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Viscoplastic Deformation of Lead Free Solder Alloy - Experiments and Simulations

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Abstract. In this paper, viscoplastic deformations of Sn-3.5Ag-0.75Cu solder alloy are discussed. First, the following experiments are conducted: (1) Pure tension at several strain rates. (2) Cyclic tension-compression loading with several strain amplitudes at several strain rates. (3) Creep tests at several stress levels. The test results show that the Sn-3.5Ag-0.75Cu solder alloy has large strain rate and temperature effects, and that there is a noticeable transient creep region in the creep curves. A viscoplastic constitutive model for the solder alloy is also discussed. The model is constructed based on the dislocation density based constitutive model proposed by Estrin [6]. The constitutive model well simulates both the time and temperature dependences on the deformation of the lead free solder alloy. Finally, the constitutive model is incorporated into a general purpose FEM program (Marc) to clarify the applicability of the model to the structural analysis.

Introduction

Recently, environmental pollution caused by the lead liquation from the solder in the wasted electronic machines becomes a serious matter of great concern. Therefore, the developments of the electronic packaging using lead free solder alloys are required, and studies of fatigue failure of the lead free solder alloys are performed [1-5].

Pao et al. [1, 2] performed thermal fatigue tests of 97Sn-3Cu solder joints and they simulated the response due to thermal loading by FEM analysis (ABAQUS). Reader [3] studied on the creep behavior of Bi-Sn solder alloys and constructed a creep constitutive model. Ren et al. [4] investigated the stress-strain response caused by pure tension and creep deformation of lead free solders and compared that with the responses of 63Sn-37Pb solder alloy. Whitelaw et al. [5] also studied on cyclic deformation and thermomechanical deformation of two lead free solder alloys and constructed a unified constitutive model.

To construct a constitutive model that can be applied to the deformation of the lead free solder alloys, a systematic experimental research is required. In this paper, a series of tests are conducted to clarify both temperature and time dependences on the deformation of the lead free solder alloys. Sn-3.5Ag-0.75Cu solder alloy is chosen as a lead free solder alloy, which is one of substitutes for Pb/Sn solder alloys. The test results are simulated by a viscoplastic constitutive model based on the dislocation density proposed by Estrin [6]. To clarify the applicability of the constitutive model to the structural analysis, the constitutive model is incorporated into a general purpose FEM program (Marc).

Experimental Procedure

The specimen used in this work was made of the Sn-3.5Ag-0.75Cu solder alloy. Figure 1 shows the geometry of the specimen. The specimen has a gauge length of 20mm and a diameter of 5mm. Considering the circumstances of solder joints used in the electronic packaging, each specimen was cast into a molding box of carbon to equalize the casting conditions. After casting, the specimen was left at room temperature for two weeks to remove residual stress, and was used as cast for the experiments.

To clarify both temperature and time dependence on the deformation of the lead free solder alloy,

Table 1. Test conditions for pure tension

Temperature, K	263, 283, 303, 323, 343, 373, 393
Strain rate, %/s	0.1, 0.01, 0.001

Table 2. Test conditions for cyclic loading

Starin amplitude, %	0.5, 1, 1.5
Temperature, K	303, 323, 343, 373, 393
Strain rate, %/s	0.1, 0.01, 0.001

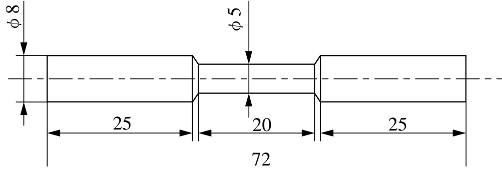


Fig. 1 Geometry of specimens

Table 3. Test conditions for creep

Temperature, K	263	283	303	323	343
Stress level, MPa	60, 50, 55	50, 45, 40	45, 40, 35	45, 40, 35	40, 35

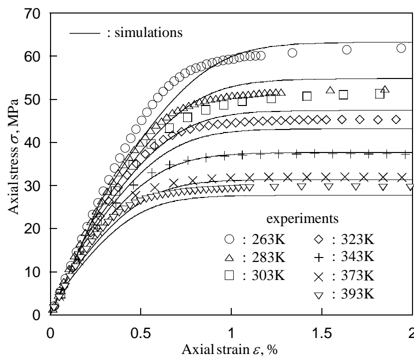


Fig. 2 Temperature dependence of pure tension (strain rate: 0.01%/s)

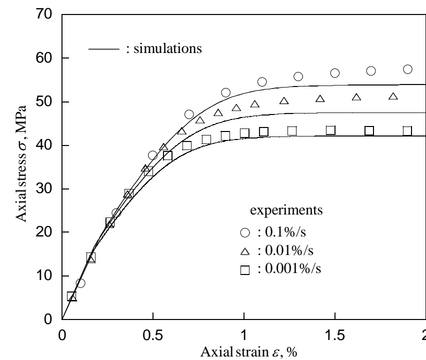
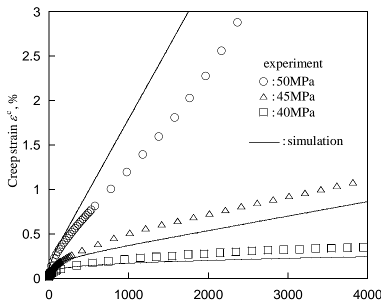
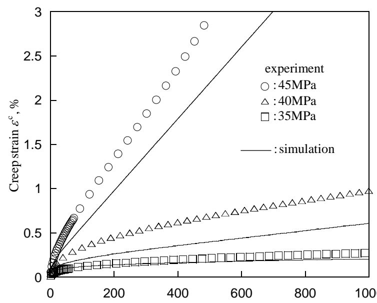


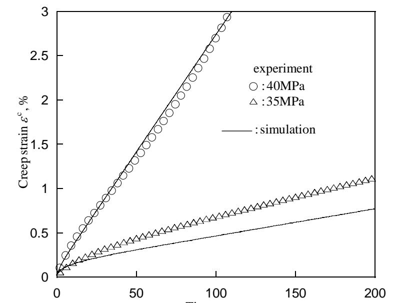
Fig. 3 Strain rate dependence of pure tension (Temperature: 303K)



(a) 283K



(b) 303K



(c) 343K

Fig. 4 Creep curves

pure tension, cyclic loading, and creep tests were conducted at several temperatures and strain rates. Tables 1~3 show the test conditions for the pure tension, cyclic loading, and creep tests, respectively

Experimental Results

Pure Tension. The symbols in Fig. 2 and 3 show the experiments of the stress-strain relation caused by the pure tensile tests. The lines in Fig. 2 and 3 are the simulations by the viscoplastic constitutive model shown later. The stress-strain relations in Fig. 2 were obtained at several temperatures and those in Fig. 3 at several strain rates. It can be seen that both the temperature and strain rate affect the work hardening, that is, higher temperatures and lower strain rates lead to higher work hardening.

Creep. Figure 4 shows creep curves at three temperatures. In Fig. 4 the lines are simulations discussed later. There are both large temperature and stress dependence on creep deformation of the

lead free solder alloy. The noticeable transient creep region is, especially, observed in creep curves at 283 and 303K. For Pb/Sn solder alloy, the transient creep region is small and it is generally negligible. That allows using a simple creep model such as Norton's law in FEM analysis. However, for the lead free solder alloy, the transient creep region can not be negligible because the transient creep region is too large. It suggests that a constitutive model to be able to accurately explain the transient creep region is required.

Constitutive Modeling and Simulations

Constitutive Modeling. Based on the dislocation based model proposed by Estrin [6], the pure tension, cyclic loading and creep deformation were simulated. The summary of the constitutive model is as follows:

Considering the dislocation density model, the viscoplastic potential is written as

$$F = \frac{\xi D^*}{m+1}\left(\frac{\bar{\sigma}}{D^*}\right)^{m+1} \tag{1}$$

In Eq. (1), $\bar{\sigma}$ is the equivalent stress defined by

$$\bar{\sigma} = \left\{\frac{3}{2}\left(\sigma_{ij}^{'} - \alpha_{ij}^{'}\right)\left(\sigma_{ij}^{'} - \alpha_{ij}^{'}\right)\right\}^{1/2} \tag{2}$$

where $\sigma_{ij}^{'}$ and $\alpha_{ij}^{'}$ are deviatoric stress and deviatoric back stress, respectively. m and ξ are material constants, and D^* is the drag stress.

From the normality rule, the viscoplastic strain rate is given by

$$\dot{\varepsilon}_{ij}^{v} = \frac{\partial F}{\partial \sigma_{ij}} = \frac{3\xi}{2\bar{\sigma}}\left(\frac{\bar{\sigma}}{D^*}\right)^{m}\left(\sigma_{ij}^{'} - \alpha_{ij}^{'}\right) \tag{3}$$

The viscoplastic work rate is given by

$$\dot{W}^{v} = \bar{\sigma}\dot{\bar{\varepsilon}}^{v} = \left(\sigma_{ij}^{'} - \alpha_{ij}^{'}\right)\dot{\varepsilon}_{ij}^{v} = \frac{3\xi}{2\bar{\sigma}}\left(\frac{\bar{\sigma}}{D^*}\right)^{m}\left(\sigma_{ij}^{'} - \alpha_{ij}^{'}\right)\left(\sigma_{ij}^{'} - \alpha_{ij}^{'}\right) = \xi\left(\frac{\bar{\sigma}}{D^*}\right)^{m}\bar{\sigma} \tag{4}$$

From Eq. (4), the equivalent viscoplastic strain rate is written by

$$\dot{\bar{\varepsilon}}^{v} = \xi\left(\frac{\bar{\sigma}}{D^*}\right)^{m} \tag{5}$$

The plastic flow law is given by the following equation from Eqs. (3) and (5).

$$\dot{\varepsilon}_{ij}^{v} = \frac{3\dot{\bar{\varepsilon}}^{v}}{2\bar{\sigma}}\left(\sigma_{ij}^{'} - \alpha_{ij}^{'}\right) \tag{6}$$

Referring to the dislocation based constitutive model, the drag stress D^* is given by

$$D^* = \sigma_0\sqrt{Y - Z} \tag{7}$$

where σ_0 is a material constant and Y is the ratio of the immobile dislocation density at time zero to the immobile dislocation density at time t, and Z is the ratio of the immobile dislocation density at time zero to the recoverable dislocation density at time t.

Y and Z are given by the following equations.

$$\frac{\partial Y}{\partial t}=\left\{A+A_1\sqrt{Y-Z}-A_2\left(\frac{\dot{\bar{\varepsilon}}^v}{\dot{\varepsilon}_0^v}\right)^{(-1/n)}(Y-Z)\right\}\dot{\bar{\varepsilon}}^v \tag{8}$$

$$\frac{\partial Z}{\partial t}=\left\{A_5\sqrt{Y-Z}-A_2\left(\frac{\dot{\bar{\varepsilon}}^v}{\dot{\varepsilon}_0^v}\right)^{(-1/n)}Z\right\}\dot{\bar{\varepsilon}}^v-A_6Z \tag{9}$$

where A, A_1, A_2, A_5, A_6, $\dot{\varepsilon}_0^v$ and n are material constants.

Now we assume that the back stress $\alpha_{ij}^{'}$ is given by the following evolution equation.

$$\dot{\alpha}_{ij}^{'}=A_3\sqrt{Y-Z}\dot{\varepsilon}_{ij}^v-A_4\alpha_{ij}^{'}\dot{\varepsilon}_{ij}^v \tag{10}$$

where A_3 and A_4 are material constants.

In the uniaxial case, the viscoplastic strain and the back stress can be reduced as follows.

$$\dot{\varepsilon}^v=\xi\left(\frac{\bar{\sigma}}{\sigma_0\sqrt{Y-Z}}\right)^m \tag{11}$$

$$\frac{\partial\alpha}{\partial\varepsilon^v}=A_3\sqrt{Y-Z}-A_4\alpha \tag{12}$$

where $\dot{\varepsilon}^v$ is the axial viscoplastic strain rate and α is the axial back stress.

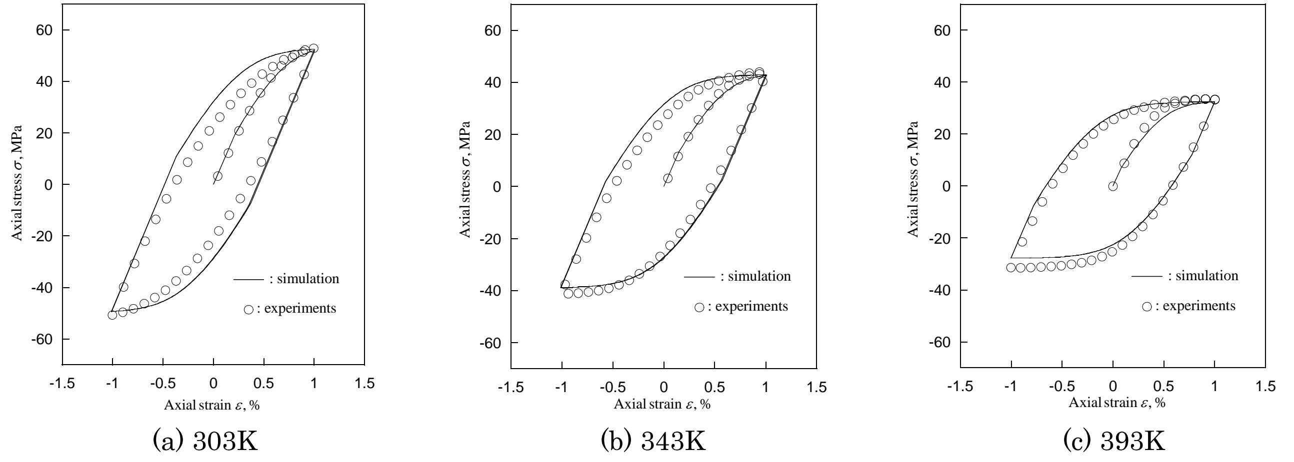
Simulations. The simulations of the pure tension, cyclic loading and creep deformation of the lead free solder alloy were performed.

The lines in Fig. 2 show the simulations of the pure tension affected by temperature. The simulations have good agreements with experiments, and the constitutive model can explain the temperature dependence of the pure tension. The lines in Fig. 3 show the simulations of the pure tension affected by the strain rate. The constitutive model can also well simulate the strain rate effect due to the pure tension.

The lines in Fig. 4 show the simulations of the creep curves. The simulations well explain the experiments at the several temperatures and stress levels. The transient creep region was, especially, well simulated by the constitutive model.

In the real life conditions, the cyclical thermal or mechanical loading act on the solder joints in the electronic packaging. Then, the constitutive model is necessary to simulate the cyclic deformation of the lead free solder alloy. Figures 5(a)~(c) are the examples of the cyclic tension-compression loading at three temperatures of 303, 343, and 393K with the strain amplitude of 1% at the strain rates of 0.1%/s, respectively. The experiments plotted by the symbols show that the stress-strain relations caused by the cyclic loading saturate during a few cycles. The simulations well explain the experiments as shown by the solid lines in Fig. 5.

It has been confirmed that the other experiments shown in Table 2 and 3 are also well simulated



(a) 303K (b) 343K (c) 393K

Fig. 5 Stress-strain relations of cyclic tension-compression loading
(temperature effect, strain rate: 0.1%/s, strain amplitude: 1%)

Table 4. Material constants

A	A_1	A_2	A_3	$A_4(1)$	A_4	A_5	A_6	ξ	Y_0	Z_0	$\dot{\varepsilon}_0^{\mathrm{v}}$
2000	10000	800	13000	850	480	9950	0	1	1	0	1

by the constitutive model though the simulations are omitted due to limitations of space.

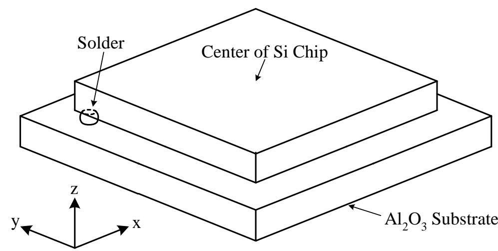
The material constants used for the simulations are shown in Table 4. In Table 4, $A_4(1)$ is A_4 for the pure tension and the first half cycle of the cyclic loading. Y_0 and Z_0 are the initial values of Y and Z, respectively. All the simulations are performed using the same values of the material constants except for m, n and σ_0. m, n and σ_0 are formulae of temperature T (K) expressed by the following equations.

$$\begin{aligned} m &= 403\exp\left(-0.011T\right) \\ n &= 86.6\exp\left(-0.0037T\right) \\ \sigma_0 &= 123\exp\left(-0.0046T\right) \end{aligned} \tag{13}$$

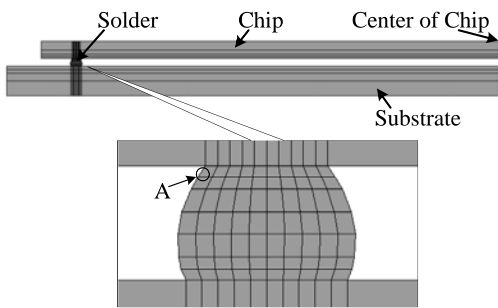
Structural Analysis. To verify the applicability of the viscoplastic constitutive model to the structural analysis the constitutive model was incorporated into a general purpose FEM program (Marc) with the user subroutine.

Figure 6 shows the finite element model of the electronic packaging, which has four solder joints at four corners (Fig. 6(a)), and the model is deal with the two dimensional axis-symmetric problem (Fig. 6(b)). Figure 7 shows temperature cycle used for the FEM analysis. The packaging is given temperature cycle from 223 to 423K for three cycles. The FEM analysis was conducted by three constitutive models. One is the viscoplastic model discussed here, and others are elastic-creep model and elastoplastic-creep model, which are prepared in Marc as default model. The elastic-creep and elastoplastic-creep model are normally used for the structural analysis to predict the fatigue failure of the solder joints in manufacturing. The creep parts of both the elastic-creep and the elastoplastic-creep model are calculated by the Norton's law, and the plastic part of the elastoplastic-creep model is calculated by the linear kinematic hardening model.

Figure 8 shows the relationship between shear strain and time in hour at point A in Fig. 6(b) obtained by the FEM analysis. The shear strain obtained by the viscoplastic model gives the largest strain. The reason of the larger shear strain simulated by the viscoplastic constitutive model is the accurate prediction of the transient creep region and interaction between plasticity and creep. It is well known that the electronic packaging bends due to the residual strain in the solder joints, which



(a)



(b)

Fig. 6 Finite element model

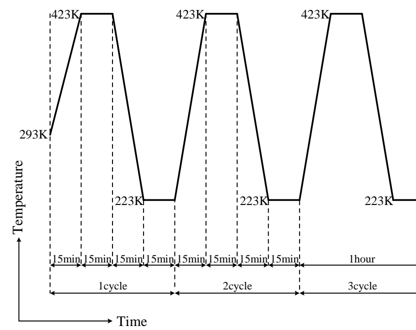


Fig. 7 Temperature cycle

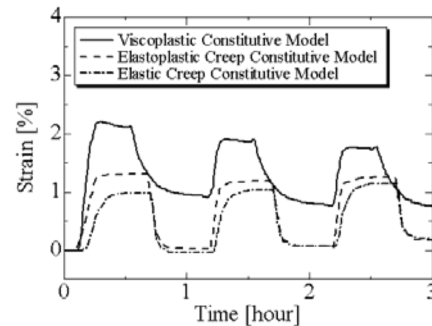


Fig. 8 Shear strain vs. time

is a cause of the failure of the chip or the substrate. Then, the viscoplastic constitutive model has a benefit to predict the bending of the electronic packaging because it well simulates the residual stress in the solder joints.

Conclusions

This paper clarified the viscoplastic deformation of the lead free solder alloys (Sn-3.5Ag-0.75Cu) by a series of tests. The viscoplastic constitutive model was constructed based on the dislocation based model proposed by Estrin [6]. The viscoplastic constitutive model was also incorporated into the general purpose FEM program (Marc). As a result, the following conclusions were obtained: (1) The lead free solder alloy has strain rate and temperature dependences. There is a noticeable transient creep region. (2) The viscoplastic constitutive model can accurately predict the pure tension, creep, and cyclic plasticity of the lead free solder alloy. (3) The viscoplastic constitutive model can be easily incorporated into the general purpose FEM program (Marc). The benefit to use the viscoplastic constitutive model for the structural analysis was pointed out.

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