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The Limited Reliability of Board-Level SAC Solder Joints under both Mechanical and Thermo-mechanical Loads

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Abstract: The trend of miniaturization, light weight, high speed and multifunction are common in electronic assemblies, especially, for portable electronic products. In particular, board-level solder joint reliability, in term of both mechanical (e.g., drop impact) and thermo-mechanical (e.g., thermal cycling) loads is of great concern for portable electronic products. The transition to lead-free solder happened to coincide with a dramatic increase in portable electronic products. Sn–Ag–Cu (SAC) is now recognized as the standard lead-free solder alloy for packaging interconnects in the electronics industry. Hence, this study review the reliability of board-level SAC solders joints when subjected to drop impact and thermal cycling loading conditions **from the viewpoints of mechanical and micro-structural properties of the bulk solder**. The finding presented in this study indicates that the best SAC composition for drop performance is not necessarily the best composition for optimum thermal cycling reliability, thus the SAC solder alloys are limited in their potential applications in the electronic industries. This contribution has its value in giving information on possible developments and the suitability for the usage of SAC solder in portable electronic devices.

Keywords: SnAgCu solders, silver content, mechanical properties, microstructure properties, thermal cycling, drop impact

Spoji pri mehaničnih in termo-mehaničnih obremenitvah

Izvleček: Trend miniaturizacije, nižja teže, višje hitrosti in večopravilnosi so običajni v elektronskih sestavih, posebej pri prenosnih elektronskih izdelkih. Zanesljivost spajkanega spoja v smislu mehanične (npr. vpliv padca) in termomehanične (termično ciklanje) obremenitve je poglavitnega pomena pri prenosnih elektronskih izdelkih. Prehod na spajko brez svinca se je zgodil istočasno z drastičnim povečanjem prenosnih elektronskih izdelkov. Zlitina Sn-Ag-Cu (SAC) danes predstavlja običajno spajko brez svinca v industriji elektronike. Pričujoča raziskava podaja pregled zanesljivosti spajkanih spojev pri obremenitvah zaradi padcev ali termičnih ciklanj v smislu mehaničnih in mikrostrukturnih lastnosti spajke. Predstavljene ugotovitve nakazujejo, da najboljša SAC zlitina pri vplivih padcev ni nujno tudi najbolj zanesljiva pri termičnem ciklanju, zaradi česar so SAC zlitine omejene na določene aplikacije v elektronski industriji. Ta prispevek podaja informacijo o možnih razvojih in ustreznostih uporabe SAC zlitin v prenosnih elektronskih izdelkih.

Ključne besede: SnAgCu spajke, vsebnost srebra, mehanične lastnsoti, mikrostrukturne lastnosti, termično ciklanje, vpliv padca

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1. Introduction

Currently, the trend in portable electronic products such as the handheld computer, mobile phone, Personal Digital Assistant (PDA) and digital camera toward miniaturization and multi-functionality, has led to electronic packages with higher density and smaller dimension, e.g. the smaller solder interconnections of Ball Grid Array (BGA) and Chip Scale Package (CSP) (Zhang, Ding et al. 2009). For portable electronic products, board-level solder joint reliability due to drop impact load and thermal cycling load is of great concern. The mechanical loads resulting from mishandling during transportation or customer usage may cause solder joint failure, which leads to malfunctioning of the product. Normally, mobile phones are designed to withstand a number of accidental drops to the floor from a height of 1.5 m, without resulting in major mechanical or functional failures (Tee, Ng et al. 2003). Besides, during use, portable electronic products are subject to temperature cycles load, induced by environmental temperature change and power on-off cycles. A typical temperature cycling test condition of -40°C to 125°C is required to ensure a reliable package performance (Tee, Ng et al. 2003; Zhang, Ding et al. 2009). There are few publications related to integrated design analysis of board-level solder joint reliability, with consideration of both drop impact load and thermal cycling load performance simultaneously.

Overall solder joint reliability is determined by the combination of service environment and system design. The service environment will determine the temperature extremes which the product must endure, the frequency of power on / off cycling, and the possibility of specific mechanical shocks (for example, drop impact) stresses. Where the system design is concerned, a series of factors that include component and substrate physical properties, solder joint geometry, bulk solder alloy microstructure and mechanical properties, the nature of the IMC layer formed and their structure at the solder joint / pads interfaces are important. Cost limitations add additional constraints, forcing hard choices to be made (Tu 2007). The robustness of a solder joint subjected to both temperature cycles load and drop impact load is influenced by a complex combination of bulk solder alloy properties and IMC layer properties (Grafe, Garcia et al. 2008). For bulk solder alloys, eutectic tin-lead, with its long established history, has been replaced with the complexity of a multitude of new and unfamiliar lead-free alloys. SAC is now recognized as the standard lead free solder alloy for packaging interconnects in the electronics industry. However, Sn-Ag-Cu alloys are not enough to meet high solder joint reliability under different loading conditions. This study present the direct correlation between mechanical and microstructure properties of SAC bulk solder alloy and the reliability of SAC solder joints in term of both drop impact and thermal cycling loading conditions.

2. Sn–Ag–Cu lead-free solders series

Of the many lead-free solder series proposed in the last decade or so, Sn–Ag–Cu (SAC) series alloys have emerged as the most widely accepted as shown in Figure 1 Soldertec's survey shows that the most popular SAC are the near eutectic SAC alloys (Nimmo 2002), which consist of 3.0–4.0% of Ag and 0.5–1.0% of copper as shown in Figure 2. The melting point of these near eutectic SAC alloys is 217°C, which is lower than the 96.5Sn–3.5Ag binary eutectic alloy at 221°C. In the SAC system, the addition of Cu both lowers the melting temperature and improves the wettability (K. Nimmo 2004). Figure 3 is the top view (2-D) of the ternary phase diagram of Sn–Ag–Cu (Ma and Suhling 2009). The area indicated in the red box is the near eutectic region. Most of the SAC alloy compositions currently in the market are within this region.

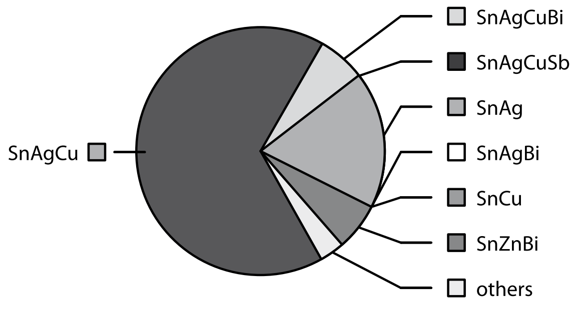


Figure 1: The market share of different lead-free solders (Nimmo 2002).

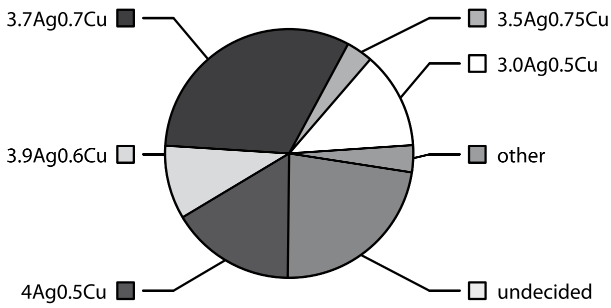


Figure 2: Survey of the market share of different types of SAC alloys (Nimmo 2002).

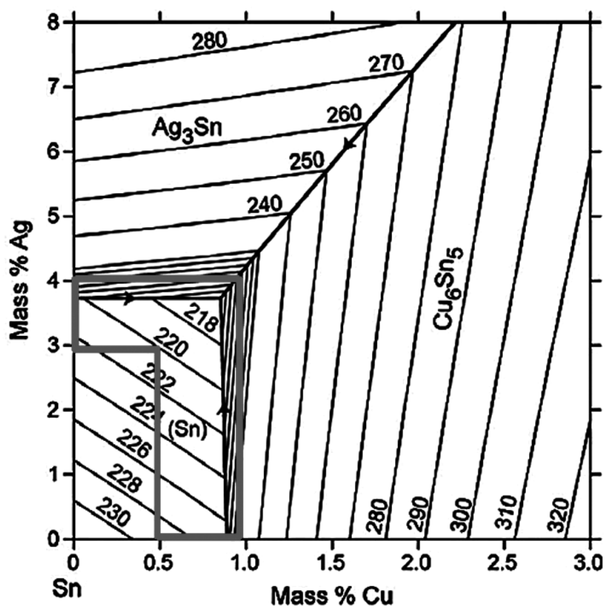


Figure 3: Sn–Ag–Cu ternary phase diagram (Ma and Suhling 2009).

3. Microstructure characteristics and mechanical properties of the Sn-xAg-Cu bulk solder

It is well known that, to a large extent, the micro-structural characteristics of an alloy determine its mechanical performance (Allen 1969; R.F Smallman 1999; Hosford 2005). The microstructure development of a solder joint is affected by the alloy system and process conditions during solder joint formation (Moon, Boettinger et al. 2000; Pang, Tan et al. 2001; Anderson 2007). Therefore, understanding the micro-structural characteristics of the SAC ternary system is essential to understanding the mechanical performance and reliability of Sn-Ag-Cu solders. These properties provide design and manufacturing engineers with the necessary information when deciding on a solder alloy for their specific application.

Silver is an essential element in SAC composition which can have different effects on the solder joint reliability, depending on the loading conditions. Currently, a wide variety of SAC solders containing different levels of silver, and maintaining a Cu level to manage substrate dissolution, such as Sn-1Ag-0.5Cu (SAC105) and Sn-3Ag-0.5Cu (SAC305), have been studied and are in use in the electronics industry for a wide range of applications. Kariya and his coworkers investigated the as-soldered microstructure or initial microstructure of Sn-xAg-Cu shown in Figure 4 (Kariya, Hosoi et al. 2004). They found that the microstructures of Sn-x Ag-Cu alloy consisted of a β-Sn matrix with dispersoids of fine Ag_3Sn and coarsened Cu_6Sn_5 inter-metallic compounds (IMC particles) (Terashima, Kariya et al. 2003; Kariya, Hosoi et al. 2004). The size of the IMC particles varied from submicron to several microns for all alloys, which is a common feature of the Sn-xAg-Cu alloys (Kariya and Plumbridge 2001). Volume fraction of the Ag_3Sn IMC particles in the microstructure tends to increase with increasing silver content. In the microstructure of SAC105, relatively large primary Sn grains and the Ag_3Sn IMC particles appeared sparsely within the matrix (Terashima, Kariya et al. 2003; Kariya, Hosoi et al. 2004). The SAC205 had cell-like primary Sn grains, and the grains were decorated with the very fine Ag_3Sn IMC particles. In the SAC305, the Ag_3Sn IMC particles formed a network structure around the primary Sn grains, and the size of the Sn grains was larger than that of the 2Ag solder. In the SAC405 alloy, the Ag_3Sn IMC particles compounds were finely dispersed within the matrix, and the inter-particle distance was smaller than that in other alloys (Terashima, Kariya et al. 2003; Kariya, Hosoi et al. 2004).

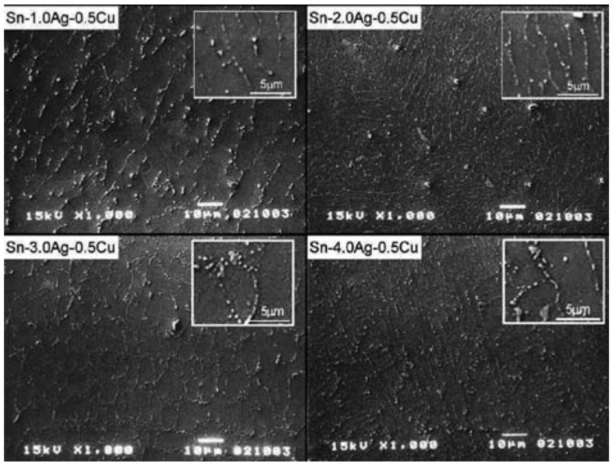


Figure 4: The initial microstructure of Sn-xAg-Cu bulk solders (Kariya, Hosoi et al. 2004).

The Ag_3Sn and Cu_6Sn_5 IMC particles possess much higher strength than the bulk material in SAC solder (R. J. Fields ; Tsai, Tai et al. 2005), while primary Sn has the lowest elastic modulus and lowest yield strength among the constituent phases in SAC solder (Kim, Suh et al. 2007; Suh, Kim et al. 2007), as shown in Table 1 (Kim, Suh et al. 2007). Fine IMC particles in the Sn matrix can therefore strengthen the alloys (S. Ganesan 2006). The number or volume fraction of the Ag_3Sn IMC particles in the microstructure of SAC solder alloy tends to increase with increasing silver content as shown in Figure 4 (Terashima, Kariya et al. 2003; Kariya, Hosoi et al. 2004); hence, high Ag content SAC solder (SAC305/SAC405) yields large numbers of Ag_3Sn IMC particles and small size of primary Sn grains. Therefore this is expected to increase the elastic modulus and yield strength and reduce the ductility of the solder (Che, Luan et al. 2008; Che, Zhu et al. 2010), as shown in Table 2 (Henshall, Healey et al. 2009). On the other hand, low Ag content SAC alloy (SAC105) gives rise to more primary Sn phase (large Sn grains) and decreased number of Ag_3Sn IMC particles as shown in Fig. 1. It is therefore expected to result in lower elastic modulus and lower yield strength than high Ag content SAC alloy (SAC 305) (Che, Luan et al. 2008; Che, Zhu et al. 2010)[39, 40], as shown in Table 2 (Henshall, Healey et al. 2009).

Table 1: Key material properties of constituent phases in SAC alloys (Henshall, Healey et al. 2009)

Phase	E [GPa]	KIC [MPa√m]	HV [Kg/mm2]
Cu6Sn5	93.5	1.4 to 2.73	351-378
Ag3Sn	74.5	$> Cu_6Sn_5$	142-120
Sn	42-50	Very high	100

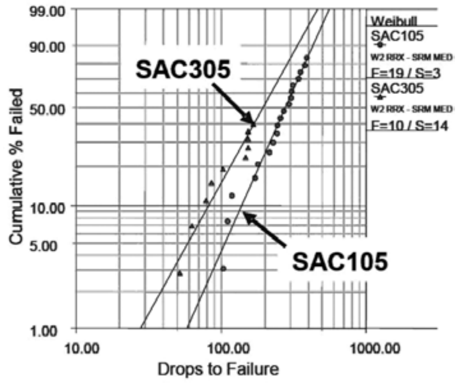
Table 2: Mechanical properties of SAC alloys vs. eutectic SnPb (Henshall, Healey et al. 2009)

Solder alloy	Primary Sn	Modulus (GPa)	Modulus Reduction	UTS (Mpa)	Elon (%)
SAC (4%Ag)	none	53.3	basline	52.4	35
SAC (3%Ag)	10%	51.0	-4%	53.3	46
SAC (1%Ag)	35%	47.0	-12%	45.2	46
Sn-Pb	n/a	40.2	-25%		50

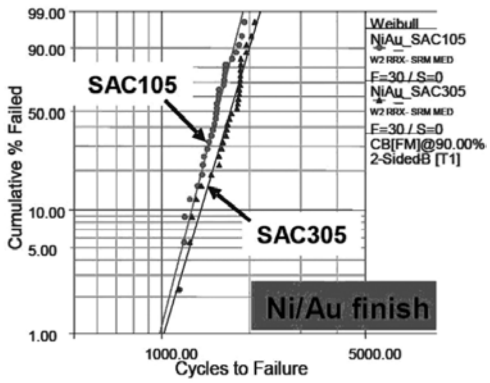
4. Limitation of SAC solder joints

A wide variety of SAC solders containing different levels of silver has been studied and is in use in electronics industry for a wide range of applications currently. The content level of silver in SAC solder alloys can be an advantage or a disadvantage depending on the application, package and reliability requirements (Henshall, Healey et al. 2009), e.g. the best level of silver content for drop performance is not necessarily the best level for optimum temperature cycling reliability (Syed, Scanlan et al. 2008). Hence, the SAC alloys are limited in their potential applications in the portable electronic products in which thermal cycling and drop/impact are the primary requirement for board level solder joint reliability.

The SAC105 and SAC305 solder ball joints for BGA interconnections (board level package) were evaluated under temperature cycling and drop (JESD22-B111) tests. The data indicates that lower silver content solder balls perform better under drop conditions, while temperature cycling reliability suffers as silver content decreases (Syed, Scanlan et al. 2008). In other words, SAC105 solder balls show better performance than SAC305 under drop loading conditions (see Figure 5a). However, the trend is reversed for temperature cycle test (see Figure 5b). The data show how the level of silver content in SAC composition can have a different effect on the board level solder joint performance depending on the loading conditions.



(a) Drop test



(b) Temperature cycle test

Figure 5: Drop and temperature cycling performance for NiAu finish packages.

5. Direct correlation between bulk SAC solder properties and drop impact reliability

Currently, high Ag SAC alloys (SAC305/SAC405) are the most common material systems for the Pb-free board level solder joints in electronic industry. However, these alloys exhibit significantly low robust in terms of high strain rate response such as drop impact conditions due to the lack of the compliance of the bulk solder materials and complex IMC formation at the solder/metal interface (Kim, Suh et al. 2007; Suh, Kim et al. 2007). The root cause of the poor high strain rate response of high Ag SAC alloys (SAC305/SAC405) lies in the bulk alloy properties (Pang and Che 2006; Pandher, Lewis et al. 2007). These high Ag alloys have high yield strength and elastic modulus and low acoustic impedance, resulting in a high bulk solder strength. Therefore under drop impact loading conditions, they more readily transfer stress to the interface IMC layers. The interface IMC layers formed during soldering are of low ductility and it is this interface that exhibits brittle fracture (Pandher, Lewis et al. 2007; Che, Luan et al. 2008; M. P. Renavikar 2008; Che, Zhu et al. 2010; Yu, Jang et al. 2010). The high yield strength and elastic modulus of the high Ag alloys is derived primarily from the precipitation hardening of the tin matrix by the Ag_3Sn IMC particles and fine Sn grain size, result in a strong and stiff bulk solder (Che, Poh et al. 2007).

The first approach to improve the drop impact performance of SAC alloys is to optimize the bulk solder properties by reducing the silver content to as low as Ag < 2 wt% (SAC105) (Syed, Kim et al. 2006; Pandher, Lewis et al. 2007). The low Ag alloys are found to have low yield strength and elastic modulus, and high ductility (Che, Poh et al. 2007; Che, Luan et al. 2008; Che, Zhu et al. 2010). This means low Ag alloys have high elastic compliance and high plastic energy dissipation ability during crack propagation which effectively toughens the crack tip and prolonges the time to reach the critical stress for the fracture under high-strain rate conditions (Kim, Suh et al. 2007). As a result low Ag alloys can dissipate more high strain rate energy through bulk solder deformation and reduce the dynamic stress transformed to interface IMC layers, resulting in good drop impact performance. The low strength properties of low Ag alloys can be attributed to large Sn grain size or more Sn primary phase (see Figure 6) and sparsely distributed Ag_3Sn IMC particles in the bulk alloy matrix, which result in a soft bulk solder (Pandher, Lewis et al. 2007; M.P. Renavikar 2008; Yu, Jang et al. 2010). The shear strength for the SAC family of alloys is shown in Figure 7. Clearly lower Ag alloys have an advantage in potentially absorbing the effect of high strain rate deformation (Pandher, Lewis et al. 2007). The second approach is to optimize the interface reaction to improve the strength of the IMC layer via adding other elements in the SAC system which can effectively modify the interface reaction (Pandher, Lewis et al. 2007; Kittidacha, Kanjanavikat et al. 2008).

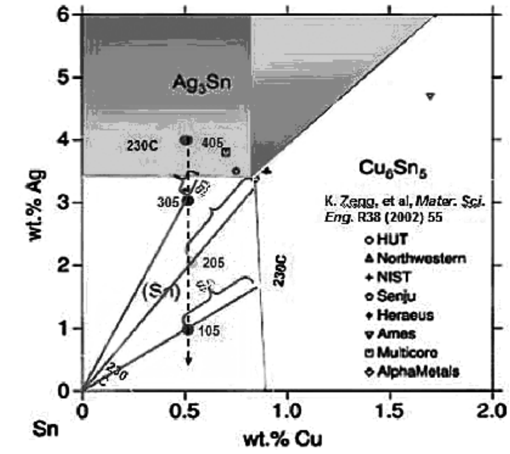


Figure 6: Sn-rich region of Sn-Ag-Cu temary phase diagram. Variation of Ag content (with fixed Cu content of 0.5%) is indicated by vertical line.
The tie line is also shown for representative SAC alloys (Kim, Suh et al. 2007).

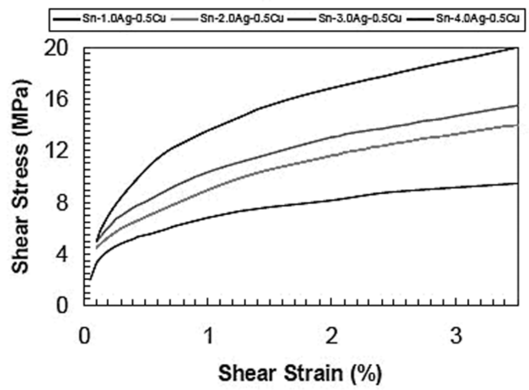


Figure 7: Mechanical (shear) properties of SAC alloys as a function of Ag content (Pandher, Lewis et al. 2007).

6. Direct correlation between bulk SAC solder properties and thermal cycling reliability

The thermal mechanical strain and elevated temperature during thermo-mechanical loading induces re-crystallization in the highly strained region of the bulk solder, leading to the development of thermo-mechanical fatigue cracks in the re-crystallized regions along large angle grain boundaries (Mattila 2005; Frear, Ramanathan et al. 2008). Hence, the degree of the coarsening indicates an accumulation of the strain or the stress imposed by the thermo-mechanical fatigue process.

The optimal silver content in the Sn-x Ag-Cu alloy is of great significance for designing a solder that has greater thermo-mechanical fatigue resistance (Terashima, Kariya et al. 2003). One of the most detailed studies on thermo-mechanical fatigue failure rate of Sn-x Ag-Cu solder joints was conducted by Terashima et al. 2003 who found that increasing Ag content increases the fatigue resistance of SAC solder. Their results, summarized in Figure 8, show that the 1Ag solder had the fastest failure rate while the 4Ag solder had twice the cycles to first failure (No) as the 1Ag solder. They observed that the 3Ag and 4Ag solder joints suppressed micro-structural coarsening, which degrades fatigue resistance, whereas a significant micro-structural coarsening occurs in the 1Ag and 2Ag solders because of the thermo-mechanical fatigue process. As compared with Figures 9 and 10, the Sn grains were coarsened, and the number of the Ag_3Sn dispersions decreased drastically as a function of the number of thermal cycles compared with the initial microstructures for the 1Ag and the 2Ag solders. While grain coarsening was not significant in the 3Ag and the 4Ag solders, these alloys retained the fine Ag_3Sn dispersions even after thermal cycling.

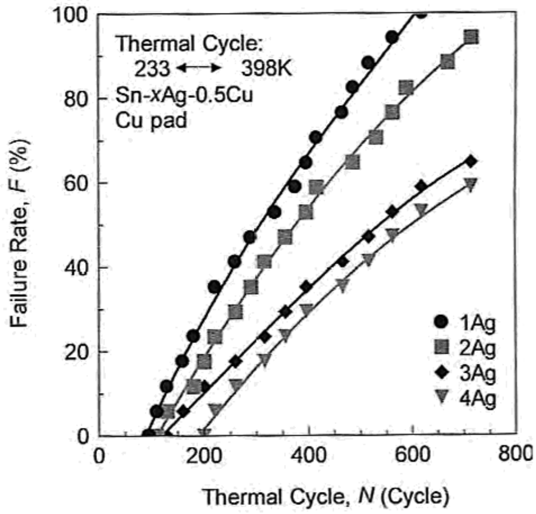


Figure 8: Effect of thermal cycles on the failure rate of Sn-xAg-0.5Cu (x = 1, 2, 3, and 4) solder joints on the Cu pads (Terashima, Kariya et al. 2003).

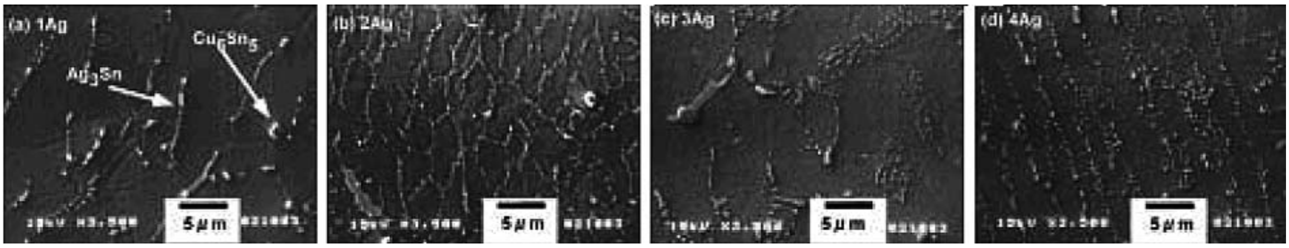


Figure 9: The initial microstructure for each Sn-xAg-0.5Cu solder joint: (a) 1Ag, (b) 2Ag, (c) 3Ag, and (d) 4Ag (Terashima, Kariya et al. 2003).

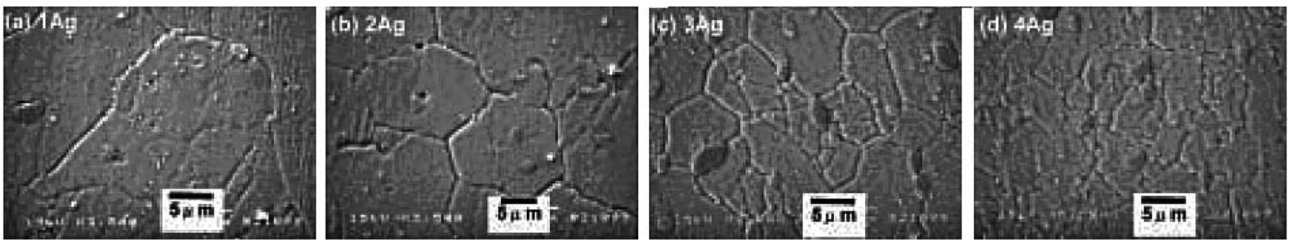


Figure 10: The microstructures at the center area for each Sn-xAg-0.5Cu solder joints after 600 cycles a) 1Ag, (b) 2Ag, (c) 3Ag, and (d) 4Ag (Terashima, Kariya et al. 2003).

It has been reported that the SAC solder has a dispersion or precipitation strengthening mechanism (Kariya, Hirata et al. 1999; Zhang, Li et al. 2002). Thus, the dispersion morphology of the Ag_3Sn IMC particles strongly affects the mechanical properties of the SAC solder. Namely, if the microstructure of an alloy has finely dispersed Ag_3Sn particles like SAC405 solder alloy, the alloy and Sn grains may show high strength bulk solder because of the Orawan looping of dislocations. Moreover, if coarsening of an alloy is inhibited because of the finely dispersed Ag_3Sn, a good fatigue resistance can be expected as a result of suppressing plastic deformation of the solder (Ye, Lai et al. 2001; Subramanian and Lee 2003; Terashima, Kariya et al. 2003; Kariya, Hosoi et al. 2004). Furthermore, if the Ag_3Sn IMC particles form a eutectic network structure around Sn grains like SAC305 solder, a good fatigue resistance can be expected as a result of inhibiting micro-structural coarsening due to Zener pinning effect (Dieter 1981; Subramanian and Lee 2003; Liu, Lee et al. 2009; Terashima, Kohno et al. 2009). In other words, the micro-structural coarsening suppression (grain size stability) can be attributed to the pinning of Sn grains boundary by the fine Ag_3Sn IMC particles due to the atomic matching, or coherency, between the lattices of the precipitates and the matrix. On the other hand, T. Kobayashi and his co-researchers studied the crack propagation morphology of SAC 105 solder joints subjected to a fatigue test. They observed that cracks were nucleated at the interface of primary β-Sn, where eutectic phase is not always observed. Hence the strength of the interface between primary β-Sn to be lower than that of the primary β-Sn interface, filled with the eutectic phase, resulting in poor fatigue resistance of SAC105 solder (Kobayashi, Kariya et al. 2007).

7. Conclusion

The Ag_3Sn and Cu_6Sn_5 IMC particles in the bulk SAC solder have much higher elastic modulus and yield more strength than the bulk material. Large amount of fine Ag_3Sn and Cu_6Sn_5 IMC particles in the Sn matrix can therefore strengthen the bulk SAC solder. On the other hand, among the constituent phases in bulk SAC solder, primary Sn has the lowest elastic modulus and yield strength. The role of Ag and Cu in SAC alloys is a straightforward issue of Cu_6Sn_5 and Ag_3Sn strengthening the Sn matrix. However, a Cu level is maintained to manage substrate dissolution. High Ag content SAC solder (SAC305/SAC405) produce large number of fine Ag_3Sn IMC particles and small sized of Sn primary grains, which make the bulk solder exhibit high strength. This will help to suppress the plastic deformation during the thermo-mechanical fatigue process. Moreover, the large number of fine Ag_3Sn IMC particles in SAC305 bulk solder forms a eutectic network structure around the primary Sn grain and suppresses the grain coarsening, which results in good thermo-mechanical fatigue cracks resistance. However the stiff or strong bulk high Ag solder prevents the drop impact energy from dissipating through the bulk solder, thereby transferring more stress to the interface IMC layers which cause brittle fracture of the solder joint. Low Ag content will decrease the strength and elastic modulus of the solder, transferring less stress to the IMC layers. This is due to increasing the amount of primary Sn relative to the Ag_3Sn and Cu_6Sn_5 phases in the low Ag alloy, which make the bulk solder more compliant. However, the low Ag alloy shows poor thermal cycling reliability due to fewer number of Ag_3Sn IMC particles compared to high Ag alloy. The content level of silver in SAC solder alloys can be an advantage or a disadvantage depending on the application, package and reliability requirements. Hence, it is highly recommended to improve both the strength and ductility of the bulk SAC solder through SAC optimization for optimal solder ball attachments in portable electronic products.

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Reference

1. Allen, D. K. (1969). Metallurgy theory and practice. Homewood, IL USA, American Technical Publishers.
2. Anderson, I. E. (2007). "Development of Sn-Ag-Cu and Sn-Ag-Cu-X alloys for Pb-free electronic solder applications." Lead-Free Electronic Solders: 55-76.
3. Che, F., J. Luan, et al. (2008). Effect of silver content and nickel dopant on mechanical properties of Sn-Ag-based solders, IEEE.
4. Che, F., J. Luan, et al. (2008). Effect of silver content and nickel dopant on mechanical properties of Sn-Ag-based solders. ECTC, IEEE.
5. Che, F., E. C. Poh, et al. (2007). Ag Content Effect on Mechanical Properties of Sn-xAg-0.5 Cu Solders. ECTC, IEEE.
6. Che, F., W. Zhu, et al. (2010). "The study of mechanical properties of Sn-Ag-Cu lead-free solders with different Ag content and Ni doping under different strain rates and temperatures." Journal of Alloys and Compounds.
7. Dieter, G. E. (1981). Mechanical metallurgy. TOKYO, McGRAW-HILL.
8. Frear, D., L. Ramanathan, et al. (2008). Emerging reliability challenges in electronic packaging. Annual International Reliability Physics Symposium, IEEE.
9. Grafe, J., R. Garcia, et al. (2008). "Reliability and Quality Aspects of FBGA Solder Joints." FORSCHUNG & TECHNOLOGIE 10: 2224-2234.
10. Henshall, G., R. Healey, et al. (2009). Addressing opportunities and risks of pb-free solder alloy alternatives, IEEE.
11. Hosford, W. F. (2005). Physical metallurgy. Boca Raton, FL USA, CRC Press, Taylor and Francis Group.
12. K. Nimmo (2004). Alloy selection. New York, Marcel Dekker.
13. Kariya, Y., Y. Hirata, et al. (1999). "Effect of thermal cycles on the mechanical strength of quad flat pack leads/Sn-3.5 Ag-X (X= Bi and Cu) solder joints." Journal of electronic materials 28(11): 1263-1269.
14. Kariya, Y., T. Hosoi, et al. (2004). "Effect of silver content on the shear fatigue properties of Sn-Ag-Cu flip-chip interconnects." Journal of electronic materials 33(4): 321-328.

15. Kariya, Y. and W. Plumbridge (2001). Mechanical properties of Sn-3.0 mass% Ag-0.5 mass% Cu alloy.
16. Kim, D., D. Suh, et al. (2007). Evaluation of high compliant low Ag solder alloys on OSP as a drop solution for the 2nd level Pb-free interconnection, IEEE.
17. Kittidacha, W., A. Kanjanavikat, et al. (2008). Effect of SAC Alloy Composition on Drop and Temp cycle Reliability of BGA with NiAu Pad Finish. ECTC, IEEE.
18. Kobayashi, T., Y. Kariya, et al. (2007). Effect of Ni Addition on Bending Properties of Sn-Ag-Cu Lead-Free Solder Joints. ECTC, IEEE.
19. Liu, W., N. C. Lee, et al. (2009). Achieving high reliability low cost lead-free SAC solder joints via Mn or Ce doping. ECTC, IEEE.
20. M.P. Renavikar, N. P., A. Dani, V. Wakharkar, G. Arrigotti, V. Vasudevan, O. Bchir, A.P. Alur, C.K. Gurumurthy, R.W. Stage (2008). "Materials technology for environmentally green micro-electronic packaging." Intel® Technology Journal 12: 1-16.
21. Ma, H. and J. C. Suhling (2009). "A review of mechanical properties of lead-free solders for electronic packaging." Journal of materials science 44(5): 1141-1158.
22. Mattila, T. (2005). Reliability of high-density lead-free solder interconnections under thermal cycling and mechanical shock loading. Espoo, Finland, Helsinki University of Technology.
23. Moon, K. W., W. Boettinger, et al. (2000). "Experimental and thermodynamic assessment of Sn-Ag-Cu solder alloys." Journal of electronic materials 29(10): 1122-1136.
24. Nimmo, K. (2002). European Lead-free Technology Roadmap, Ver1: February 2002, Soldertec at Tin Technology Ltd.
25. Pandher, R. S., B. G. Lewis, et al. (2007). Drop shock reliability of lead-free alloys-effect of micro-additives, IEEE.
26. Pang, H., K. Tan, et al. (2001). "Microstructure and intermetallic growth effects on shear and fatigue strength of solder joints subjected to thermal cycling aging." Materials Science and Engineering: A 307(1-2): 42-50.
27. Pang, J. H. L. and F. Che (2006). Drop impact analysis of Sn-Ag-Cu solder joints using dynamic high-strain rate plastic strain as the impact damage driving force, IEEE.
28. R. J. Fields, S. R. L. "Physical and mechanical properties of intermetallic compounds commonly found in solder joints." Retrieved April 20, 2011, 2011, from http://www.metallurgy.nist.gov/mechanical_properties/solder_paper.html.
29. R.F Smallman, R. J. B. (1999). Modern physical metallurgy and materials engineering. Oxford, Butterworth- Heinemann
30. S. Ganesan, M. P. (2006). Lead-free electronics. New York, Wiley-Interscience Publication.
31. Subramanian, K. and J. Lee (2003). "Physical metallurgy in lead-free electronic solder development." JOM Journal of the Minerals, Metals and Materials Society 55(5): 26-32.
32. Suh, D., D. W. Kim, et al. (2007). "Effects of Ag content on fracture resistance of Sn-Ag-Cu lead-free solders under high-strain rate conditions." Materials Science and Engineering: A 460: 595-603.
33. Syed, A., T. S. Kim, et al. (2006). Alloying effect of Ni, Co, and Sb in SAC solder for improved drop performance of chip scale packages with Cu OSP pad finish. ECTC, IEEE.
34. Syed, A., J. Scanlan, et al. (2008). Impact of package design and materials on reliability for temperature cycling, bend, and drop loading conditions. IEEE-ECTC, IEEE.
35. Tee, T. Y., H. S. Ng, et al. (2003). Design for enhanced solder joint reliability of integrated passives device under board level drop test and thermal cycling test, IEEE.
36. Terashima, S., Y. Kariya, et al. (2003). "Effect of silver content on thermal fatigue life of Sn-xAg-0.5 Cu flip-chip interconnects." Journal of electronic materials 32(12): 1527-1533.
37. Terashima, S., T. Kohno, et al. (2009). "Improvement of thermal fatigue properties of Sn-Ag-Cu lead-free solder interconnects on Casio's wafer-level packages based on morphology and grain boundary character." Journal of electronic materials 38(1): 33-38.
38. Tsai, I., L. J. Tai, et al. (2005). Identification of Mechanical Properties of Intermetallic Compounds on Lead Free Solder, IEEE; 1999.
39. Tu, K. (2007). Solder joint technology: materials, properties, and reliability, Springer Verlag.
40. Ye, L., Z. Lai, et al. (2001). "Microstructure investigation of Sn-0.5 Cu-3.5 Ag and Sn-3.5 Ag-0.5 Cu-0.5 B lead-free solders." Soldering & surface mount technology 13(3): 16-20.
41. Yu, A., J. W. Jang, et al. (2010). Improved reliability of Sn-Ag-Cu-In solder alloy by the addition of minor elements. ECTC, IEEE.
42. Zhang, B., H. Ding, et al. (2009). "Reliability study of board-level lead-free interconnections under sequential thermal cycling and drop impact." Microelectronics Reliability 49(5): 530-536.
43. Zhang, F., M. Li, et al. (2002). "Failure mechanism of lead-free solder joints in flip chip packages." Journal of electronic materials 31(11): 1256-1263.

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