Description of Temperature Dependence and Creep Deformation of 60 Sn-40 Pb Solder Alloys*

Ken-ichi OHGUCHI** and Katsuhiko SASAKI***

This paper shows the temperature effect on the deformation of 60 Sn-40 Pb solder alloys and a simulation using a constitutive model for viscoplasticity. First, a series of tests, such as creep, pure tension, and cyclic tension-compression loading were conducted to clarify the temperature effect on the deformation of 60 Sn-40 Pb solder alloys. The test results showed that the deformation of the solder alloys has a large temperature dependence. Simulations of the temperature effect on the deformation were also conducted by a constitutive model previously proposed. The parameters used in the model can be determined simply from pure tension and cyclic tension-compression loading tests at several temperatures. It was also found that the constitutive model describes not only the temperature effect on the pure tension and the cyclic tension-compression loading but also the creep curves after cyclic tension-compression preloading.

Key Words: 60 Sn-40 Pb Solder Alloys, Temperature Effect, Viscoplasticity, Creep, Cyclic Loading, Constitutive Model, Electronic Packaging

1. Introduction

Recently, thermal fatigue failure of solder joints in electronic packaging has become a matter of great concern, and the development of estimation methods for the fatigue life of solder joints has become important. Many methods to estimate the fatigue life of solder alloys have been proposed(1)-(5). For example, Yu et al.(4) estimated the thermal fatigue strength of solder joints in electronic packaging applying the calculated total inelastic strain range to Coffin-Manson's law. The authors here have proposed a method to estimate the fatigue life of 60 Sn-40 Pb solder alloys using the concept of plastic strain work density per unit time(6).

To estimate the fatigue life of real-life structures using FEM analysis, a constitutive model incorporated in the analysis should accurately simulate important features of the deformation of solder alloys, such as large time-dependent and temperature-dependent inelastic deformations(6). A previous paper(6) proposed a constitutive model for 60 Sn-40 Pb solder alloys. The model was constructed assuming deformation of solder alloys can be divided into three parts: elastic, plastic, and creep deformation. The model incorporated independent equations for elastic, plastic, and creep strain, and the total strain is given by a summation of the three parts. The authors also showed that the model could apply to the characteristic time-dependent deformation of 60 Sn-40 Pb solder alloys caused by strain rate changes during the loading.

This paper discusses the applicability of the proposed constitutive model(6) to the temperature dependent deformation of solder alloys. To clarify the temperature dependent deformation of solder, a series of tests of pure tension, cyclic tension-compression loading, and creep were first performed using 60 Sn-40 Pb solder alloys at three temperatures. The applicability of the constitutive model to the
temperature dependence of 60 Sn–40 Pb solder alloys is verified. Finally, the simulations of the deformation due to creep combined with pure tension and cyclic tension-compression loading were conducted.

2. Experimental Procedure

2.1 Specimen and testing machine

The specimens had a gauge length of 20 mm, a diameter of 5 mm, and were made of 60 Sn–40 Pb. Considering the circumstances of solder joints used in electronic packaging, the specimens were cast with a molding box of carbon to create uniform casting conditions. After casting, specimens were left at room temperature for two weeks to remove residual stresses and were then used as cast in the experiments.

The testing machine was an Instron Model 5565. The axial strain was calculated from the travel distance of the cross head and gauge length of the specimen. The temperature was kept constant during all the tests.

2.2 Test program

The following tests were performed:

1. Pure tensile tests were conducted under strain rates of 0.001, 0.01, and 0.1%/s at 303, 323, and 343 K.

2. Creep tests were conducted at stress levels of 7.5, 10.0, and 12.5 MPa at 303 K; 5.0, 7.5, and 10.0 MPa at 323 K; and 4.0, 5.0, and 6.0 MPa at 343 K as shown in Table 1. The loading conditions until the stress reached the required stress levels were pure tension under a strain rate of 0.1%/s.

3. Cyclic tension-compression loading tests:
The tests were conducted with a strain amplitude of 0.5% under strain rates of 0.001, 0.01, and 0.1%/s at 303, 323, and 343 K.

4. Creep test after cyclic tension-compression loading: First, the specimen was subjected to 50 cycles of cyclic tension-compression loading with a strain amplitude of 0.5% under a strain rate of 0.1%/s at 303 K. Then, the creep test was performed on the tensile peak stress of the hysteresis loop of the 50th cycle.

3. Results and Discussions

3.1 Pure tensile tests

Figure 2 shows the stress-strain curves under a strain rate of 0.1%/s at 303 (○), 323 (□), and 343 K (△). The stress levels of the stress-strain curves become smaller with increases in the temperature. For example, the stress on a 1% strain at 303 and 343 K are 30 and 16 MPa, respectively. It is noticeable that the stress difference factor is about 2 in spite of the small 40 K temperature difference. The test results suggest that solder joints at room temperature are under severe loading condition as the deformation of the 60 Sn–40 Pb solder alloys is strongly affected by small temperature differences around room temperature.

3.2 Creep tests

Figures 2(a) – (c) show creep curves at the temperatures of 303, 323, and 343 K. The creep strain becomes larger with increases in the stress, and the effect of the stress level becomes larger with increases in the temperature. At 343 K, the creep curves are very different while the differences in stress levels at 1 MPa are small. It is also clear that the creep strain becomes larger with increases in temperature.

3.3 Cyclic tension-compression loading test

Figure 3 shows the hysteresis loops under a strain rate of 0.1%/s at 303 (○), 323 (□), and 343 K (△). The shape of the hysteresis loop subjected to cyclic tension-compression loading depends on the temperature, and the stress levels in the hysteresis loop becomes smaller with increases in temperature.

As shown in Figs. 1 - 3, the inelastic deformation of the solder alloys are strongly affected by temperature, and it may be expected that the creep strain part in the total strain increases with increases in temperature. Then, it was assumed that the total strain increment is the sum of the elastic, plastic, and creep increments, and that the elastic and the plastic strain increments are time and temperature independent.

![Figure 1](image-url)

**Table 1 Stress levels for the creep tests**

<table>
<thead>
<tr>
<th>Number of specimen</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature, K</td>
<td>303</td>
<td>323</td>
<td>343</td>
<td>303</td>
<td>323</td>
<td>343</td>
<td>303</td>
<td>323</td>
<td>343</td>
</tr>
<tr>
<td>Stress level, MPa</td>
<td>7.5</td>
<td>10.0</td>
<td>12.5</td>
<td>5.0</td>
<td>7.5</td>
<td>10.0</td>
<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Fig. 1 Temperature effect on the stress-strain relation under pure tension (strain rate=0.1%/s)
Fig. 2 Creep curves

while the creep strain increment is time and temperature dependent.

4. Constitutive Model for Viscoelasticity

The constitutive model for viscoelasticity of the 60 Sn–40 Pb solder alloys made the following assump-

tions based on the experimental results: (i) Inelastic deformation of the 60 Sn–40 Pb solder alloy can be divided into elastic, plastic, and creep deformation parts. (ii) The elastic and plastic parts are time and temperature independent while the creep is time and temperature dependent. (iii) The direction of the elastic, plastic, and creep strain increments are the same at all times. (iv) Anisotropy is not induced by the viscoplastic deformation.

With these assumptions, a deviatoric total strain rate \( \dot{\varepsilon} \) is expressed by

\[
\dot{\varepsilon} = \frac{\dot{\varepsilon}_y - \dot{\varepsilon}_u}{2\mu} + \frac{3B}{2} \left( \frac{\sigma}{D} \right)^m \frac{1}{\sigma_2(b_x - b_y)(s_{xx} - b_{xy})} \times (s_{xx} - b_{xy}) + \frac{3A}{2} \sigma^{n-2}(s_{yy} - b_{yy})
\]

(1)

In Eq. (1), the first term on the right hand side is the deviatoric elastic strain rate with the deviatoric stress rate \( \dot{\varepsilon}_y \), deviatoric back stress rate \( \dot{\varepsilon}_u \), and modulus of transverse elasticity \( \mu \); \( s_{xx} = \sigma_{xx} - \sigma_{xy} \delta_{xy} / 3 \) and \( \mu = E/2(1+2\nu) \). The second term on the right hand side is the plastic strain rate with the deviatoric stress \( s_{yy} \), deviatoric back stress \( b_{yy} \), and material constant \( B = 3K(m+1)/2E \); \( D \) is the reference stress, \( m \) is the hardening exponent, and \( \sigma \) is the equivalent stress based on von Mises type yield criterion expressed as \( \sigma = (3/2(s_{yy} - b_{yy})(s_{yy} - b_{yy})^{1/2}). \) The third term on the right hand side is the creep strain increment calculated by Norton’s Law, and \( A \) and \( n \) are material constants.

\( D \) and \( m \) in Eq. (1) are expressed by the following
equations:

\[
D = D_0 \left[ 1 - \alpha \exp \left( -\frac{p}{C_1} \right) \right] \tag{2}
\]

\[
m = m_0 \left[ 1 - \beta \exp \left( -\frac{p}{C_2} \right) \right] \tag{3}
\]

where \(D_0\), \(\alpha\), \(C_1\), \(m_0\), \(\beta\), and \(C_2\) are material constants; \(p\) is the accumulated plastic strain until \(n\) changes of loading direction and given by \(p = \int_{-1}^{n} d\varepsilon^p\).

Using a Prager-Ziegler type assumption and Prager's consistency condition, the deviatoric back stress rate is given by

\[
\dot{\sigma}_d = \frac{3}{2} \dot{\varepsilon} \left( (\sigma_{ij} - \sigma) (\dot{\varepsilon}_{ij} - \dot{\varepsilon}) \right) + \frac{1}{C_3} \dot{\varepsilon} \left( R_0 - R \right) (\dot{\varepsilon}_{ij} - \dot{\varepsilon}) \left( \frac{\sigma}{D} \right)^n (\sigma_{ij} - \sigma)
\]

\[
\times (\sigma_{ij} - \dot{\varepsilon}) \tag{4}
\]

In Eq. (4), \(R\) is the isotropic flow stress expressed by

\[
R = R_0 \left[ 1 - \lambda \exp \left( -\frac{p}{C_4} \right) \right] \tag{5}
\]

where \(R_0\), \(\lambda\), and \(C_4\) are the material constants; \(p\) is the accumulated plastic strain during all the time of the loading and it is expressed as \(p = \int d\varepsilon^p\).

From Eqs. (1) and (4), the constitutive model can be reduced to the uniaxial loading case as the following equations.

\[
\dot{\varepsilon} = \frac{\dot{\varepsilon}}{E} - \dot{\varepsilon} - \frac{2B}{3} \left( \frac{\sigma - \sigma_t}{D} \right)^n (\dot{\varepsilon} - \dot{\varepsilon})
\]

\[+ A \left( \sigma - \sigma_t \right)^n \text{sgn} (\sigma - \sigma_t) \tag{6}
\]

\[
\dot{\sigma}_t = \dot{\sigma}_t - \frac{2B}{3} \left( R_0 - R \right) \left( \frac{\sigma - \sigma_t}{D} \right)^n (\dot{\sigma}_t - \dot{\sigma}_t) \tag{7}
\]

Now, it is assumed that the back stress is constant during the current loading and until the loading direction changes; \(\dot{\sigma}_t\) is employed as the back stress during the current loading. Considering \(\dot{\sigma}_t = 0\) in the current loading, Eqs. (6) and (7) are reduced to

\[
\dot{\varepsilon} = \frac{\dot{\varepsilon}}{E} - \frac{2B}{3} \left( \frac{\sigma - \sigma_t}{D} \right)^n (\dot{\varepsilon} - \dot{\varepsilon})
\]

\[+ A \left( \sigma - \sigma_t \right)^n \text{sgn} (\sigma - \sigma_t) \tag{8}
\]

\[
\dot{\sigma}_t = \dot{\sigma}_t - \frac{2B}{3} \left( R_0 - R \right) \left( \frac{\sigma - \sigma_t}{D} \right)^n (\dot{\sigma}_t - \dot{\sigma}_t) \tag{9}
\]

It is also assumed that the material constant \(A\) in Eq. (8) gradually approaches \(A_0\) with increases in strain measured from the origin of the current loading. Then, the material constant \(A\) is expressed by

\[
A = \left( 1 + C \exp \left( -\frac{|\dot{\varepsilon}|}{C_4} \right) \right) \left( \frac{\sigma_{\text{min}} - \sigma_t}{\sigma_{\text{min}} - \dot{\varepsilon}} \right)^n A_0 \tag{10}
\]

where \(\dot{\varepsilon}\) is the strain at back stress \(\sigma_t\); \(\sigma_{\text{min}}\) is the constant stress observed in the stress-strain relation of the 60 Sn-40 Pb solder alloys subjected to pure tension or cyclic tension-compression loading\(^{39}\); \(A_0\), \(n\), \(C\), and \(C_4\) are temperature dependent material constants.

5. Simulations Using the Constitutive Model for Viscoplasticity

5.1 Determination of material constants

The material constants are determined from the results of both pure tensile and cyclic tension-compression loading tests.

Figure 4 shows the relationship between strain rate \(\dot{\varepsilon}\) and constant stress \(\sigma_{\text{min}}\) at 303, 323, and 343 K, which were obtained from the pure tensile tests. The relationship can be expressed by

\[
\ln \dot{\varepsilon}_t = 3.08 \ln \sigma_{\text{min}} - 12.9 \text{ at 303 K},
\]

\[
\ln \dot{\varepsilon}_t = 3.11 \ln \sigma_{\text{min}} - 11.9 \text{ at 323 K},
\]

\[
\ln \dot{\varepsilon}_t = 3.16 \ln \sigma_{\text{min}} - 11.0 \text{ at 343 K}. \tag{11}
\]

The material constants \(n\) and \(A_0\) in Eq. (10) can be obtained from the proportionality coefficient and the intercept of the normal axis in Eq. (11), respectively. They are expressed by the following formula with the temperature \(T\) in K:

\[
A_0 = 2.22 \times 10^{-4} T^{1.49}
\]

\[
n = 2.10 \times 10^{-5} T + 2.44 \tag{12}
\]

The material constants \(E\), \(D_0\), \(m_0\), \(R_0\), \(\alpha\), \(\beta\), \(\lambda\), \(C_4\), and \(C_1\) were determined from the simulations of cyclic tension-compression loading tests at 303 K with Eq. (12):

\[
E = 10.0 \text{ GPa}; \quad D_0 = 36.0 \text{ MPa},
\]

\[
m_0 = 1.20; \quad R_0 = 15.0 \text{ MPa},
\]

\[
\alpha = 0.200; \quad \beta = 0.100; \quad \lambda = 5.00 \times 10^{-4},
\]

\[
c_1 = 5.00 \times 10^{-4}; \quad c_2 = 5.00 \times 10^{-4}; \quad c_3 = 5.00 \times 10^{-4} \tag{13}
\]

The material constants \(C\) and \(C_4\) in Eq. (10) were determined from the cyclic tension-compression loading tests at the three temperatures, as:

\[
C = 5.00; \quad C_4 = 2.00 \times 10^{-4} \text{ at 303 K},
\]

\[
C = 13.0; \quad C_4 = 1.00 \times 10^{-4} \text{ at 323 K},
\]

\[
C = 18.0; \quad C_4 = 6.00 \times 10^{-4} \text{ at 343 K}. \tag{14}
\]

Then, \(C\) and \(C_4\) can be expressed by

![Experiment Least square fit Temperature](image-url)

Fig. 4 Relation between the strain rate \(\dot{\varepsilon}\) and \(\sigma_{\text{min}}\)
Fig. 5  Simulation of the temperature effect on the stress-strain relation under pure tension (strain rate = 0.1%/s)

Fig. 6  Simulation of the temperature effect on the hysteresis loop subjected to cyclic tension-compression loading (strain rate = 0.1%/s, strain amplitude = 0.5%)

\[ C = 9.65 \times 10^{-26} T^{0.4}, \quad c_1 = 4.99 \times 10^{-17} T^{-7.43} \]  \hspace{1cm} (15)

Figure 5 shows the simulated stress-strain relation with pure tension under a strain rate of 0.1%/s at the three temperatures 303, 323, and 343 K. Comparing the simulations with the experiments, the simulations express the temperature effect on the deformation due to the pure tension very well.

Figure 6 is a comparison of the experiments with the simulations in cyclic tension-compression loading with a strain amplitude of 0.5% under a strain rate of 0.1%/s at 303, 323, and 343 K. Only the stabilized loops are shown in Fig. 6 to avoid cluttering the figure. The simulations express the temperature effect on the hysteresis loop except for a slight difference at 343 K. As a result, the proposed constitutive model with the material constants in Eqs. (12), (13), and (15) predicts the temperature effect on the stress-strain relation of both the pure tension and cyclic tension-compression loading.

5.2 Simulations and discussion

Simulations of creep and creep after cyclic tension-compression loading using the proposed constitutive model with the material constants in Eqs. (12), (13), and (15) are detailed below.

5.2.1 Simulation of creep  Generally, creep deformation is described by a summation of the instantaneous strain calculated by Hooke’s Law and the creep strain calculated by a constitutive model for creep, such as Norton’s Law. However, considering actual use in electronic packaging, the creep deformation of the solder joints occurs due to thermal and mechanical loading. As a result, the constitutive model for creep of the solder joints must predict creep deformation during loading such as pure tension. The proposed constitutive model can be applied to the pure tension or cyclic tension-compression loading and the creep curves after the preloading, because the creep strain in the current loading is calculated for all times as shown in the previous section.

Figures 7(a) - (c) show comparisons of simulations and experiments. The axial strains in Figs. 7(a) - (c) include the strains caused by pure tension until creep deformation at 303, 323, and 343 K. The experimental results are simulated well at the three temperatures.

5.2.2 Simulation of creep after cyclic tension-compression loading  Finally, the simulation of creep curve after the cyclic tension-compression preloading was performed. The specimen was subjected to cyclic tension-compression loading for 50 cycles with a strain amplitude of 0.5% under a strain rate of 0.1%/s at 303 K. Next the creep test was performed at the peak stress on the tensile side of the hysteresis loop of the preloading. The experimental result is shown in Fig. 8. The terminal stress of the hysteresis loop at the 50th cycle is 26.5 MPa, and the subsequent creep test was performed at a stress of 26.5 MPa. Figure 9 shows the simulation of the stress-strain relation under the same load condition as in Fig. 8. The simulated peak stress of the hysteresis loop of the preloading is 26.3 MPa, and it almost coincides with the experimental result at 26.5 MPa.

Figure 10 shows the creep curves of the subsequent creep test. In Fig. 10, the time to start the
subsequent creep test is set to zero. The simulated creep curve is in good agreement with the experiment. Namely, the proposed model describes the creep curve after the preloading of both the pure tension and cyclic tension-compression loading using the material constants in Eqs.(12), (13), and (15).

6. Conclusions

In this paper, the temperature effect on the deformation of 60 Sn-40 Pb solder alloys are clarified by creep and cyclic tension-compression loading tests at
three temperatures. A constitutive model to describe the effect was also discussed. As a result, the following conclusions were obtained.

(1) The creep strain becomes larger with increases in the stress level, and the effect of the stress level becomes larger with increases in the temperature.

(2) The stress levels in the stress-strain relation caused by the pure tension become smaller with increases in the temperature.

(3) The shape of the hysteresis loop subjected to cyclic tension-compression loading depends on the temperature, and the stress levels in the hysteresis loop become smaller with increases in the temperature.

(4) From conclusions (2) and (3), it is assumed that the creep strain part in the total strain increases with increases in temperature, and that the value of the creep strain controls the temperature effect.

(5) The material constants used in the proposed constitutive model can be determined simply from the experimental results of the pure tension and cyclic tension-compression loading tests under three kinds of the strain rates at the three temperatures.

(6) Using the proposed constitutive model with the material constants determined in conclusion (5), the constitutive model can simulate the temperature effect on the stress-strain relation of 60 Sn-40 Pb solder alloys caused by the pure tension and cyclic tension-compression loading. The model can also predict the creep curves after the preloading of both the pure tension and cyclic tension-compression loading with the same material constants.

References


