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Tensile Properties of Sn-0.7mass%Cu Lead-free Solder

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The tensile properties of a Sn-0.7mass%Cu lead-free solder were investigated and compared with those of a Sn-3.5mass%Ag lead-free solder and a Sn-37mass%Pb solder. The tensile strength of Sn-0.7Cu was lower than those of Sn-3.5Ag and Sn-37Pb in the strain rate ranging from 1.67×10^{-4} s^{-1} to 1.67×10^{-2} s^{-1} at room temperature. The elongations of the lead-free solders were inferior to that of Sn-37Pb in the strain range ranging from 1.67×10^{-4} s^{-1} to 1.67×10^{-3} s^{-1} at room temperature. The elongations of the lead-free solders were relatively stable at approximately 40% in the temperature ranging from -40℃ to 120℃. From the results of strain-rate-change tests, the stress exponents of Sn-0.7Cu were determined to be 11, 11 and 10 at 25℃, 80℃ and 120℃, respectively. They were stable and higher than those of Sn-37Pb at the temperatures investigated. The activation energy for creep of the Sn-0.7Cu solder was investigated to be 39.7kJ/mol. It is close to that for creep of tin controlled by pipe diffusion.

Key words: lead-free solder, Sn-0.7mass%Cu, tensile properties, strain rate sensitivity, activation energy for creep

1. INTRODUCTION

Many studies of lead-free solders and soldering have been performed due to the toxicity of Pb present in Sn-Pb solders used in many electronic products [1-3]. Most of them have focused on Sn-based alloys. For reflow soldering, Sn-Ag -(Cu) alloys are expected to be a substitute for the Sn-Pb eutectic solder, because they have better mechanical properties (ductility, creep resistance and thermal resistance) than the Sn-Pb solder [4]. Thus, the Sn-Ag alloy system was applied as the first lead-free solder in the world [5].

For flow soldering, in addition to Sn-Ag alloys, Sn-Cu alloys are also expected to be a substitute for the Sn-Pb solder [6]. Although the melting point of the Sn-Cu alloy is higher than those of other lead-free solders such as Sn-Ag alloys, the material cost of the Sn-Cu alloy is relatively low because of the absence of silver in the alloy. Generally, the eutectic Sn-0.7mass%Cu is expected to be the lead-free solder for flow soldering. Several works for the hypoeutectic Sn-0.5mass%Cu alloy have been performed, and the mechanical properties and creep properties of Sn-0.5Cu have been reported [7, 8]. However, the works of the eutectic Sn-0.7Cu alloy are little.

In this study, the tensile properties of Sn-0.7Cu were investigated under various test conditions. In particular, the effects of strain rate and test temperature on the tensile properties were investigated. Moreover, the tensile properties of Sn-0.7Cu were compared with those of a Sn-3.5mass%Ag lead-free alloy and a Sn-37mass%Pb alloy.

2. EXPERIMENTAL PROCEDURE

Table I shows the chemical composition of the Sn-0.7Cu alloy used in this study. Dog-bone-type specimens, with 50 mm gauge length and 10 mm diameter, were prepared by casting and machining. A more detailed description of the specimen details is available elsewhere [9]. Specimens were annealed at 100 ℃ for 1 h before the test. Tensile tests and strain-rate-change (SRC) tests were performed. Tensile tests were performed at tensile strain rates ranging from 1.67×10^{-4} s^{-1} to 1.67×10^{-2} s^{-1}, and at temperatures of -40±2 ℃, 20±4 ℃ (room temperature) and 120±2 ℃. The strain rate was controlled by a crosshead displacement rate, and was maintained until specimen failure occurred. Three specimens were tested under each conditions except that at -40 ℃. In the case of -40 ℃, one specimen was tested.

For SRC tests, the strain rate was maintained at the lowest level up to a total plastic strain of

Table I Chemical composition of Sn-0.7Cu studied.

Cu	Pb	Sb	Bi	Fe	As	Sn (mass%)
0.686	0.022	0.008	0.006	0.003	0.001	Bal.

approximately 5 % and increased in two steps to the highest level of the test. Each strain-rate step was maintained for a plastic strain of approximately 4 %. The lowest rate, which was the starting strain rate, was 8.3 x 10^{-5} s^{-1} or 1.67 x 10^{-4} s^{-1}, and the strain rate was changed at each step by a factor of ten. SRC tests were performed at 25±5 ℃ (room temperature), 80±2 ℃ and 120±2 ℃. Data of SRC tests, for which the specimens exhibited no significant necking, were used in this study.

Specimens were sectioned by a cutter. They were ground with SiC paper until #1200, and then mechanically polished with two grades of Al_2O_3 paste (1 μm and 0.3 μm). After etching in a solution of 20 mℓ HCl, 14 g $FeCl_3 \cdot 6H_2O$ and 140 mℓ CH_3OH, they were observed both with a scanning electron microscope (SEM) at an accelerating voltage of 15 kV and with an optical microscope (OM).

3. RESULTS AND DISCUSSION

3.1 Microstructures

Figure 1 shows the microstructure of Sn-0.7Cu after annealing at 100 ℃ for 1 h. The bright-gray areas and the dark-gray areas shown in Fig. 1 are primary Sn phases and eutectic phases, respectively. Although Sn-0.7Cu is a eutectic solder, hypoeutectic microstructure are observed. Similar hypoeutectic microstructures have been also reported for Sn-rich lead-free solders such as Sn-3.5Ag, Sn-3.5Ag-0.75Cu and Sn-3Ag-2Bi [10]. The primary Sn phases were elongated along the tensile direction during the tensile test. Similar deformation behaviors of primary Sn phases have been also observed in Sn-3.5Ag [9].

3.2 Tensile Tests

3.2.1 Effect of strain rate on mechanical properties

Figure 2 shows the effect of strain rate on the mechanical properties of Sn-0.7Cu at room temperature. The data of Sn-3.5Ag and Sn-37Pb [10] are also indicated in Fig. 3 to compare with Sn-0.7Cu. The tensile strength of Sn-0.7Cu is smaller than those of Sn-3.5Ag and Sn-37Pb over the strain rate range investigated. The tensile strength of Sn-0.7Cu increases with increasing strain rate, similarly to other solders. A linear relationship is observed between the tensile strength and the strain rate for all solders in Fig. 3. This means that the relationship obeys the following equation:

$$\sigma = A \dot{\varepsilon}^{m} , \quad \text{---(1)}$$

where σ is tensile strength, $\dot{\varepsilon}$ is strain rate, m is the strain rate sensitivity and A is a constant. The slope of each line in Fig. 2 gives the strain

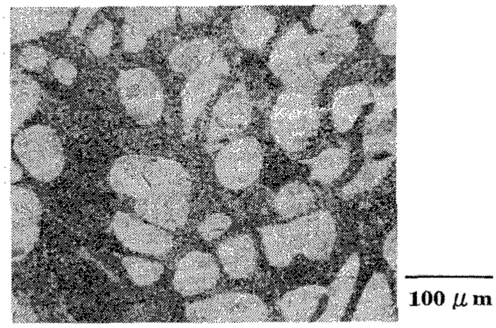

Fig. 1 Microstructure of Sn-0.7Cu after annealing at 100℃ for 1h (OM image).

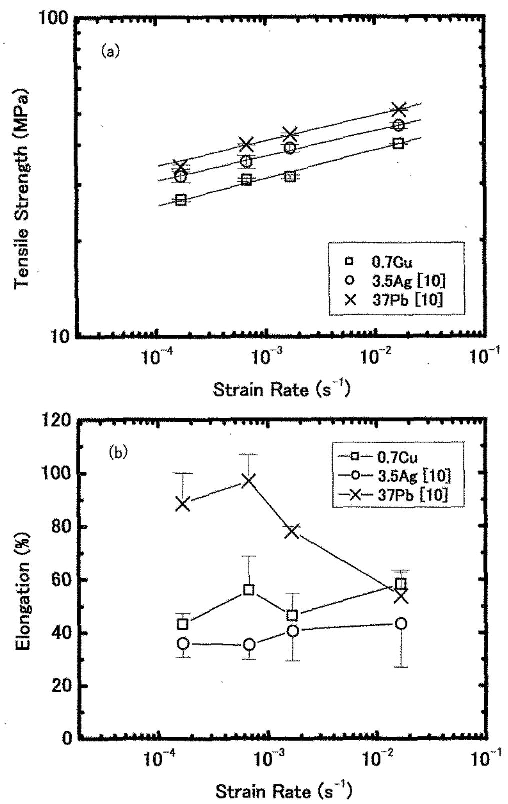

Fig. 2 Effect of strain rate on mechanical properties at R.T. (a) Tensile strength, (b) Elongation.

rate sensitivity, *m*. The *m* values were calculated to be 0.09, 0.08 and 0.09 for Sn-0.7Cu, Sn-3.5Ag and Sn-37Pb, respectively.

The elongations of Sn-0.7Cu are relatively stable at 50% and are a little superior to those of Sn-3.5Ag in the strain range investigated. The elongations of Sn-37Pb show excellent values, which are approximately 100 %, when the strain rate is less than 10^{-3} s^{-1}. However, the elongations decrease drastically with increasing the strain rate over 10^{-3} s^{-1} and become similar to that of Sn-0.7Cu at the strain range of 1.67 x 10^{-2} s^{-1}.

3.2.2 Effect of test temperature on mechanical properties

Figure 3 shows the effect of test temperature on the mechanical properties of Sn-0.7Cu. All data are plotted from the results of tensile tests performed at the same strain rate of 1.67 x 10^{-3}

s^{-1}. The tensile strength of Sn-0.7Cu decreases with increasing test temperature. The tensile strength of Sn-0.7Cu is smaller than those of Sn-3.5Ag and Sn-37Pb over the temperature range investigated except at 120 ℃. The tensile strength of Sn-0.7Cu is very close to that of Sn-37Pb at 120 ℃.

The elongations of Sn-0.7Cu are approximately 40 % and independent of the temperature between -40 ℃ and 120 ℃. Similar tendency is observed in Sn-3.5Ag. On the other hand, the elongation of Sn-37Pb increases linearly with increasing temperature, although it is very close to those of lead-free solders at -40 ℃.

3.3 SRC tests

Figures 4 show the relationship between true strain rate and true stress obtained from the results of the SRC tests at 25 ℃, 80 ℃ and 120 ℃, respectively. The slope of each line fitted to the data gives the stress exponent, *n*. Moreover, the strain rate sensitivity, *m*, is given by *1/n*. Table II lists the stress exponent, *n*, and the strain rate sensitivity, *m*, for each solder. The stress exponents of Sn-0.7Cu are stable at high values over 10 in the temperature range from 25 ℃ to 120 ℃, similarly to those of Sn-3.5Ag. As described above, the deformation of Sn-0.7Cu and Sn-3.5Ag are mainly controlled by the deformation of the primary Sn phases at the temperatures investigated. Thus, the stress exponents of Sn-0.7Cu and Sn-3.5Ag are similar

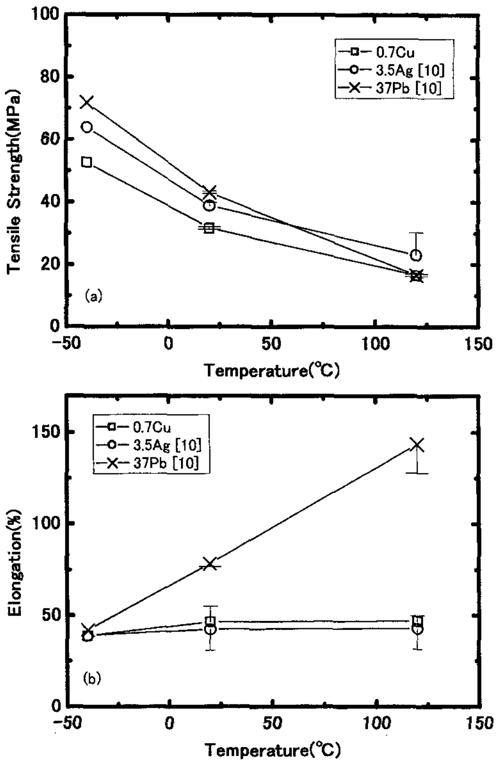

Fig. 3 Effect of test temperature on mechanical properties (a) Tensile strength, (b) Elongation (strain rate: 1.67 x 10^{-3} s^{-1}).

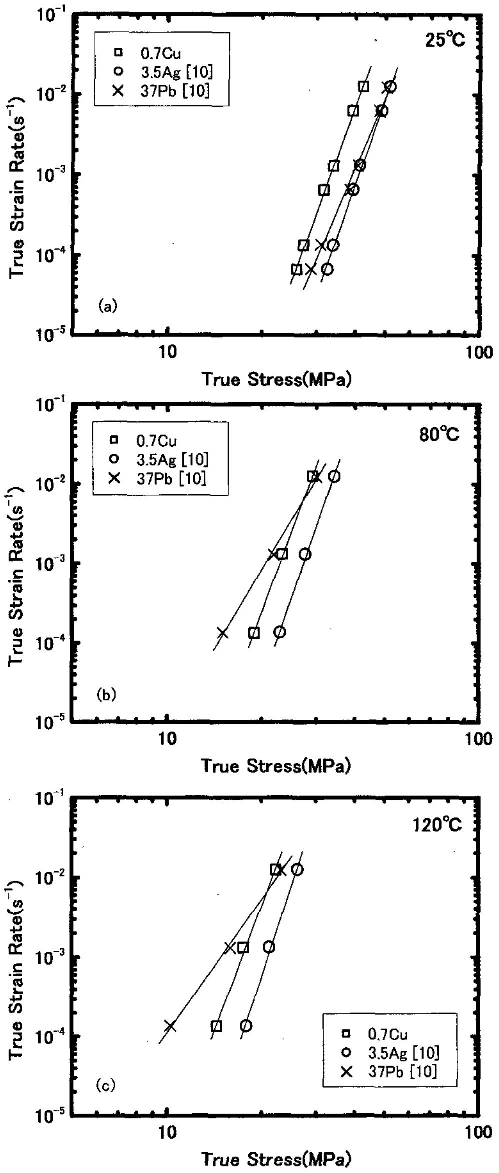

Fig. 4 SRC test results at (a) 25℃, (b) 80℃ and (c) 120℃.

Table II Stress exponent, *n* and strain rate sensitivity, *m*.

Solder(mass%)	Temperature(℃)	*n*	*m*
Sn-0.7Cu	25	11	0.09
	80	11	0.10
	120	10	0.10
Sn-3.5Ag [10]	25	11	0.09
	80	11	0.09
	120	12	0.08
Sn-37Pb [10]	25	9	0.11
	80	6.5	0.15
	120	5.5	0.18

value and relatively stable at the temperature investigated. The tendency of lead-free solders is different from Sn-37Pb, which has a eutectic microstructure and in which stress exponents decrease with increasing temperature.

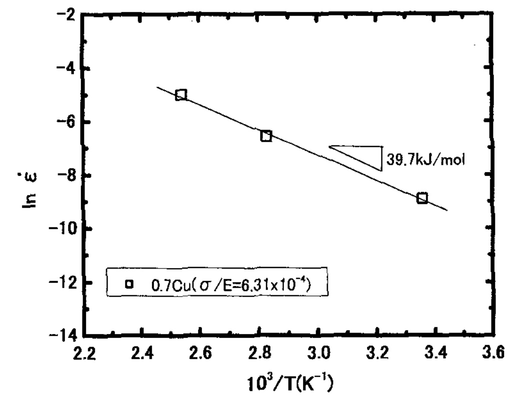

Fig. 5 Ahhrenius plot for strain rate vs. reciprocal temperature.

For the strain rate sensitivities, the similar tendencies to the stress exponent are observed. That is, the strain rate sensitivities are relatively stable in lead-free solders. These at 25 ℃ are in good agreement with the values of *m* calculated from Fig. 2 (refer to 3.2.1). Generally, superplasticity is observed when *m* is equal to or larger than 0.3. In this study, all *m* values are less than 0.3. Therefore, superplastic behavior did not occur in Sn-0.7Cu.

The steady-state creep is generally described by a power law equation of the form:

$$\dot{\varepsilon} = A(\sigma/E)^n \exp(-Q/RT), \quad \text{---(2)}$$

where $\dot{\varepsilon}$ is steady-state strain rate, σ is applied stress, E is Young's modulus, Q is the activation energy for creep, T is the absolute temperature, R is the gas constant, and A is a material-dependent creep constant. The activation energy for creep can be determined by fitting the data to Eq. (2). In this study, the temperature dependence of Young's modulus for tin is used for the analysis, because the matrix of Sn-0.7Cu is principally tin. The modulus of tin is described by following equation [11],

$$E(\text{MPa}) = 76087 - 109 \times T(\text{K}), \quad \text{---(3)}$$

Figure 5 shows the relationship between strain rate and reciprocal temperature at a certain stress for the Sn-0.7Cu solder. The data of the Sn-0.7Cu solder fall on a straight line. The slope of the line gives the activation energy for creep of Sn-0.7Cu. The activation energy was estimated to be 39.7kJ/mol. It is much lower than the activation energy for the lattice self-diffusion of tin (102kJ /mol[12]). The activation energy investigated in this study is relatively close to that for creep of tin controlled by pipe diffusion [13], and thus the creep behavior can be related to pipe diffusion controlled by dislocation climb. Therefore, the creep of Sn-0.7Cu is dominated by pipe diffusion-controlled climb in the strain rate range investigated.

5. CONCLUSIONS

The tensile properties of Sn-0.7Cu were investigated and compared with those of Sn-3.5Ag and Sn-37Pb. The results are summarized as follows.

(1) The tensile strength of Sn-0.7Cu is a little smaller than those of Sn-3.5Ag and Sn-37Pb under the strain rate and test temperature conditions investigated.

(2) The ductility of Sn-0.7Cu is relatively stable in the strain rate ranging from 1.67 x 10^{-4} s^{-1} to 1.67 x 10^{-2} s^{-1} at room temperature.

(3) The ductility of Sn-0.7Cu is relatively stable at the temperature ranging from -40 ℃ to 120 ℃.

(4) The stress exponents for Sn-0.7Cu are high values more than 10 and stable at temperatures ranging from 25 ℃ to 120 ℃.

(5) The activation energy for the creep of Sn-0.7Cu was investigated to be 39.7kJ/mol. It corresponds to that of the creep controlled by pipe diffusion.

Acknowledgement

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