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Investigation of Potting Compounds on Thermal-Fatigue properties of Solder Interconnects

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***Abstract*—The objective of this article is to investigate the thermal-fatigue properties of a commercially available lead-free solder alloy (SnBiAgCu) under the use of different types of potting compounds. Solder alloys with lower silver content are expected to substitute the conventional solder alloys SAC305 (Sn-3.0Ag-0.5Cu). First, the tensile behavior and creep behavior of the SnBiAgCu solder alloys were studied at three temperatures (25°C, 75°C, 125°C). Results show that this type of solder alloys presented higher tensile strength and creep deformation endurance than conventional SAC305 solder alloys. Second, a dynamic mechanical analysis was performed to get the storage modulus and glass transition temperature of three types of potting compounds, which were used in the thermal-fatigue simulation. Third, the experimentally determined material data was used for the averaged strain energy density increment calculated by the finite element method. This simulation approach was selected as damage metrics to evaluate solder interconnect reliability under different combinations of materials. It is found that the application of potting compounds will increase strain energy density significantly when compared with the strain energy density calculated without potting compound, which means that potting compounds will deteriorate the thermal-fatigue reliability of solder interconnects. These accurate data-driven simulation models can in the future form the basis for compact digital twins for predicting useful remaining lifetime.**

***Keywords*—solder alloys, potting compounds, creep, thermal-fatigue, strain energy density**

I. INTRODUCTION

Reliability of solder interconnects is a critical concern because they function as both the thermal, electrical and mechanical connection between components and the printed circuit board (PCB). The mechanical stress caused by thermal cyclic processes will induce fatigue damage in the solder interconnects during the normal operation of electronic components in their use-case application, which is a major source of failure of solder inerconnects on board level reliability of electronic packaging [1]. This type of fatigue failure is fundamentally attributed to the mismatch of coefficient of thermal expansion (CTE) between the electronic components and PCB [2, 3].

Lead-free solder alloys (e.g. SnCu, SnAgCu) have become mainstream as interconnected electronic materials which substituted the leaded solder alloys (SnPb) for environment protection. Up to now, many studies have investigated the fatigue behavior of SnAgCu solder alloys by combining experiments (thermal cycling, tensile fatigue tests etc.) and simulation [4-7]. For example, Raed et al [4] revealed that increasing the aging temperature and time would lead to lower fatigue resistance of SnAgCu solder alloys, which caused more damage per cycle and less number cycles to failure for solder interconnects. Mohammad et al [5] performed high temperature creep tests of SnAgCu solder alloys from 125°C to 200 °C and found that there was a significant increase of secondary creep strain rate at higher temperatures. Sn-3.0Ag-0.5Cu (SAC305) is the most widely used solder alloys for electronic packaging with acceptable fatigue resistance and mechanical properties. It is known that the effect of creep on fatigue evolution can markedly decrease the lifetime. Vahid [6] revealed that the consideration of creep on fatigue process caused 34% difference in the lifetime prediction. While comparison of the results for different solders has shown that the addition of dopants (e.g. Bi, Ni, and Sb) in the traditional SAC alloys improve their properties significantly. Recently, an alternative solder alloy (SnBiAgCu) with lower silver content is expected to substitute SAC305 solder alloys. It was reported by Jakub [8] that this solder alloy achieved higher shear strength than SAC305 solder alloy after the thermal stress tests. However, the detailed mechanical analysis of this solder alloy for various creep-strain test conditions is still missing. Thus, it is important to evaluate different solder alloys in terms of tensile and creep properties experimentally so accurate numerical simulation methods can be performed with the correct material data.

Potting compounds are originally used to provide protection for electronic components from vibration, moisture and temperature change, especially under harsh environments [9]. However, it was reported that there was a large reduction in fatigue life when shrink or expansion stresses exist in the solder due to the thermal expansion of the potting compounds [10]. It means that the potting compounds will accelerate the fatigue failure process of solder interconnects to some extent. Zhu et al [11] studied the effect of viscoelasticity behavior of potting compounds by changing the curing temperature. They concluded that potting compounds cured at lower temperature are prone to induce more or less stress damage than those cured at higher temperature. Thus, the effect of potting compounds on thermal-fatigue properties of solder interconnects need to be investigated.

In this paper, we performed tensile and creep tests of a commercially available solder alloy to fit to the Garofalo-Arrhenius creep model. The dynamic mechanical analysis (DMA) tests were used to get the storage modulus (E') and glass transition temperature (T_g) of the potting compounds. Then, thermo-mechanical simulations based on the finite element method (FEM) are used to study the effect of solder and potting compounds on the thermal-fatigue properties of solder interconnects.

II. Experimental Methods

A. Tensile tests and creep tests of solder materials

Instron 5948 micro-mechanical tester was utilized to perform tensile tests and creep tests of solder materials at three temperatures (25℃, 75℃, 125℃). Fig. 1a shows the system and the schematic diagram of test samples for tensile and creep tests, in which the dimension is 3mm×0.5mm×100mm. The gauge length is set up to 25mm. An Instron chamber with EUROTHERM 2408 controller is used to heat the sample to the target temperature. A thermometer is installed inside the chamber to measure the temperature during the tests. In addition, cooled water is pumped within the system via chiller to avoid overheating of load cell and actuator.

Firstly, uniaxial tensile tests were performed with a strain rate of $0.001s^{-1}$ to determine the stress-strain curves of the solder alloys under different temperatures (25℃, 75℃, 125℃). Three specimens were tested for each temperature level. Then, four creep stress levels were determined based on ultimate tensile strength (UTS) measured from tensile tests, which were 0.25UTS, 0.35UTS, 0.45UTS and 0.55UTS respectively. After that, creep tests were performed under three temperatures (25℃, 75℃, 125℃).

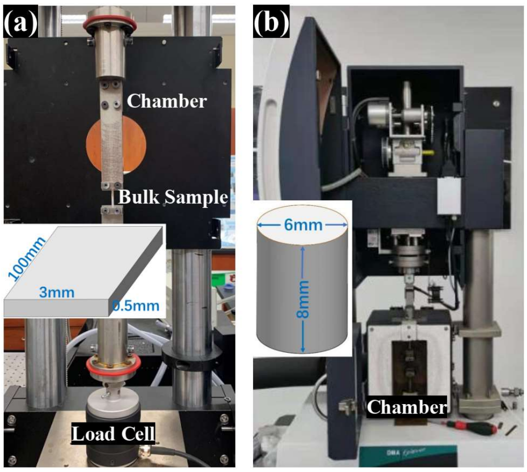

Fig. 1. (a) Instron 5948 test machine with diagram of tensile and creep specimens; (b) Dynamic mechanical analysis test machine with the diagram of specimens.

B. DMA tests of potting compounds

Potting compound is one type of viscoelastic materials, for which the stress-strain curve is strongly influenced by temperature. The elasticity of potting compounds will decrease with the increase of temperature while the viscidity will increase, which means the strain response will be delayed with the increase of temperature. Generally, viscoelasticity can be investigated by DMA tests, in which the sample is subjected to oscillating force and the resultant displacement is measured. The storage modulus, E', refers to the stored energy in the material and represents the elastic portion. Loss modulus, E'', is a measure of the energy which is dissipated as heat during displacement and represents the viscous portion [11]. It is obvious that the higher the loss modulus, the greater the viscous portion and the higher energy dissipation of the material. In order to study the effect of potting compounds on thermal fatigue properties of solder interconnects, it is necessary to get the storage modulus and loss modulus of potting compounds. In this study, DMA tests are performed for three types of potting compounds (Potting A, Potting B, Potting C) over a temperature range of -50℃ to 30℃. The test frequency is set as 3 Hz.

C. Thermal-fatigue simulation

To investigate the effect of solder materials and potting compounds on thermal-fatigue properties of solder interconnects, FEM simulation is utilized to calculate thermal-mechanical responses of solder interconnects during thermal cycling. It is noted that only thermal-fatigue was considered in order to establish the relationship between materials properties and strain energy density. In this study, a package (SOD323) with gull-wing leads containing a diode is considered, which is widely used in LED drivers. The diode is soldered on PCB and encapsuled by potting compound. As shown in Fig. 2, a three-dimensional (3D) finite element model which represents a quarter of a diode is established by Ansys workbench. To improve the calculation efficiency of FEM, a substructure technique is used, which is reported by Fan [12]. Substructure techniques are used to obtain FEM results without loss of calculation accuracy. It is noted that the displacement in the directions which are perpendicular to the symmetric planes are set as 0. And the vertex on the intersection of symmetric planes shown in Fig. 2 is fixed.

A summary of the materials used in the present study is shown in Table I. All materials are modeled as linear elastic except for the solder materials and potting compounds. The PCB is FR-4, which is highly anisotropic. It is because the in-plane stiffness and tensile strength of PCBs are much larger than the out-of-plane stiffness and tensile strength. Considering that the solder interconnects will endure creep deformation during thermal cyclic condition, the Garofalo-Arrhenius creep model [13] is used to simulate the creep behavior of the solder interconnects, which is shown below:

$$\dot{\varepsilon} = A\left[\sinh\left(\alpha\sigma\right)\right]^{n}\exp\left(-\frac{Q}{RT}\right) \tag{1}$$

where A is the material constant, α is the stress level parameter, n is the stress exponent constant, σ is the steady state flow stress, Q is the activation energy, R is the universal gas constant, T is the temperature.

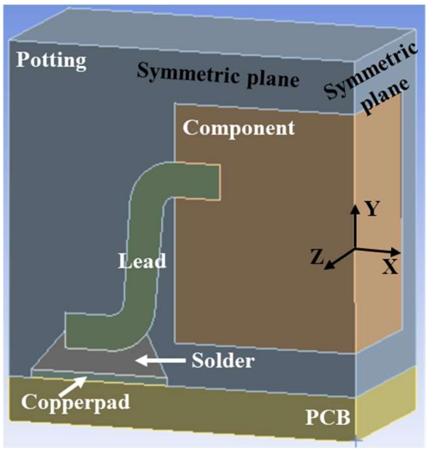

Fig. 2. Quarter finite element model for a diode with potting compound.

The plot of temperature profiles as a function of the time steps used in this investigation is presented in Fig. 3. It is shown that the temperature range is -40°C to 80°C and the initial temperature is set to 80°C. According to Fan's study [12], the solder materials will readjust the stress state during thermal cycling to stress-free condition after a few cycles. The temperature change rate does not exceed 10°C per minute. The maximum temperature is maintained for 15 min, and each cycle lasts 1 h.

TABLE I. MATERIAL PROPERTY DETAILS

Materials	Young's modulus (GPa)	CTE ($^{\circ}C^{-1}$)	Poisson ratio (-)
SAC305	N/A	2.5E-5	0.36
SnBiAgCu	N/A	2.55E-5	0.4
Potting A	*E'*	<-17°C 5E-5; >-17°C 1.92E-4	0.3
Potting B	*E'*	<-20°C 5E-5; >-20°C 1.85E-4	0.3
Potting C	*E'*	<-10°C 5E-5; >-10°C 2E-4	0.3
Copperpad	120	1.7E-5	0.35
Lead frame	120	1.7E-5	0.35
PCB	X&Y direction: 28	1.76E-5	0.39
	Z direction: 12	7E-5	0.11
Component	22	8E-6	0.25

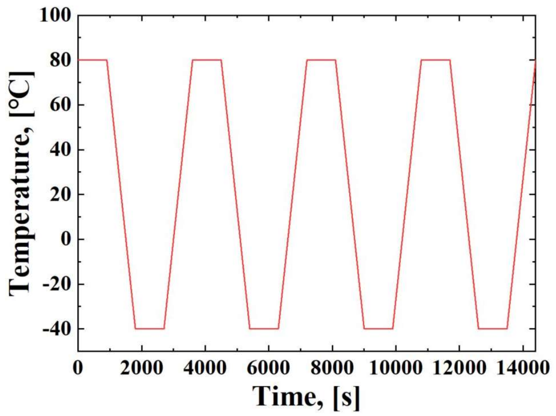

Fig. 3. Temperature cycling condition.

III. RESULTS AND DISSCUSION

A. *Effect of temperature on tensile and creep properties of solder materials*

The stress-strain curves under three temperatures (25°C, 75°C, 125°C) are shown in Fig. 4. Here, the values of UTS show significant decrease with the increase of temperature. When temperature increase from 25°C to 75°C, the UTS decreases from 47.2MPa to 37.2MPa. And the UTS continues to decrease down to 25.5MPa when temperature increases up to 125°C. This agrees with that higher temperature will deteriorate the strength of solder materials. The elongation locates in the range of 2.5% to 8%. It seems that the elongation is not sensitive to temperature change from 25°C to 75°C if we ignore the discreteness. But the higher temperature of 125°C will influence the homogeneity of elongation significantly. Fig. 4d shows a comparison between SnBiAgCu and SAC305 solder alloys. It is obvious that the strengths of SnBiAgCu are higher than SAC305 solder alloys but the elongation are lower than those of SAC305 solder alloys. It can be concluded that the adoption of Bi atom increases the strength of solder but deteriorates the plasticity.

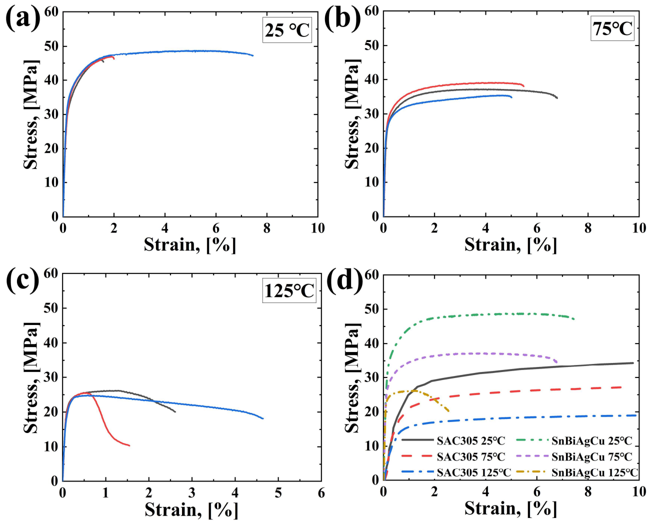

Fig. 4. Uniaxial tensile curves of solder materials under different temperatures: (a) SnBiAgCu, 25°C; (b) SnBiAgCu, 75°C; (c) SnBiAgCu, 125°C; and (d) comparison between SnBiAgCu and SAC305 solder alloys.

The creep-time curves of solder specimens (SnBiAgCu) under different temperature are provided in Fig. 5a-c. It is shown from Fig. 5a that sigmoidal creep would occur at low temperature (25°C) where there would be less thermal activation energy with which to increase an initially low defect density. While at higher temperatures, thermal activation would assist defect generation and/or motion, thereby eliminating the incubation period that characterizes the sigmoidal shape [14]. Therefore, the strain-time curves shown in Fig. 5b and c suggest that the typical sigmoidal shape of creep curves disappear. Fig. 5d shows the steady creep rate of solder specimens under different temperatures which are calculated from creep curves. The values of creep rate were used to fit the constants of the Garofalo-Arrhenius creep model and the results are shown in Table II. Here, we also list the constants of SAC305 according to Schubert [13]. The effect of SnBiAgCu solder alloys compared with SAC305 solder alloys in terms of averaged inelastic strain energy density increment will be calculated in the following section. Fig. 5d also shows the steady creep rate of SAC305 solder alloys at the temperature of 25°C, which is higher than that of SnBiAgCu solder alloys obviously. Combining the results from tensile tests and creep tests, it can be concluded that SnBiAgCu solder alloys present higher strength and creep endurance than SAC305 solder alloys.

TABLE II. CONSTANTS FOR GAROFALO-ARRHENIUS CREEP MODEL

Constants	SAC305	SnBiAgCu
A	277984 s^{-1}	4.03E10 s^{-1}
α	0.02447 MPa^{-1}	0.08771 MPa^{-1}
n	6.41	3.159
Q	5.4E4 J/mol	1.18E5 J/mol

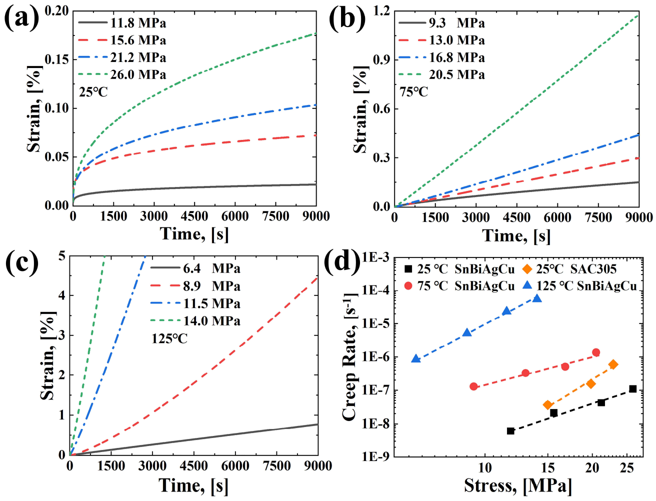

Fig. 5. Creep curves of solder alloys under different temperatures: (a) SnBiAgCu, 25°C; (b) SnBiAgCu, 75°C; (c) SnBiAgCu, 125°C; and (d) creep rate of SnBiAgCu and SAC305.

B. DMA curves of potting compounds

Fig. 6 presents DMA curves of the three potting compounds, which are named as Potting A, Potting B and Potting C, respectively. The storage modulus (E') denotes the stiffness of the material, which represents the capacity of a material to bear a load. The loss modulus (E'') refers to the energy dissipation or the heat loss at the same strain amplitude of a different system. It is shown that as the temperature is raised, the values of E' for all types of the potting compounds are diminished. The temperature-storage modulus relationship was due to the increase in the molecular mobility, which lowered the rigidity of the potting compounds and eased their deformation. The stiffness of potting compounds is in order of Potting A, Potting C and Potting B, which means that Potting A presents higher stiffness than others. It is widely known that the peaks of the loss modulus curves indicate the glass transition temperature (T_g) value of the potting compounds. Thus, the Potting B presents the lowest value of T_g which is about -20°C, while the T_g values of Potting A and Potting C are -17°C and -10°C respectively. Generally, potting compounds show high CTE at temperatures above their T_g. When low CTE potting compounds are heated past their T_g, the large expansion could subject solder interconnects to excessive bending and normal stresses and lead to accelerated failure of components [15]. It is thus important to optimize the CTE of potting compounds close to the solder materials and to adjust the T_g according to their real application environment.

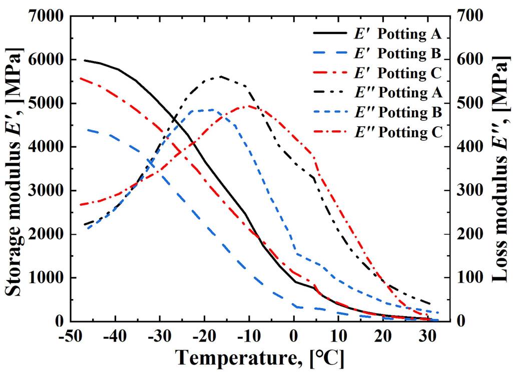

Fig. 6. Temperature dependence of the DMA curves of storage modulus E' and loss modulus E'' for the potting compounds.

C. Results of finite element modeling

The finite element modeling simulation is performed to investigate effect of different combinations of solder materials and potting compounds on the thermal-fatigue properties. In general, the per-cycle inelastic strain energy density is used as damage metrics to evaluate solder interconnect reliability. And the accumulated increase in inelastic strain energy density per cycle is stable after 3 cycles [16]. Therefore, 4 cycles were performed in FEM simulation. The averaged elastic energy density is defined as below:

$$W_{ave} = \frac{\sum_{i=1}^{N} v_i W_i}{\sum_{i=1}^{N} v_i} \quad (2)$$

Where N is the total number of selected analysis elements, i is the element number, v is the element volume with element number i. The volume averaged inelastic strain energy density per cycle is given by:

$$\Delta W_{ave} = W_{ave,n} - W_{ave,n-1} \quad (3)$$

Fig. 7 shows the distribution of strain energy in the solder interconnect, which presents that the maximum energy occurs at the interface among solder interconnect, copper pad and potting compound. However, it is obvious that most elements in the center of the solder interconnects have low strain energy, which are irrelevant to the crack initiation. Therefore, in this study, we selected the elements with the top 10% strain energy to calculate the averaged strain energy density. These most critical elements were mainly located around the interfaces, which are responsible to fatigue crack initiation. Fig. 7b shows the strain energy distribution of solder interconnect with the use of potting compounds. It is shown that potting compound will increase the strain energy significantly, which can be to CTE mismatch between potting compounds and solder interconnects. Hence, potting compound will accelerate the thermal-fatigue failure of solder interconnects and failure is prone to occur at the interfaces as shown in Fig. 7b.

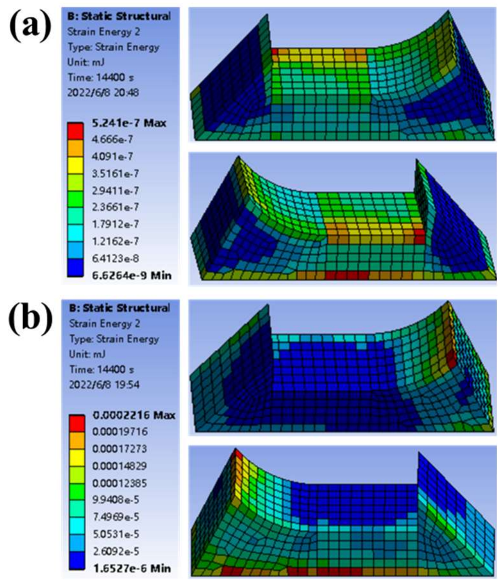

Fig. 7. Strain energy distribution of the solder interconnect.

The ΔW_{ave} values for different combinations of solder materials and potting compounds are listed in Table III. It is shown that the inelastic strain energy density per cycle of SnBiAgCu are totally lower than those of SAC305 solder alloys, which further proves that SnBiAgCu can be used to substitute SAC305 solder alloys. For the SnBiAgCu solder alloys, Potting A caused the lowest inelastic strain energy density of all three potting compounds. It is supposed that the relative higher storage modulus of Potting A caused the less strain deformation. Thus, the optimal combination of solder materials and potting compounds are SnBiAgCu and Potting A. Although the absence of potting compounds leads to significantly lower inelastic strain energy density, the potting compounds will still be used in real condition in order to protest the electronic components from mechanical vibration and the thermal shock etc. Thus, it is very important to consider the more types of potting compounds with various CTE, T_g and E' in the future to establish the relationship between materials properties and the inelastic strain energy density.

TABLE III. MATERIAL PROPERTY DETAILS

Cases	Solder type	Potting compound	Averaged inelastic energy density per cycle, mJ/mm^3
1	SAC305	——	0.0253
2	SAC305	Potting A	3.77
3	SAC305	Potting B	4.54
4	SAC305	Potting C	5.09
5	SnBiAgCu	——	0.00315
6	SnBiAgCu	Potting A	2.45
7	SnBiAgCu	Potting B	3.39
8	SnBiAgCu	Potting C	4.31

IV. CONCLUSION

In this study, a type of SnBiAgCu solder alloy with lower silver content is compared with the standard solder alloy SAC305 in terms of tensile, creep and thermal-fatigue properties. The effect of potting compounds on thermal-fatigue properties of solder interconnects was also investigated. Results from tensile tests and creep tests show that SnBiAgCu solder alloys present higher tensile strength and creep-fatigue endurance than SAC305 solder alloys. And the averaged inelastic strain energy density per cycle calculated from FEM simulation for SnBiAgCu is lower than that of SAC305 under use of the same potting compound, which means that SnBiAgCu solder alloys have the better thermal-fatigue resistance than that of SAC305 solder alloys. From the above results, it can be concluded that in terms of thermal-fatigue of solder interconnects, the SnBiAgCu solder alloy can be used as a replacement for SAC305 solder alloy. However, the application of potting compound will increase the inelastic strain energy density significantly. It is found that potting compound with higher storage modulus caused lower inelastic strain energy density. This offers the guidance for the future optimization of material selection for electronic packaging. The effect of potting compounds on thermal fatigue properties of solder interconnects need to be investigated deeply in the future. This paper reports the reliability analysis of solder interconnects by considering different solder materials and potting compounds on board level based on energy method, it can also be extended to packaging level. The simulation results can be used to establish a digital twin model for remaining useful life prediction.

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