Effect of 60% thickness reduction of Sn-Cu solder alloy on localized micromechanical properties via nanoindentation approach

F. A. Mohd Yusof1, 2, Maria Abu Bakar1, Azman Jalar1, 2
1 Institute of Microengineering and Nanoelectronics, The National University of Malaysia, 43600 Bangi, Selangor Darul Ehsan, Malaysia
2 Department of Applied Physics, The National University of Malaysia, 43600 Bangi, Selangor Darul Ehsan, Malaysia

Abstract: The relationship between a process and mechanical properties is important in understanding the behaviour of a material under certain conditions. This indicate that mechanical properties of the materials can be modified through certain processing. Hence, this paper investigates the effect of 60% thickness reduction of Sn-Cu alloy in thermomechanical treatment on the localized micromechanical properties. A bar-shape of Sn-Cu solder alloy is subjected to heat treatment at 30°C, 60°C, 90°C, 120°C and 150°C for 20 minutes, followed by 60% thickness reduction via compression process. Sample without compression process was used as control sample. Nanoindentation approach was used to characterize the localized micromechanical properties of the samples. The results show the hardness value for control samples reduced approximately 56%, from 181 MPa at 30°C to 79 MPa at 150°C. Reduced modulus of control sample has shown similar decreasing trend from 149 GPa at 30°C to 85 GPa at 150°C, approximately 43% changes. Lower changes in hardness and reduced modulus observed for thermomechanical treated sample approximately 20% and 18%, respectively. These findings show that thermomechanical treatment has given significant effect on the localized micromechanical properties of Sn-Cu solder alloy.

1 Introduction

Smartphones, wearable devices, and various portable gadgets are examples of electronic devices that are becoming smaller and increasing in functionality, enabled by the development of miniaturization [1]. Solder alloy is widely used as one of the metallurgical interconnection materials to join the electronic component and printed circuit board (PCB). The solder joint provides electrical connection which enable the functionality of the electronic devices together with mechanical support for structural integrity. The lifetime of these electronic products are highly dependent on the reliability of the solder joint [2]. Moreover, the reliability of the solder joint is very much dependent on the material and processing involved. Therefore, it is very crucial to understand the mechanical properties of the solder material when subjected to a certain processing.

Thermomechanical treatment is commonly used purposely to modify material microstructure and then altered the material properties. Therefore, this treatment is often used to a material for structural integrity dedicated in automotive and construction industries. Good structural materials possess high mechanical strength and reliability so that they can be used in the long term [3]. Thermomechanical treatment is a combination of heat treatment and mechanical processing whereby the occurrence of plastic deformation and microstructural changes [4]. This treatment resulted in deformation of the material when subjected to a certain temperature together with mechanical loading. For example, mechanical loading such as compression load led into certain thickness reduction of the material and contributed to the changes in mechanical properties. Jo et al. [5] have conducted thermomechanical treatment on the wire with variation reduction percentage. Their finding show that the hardness has increased at a higher percentage of reduction, which was influenced by the refinement of the grains and the more efficient dislocation density. Therefore, understanding the relationship between the processes and properties in a study is important as these two components are interrelated.

To study such relationships, characterization of solder materials on a small scale is necessary to determine the reliability of electronic packaging. Previous studies have used conventional methods in obtaining the mechanical properties of solder alloys namely microhardness test, shear test, impact test, Vickers test, bending test and tensile test [6]. A study of mechanical properties of SAC solder alloys using Vickers method by making indentations on the solder area and substrate area have been reported [7]. However, the method is a conventional method and can only provide mechanical properties in bulk. Therefore, the nanoindentation approach technique is adapted to characterize localized mechanical properties [8].Nanoindentation
approach have been widely used in characterizing mechanical properties on small scale structures without damaging samples. This method can also provide control over the load, depth, and precise test position. Based on the load versus depth curve, information on mechanical properties as well as distortions on small scale structures can be obtained. A study of mechanical properties of intermetallic compounds (IMC) at the Sn-3.0Ag-0.5Cu/Cu solder connection interface has been done using nanoindentation method [9]. From the study, the hardness, elastic modulus and creep properties of IMC Cu3Sn and Cu6Sn5 can be determined. This paper is aims to investigate the effect of 60% thickness reduction during thermomechanical treatment on the micromechanical changes of Sn-Cu solder alloy. Therefore, nanoindentation approach is adopted to characterize localized micromechanical properties in terms of hardness and reduced modulus.

2 Material and methodology

A commercial Sn-Cu bar-shaped solder alloy with a purity of 99.3 wt% Sn and 0.7 wt% Cu is used. The bar shaped Sn-Cu solder alloy was cut into small samples with dimensions of 6 mm (L) X 6 mm (W) X 10 mm (H) as shown in fig. 1 (a). In this study, the sample was subjected to thermomechanical treatment by heating the sample in an oven individually at 30℃, 60℃, 90℃, 120℃ and 150℃ for 20 minutes. Subsequently, the sample were then compressed with a push-pull gauge until the thickness was reduced to 60% from its original thickness. Next the sample were cooled in water medium. Fig. 1 (b) shows Sn-0.7Cu sample after thermomechanical treatment at 30℃ with 60% thickness reduction from 10 mm to 4 mm. The control sample is a sample undergo heat treatment without thickness reduction or compression processing. The samples were prepared in cross-section using metallographic technique prior nanoindentation test for localized micromechanical properties characterization. The samples were cold mounted in epoxy resin and cured at room temperature for four hours. After cold mounting process, the samples were then ground with 800, 1000, 1200, 2000 and 4000 grits of silicon carbide (SiC) abrasive paper. The samples were then polished using a polishing cloth (Dp-Nap) and diamond sprays of 6 μm and 1 μm. Localized micromechanical properties of the Sn-Cu solder alloys after thermomechanical treatment were characterized by nanoindentation testing. The testing parameters are maximum load of 10 mN, whereby the loading and unloading rate was 0.5mN/s, and dwell time of 540 seconds. The localized micromechanical properties provided from the nanoindentation testing is hardness and reduced modulus.

Fig. 1. Cube shape Sn-0.7Cu solder alloy (a) control sample and (b) thermomechanical treated sample at 30℃.

3 Result and discussion

3.1 P-h profile

Fig. 2 shows a typical curve for a nanoindentation test, whereby the y-axis is load (P) while x-axis is depth (h) for control sample and thermomechanical treated Sn-Cu alloy. During nanoindentation test, a load or force is applied to the indenter (known as loading) which resulted in the indenter tip starting to penetrate the surface of the sample and enter its structure. Along with increasing of load, the depth also simultaneously increases until the maximum load (Pmax) of 10 mN has reached. At maximum load, the indenter tip is left static at the solder alloy structure for 540 seconds and this time is known as dwell time. After the dwell time ends, the load begins to decrease or removed from the sample’s structure (known as unloading) and causes the depth of indentation also decreases but at a very small rate. From the P-h profile, the highest depth was exhibited by control sample with temperature of 150℃ (Fig. 2a) whereas thermomechanical treated shows deepest depth is at 120℃ (Fig. 2b).
Fig. 2. Plots of load versus depth for (a) control samples and (b) thermomechanical treated samples with variation of thermomechanical temperature.

3.2 Hardness

In the nanoindentation test, the hardness properties were obtained from the $P-h$ profile (Fig. 2) using the Oliver-Pharr method [10] as per equation (1) below,

$$H = \frac{P_{\text{max}}}{A_c}$$  \hspace{1cm} (1)

where $H$ is the hardness value of the material in units of MPa, $P_{\text{max}}$ is the maximum load applied to the material and $A_c$ is the contact area of the indentation. Fig. 3 shows the hardness ($H$) values for control and thermomechanical treated samples with variation of thermomechanical temperature. Control sample possessed increasing hardness value from 181 MPa at 30°C to 236 MPa at 90°C, and the decreased abruptly to 79 MPa at 150°C. Thermomechanical treated sample also shows the similar trend of hardness changes from 94 MPa at 30°C has increased to 123 MPa at 90°C, and slightly decreased to 113 MPa at 150°C. The finding on decreasing of hardness shows that there is a softening effect on the solder alloy after heat treatment [11]. Thermomechanical treatment temperature of 30°C and 150°C were selected to compare the hardness values changes. It is shown that the hardness value for control sample changed approximately about 57% or 102 MPa from 30°C to 150°C. Lower changes in hardness value is shown for thermomechanical treated sample whereby only 19 MPa (approximately 20%) changes from 30°C to 150°C. The findings show that the thermomechanical treated sample obtained lower changes of hardness with variation of thermomechanical treatment temperatures.

Fig. 3. Hardness result for control and thermomechanical treated samples with variation of thermomechanical temperature.
3.3 Maximum depth

Hardness is the measurement of the resistance of a material to plastic deformation [12]. Definition of hardness in nanoindentation test refer to the resistance of sample to withstand the indenter as it penetrates the surface of sample when a load is applied. This gives understanding that reduction of indentation depth influenced an increase in hardness [13]. The maximum depth for samples in this study are in line with the above statements (Fig. 4). For instance, maximum depth value for control sample increased from 1494 nm (30°C) to 2285 nm (150°C) when the hardness value decreased from 181 MPa to 79 MPa at the same temperature. The decreased in hardness values occurred due to the easy penetration of indenter tip into the structure of sample when load is applied and vice versa. This is due to the occurrence of softening caused by microstructural changes due to thermally activated process such as temperature [14].

![Fig. 4. Maximum depth and hardness versus thermomechanical temperature for control sample](image)

3.4 Reduced modulus

In addition to the hardness property, $E_r$ (reduced modulus) can also be obtained through the curve $P$ against $h$. The calculation for $E_r$ is as in equation (2) below,

$$
\frac{1}{E_r} = \frac{(1 - v^2)}{E_s} - \frac{(1 - v_i^2)}{E_i}
$$

(2)

where $E_s$ and $v_s$ are the Young's modulus and the Poisson's ratio for the sample, while $E_i$ and $v_i$ are the Young's modulus and the Poisson's ratio for the indentation. Fig. 5 shows that reduced modulus of Sn-Cu solder alloy having similar trend with hardness result. However, the findings shows that the control sample produced a larger change in reduced modulus as compared to thermomechanical treated sample. For instance, control sample produced high reduced modulus values changes of 64 GPa (approximately 43% changes) when the temperature increased from 30°C (149 GPa) to 150 °C (85 GPa). On the other hand, thermomechanical treated sample has given a smaller reduced modulus values changes of 10 GPa (approximately 18% changes) from 56 GPa at 30°C to 66 GPa at 150 °C.
Analysis from the localized micromechanical properties via nanoindentation approach has clearly shown that the thermomechanical treated sample of 60% thickness reduction has marked the most stable localized micromechanical properties as compared to control samples. This is because, thermomechanical treated samples produced smaller changes of localized micromechanical properties in terms of values changes between of each temperature interval. Hence, the relationship between thermomechanical process with localized micromechanical properties of Sn-Cu solder alloy is valid to predict the relationship of processing-properties.

4 Conclusions

The effect of thickness reduction on Sn-Cu solder alloy during thermomechanical treatment in terms of changes in micromechanical properties such as hardness and reduced modulus were successfully investigated by nanoindentation approach. The result shows the changes of hardness and reduced modulus for thermomechanical treated sample from 30℃ to 150℃ approximately 20% and 18%, respectively. Higher changes of hardness and reduced modulus of control sample approximately 56% and 43%, respectively. The results show that the thermomechanical treated sample of 60% thickness reduction along with variation of thermomechanical temperature have the least changes in localized micromechanical properties as compared to the control samples. This indicates that the thermomechanical treatment is able to stabilize the micromechanical properties of Sn-Cu alloy in terms of reduced modulus and hardness.

The authors would like to acknowledge the financial support provided by Universiti Kebangsaan Malaysia and Ministry of Higher Education, Malaysia (grant number FRGS/1/2019/STG07/U/UKM/03/1).

References

1. G. Ren, M. N. Collins, J. Punch, E. Dalton, R. Coyle, “Handbook of Materials Failure Analysis,” Elsevier, 107–51 (2020)
2. Y. Leong, A. S. M. A. Haseeb, Mater. 9, 522 (2016)
3. J. Hui, Z. Feng, W. Fan, X. Yuan, Mater. Charact. 144 611–20 (2018)
4. M. Wagner, “Thermal Analysis in Practice (München: Carl Hanser Verlag GmbH & Co. KG),” 187–209 (2017)
5. H. S. Joo, S. K. Hwang, Y-T. Im, Procedia Manuf. 15, 1525–32 (2018)
6. A. Jalar, M. A. Bakar, R. Ismail, Metall. Mater. Trans. A 51, 1221–8 (2020)
7. D. Giuranno, S. Delsante, G. Borzone, R. Novakovic, J. Alloys Compd. 689, 918–30 (2016)
8. I. Abdullah, M. N. Zulkifli, A. Jalar, R. Ismail, Solder. Surf. Mt. Technol. 30, 194–202 (2018)
9. G. Xiao, X. Yang, G. Yuan, Z. Li, X. Shu, Mater. Des. 88, 520–7 (2015)
10. M. Dada, P. Popoola, N. Mathe, S. Adesosan, S. Pityana, Int. J. Light. Mater. Manuf. 4, 339–45 (2021)
11. A. M. Afdaluddin, M. A. Bakar, Sains Malaysiana 49, 3029–36 (2020)
12. N. Ismail, A. Jalar, M. Abu Bakar, R. Ismail, N. S. Safee, A. G. Ismail, N. S. Ibrahim, Sains Malaysiana 48, 1267–72 (2019)
13. G. Zhou, J. Guo, J. Zhao, Q. Tang, Z. Hu, Metals (Basel). 10, 125 (2020)
14. N. Ismail, A. Jalar, M. A. Bakar, R. Ismail, Sains Malaysiana 47, 1585–90 (2018)