solder is the weakest structure in the electronic packaging structure and the most probably cause failure. The solder interconnect in the electronic product give electrical contact and heat dissipation pathway within the electronic package [1]. Hence, the reliability of the solder joints in electronic manufacturing can influences the reliability of electronic devices and even the entire electronic system.

The germination and development of excessive IMC layer at the solder and substrate interconnect will cause serious degradation of the joint reliability issue. This is due to the interfacial microstructure of IMC is generally brittle and have weak metallurgical bonding strength [2]. Thus, the microstructural properties, mechanical performances, and failure mode of Pb-free solder connections in electronics packaging remain emerge throughout the service life of the electronic devices.

The temperature differences during the device operation condition can alter the internal structure and internal stress initiate in the solder joint and cause substantial consequence on the performances of the solder connection which can cause the deterioration of solder joint [3, 4]. Electronic component failure mainly is caused by the failure at the solder joint, so it is essential to investigate the influence of temperature on the reliability of the solder joint throughout the component service life in the specific condition, so as to evaluate the lifetime of electronic package. This paper writes on the overview of the
study progress on Pb-free solder joints reliability and review the thermal effect on solder joint reliability. This can provide theoretical fundamental for the future research about solder interconnect reliability of electronic package in its service life.

2. Aging effect on the solder joint

As the melted solder interacts with the electronic package substrate, an intermetallic compound (IMC) is developed through solid-state inter-diffusion among the solder system and the substrate. With subsequent aging process, the solder joint internal structure is coarsening and the interfacial IMC is thickening at the solder joint. The IMC formation causes a volume expansion at the interconnect which readily lead to stress concentration. Thus, stimulate the initiation and enlargement of the crack at the solder joint and eventually cause the electronic devices failure. So, the study of the influence of aging on the solder joints reliability is very important. Several thermal aging studies were done to investigate the isothermal effect on the microstructural behavior and the mechanical properties of the solder joint reliability.

Li et al. [5] found that the thickness of interface Cu$_6$Sn$_5$ IMC at the solder joints Cu/SAC305/Cu in increase significantly with the prolonged of aging time as illustrated in figure 1. The particles of Ag$_3$Sn is a comparatively uniform compound is scattered within the solder connection can improve the metallurgical bonding of the solder strength and fatigue life [6]. With increasing of aging duration, the Ag$_3$Sn particle size increases significantly as shown in figure 1(b–d), consequently cause changing in the motion of revolution in the high-energy discharge area. This phenomenon resulted the rupture behavior of the solder joint change gradually, thus the mechanical reliability of the solder joint is decreasing. Further aging process will cause the precipitation of Cu$_3$Sn phase underneath the Cu$_6$Sn$_5$ layer due to the thermodynamically unstable Cu$_6$Sn$_5$ phase which gives rise to the reaction as shown in figure 1(d).

![Figure 1. SEM images of cross-sectional Cu/SAC305/Cu solder during aging process: (a) 0 hr; (b) 120 hrs; (c) 240 hrs; and (d) 360 hrs [5].](image)

Mustafa et al. [7] disclosed that the fatigue life of Pb-free solder joints drop off continuously during the prolonged of aging process. This is because the coarsening of IMC and grains formed are increasing
during the progression of aging. These IMCs are brittle phase which is easily lead to stress concentration, cause grain coarsening and recrystallization in the high-strain area, crack induced along the grain boundary joint, thus cause decreasing greatly in the solder joints fatigue life.

Wang et al. [8] revealed that the significant reduction in tensile and shear strength of the SAC305 solder joints with rising isothermal aging time. This is because of the coarsening of the solder microstructure that developed from the atomic diffusion rate increases in the solder alloy with increasing of isothermal aging time cause alternation of the internal structure and internal stress. This condition will cause the substantial consequence on the performances of the solder connection which can cause the solder joint failure. Yet, during the initial phase of aging, the solder joints tensile strength is increased slightly because of the development of the interfacial IMC are inhibited because of the restraining process of the solder and substrate structure [9].

3. Metallurgical methods in retarding aging effects on the solder joints

Aging process can change the microstructural properties of the bulk solder and the solder interconnect, hence negatively impact the solder mechanical behavior. Based on the results of recent researches have been done, incorporation of alloying element or metal particles in the solder alloys can enhance specific or entire performances of the solder [10-16], thus decreasing the impact of aging on solder joint reliability. Liu and Lee [11] discussed the effect of alloying small amounts elements (Mn, Ce, Ti, Bi, and Y) on the impact test properties, creep resistance properties, and microstructural properties to family of SAC solder interconnect on electroplated Ni/Au. It revealed that of these modified solder alloys have shown significantly higher impact strength. Additionally, it was found that the alloying of these elements has negligible effect on the original SAC solder alloys melting properties which proves that the alloying of SAC solder can be applied at the similar processing environments with conventional SAC alloys.

De Sousa, et al. [15] explored the small quantities of Co, Fe, In, Ni, Zn and Cu elements doping had comparable effects on the interphase IMC germination and growth, solidification properties, solder behavior, and interphase void creation at the cathode-anode sites of SAC305 solder and Cu substrate. However, Zn doping can notably decrease the precipitation rate of Cu3Sn, the Cu pad depletion rate, and formation of Kirkendall void along the interconnect the thermal aging process. Tang et al. [17] disclosed the alloying of TiO2 nanoparticles can significantly constrain the development of IMC at the SAC305 solder joint interface at thermal aging process. This is because of the incorporation of TiO2 nanoparticles can increases the IMC phase activation energy and decreases the atomic inter-diffusion rate of the Cu atoms and Sn atoms, thereby obviously impeding the IMC germination and development.

Kanlayasiri et al. [18] discovered that the precipitation ratio between Cu3Sn precipitation layer and Cu6Sn5 precipitation layer reduced effectively with the increase of In addition in the small-silver (Ag) content in the SAC solder interconnect throughout the aging process. The incorporation of In obviously hinders the precipitation of the Cu3Sn IMC, thus greatly enhance the strength of the solder interconnect. Che et al. [12] concluded that doped 0.05 wt.% of Ni into SAC105 alloys showed greater elongation on the mechanical strength of SAC solders, nevertheless lower modulus, yield strength and ultimate tensile strength. Associated study by Guo, et al. [14] also described the incorporated of Ni particles can effect on the mechanical performances and microstructural behavior of Pb-free solders under thermal aging process. Gain et al. [19] discovered that the incorporation of 3% mass fraction Al nanoparticles can greatly enhance the mechanical strength of SAC solder interconnect. This is mainly due to the incorporation of the 3% of Al nanoparticles suppress the thickening of the IMC precipitation on the interconnection of the solder joint, the brittle structure of the IMC precipitation is effectively diminished and the mechanical shear strength of the solder interconnect is improved.

Cu is commonly applied as a substrate in the electronic industries because of it good solderability and thermal conductivity. The Sn-based solder will react fast with the bare Cu substrate and form Cu6Sn5 IMC precipitation at the interconnection phase. In order to constrain the germination and growth rate of the interfacial IMC, the elements such as Ni, Ag, and Au can be electroplated on Cu substrate. On Ni plated Cu, Ni can serve as a barrier and can impede the reaction among solder and Cu, thus resulting the formation of the interfacial IMC is slower [20, 21]. Ag or Au plated on Ni substrates, can constrain the
motion of reactions between Ni atom and Sn atom to create Ni₃Sn₄, thus the IMC thickness is comparatively low compared to Ni electroplated substrates [23]. The electroless Ni/immersion Au plating is also widely applied in the research studies as its excellent wetting properties. The deposition of Au can protect the Cu substrate surface from corrosion and oxidation. The electroless Ni deposition can greatly decrease the atomic diffusion rate of Cu atom and Sn atom [22-24].

Besides, the incorporation of alloying elements to the Cu substrate can alter the internal structure of the substrate, therefore enhancing the properties of the Cu substrate. Maeshima et al. [25] discovered that the incorporation of optimum amount of Ni element on Cu substrates can effectively retard the development of IMC. This is because the Ni element transform the IMC layer to the (Cu₁₋ₓNiₓ)₆Sn₅ layer along the Cu substrate, thus retarding the development of the IMC thru the thermal aging process and enhancing the mechanical strength of the solder interconnect. Yet, if incorporation of Ni content too much, it can cause loose IMC precipitate at the solder connection interface, causing the deterioration of solder joint strength consequently the degrade the reliability of solder joints.

Annealing the substrate before soldering can alter its microstructure, hence retarding the development of IMC and enhancing the solder joints mechanical properties. Kim et al. [25] reported the annealing of Cu substrate can significantly constrain the development of interfacial IMC phase. The Cu substrate grain structure is refined throughout the annealing process, where the microstructure is more homogeneous and regular in size. Besides, the internal stress induced and the defects within the Cu substrate structure are removed during the annealing process, thus can adequately decrease the diffusion rate of Cu atoms with the solder alloy, thus inhibiting the development of the interfacial IMC phase.

4. Summary
In view of the very rapid market growth in consumer electronic products, the packaging of these handheld devices needs smaller solder joints. Although tremendous venture on the research studies of the Pb-free solder joint for electronic manufacturing has been carried out, and certain results are accomplished. But the reliability of the metal interconnection materials is still remaining in the experimental research stage and problematic in replacing the traditionally leaded solder have been used in the electronic assembling industries. All the IMC structure at the solder joint will coarsen with increasing of aging temperature and time. The IMC phase are brittle and need mechanical strengthening. The studies have been done on strengthening the mechanical performances of the solder by alloying or metal particle strengthening of the solder alloy or the metal substrate, and annealing the metal substrate to improve the mechanical performances of the solder especially by retarding the IMC formation. However, the properties of lead-free still cannot meet as the leaded solder especially for advance applications. To further improve the properties of the lead-free solders, future development like superconducting solder can be carried out in the electronic industries. The relationships between the structure-performance of the Pb-free superconducting solder and potential reliability problems of Pb-free superconducting solders joints formed in various service environments is required.

References
[1] Lee H, Kim C, Heo C, Kim C, Lee J H and Kim Y 2018 *Microelectron. Reliab.* 87 6
[2] Choubey A, Yu H, Osterman M, Pecht M, Yun F, Yonghong Land Ming X 2008 *J. Electron. Mater.* 37 1130
[3] Zhu Y, Li X, Gao R and Wang C 2014 *J. Mater. Sci.: Mater. Electron.* 25 1167
[4] Thompson P B, Johnson R and Nadimpalli S P V 2018 *Eng. Fract. Mech.* 199 730
[5] Li Y, Long W, Hu X and Fu Y 2018 *Materials (Basel)* 11 11
[6] Tian Y, Ren N, Jian X, Shang S and Sitaraman S K 2018 *Sci Technol Weld Joi* 23 940
[7] Mustafa M, Suhling J C and Lall P 2016 *Microelectron. Reliab.* 56 136
[8] Wang J and Nishikawa H 2014 *Microelectron. Reliab.* 54 435
[9] Li X, Li F, Guo F and Shi Y 2011 *J. Electron. Mater.* 40 687
[10] Anderson I E and Harringa J L 2006 *J. Electron. Mater.* 35 479
[11] Liu W and Lee N C *JOM.* 59 (2007)
[12] Che FX, Luan J E and Baraton X. 2008 Electronic Components and Technology Conf. (USA: Lake Buena Vista, FL) p 485
[13] Wade N, Wu K, Kunii J, Yamada S and Miyahara K 2001 J. Electron. Mater. 30 739
[14] Guo F, Lee J, Choi S, Lucas J P, Bieler T R and Subramanian K N 2001 J. Electron. Mater. 30 1268
[15] Song J M, Huang C F and Chuang H Y 2006 J. Electron. Mater. 35 2154
[16] Wang F J, Gao F, Ma X and Qian Y Y 2006 J. Electron. Mater. 35 1818
[17] Tang Y, Li GY, and Pan Y C 2013 J. Alloys Compd. 554 195
[18] Kanlayasiri K and Sukpimai K 2016 J. Alloys Compd. 668 169
[19] Gain A K, Fouzder T, Chan Y C, Sharif A, Wong N B and Yung W K C 2010 J. Alloys Compd. 506 216
[20] A R Irfan, M Z M Zarhamdy, S M S Saad, H M Hafiz, A Azlida 2018 AIP Conference Proceedings 2030 020312
[21] Yu D Q, Wu C M L, He D P, Zhao N, Wang L and Lai J K L 2005 J. Mater. Res. 20 2205
[22] A R Irfan, M Z M Zarhamdy, S M Sazli, H M Hafiz, A Azlida 2018 AIP Conference Proceedings 2030 020313
[23] Yin H, Shen J and Tang Q 2012 Int. Conf. on Electronic Packaging Technology & High Density Packaging (China: Guilin) p 280
[24] Lee YH and Lee H T 2007 Mater. Sci. Eng. 444 75
[25] Maeshima T, Ikehata H, Terui K and Sakamoto Y 2016 Mater. Des. 103 106