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Nanoindentation Approach on Investigating Micromechanical Properties of Joining from Green Solder Materials

(Kaedah Perlekukan Nano dalam Mengkaji Sifat Mikromekanik Sambungan Bahan Aloi Pateri Hijau)

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ABSTRACT

This work investigates the micromechanical properties of Sn96.5Ag3.0Cu (SAC 305) on Immersion Tin (ImSn) surface finished after subjected to high temperature storage (HTS) at 180°C for 200 to 1000 h period. Nanoindentation approach was used to measure the micromechanical properties of the solder. It was observed that the indentation depth and plastic depth were increased and a clear trend of decreasing hardness as opposed to the increasing reduced modulus as the HTS time lengthened. The plasticity-asscociated properties become stronger meanwhile the elasticity-associated properties decreased with the HTS time. These findings indicate that nanoindentation approach can clearly determine the plastic and elastic deformation occurance throughout the test.

Keywords: Lead-free solder; micromechanical properties; nanoindententation

ABSTRAK

Penyelidikan ini mengkaji sifat mikromekanik Sn96.5Ag3.0Cu (SAC 305) pada substrat dengan kemasan permukaan rendaman timah (ImSn) selepas didedahkan pada penyimpanan suhu tinggi (HTS) pada suhu 180°C selama 200 hingga 1000 jam. Kaedah perlekukan nano digunakan untuk mengukur sifat mikromekanik aloi pateri. Didapati bahawa kedalaman perlekukan dan plastik meningkat dan terdapat tren kekerasan yang jelas menurun bertentangan dengan modulus terkurang dengan pemanjangan masa HTS. Sifat berkaitan plastik menjadi semakin kuat dan sebaliknya bagi sifat elastik yang menurun dengan pemanjangan masa HTS. Keputusan menunjukkan pendekatan menggunakan kaedah perlekukan nano dapat mengenal pasti kewujudan canggaan plastik dan elastik sepanjang uji kaji.

Kata kunci: Pateri bebas plumbum; perlekukan nano; sifat mikromekanik

INTRODUCTION

In electronic packaging industry, mechanical properties provide essential information leading to the reliability of solder joint. There are many methods to investigate the mechanical properties of electronic materials via mechanical testing such as shear test (Sauli et al. 2014), drop test (Yeh & Huang, 2014), pull test (Ramos et al. 2012), impact test (Kim et al. 2013), tensile test (Karamouz et al. 2013) and hardness test (Tsukamoto et al. 2010; Wang et al. 2013). Generally, the mechanical test were carried out in accordance to the code and practices standard (JEDEC/ASTM). For bulk properties, all of these techniques were well established and accepted. Nevertheless, in electronic industries where miniaturisation effort such as the adoption of solder paste instead of solder ball in current assemblies has posed challenges in testing methods especially using conventional method or bulk test.

Nowadays, our electronic industry has move forward with the utilisation of smaller solder particles. With this scenario, the conventional test, for example, shear test is no longer adequate to provide dependable results due to its limitation for smaller samples. Bui and Jung (2014) used shear test to evaluate the mechanical properties of low-Ag grid array solder joints. Their findings only reported values limited to shear strength and shear energies. Obviously, this information only provides information on bulk properties, therefore in order to facilitate the restriction of shear test, Advanced Semiconductor Packaging (ASPAC) research group has adopted and developed nanoindentation approach as alternative to current practice to investigate the mechanical properties of electronic materials (Abdullah et al. 2009; Zulkifli et al. 2013). This method gave an advantage of localised micromechanical properties in addition to other mechanical properties in conventional stress-strain data. Figure 1 shows the schematic diagram of shear test and nanoindentation test. It is shown that in shear test, a shearing arm will push a ball or wedge bond during testing while for nanoindentation test, micro sized indentations point were made on the solder surface. Moharrami and Bull (2014) reported that the nanoindentation has the capability with high level of accuracy to measure the mechanical properties for small volume of bulk materials and also can be applied for thin film. Figure 2 illustrates the shear stress-displacement curve from shear test and load-displacement curves which were obtained from nanoindentation test.

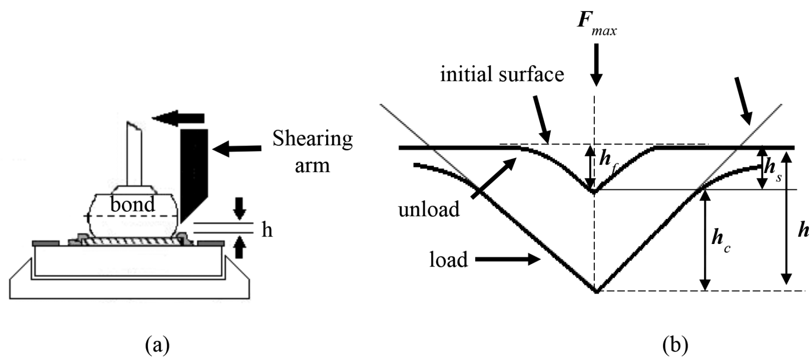

FIGURE 1. Schematic diagram of: (a) shear test and (b) nanoindentation test

The objective of this work was to report the suitability of using nanoindentation test to measure the relevant micromechanical properties of solder joint. Lead free solder, Sn96.5Ag3.0Cu (SAC 305) on Immersion Tin (ImSn) surface finished test board were subjected to different storage time of high temperature storage (HTS) at 180°C.

MATERIALS AND METHODS

Green lead free solder paste, Sn96.5Ag3.0Cu (SAC305) and standard test board (11 × 10 × 0.2 cm) from Redring Solder (M) Sdn. Bhd. with surface finish of Immersion Tin (ImSn) was used in this study. The solder paste was manually printed on the test board using a stencil. The printed solder paste was reflowed at 215°C for 8 s using reflow oven (Madell Technology Corporation). Subsequently, the test board cooled at room temperature after reflow process. Following that, the test board was cut into a small pieces (0.5 × 0.4 × 0.2 cm), containing few soldered pitch using diamond cutter blade machine. The samples were placed in an oven for high temperature storage (HTS) at 180°C for 200, 400, 600, 800 and 1000 h. As the HTS test completed, the sample was prepared for nanoindentation test. The samples were cold mounted in epoxy resin. The cold mounted sample were then ground starting from 800, 1000 and 1200-grit of SiC paper and polished using diamonds sprays of 6 and 1 μm.

The nanoindentation technique was performed by using Micro Materials Nanotest™ indenter. The nanoindentation test machine is shown in Figure 3. This machine is equipped with a Berkovich diamond tip. Three indentations were made on the middle of the solder. Nanoindentation was conducted at room temperature. A constant of loading and unloading rate of 0.5 mN/s was applied to the sample surface until maximum load of 10 mN was reached. The dwell time was 30 s at the maximum load followed by the unloading process. The thermal drift correction of 60 s hold time was applied at 90% unloading. The unloading curve was considered as the elastic recovery of the material (refer to schematic illustration in Figure. 2). The hardness and the reduced Young's modulus were obtained from the load-depth data which is based from Oliver and Pharr's (1992) method. The hardness H is determined as:

$$H = \frac{P_{max}}{A}, \tag{1}$$

where P_{max} is the maximum load; and A is the area of contact. The reduced modulus, is calculated as follow:

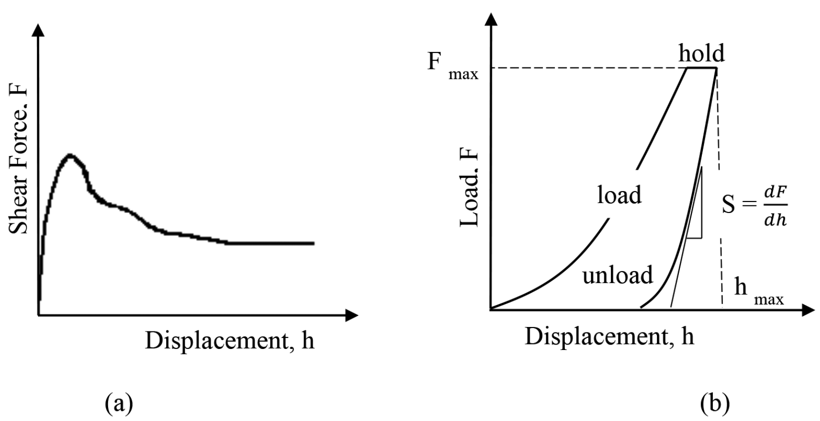

FIGURE 2. Plot of (a) shear stress-displacement curve from shear test and (b) load-displacement curve from nanoindentation test

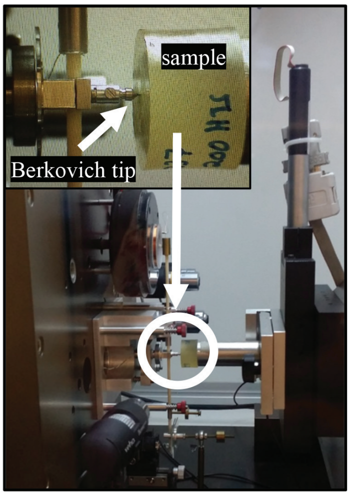

FIGURE 3. Nanoindenter test machine

$$E_r = \frac{S\sqrt{\pi}}{\sqrt{A_C}}, \quad (2)$$

where S is the contact stiffness which correspond to the slope of unloading curve; and A_c is the area of contact, is also given by:

$$\frac{1}{E_r} = \frac{\left(1-v_S^2\right)}{E_S} + \frac{\left(1-v_i^2\right)}{E_i}, \quad (3)$$

where and are modulus Young's of the sample and the indenter, respectively; and are the Poisson's ratio of the sample and the indenter. The Poisson's ratio value of indenter used in this work is 0.07 and Young's modulus of 1140 GPa.

RESULTS AND DISCUSSION

Conventional shear test and other test such as pull, compression and drop test have been used to characterise the mechanical properties of joining and interconnection including solder joint. These tests are extremely important in predicting the reliability and life span of the joining. From the fundamental aspect, in mechanical test point of view, stress-strain data is probably the most useful and provides more accurate information of mechanical joining properties as compared to other tests such as hardness test. Due to dimension and architecture of the soldering in microelectronics packaging, the conventional tensile test may not be suitable. Thus, JEDEC standard was suggested to use such as pull and shear test.

The nanoindentation test provides almost similar information to stress-strain test using depth-sensing approach. Among the details that were obtained from the nanoindentation test include plastic depth, elastic recovery parameter, hardness, reduced modulus, plastic work and elastic work. These observation are in line with conventional stress-strain curve. Figure 4 shows the indentations point made on the middle of the soldered sample. Figure 5 illustrates the *p-h* profiles for indentation of SAC305/ImSn subjected to different high temperature storage. Different curve of *p-h* profile was obtained, indicating that the value of load and response of unload of SAC305/ImSn is different when subjected to high temperature storage. Variation of maximum depth and plastic depth for SAC305/ImSn subjected to HTS is shown in Figure 6. By applying the same load of 10 mN, it was observed that the maximum load increased from 1312.94 to 1692.75 nm with the prolonged of the HTS. Similar trending happened for plastic depth of SAC305/ImSn, 1293.00 nm for 0 h and increased to 1681.17 nm for 1000 h. From this load-unload curve, the micromechanical and localised properties can be represent as in Figure 7. For this study, the value of hardness and reduced modulus has been chosen to demonstrate the effect of the high temperature storage (HTS) followed by the reflow process. The hardness was decreased with the increasing of HTS. However, the reduced modulus was increased up to 600 h and then fluctuated down and up after 600 h. Figure 8 shows the variation of plastic and elastic work for SAC305/ImSn after subjected to HTS. The plastic work result showed an increasing trend while decreasing trend was observed for elastic work.

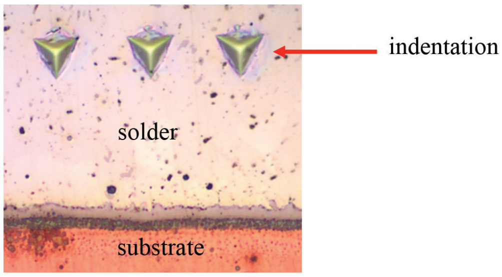

FIGURE 4. Nanoindentation test on solder

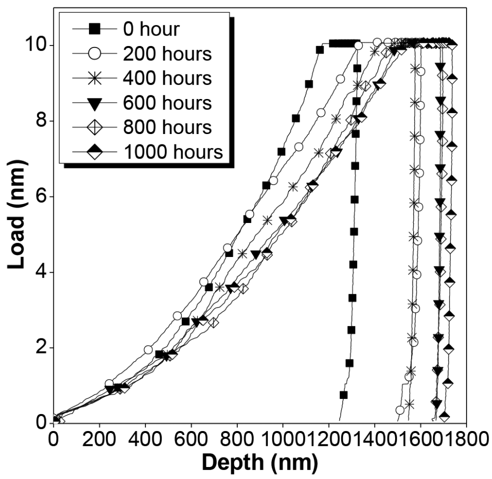

FIGURE 5. profiles for indentation of SAC305/ImSn subjected to different high temperature storage

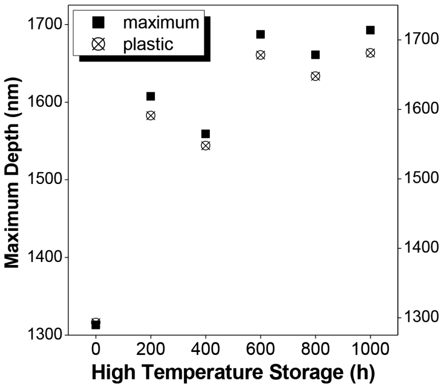

FIGURE 6. Variation of maximum depth and plastic depth for SAC305/ImSn subjected to high temperature storage

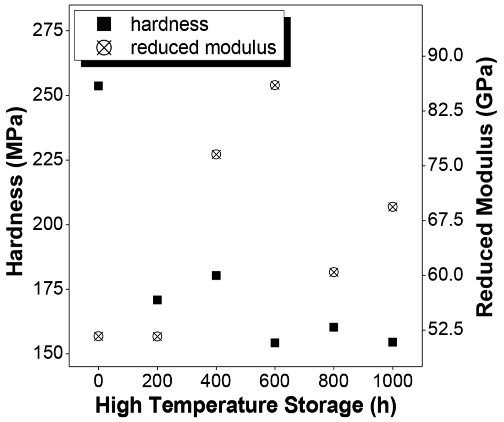

FIGURE 7. Variation of hardness and reduced modulus for SAC305/ImSn subjected to high temperature storage

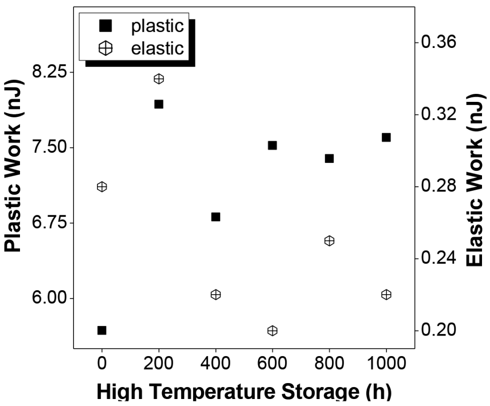

FIGURE 8. Variation of plastic work and elastic work for SAC305/ImSn subjected to high temperature storage

From these results, it was clear that plastic and elastic behaviour of the solder can be deeply explained. As the exposure time in HTS prolonged, the plasticity-associated properties become stronger which the elasticity-associated properties decreased with the HTS time. The elastic work was decreased with HTS time, however, maintained in the small value and range (0.20-0.34 nJ). This indicates that the plastic-associated properties were more dominant throughout the test compared to elastic properties. It shows that the solder became softer with the prolonged of the HTS which in agreement with Siviour et al. (2005) and Yoon et al. (2007) whom reported that the thermal ageing affects the strength of the material through the grain growth. It indicated that hardness value is a reflection to micro plastic properties and reduced modulus which is associated to the elastic properties of the solder. The present finding is contradicted with common result with shear test which reported that the joining become more brittle throughout the HTS (Lee et al. 2002). However, the 'brittleness' probably can be link to the interface between intermetallic compound (IMC) and the structure of IMC itself (coefficient of thermal expansion, CTE of solder/IMC). This result showed that the behaviour of solder alloy and the understanding of its micromechanical together with mechanical and physical behaviour of IMC were established in order to completely understand the joining properties phenomenon. The understanding of plastic and elastic properties obtained from the nanoindentation test in this work was very useful in evaluating the micromechanical and localised properties of solder, SAC305/ImSn subjected to HTS.

CONCLUSION

The ability of nanoindentation approach in providing wide range of micromechanical properties data including plastic-elastic deformation together with localized analysis was believed to give more useful and accurate representation of the lead free solder joint. The value of indentation depth, plastic depth, hardness, reduce modulus, plastic work and elastic work show the variation of micromechanical properties of the solder joint. The micromechanical data from nanoindentation test which was not only in line with the conventional standard test but provide more understanding on reliability of the solder joint.

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