Environmental Friendly Low Mass 20g-Sn58Bi/Cu Solder Alloy as an Alternative to Lead SnPb and Its Properties Study

S. Amares 1,2* and D. Rajkumar 2

1 Centre for Advanced Materials and Manufacturing (CAMM), SEGi University, Jalan Teknologi, Taman Sains Selangor, Kota Damansara PJU 5, 47810 Petaling Jaya, Selangor, Malaysia.
2 Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, Jalan Sungai Long, Bandar Sungai Long, 43000 Kajang, Selangor, Malaysia.
E-mail: amaresinghgill@segi.edu.my

Abstract. The SnBi solder system are argued to be the possible replacement for the lead and hazardous SnPb solder alloy. The features that differs in this study from the other types of Sn58Bi/Cu is the low mass usage of 20g. This low mass serves as to preserve materials and reduce waste. Yet, the main objectives to provide substantial data in term key properties of melting temperature, hardness and contact area properties of this Sn58Bi solder. The melting point of the Sn58Bi solder alloy is 142.25°C, close to the eutectic temperature. The average Vickers hardness value produced by the Sn58Bi was 28.8Hv, considerably high and close to the SnPb. The spreading area of the Sn58Bi solder alloy on the Cu substrate was calculated to 14.85mm², at the soldering temperature 230°C. These properties are based on 20g of SB that can be predicted to be quite standout, and at the same time provides less waste of materials. Insight discussions are elaborated in this paper.

1. Introduction

Solder alloys are used as medium to provide bonding between the electronic components and the substrate, usually a Printed Circuit Board (PCB) in the electronic packaging industry. This is achieved by a metallurgical joining process of soldering [1]. The temperature dealt in this process is low (< 250°C) and thus, in need of efficient solder alloys to be used in the soldering process [2, 3]. In this process, the solder alloy brings the component in contact with the substrate, whereby the preferred melting point of the solder alloy to be less than 425°C [3]. Ever since old days, the SnPb solder’s enhanced properties in terms of low melting temperature (183°C) [4, 5], high load resistance (hardness) [5] and good wettability to the PCB made this solder the ideal solder alloy. However, the furthering with the enhancement of the solder alloy on its on properties, the attention has to be given in its aspect to the environment. The SnPb provides greatness in its properties but fails in satisfying the crucial part of being a safe material [6, 7]. The Pb contain in the alloy causes debate as the Pb is recognised as harmful element that can cause health problem to human [5, 8]. Without a doubt, in the soldering industry the contribution of human is a necessity and thus such exposure to Pb could harm the health. The Environmental Protection Agency (EPA) listed the Pb as among the top 17 chemicals [9]. This prompts to finding alternative lead free solder that could replace the SnPb solder alloy. Numerous studies carried out to find the potential candidate for replacement and among the vast researched solder is the SnAgCu solder alloy [10, 11]. One of the standout properties of this solder alloy is its proficiency in the mechanical strength (hardness and shear strength) [12]. Notwithstanding that, this solder alloy produces IMC in the solder alloy itself to contribute to a well-defined microstructure.
Nevertheless, with high melting temperature (217°C), this solder alloy’s credential is still questionable. This is added with thick IMC production in this SnAgCu solder if exposed to high temperature [13,14]. Table 1 shows some of the discussed and researched solder alloy. Then again, some solder alloys such as SnBi that known to have low melting point would be taken in to consideration of replacing the SnPb solder alloy. Although, there are studies conducted on the SnBi solder alloy, not many have reported a low mass composition as taken in to attention in this paper. Studies shows that binary element solder are naturally weak in mechanical aspect and in need of high amount of mass consumption to rectify this situation. Taking this as a contest, this research investigates the melting temperature, hardness and contact area of the low mass consumption of the Sn58Bi solder alloy.

Table 1. Some common researched solder alloy with its properties.

| Solder Alloys | Characteristics         | Aces                          | Concerns                                      |
|---------------|-------------------------|-------------------------------|-----------------------------------------------|
| Sn-37Pb       | - Low melting temperature (183°C) | - High shear/tensile strength | - Good wettability                           |
|               |                         | - Good interfacial property  | - High toxicity (Pb)                         |
| Sn-3.0Ag-0.5Cu| - High hardness and shear/tensile strength | - Good wettability | - High melting temperature (217°C) |
|               |                         | - Good interfacial property (at low soldering/refix temperature and short time usage) | - Excessive growth of Cu6Sn5 layer upon aging and high temperature |
|               |                         | - Availability               | - Grains coarsening                           |
| Sn-3.5Ag      | - High hardness and shear/tensile strength | - Availability               | - High melting temperature (221°C)             |
| Sn-0.7Cu      | - High hardness and shear/tensile strength | - Availability               | - High melting temperature (227°C)             |
|               |                         |                               | - Excessive growth of Cu6Sn5 IMC layer        |
| Sn-50In       | - Low melting temperature (125°C) | - High hardness               | - Expensive                                   |
|               |                         | - Good microstructural properties, smaller grains | - Rare element (Indium)                      |
|               |                         |                               | - Decrease in properties at high concentration of indium |
| Sn-9Zn        | - High performance in mechanical strength, especially in tensile strength | - Availability               | - High melting temperature (198°C)             |
|               |                         |                               | - Prone to corrosion (oxidation)              |
| Sn-58Bi       | - Low melting temperature (139°C) | - Large spreading area        | - Low mechanical properties                   |
|               |                         | - High wettability            |                                               |
|               |                         | - Low CTE                     |                                               |
|               |                         | - Availability                |                                               |
|               |                         |                               |                                               |

2. Experimental procedures
The Sn58Bi solder alloy was prepared from 8.4g of tin (99.9%, Alfa Aesar), 11.6g of bismuth (99.9%, Alfa Aesar) that was melted in a furnace at 600°C for 1 hour soaking time to make sure a homogenous mixture. To enable a proper mixing of these elements the solder alloy was re-melted using a hot plate at 300°C. The Sn58Bi solder alloy was flattened into billets for the melting, hardness and wetting test. The wettability test was performed by soldering the Sn58Bi solder alloy on to the Copper (Cu) substrate and the contact spearing area was measured using the VIS Pro software. The spreading rate, K was calculated using the equation (1) and Figure 1 shows the parameter needed. The melting properties analysis meanwhile was studied by using the Differential Scanning Calorimetry (DSC)
machine. As for the microhardness properties, the Vickers Hardness test was implemented with load of 1kgf applied to the Sn58Bi solder billets.

\[ K = \frac{D-H}{D} \times 100\% \]  

(1)

3. Melting properties analysis

The first properties that was concerned in this research was the melting properties. Commonly the solidus, liquidus and peak temperature are important aspects that are reflected from the thermal analysis. These are among the important parameters that could influence the microstructural of the solder alloy, and further related to the mechanical properties. Lower melting temperatures are desirable in the electronic industries mainly to avoid board warpage or deterioration to the PCB board [15, 16, 17]. According to [17], higher reflow temperature would cause evaporation of entrapped moisture that causes crack. The Sn58Bi solder in this research produces a solidus temperature, \(T_S\) of 141.18°C, liquidus temperature, \(T_L\) of 147.45°C and peak temperature, \(T_M\) of 142.25°C (Figure 2). The temperature of the Sn58Bi was not as the eutectic temperature (139°C) because some elements of Bi and/or Sn may be left out during the remelting process and such occurrence is usual in an experiment study. One of the important analysis that could be extracted from these thermal properties is the pasty range (\(T_M - T_S\)), producing 1.07°C and with the range of less than 5°C; the Sn58Bi solder alloy could stimulate good microstructural properties. Although the microstructure aspect of the Sn58Bi solder alloy is not discussed in this study, the pasty range could provide a sight of advantage in the microstructure formation [15]. This observation was comparable to the report made by [16]. The low melting temperature for this solder alloy allows lower reflow temperature which underwrites to a lower thermal environment during soldering and at the same time avoid any thermal damage of other components.

4. Microhardness

In the midst of mechanical properties that been investigated by most researches is the mirohardness of the solder alloy. The hardness of a solder alloy provides the information on the ability of the solder to resist penetration upon load. The Sn58Bi solder alloy’s Vickers microhardness is tabulated in Table 2. The average Vickers hardness of the Sn58Bi solder alloy was calculated to be 28.78Hv. The result is comparably high compared to the Sn1.0AgCu solder alloy that produces an average of 9.78Hv [17] and even compared to the SnPb solder that produces 12.64Hv in a study conducted by [18]. The high hardness value of the Sn58Bi solder in this study could be first attributed to the low pastry range that can improve microstructural properties by producing finer structures [11,19]. Besides that, the SnBi solder system has a unique characteristic that the Sn and Bi element will not diffuse to produce any IMC compound but rather exist as single elements [20]. Also, the low melting temperature of the Sn58Bi solder here permits a better nucleation of grains in the microstructure at the soldering temperature of 230°C [21]. This will be opposing to the high melting temperature solders as these solders would need to be reflowed at even higher temperature to achieve a better grain production to enhance the microstructure. Thus, the Sn58Bi solder could be able to resist further penetration and increase the hardness.
Figure 2. DSC curve of Sn58Bi.

Table 2. Vickers microhardness results for Sn58Bi solder.

| Indentation Number | Diameter of Indentation (μm) | Vickers microhardness Number (Hv) |
|-------------------|-----------------------------|----------------------------------|
| 1                 | \(D_1:81.60\) \(D_2:81.60\) | 27.84                            |
| 2                 | \(D_1:80.30\) \(D_2:83.65\) | 27.59                            |
| 3                 | \(D_1:81.50\) \(D_2:73.35\) | 29.39                            |
| 4                 | \(D_1:78.60\) \(D_2:80.60\) | 29.26                            |
| 5                 | \(D_1:78.10\) \(D_2:79.60\) | 29.82                            |

Average = 28.78

5. Spreading area and spreading rate

The wettability aspect of the Sn58Bi was investigated using the spreading area (Figure 3) and the spreading rate. The spreading area of the Sn58Bi solder alloy on the copper substrate was calculated to show the ability of this low melting solder alloy’s spreading capability. In fact, the spreading area is influenced by the surface tension of the molten solder alloy during soldering. This interaction between the solder and the substrate also determines the production of IMC layers effecting the spreading area. Low surface tensions together with low viscosity of the molten solder are the desired outcome in providing a better wettability [22]. As mentioned by [23], larger spreading area is desirable to produce a good joint, as these features are known to produce thin IMC layer and is void-free. Saying that, no baseline of limitation of the spreading area was mentioned by any studies, hence, this paper will be comparing the literatures availability of the SnPb and other researched solder alloy to relate with the Sn58Bi’s spreading area. The average spreading area of the Sn58Bi solder alloy was 14.85mm². The spreading rate of the Sn58Bi was also calculated as per equation (1), and the average was 67.2%, provide in Table 3. As previously mentioned, the spreading area and spreading rates does not have a
standard to differentiate the good and bad wettability, nonetheless, the other solder alloy’s readings will be compared as to assess this current study. The spreading rate of the Sn3.8Ag0.7Cu was 82.48% and is high since the high melting point of the solder permits lower viscosity due to high thermal energy [23, 24]. In a different study, the spreading rate of the Sn3.0Ag0.5Cu was 90.15%, again contributed due the high melting point [24]. Although the spreading rate of the Sn58Bi is only 67.2%, yet this range is acceptable since the difference of comparing the high melting point solder is only about 20% difference. The low melting point is the reason for this spreading rate. Looking at the spreading area, this is also common for the high melting temperature solders to have better spread, for example, the Sn6Zn4Bi solder alloy had a spreading area of 23mm² at 230°C [7] compared to 14.9mm² for the Sn58Bi solder in this study. The low melting point of the Sn58Bi solder prohibits the larger spreading such as the Sn6Zn4Bi and Sn3.0Ag0.5Cu solder alloys, as the surface tension is high in the current solder. Even so, the spreading rate is not that much of a variance in difference and the Sn58Bi solder can be suggested to also provide satisfactory spreading rate and area [25]. In a study done by [26], the spreading area produced of the SnPb solder was 3.2mm², lower compared to the Sn58Bi solder in this study. Once again, the higher surface tension of the SnPb solder alloy is justified as the reason of this low spreading area. Concerning this, the Sn58Bi solder still manages to produce efficient spreading area and rate.

![Image of samples](image1)

**Figure 3.** Samples and spreading area of the Sn58Bi solder alloy.

### Table 3. Spreading rate of Sn58Bi.

| Samples | Spreading Diameter (mm), (D) | Spreading Height (mm), (H) | Spreading Rate, (K), (%) |
|---------|-----------------------------|---------------------------|-------------------------|
| 1       | 4.44                        | 1.61                      | 63.7                    |
| 2       | 4.57                        | 1.39                      | 69.6                    |
| 3       | 4.88                        | 1.64                      | 66.4                    |
| 4       | 4.48                        | 1.45                      | 67.6                    |
| 5       | 4.41                        | 1.61                      | 63.4                    |

Average = 67.2
6. Conclusion
The scope of the paper to produce the analysis on the properties of the low mass composition Sn58Bi solder alloy was successfully completed. The melting properties shows advantageous influence as the melting temperature was lower than the SnPb solder alloy and accompanied with shorter pasty range. The mechanical aspect in terms of the microhardness was experimented and the outcome of the result showed that the Sn58Bi solder alloy could compete with the SnPb and other lead free solder alloys and the contribution was predicted because the microstructural aspect of Sn and Bi that acts as discrete elements upon solidification. Taking in to concern on the wettability property, the spreading area and rate yields satisfactory result as the Sn58Bi solder alloy harvests better spreading area compared to the SnPb solder alloy and had minimal difference compared to the efficient spreading rate of a high melting temperature lead free solder alloys. Overall, the Sn58Bi low mass composition solder provided positive result based on the thermal, hardness and wettability that could be taken as reference for further investigation and implementation.

7. References
[1] Manko, H. H. (2001). Solderers and Soldering. McGraw Hill 4th Edition.
[2] Yoon, J.-W., Noh, B.-I., Kim, B.-K., Shur, C.-C., & Jung, S.-B. (2009). Wettability and interfacial reactions of Sn–Ag–Cu/Cu and Sn–Ag–Ni/Cu solder joints. Journal of Alloys and Compounds, 486(1–2), pp 142-147.
[3] Humphston, G., & Jacobson, D. (2004). Principles of Soldering, ASM International.
[4] C R Sivour, S M Walley, W G Proud and J E Field (2005). Mechanical properties of SnPb and lead-free solders at high rates of strain Journal of Physics D: Applied Physics, 38, pp 4131 4139.
[5] M.A. Fazal, N.K. Liyana, Saeed Rubaiee, A. Anas, (2019). A critical review on performance, microstructure and corrosion resistance of Pb-free solders, Measurement, 134, pp 897–907.
[6] W. Kinzy Jones, Yanqing Liu, Milind Shah and Robert Clarke (1998). Mechanical properties of Pb/Sn Pb/In and Sn-In solders, Soldering & Surface Mount Technology, 10(1), pp 37–41.
[7] Ervina Efzan M.N. and Tan S.Y, (2013). Wettability of molten Sn-Zn-Bi solder on Cu substrate, Applied Mechanics and Materials, 315, pp 675-680.
[8] S. Amares, M.N. Ervina Efzan and T.C. Yap, (2014). Characterizations of Physical Properties of Sn-Bi Solder Alloy, Advanced Materials Research, 845, pp 261-265.
[9] Seelig, K. U. and David Surask. (2001). “Advanced materials considerations for lead-free electronics assembly.”
[10] Amares Singh, Rajkumar Durairaj, Ervina Efzan Mhd Noor,Sia Way Woong, (2018). Reliability Study of Lead Free Sn-3.8Ag-0.7Cu and Copper (Cu) Substrate based on the Microstructure, Physical and Mechanical Properties. Journal of Mechanical Engineering, 5(2), pp 169-180.
[11] Efzan M.N. Ervina and Amares Singh (2014). Review on the effect of alloying element and nanoparticle additions on the properties of Sn-Ag-Cu solder alloys, Soldering & Surface Mount Technology, 26(3), pp 147-161.
[12] Liang Zhang, Cheng-wen He, Yong-huan Guo, Ji-guang Han, Yong-wei Zhang, Xu-yan Wang, (2012). Development of SnAg-based lead free solders in electronics packaging, Microelectronics Reliability, 52, pp 559–578.
[13] Ming Yang, Hongjun Ji, ShuaiWang, Yong-Ho Ko, Chang-Woo Lee, JianxinWu ,Mingyu Li, (2016). Effects of Ag content on the interfacial reactions between liquid Sn-Ag-Cu solders and Cu substrates during soldering. Journal of Alloys and Compounds, 679, pp18-25.
[14] Shunfeng Cheng, Chien-Ming Huang, Michael Pecht, (2017). A review of lead-free solders for electronics applications. Microelectronics Reliability, 75, pp 77–95.
[15] Fen Peng, Wensheng Liu, Yunzhu Ma, Chaoping Liang, Yufeng Huang, Siwei Tang, (2019). Microstructure of Sn-20In-2.8Ag solder and mechanical properties of joint with Cu, Soldering & Surface Mount Technology, 31(1), pp 1-5.
[16] Hiren R. Kotadia, Philip D. Howes, Samjid H. Mannan (2014). A review: On the development of low melting temperature Pb-free solders. *Microelectronics Reliability*, 54(6-7), pp 1253-1273.

[17] Yee Mei Leong and A.S.M.A. Haseeb, (2016). Soldering Characteristics and Mechanical Properties of Sn-1.0Ag-0.5Cu Solder with Minor Aluminum Addition, *Materials*, 9, 522.

[18] C.Z. Liu and J. Chen, (2007). Nanoindentation of lead-free solders in microelectronic packaging, *Materials Science and Engineering: A*, 448(1-2), pp 340-344.

[19] Ervina Efzan Mhd Noor, Amares Singh and Yap Tze Chuan (2013). A review: influence of nano particles reinforced on solder alloy. *Soldering & Surface Mount Technology*, 25 (4), pp 229-241.

[20] Li Yanga, Lu Zhu, Yaocheng Zhang, Shi yuan Zhou, Guo qiang Wang, Sai Shen, Xiaolong Shi, (2019). Microstructure, IMCs layer and reliability of Sn-58Bi solder joint reinforced by Mo nanoparticles during thermal cycling, *Materials Characterization*, 148, pp 280–291.

[21] T.L. Yang, J.Y. Wu, C.C. Li, S. Yang, C.R. Kao, (2015). Low temperature bonding for high temperature applications by using SnBi solders, *Journal of Alloys and Compounds*, 647, pp 681-685.

[22] S.L. Tay, A.S.M.A. Haseeb, Mohd Rafie Johan, P.R. Munroe, M.Z. Quadir, (2013). 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*, 33, pp 8-15.

[23] K. Kanlayasiri, M. Mongkolwongrojn and T. Ariga (2009). Influence of indium addition on characteristics of Sn–0.3Ag–0.7Cu solder alloy, *Journal of Alloys and Compounds*, 485(1), pp 225-230.

[24] S.L. Tay, A.S.M.A. Haseeb and Mohd Rafie Johan, (2011). Addition of cobalt nanoparticles into Sn-3.8Ag-0.7Cu lead-free solder by paste mixing, *Soldering & Surface Mount Technology*, 23 (1), pp10 –14.

[25] Srivalli Chellvarajoo and M.Z. Abdullah, (2018). Investigation on nano-reinforced solder paste after reflow soldering part 1: Effects of nano-reinforced solder paste on melting, hardness, spreading rate, and wetting quality. *Microelectronics Reliability*, 84, pp 230-237

[26] H.K. Yeo and K.H. Han, (2009). Wetting and spreading of molten SnPb solder on a Cu–10%Nb micro-composite, *Journal of Alloys and Compounds*, 477, pp 278–282.