Tensile Properties of Sn–3.5Ag and Sn–3.5Ag–0.75Cu Lead-free Solders

Ikuo Shohji[1], Tomohiro Yoshida[1], Takehiko Takahashi[2] and Susumu Hioki[2]

[1]*Faculty of Engineering, Gunma University, Kiryu 376-8515, Japan*
[2]*Akita Prefectural University, Honjo 015-0055, Japan*

The tensile properties of Sn–3.5Ag and Sn–3.5Ag–0.75Cu lead-free solders were investigated. The effect of annealing at 100°C for 1 h before the tensile test on mechanical properties was small in both solders. The tensile strength decreased with decreasing strain rate, and with increasing test temperature. However, the ductility of each solder was relatively constant in the strain rate ranging from $1.67 \times 10^{-4}\,\mathrm{s}^{-1}$ to $1.67 \times 10^{-2}\,\mathrm{s}^{-1}$ and in the test temperature ranging from −40 to 120°C. From the results of the strain-rate-change tests, the strain sensitivity for Sn–3.5Ag and Sn–3.5Ag–0.75Cu were found to be 0.077 and 0.078, respectively.

1. Introduction

Due to the toxicity of Pb present in a Sn–Pb solder, an alternative solder needs to be considered. Many studies of lead-free solders and soldering have been performed from such a viewpoint.[1,2] Most of them preferred Sn-based alloys. In particular, Sn–Ag 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.[3] Thus, the Sn–Ag alloy system was applied as the first lead-free product in the world,[4] although the melting temperature is higher and the wettability is poorer than the Sn–Pb eutectic solder.

Since the implementation of the Sn–Ag solder to many electronics products has been spreading gradually, more studies are required to investigate its material characteristics in terms of melting temperature, solderability, mechanical strength, ductility, creep resistance, thermal fatigue resistance, corrosion resistance, and so on. Of these, the mechanical properties are very important, because such properties of the solder itself determine the fracture and the thermal fatigue of the solder joint. Therefore, the mechanical properties of the solder, such as tensile strength and ductility, under various conditions need to be investigated. They are necessary for structural analysis and evaluation of the thermal fatigue life of the solder joint.

The aim of this study is to determine the tensile properties of Sn–3.5Ag and Sn–3.5Ag–0.75Cu solders under various test conditions. In particular, the effects of strain rate and test temperature on the tensile properties were investigated.

2. Experimental Procedure

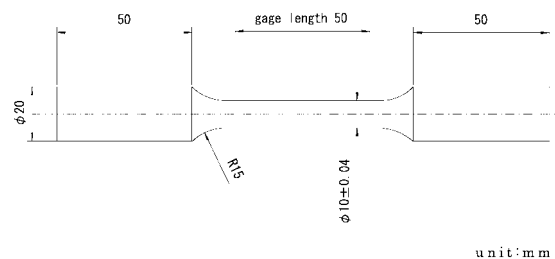Table 1 shows the chemical compositions of the solders

Fig. 1 Dimensions of tensile specimen.

used in this study. Each solder was prepared as a cylindrical ingot by casting. The diameter and length of the cylinder were 30 mm and 250 mm, respectively. The tensile specimen was machined from the ingot of each solder. Figure 1 shows the dimensions of the tensile specimen. Each sample was annealed at 100°C for 1 h before the test. Samples without annealing were also prepared in order to determine the effect of annealing on the mechanical properties of the solders.

Two types of tensile tests were performed using an electromechanical testing system: elongation-to-failure (EF) tests and strain-rate-change (SRC) tests. EF tests were performed at tensile strain rates ranging from 1.67×10^{-2} to $1.67 \times 10^{-4}\,\mathrm{s}^{-1}$, and at temperatures of −40°C, R.T. and 120°C. The strain rate was controlled by the crosshead displacement rate, and was maintained until sample failure occurred. Three samples were tested under each condition except that at −40°C. In the case of −40°C, only one sample was tested.

For SRC tests, the strain rate was maintained at the lowest level up to a total plastic strain of approximately 5 pct 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 pct. The lowest rate, which was the starting strain

Table 1 Chemical compositions of solders studied.

Solder type	Ag	Cu	Pb	Sb	Fe	Bi	As	Sn (mass %)
Sn–3.5Ag	3.498	0.000	0.024	0.011	0.004	0.010	0.001	Bal.
Sn–3.5Ag–0.75Cu	3.546	0.781	0.026	0.005	0.005	0.002	0.002	Bal.

Table 2 Data of Elongation to Failure tests.

Solder	Anneal		T (°C)	Strain rate (s^{-1})	Tensile strength (MPa)	Elongation %	Reduction of area (%)
Sn–3.5Ag	100°C	1 h	R.T.	1.67×10^{-2}	45.8	43.0	77.0
	100°C	1 h	R.T.	1.67×10^{-3}	38.7	42.5	81.4
	100°C	1 h	R.T.	6.67×10^{-4}	35.2	39.0	77.4
	100°C	1 h	R.T.	1.67×10^{-4}	31.6	39.0	75.0
	Non		R.T.	1.67×10^{-3}	38.0	36.0	75.6
	100°C	1 h	120	1.67×10^{-3}	19.8	43.0	81.5
	100°C	1 h	−40	1.67×10^{-3}	64.0	39.0	65.0
Sn–3.5Ag–0.75Cu	100°C	1 h	R.T.	1.67×10^{-2}	56.7	44.0	73.8
	100°C	1 h	R.T.	1.67×10^{-3}	46.5	41.5	63.3
	100°C	1 h	R.T.	6.67×10^{-4}	43.0	34.3	64.0
	100°C	1 h	R.T.	1.67×10^{-4}	38.6	36.7	60.9
	Non		R.T.	1.67×10^{-3}	46.2	39.3	67.5
	100°C	1 h	120	1.67×10^{-3}	22.1	35.5	63.8
	100°C	1 h	−40	1.67×10^{-3}	76.6	35.0	66.1

rate, was $8.3 \times 10^{-5}\,\text{s}^{-1}$ or $1.67 \times 10^{-4}\,\text{s}^{-1}$, and the strain rate was changed at each step by a factor of ten. All SRC tests were performed at R.T.

After the EF tests, microstructure observation was performed. The samples were excised from the grip region and the failure region, and were molded into epoxy resin. The molded samples were polished mechanically, etched in a solution of 20 mL HCl, 14 g FeCl$_3 \cdot$6H$_2$O and 140 mL CH$_3$OH, and then observed with an optical microscope.

3. Results and Discussion

3.1 EF tests
3.1.1 Effect of strain rate on mechanical properties

Table 2 summarizes the results of EF tests, and each data is the average of the results of three samples except for the data obtained at −40°C. Figure 2 shows the effect of strain rate on the mechanical properties of Sn–3.5Ag and Sn–3.5Ag–0.75Cu. Solid symbols indicate the results for samples without annealing at 100°C for 1 h before the tensile test. Little difference in tensile strength is found between the samples with and without annealing. Although the elongation is slightly larger in the annealed samples than in the sample without annealing, no improvement is observed in the reduction of area. Therefore, the effect of annealing before the test on the mechanical properties is negligible. The same tendency was reported from the results of Vickers hardness measurement of aged Sn–3.5Ag.[5]

The tensile strength of Sn–3.5Ag–0.75Cu is greater than that of Sn–3.5Ag over the strain rate range investigated in this study. It decreases with decreasing strain rate in both solders. A linear relationship is observed between the tensile strength and the strain rate in Fig. 2. This means that the relationship obeys the following equation:

$$\sigma = A\dot{\varepsilon}^{m}, \qquad (1)$$

where σ is tensile strength, $\dot{\varepsilon}$ is strain rate, m is the strain sensitivity and A is a constant. The slope of the line in Fig. 2 gives the strain sensitivity, m. The m values were calculated to be 0.081 and 0.084 for Sn–3.5Ag and Sn–3.5Ag–0.75Cu, respectively. It has been reported that creep deformation occurs when the strain rate is below $10^{-4}\,\text{s}^{-1}$,[6] so that the effect of creep deformation cannot be neglected in that range. The ductility decreases gradually with decreasing strain rate. However, no significant tendency was found in either solder.

3.1.2 Effect of test temperature on mechanical properties

Figure 3 shows the effect of test temperature on the mechanical properties of each solder. The tensile strength of each solder decreases linearly with increasing test temperature. The strength of Sn–3.5Ag–0.75Cu is higher than that of Sn–3.5Ag at −40°C and R.T. However, the strength of the two solders is almost the same at 120°C.

The elongation of each solder is approximately 40% and independent of temperature between −40°C and 120°C, although it is slightly larger in Sn–3.5Ag than in Sn–3.5Ag–0.75Cu at all temperatures. A similar tendency is found for the reduction of area.

3.1.3 Microstructure

Figure 4 shows the microstructures of Sn–3.5Ag solders before and after the EF test. The primary Sn phase (bright-gray area) and the eutectic phase (dark-gray area) are observed in as-cast solder. A hypoeutectic microstructure has been reported in Sn–3.5Ag solder at a solidification rate of 12°C/s,[7] which is close to the cooling rate used during casting in this study of 10°C/s. Thus, formation of the hypoeutectic microstructure occurred during solidification. A similar microstructure is observed in the sample annealed at 100°C for 1 h (Fig. 4(b)). This is because the annealing at 100°C for 1 h before the tensile test has no effects on the mechanical properties, as shown in Fig. 2.

A primary Sn phase elongating along the tensile direction is observed in a specimen subjected to a strain rate of $1.67 \times 10^{-4}\,\text{s}^{-1}$ at R.T. (Fig. 4(c)). The primary Sn phase also elongates in a sample tested at −40°C (Fig. 4(d)). A similar microstructure is observed generally in Sn–3.5Ag and in

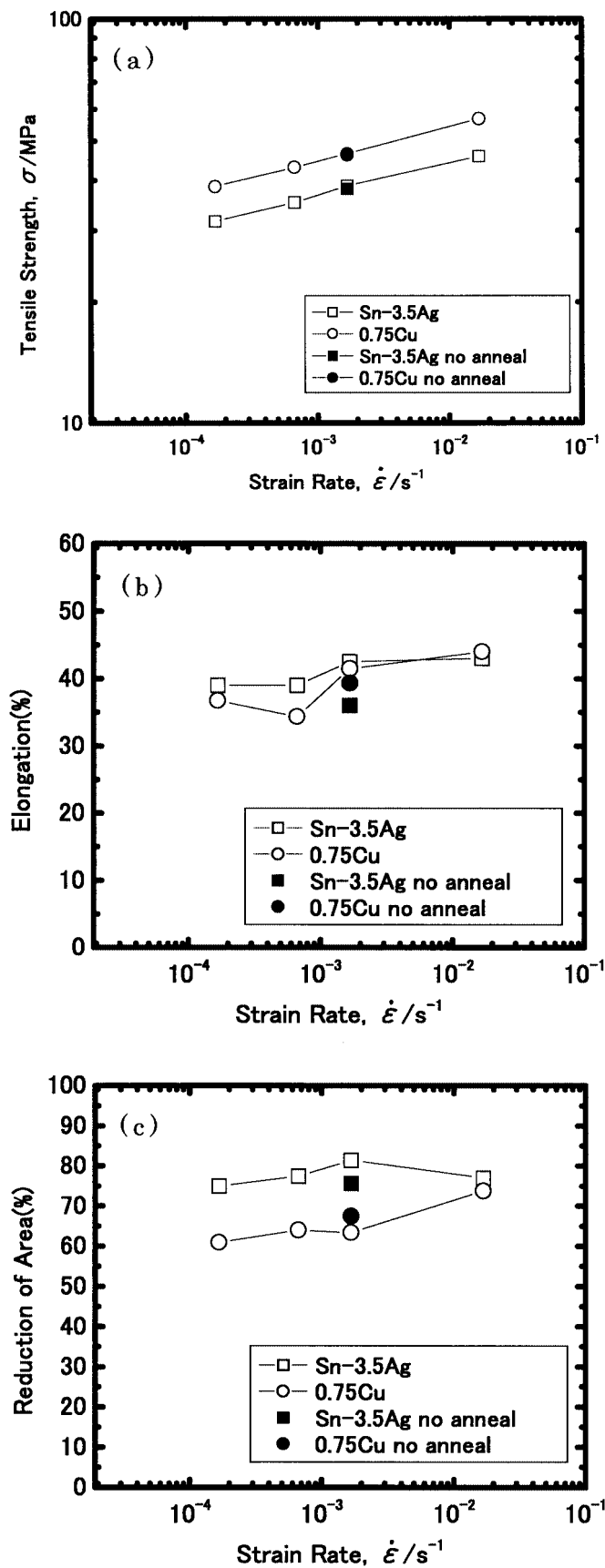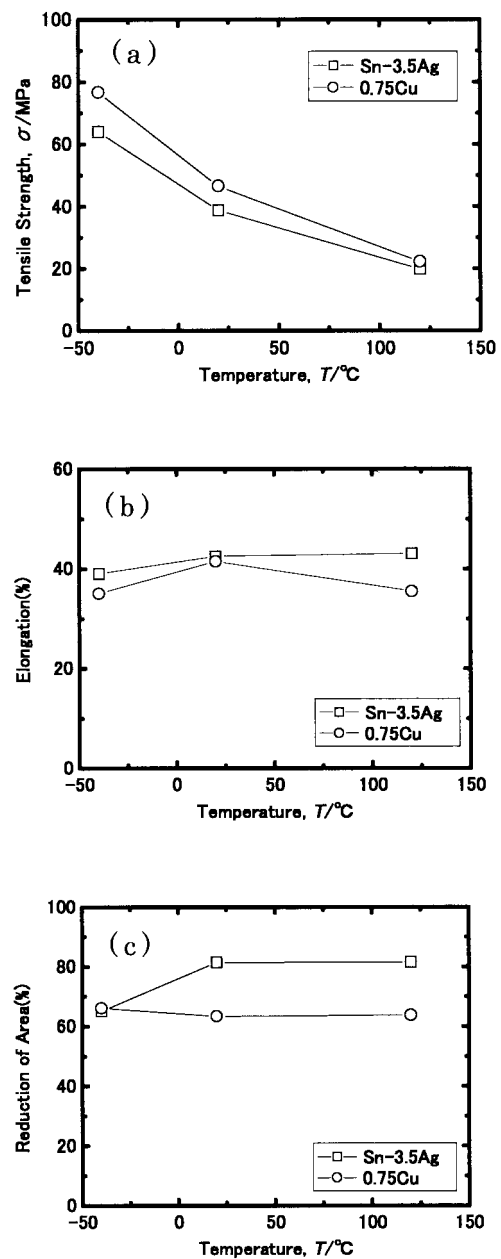Fig. 3 Effect of test temperature on mechanical properties. (a) Tensile strength, (b) Elongation, (c) Reduction of area.

Sn–3.5Ag–0.75Cu solders. Therefore, the primary Sn phase deforms easily in the tensile direction, leading to the ductility of Sn–3.5Ag and Sn–3.5Ag–0.75Cu, as shown in Figs. 2 and 3. Therefore, the ductility of the two solders is insensitive to the strain rate and the test temperature.

3.2 SRC tests

Figure 5 shows the results of SRC tests. The slope of the lines fitted to the data gives the stress exponent, n. The calculated n values were 13.0 and 12.9 for Sn–3.5Ag and Sn–3.5Ag–0.75Cu, respectively. The strain sensitivity, m, is given by $1/n$ and hence is 0.077 and 0.078 for Sn–3.5Ag and Sn–3.5Ag–0.75Cu, respectively, in good agreement with the values of m calculated from Fig. 2 (refer to Section 3.1.1). Moreover, these values are in good agreement with the value of m previously reported for as-cast Sn–3.5Ag, 0.08.[8] As

Fig. 2 Effect of strain rate on mechanical properties. (a) Tensile strength, (b) Elongation, (c) Reduction of area.
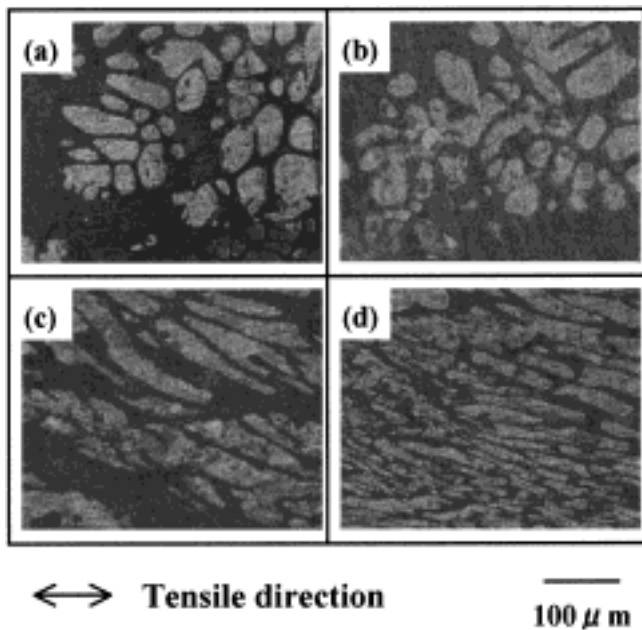
Fig. 4 Optical micrographs of Sn–3.5Ag samples after EF test. (a) As cast, (b) Grip region (annealed at 100°C for 1 h), (c) Failure region (R.T., strain rate: $1.67 \times 10^{-4}\,\text{s}^{-1}$), (d) Failure region ($-40$°C, strain rate: $1.67 \times 10^{-3}\,\text{s}^{-1}$).

Fig. 5 Relationship between strain rate and stress from SRC tests.

shown in Fig. 4, the annealing at 100°C for 1 h did not change the microstructure. Therefore, the m value of this study was close to that of the as-cast Sn–3.5Ag. Moreover, the m value of Sn–3.5Ag–0.75Cu was close to that of Sn–3.5Ag. Generally, superplasticity is observed when m is equal to or larger than 0.3. Since the primary Sn phase was elongated in the tensile direction (refer to Fig. 4), superplastic behavior did not occur in Sn–3.5Ag and Sn–3.5Ag–0.75Cu solders.

4. Conclusion

The tensile properties of Sn–3.5Ag and Sn–3.5Ag–0.75Cu lead-free solders were investigated. The results are summarized as follows.

(1)   The effect of annealing at 100°C for 1 h on the mechanical properties is small in both solders.

(2)   The tensile strength decreases with decreasing strain rate.

(3)   The ductility of each solder is independent of the strain rate between $1.67 \times 10^{-4}\,\text{s}^{-1}$ and $1.67 \times 10^{-2}\,\text{s}^{-1}$.

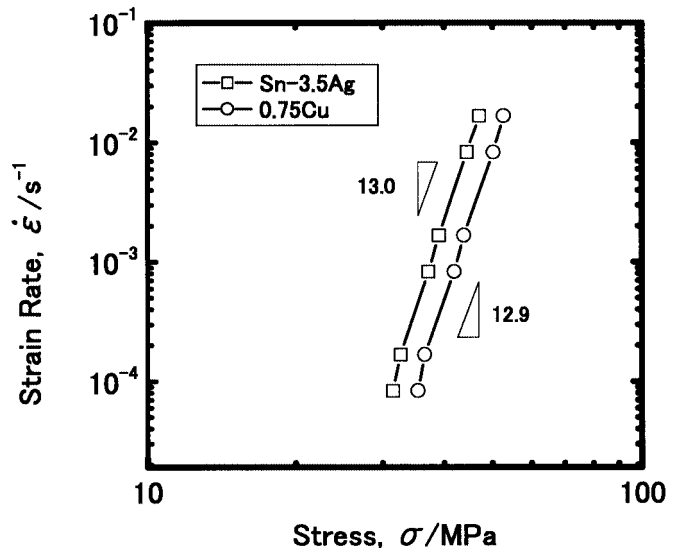(4)   The tensile strength of each solder decreases monotonously with increasing test temperature, while the ductility remains nearly constant.

(5)   The elongation of the primary Sn phase along the tensile direction was observed after the tensile test.

(6)   The strain sensitivities for Sn–3.5Ag and Sn–3.5Ag–0.75Cu were found to be 0.077 and 0.078, respectively.

Acknowledgements

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