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Elastic Properties of Sn-Based Pb-Free Solder Alloys Determined by Ultrasonic Pulse Echo Method

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The Young's modulus (E) and Poisson's ratio (ν) of Sn-based lead-free solders as Sn–3.5Ag, Sn–58Bi and Sn–9Zn (compositions in mass%) were measured at various temperatures between −50 and 100°C using an ultrasonic pulse echo method. The values of Young's modulus and Poisson's ratio were obtained at 25°C. These values coincide with the room temperature values in the literature. The Young's modulus and Poisson's ratio between −50 and 100°C were also measured for Sn–58Bi, Sn–9Zn, and Sn–37Pb.

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1. Introduction

Electronic parts, especially in printed circuit boards, are joined using various solders and the integrity of a solder interconnection is essential to produce electronics products of high reliability. Simulation is widely used in the design of electronic products.[1,2] In simulation calculations, the mechanical properties of solders, such as the Young's modulus and Poisson's ratio, must be known in detail. For most solders, the operating temperature can be as high as 0.5 to 0.8 T_m (T_m: melting point temperature) of the solders. In these high temperature regimes, the mechanical properties of solders are strongly dependent on the temperature, and the precision of computer simulations is largely influenced by the temperature dependence of the mechanical properties of the solders. Measurements of the temperature dependence of the mechanical properties of solders are required for thermomechanical modeling of solder joints in electronic products.

The Sn–37Pb solder has so far been widely used, but Pb containing solders have to be replaced by Pb-free solders in the near future because the toxicity of Pb has become an environmental issue.[3] The mechanical properties of Pb-free solders have been studied widely and the data are available to the public on the Internet.[4] However, there are few data of the Young's modulus and the Poisson's ratio and the temperature dependence of Pb-free solders. In the study reported here, the Young's modulus and the Poisson's ratio of Sn-based eutectic solders containing Bi, Ag, and Zn were measured using an ultrasonic pulse echo method at various temperatures. Those of Sn–37Pb solder were also measured for comparison purposes. For the Sn–9Zn, Sn–58Bi and Sn–37Pb solders, the Young's modulus and Poisson's ratio were measured as a function of temperature between −50 and 100°C, and the temperature dependence of an Young's modulus and Poisson's ratio are discussed.

2. Experimental Procedures

The solders used are commercially available, and their compositions (mass%) are Sn–58Bi, Sn–9Zn, and Sn–3.5Ag, as well as Sn–37Pb. All the samples were melted in eutectic temperature plus 50°C and cast. The microstructure of Sn–58Bi solder is a eutectic structure consisting of the Bi and Sn phases, and that of Sn–9Zn solder consisting of the Zn and Sn phases as well as Sn–37Pb solder from binary phase diagrams. The microstructure of Sn–3.5Ag solder is a eutectic structure consisite of the Ag_3Sn and Sn phases. The average lamellar spacing of a Sn–37Pb solder is about 4 µm. The size of the samples was 30 mm diameter and 10 mm high. The density ρ was measured using an Archimedes method with water as the solvent.

An ultrasonic pulse echo method was adopted to measure the Young's modulus and Poisson's ratio of the solders, and a Toshiba Tungaloy Tungsonic model, UMS-L, equipped with a 1.6 MHz sensor of longitudinal waves and a 5 MHz sensor for shear waves was used. These sensors were PZT transducer and 15 mm diameter. The sample was fixed to the sensors with the screw. The coupling medium between the sample and the sensors was glycerin paste. The Young's modulus E and the Poisson's ratio ν were calculated using formulas,

$$E = \frac{3\rho V_s{}^2\left(V_l{}^2 - \frac{4}{3}V_s{}^2\right)}{V_l{}^2 - V_s{}^2}$$

$$\nu = \rho(V_l{}^2 - V_s{}^2)$$

Where V_l is the velocity of the longitudinal wave and V_s is the velocity of the shear wave. The temperature dependencies of the Young's modulus and Poisson's ratio were obtained from −50 and 100°C.

3. Results

Table 1 lists the Young's modulus and Poisson's ratios of the solders at room temperature measured in this work, and the data from the literature[1,2] are also given for comparison. There are good agreements between the values of E and ν obtained in this investigation and those in the references.

Figure 1 shows changes of the Young's modulus and the

Table 1 Young's modulus and Poisson's ratio of the various solders.

	This investigation		After Lau *et al.*[1,2]	
Samples	Young's modulus, E/GPa	Poisson's ratio	Young's modulus, E/GPa	Poisson's ratio
Sn–37Pb	40.9 ± 0.1	0.37 ± 0.01	38.6	0.36
Sn–58Bi	39.4 ± 0.1	0.35 ± 0.01	41.3	—
Sn–3.5Ag	51.0 ± 0.1	0.36 ± 0.01	52.7	0.36
Sn–9Zn	53.3 ± 0.1	0.35 ± 0.01	—	—

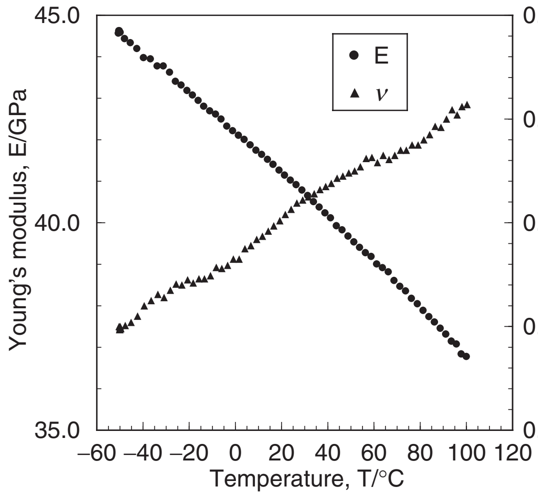

Fig. 1 Effect of temperature on the Young's modulus and Poisson's ratio of a Sn–37Pb solder.

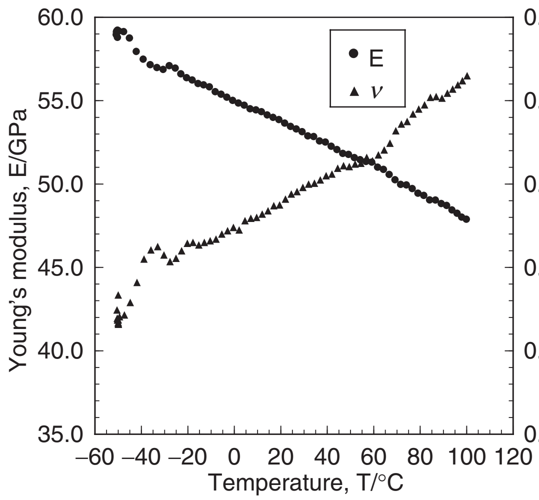

Fig. 2 Effect of temperature on the Young's modulus and Poisson's ratio of a Sn–9Zn solder.

Poisson's ratio for Sn–37Pb with temperatures between −50 and 100°C. With increasing temperature, the Young's modulus decreased gradually, while the Poisson's ratio of the solders increased linearly. Figure 2 shows changes of the Young's modulus and the Poisson's ratio for Sn–9Zn with temperature between −50 and 100°C. The behavior of the temperature dependence of the Young's modulus and Poisson's ratio for Sn–9Zn is similar to that for Sn–37Pb.

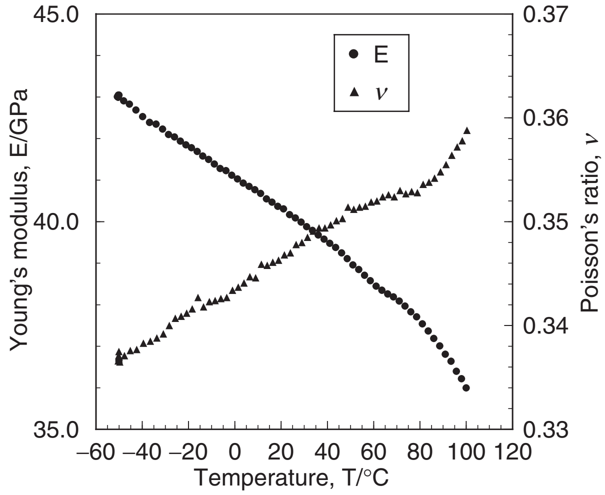

Fig. 3 Effect of temperature on the Young's modulus and Poisson's ratio of a Sn–58Bi solder.

The temperature dependence of the Young's modulus and the Poisson's ratio of Sn–58Bi were measured between −50 and 100°C, and it is shown in Fig. 3. The Young's modulus decreased linearly from 43.0 GPa at −50°C to 38.4 GPa at 60°C and then it decreased rapidly above 80°C. The Poisson's ratio increased linearly from 0.336 at −50°C to 0.352 at 60°C and then it increased rapidly above 80°C. The Young's modulus and Poisson's ratio for Sn–3.5Ag were only obtained at room temperature in the present work.

4. Discussion

The mechanical properties of solders are not well established due to the complexity of material composition, and differed in cooling rate, and heat treatment. The temperature dependence of the mechanical properties for solders can be approximated with polynominals as

$$Y(T) = a_0 + a_1T + a_2T^2 + a_3T^3 + \cdots$$

where Y is the mechanical property; a_i, $i = 0, 1, 2, 3, \ldots$ are constants, and T is temperature in °C.[2] With curve fitting by the least square method, the temperature dependence of the Young's modulus E(GPa) for Sn–37Pb can be expressed as a quadratic function of temperature, $E = 42.2–4.93 \times 10^{-2}T–4.64 \times 10^{-5}T^2$. Likewise, the temperature dependence of the Young's modulus E(GPa) for Sn–9Zn can be expressed by the equation $E = 55.1–7.34 \times 10^{-2}T + 3.69 \times 10^{-5}T^2$.

The data for the Young's modulus of the Sn–57Bi solder reported by Kamioka[5] and the present work are plotted in Fig. 4. The temperature dependence obtained by Kamioka is similar to the present work. Although there is a 1% difference in the sample compositions, Kamioka's data are relatively high. The material factors, such as texture, grain size, temperature, and residual stress, affect the velocity of the longitudinal and shear waves,[6] and it is suggested that the microstructure (*i.e.*, grain size and texture) of the samples affected both of the above Young's modulus data.

The ultrasonic pulse echo method used in the present investigation yields information of internal friction for

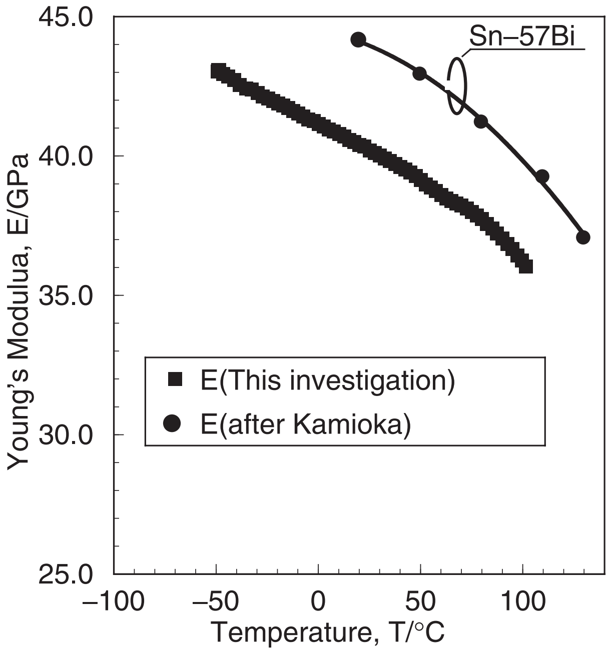

Fig. 4 Present data and that in Kamioka[5] for the temperature dependence of the Young's modulus for a Sn–Bi solder.

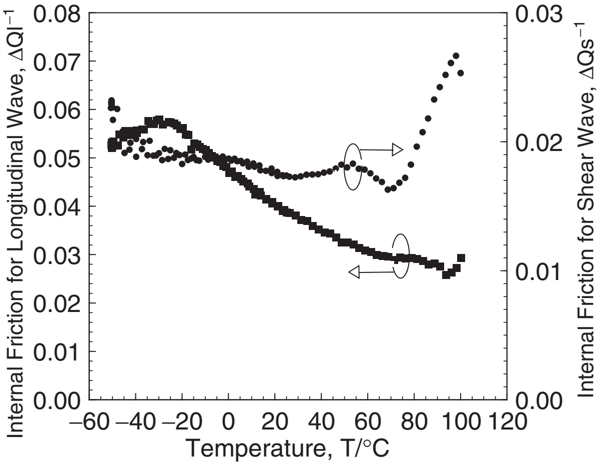

Fig. 5 Effect of temperature on internal friction for longitudinal and shear waves in a Sn–58Bi solder.

longitudinal and the shear waves, and the measurement of internal fricton with the ultrasonic pulse echo method is investigated by M. Fukuhara and I. Yamauchi.[7] Figure 5 shows changes in the internal frictions for longitudinal and the shear waves of Sn–58Bi with temperature. The internal friction for the longitudinal wave decreased monotonically with temperature, whereas the internal friction for the shear wave decreased slowly up to 80°C and then increased rapidly. Both the temperature dependence of the Young's modulus and the internal friction data suggest that the rapid decrease in Young's modulus above 80°C may arise from atomic motion along dislocations and/or grain boundaries.

5. Conclusions

(1) An ultrasonic pulse echo method was used to measure the Young's modulus and the Poisson's ratio of Sn-based Pb-free solders containing Bi, Ag, and Zn as well as a Sn–Pb eutectic solder at various temperatures.
(2) The Young's modulus and Poisson's ratio of Sn–9Zn and Sn–37Pb were measured at temperatures between −50 and 100°C, and the Young's modulus E(GPa) is given by the following equations:
For the Sn–9Zn solder,

$$E = 55.1–7.34 \times 10^{-2}T + 3.69 \times 10^{-5}T^2$$

For the Sn–37Pb solder,

$$E = 42.2–4.93 \times 10^{-2}T - 4.64 \times 10^{-5}T^2$$

(3) The Young's modulus of Sn–58Bi rapidly decreased at temperatures above 80°C. From the dependency of the Young's modulus and the shear friction, it was considered that the atomic motion along dislocations and grain boundaries causes the rapid decrease in the Young's modulus above 80°C.

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