A CREEP MODEL FOR SOLDER ALLOYS

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ABSTRACT
Demand for long-term reliability of electronic packaging has lead to a large number of studies on viscoplastic behavior of solder alloys. Various creep models for solder alloys have been proposed. They range from purely empirical to mechanism based models where dislocation motion and diffusion processes are taken into account. In this study, most commonly used creep models are compared with the test data and implemented in ABAQUS to compare their performance in cycling loading. Finally, a new creep model is proposed that combines best features of many models. It is also shown that, while two creep models may describe the same material stress-strain rate curves equally well, they may yield very different results when utilized for cycling loading. One interesting observation of this study is that the stress exponent, n, also depends on the grain size.

INTRODUCTION
Solder alloys are extensively used in electronic packaging because of their favorable wetting properties and low melting temperature. However, most electronic packaging solder alloys operate at thermally-activated condition at room temperature, due to their low melting point. Several thermally activated processes, including dislocation glide, dislocation climb, grain boundary diffusion, and lattice diffusion produce and accumulate a large amount of creep deformation which leads to various types of failure in electronic packaging soldered joints.
Electronic packaging consists of materials with very different thermal and mechanical properties. During service, mismatch of thermal expansion coefficient of various materials induces cycling shear stress on solder joints. These stresses cause fatigue failure of solder joints, and the reliability of electric packaging is usually determined by fatigue life of solder joints. This latter fact is the driving force behind extensive studies of creep behavior of solder alloys. Quite a few of researches developed creep models for viscoplastic behaviors of solder joints. Basaran et al [2005], Gomez and Basaran [2006] have extensively listed these references on constitutive modeling of solder alloys. The studies have revealed that the creep behavior of a solder alloy significantly depends on age, temperature, stress, and grain size. However, a comprehensive review and a comparison of these models have never been published.

THEORETICAL AND PHENOMENOLOGICAL MODELING APPROACHES

Solder alloys have a low melting temperature, $T_m$, i.e. $T_m = 456$ K on 63Sn/37Pb and $T_m = 500$ K on SAC405, therefore most solder alloys are at above $0.4T_m$ at room temperature. At temperature above $0.4T_m$, a creep curve consists of three regimes; primary, secondary (or steady-state), and tertiary. Since creep behavior of solder alloy is considerably dependent on the secondary stage, it is widely accepted that the secondary stage dominates the creep behavior. It is assumed that during steady-state stage, the creep strain rate remains constant with increasing time. This assumption considerably simplifies the problem of modeling the creep behavior. The experimental data shown in Figure 1, does not support this assumption in the strict sense. However, for sake of simplicity we will follow this common assumption.

![Figure 1. Creep-time curve for 63Sn/37Pb solder alloy, after Shi et al [2]](image)

Figure 1. Creep-time curve for 63Sn/37Pb solder alloy, after Shi et al [2]
I. Diffusional creep model

Time-dependent deformation of polycrystalline metals via creep processes involves transport of atomic vacancy by diffusion. Nabarro and Herring creep mechanism describes the lattice-diffusional creep model which normally occurs due to the presence of vacancies within the crystal lattice. However, according to Coble creep process in poly-crystalline metals, vacancies can transfer from tensile grain boundaries to those under compression not only through the lattice but also along the grain boundaries. Figures 2 and 3 show the vacancy transfer process under tensile stress for each creep model respectively. Even though creep models by Nabarro and Herring and Coble are not applicable to all materials, they show that creep is not only dependent on stress and temperature, but also on the grain size.

![Figure 2. Nabarro and Herring creep model](image1)

![Figure 3. Coble creep model](image2)

II. Dislocation creep model

According to Orowan model, dislocations in atomic lattice structure are an important part of the creep process. The strain rate is proportional to an average velocity of dislocation motion, and the density of mobile dislocation. A model based on the general concept of internal stresses generated by dislocation-dislocation interactions is the Taylor model. In this approach, it is assumed that average velocity of dislocation and the shear stress are proportional to the velocity of climb of the dislocation and the normal stress. It shows the expression of strain rate in terms of shear stress, temperature and diffusivity.

III. Phenomenological Creep Models
It is well known that the theoretical creep approaches introduced above work for some materials, but not all materials, especially low melting point solder alloys. Based on empirical studies these theoretical equations are regularly modified to curve fit test data to these models. Phenomenological approach allows modified theoretical models to fit experimental creep data. Stress and grain size exponents are generally modified as \( n \) and \( p \). In order to account for temperature dependency of diffusivity, Arrhenius’s law is used. In this approach, one of the most popular creep equations is Dorn Equation.

At high stress region \((\tau > 10^{-3}G)\) for most metals creep strain rate is not proportional to the stress exponent term. Garofalo proposed a power law equation improved by including a hyperbolic-sine term.

**SOLDER ALLOY CREEP MODELS**

In electronic packaging literature many researchers have been proposing varying combinations of creep constitutive models discussed above. In here, these various creep models used for solder alloys were studied. Among the models presented above, the best models are compared with experimental data and implemented in ABAQUS finite element analysis package to compare their performance in a cycling loading analysis,

Model A, called Dorn equation is one of the most commonly used creep models, [3, 5]. Model A shows the influence of grain size and the stress exponent term that is represented by the shear stress divided by the shear modulus.

\[
\dot{\gamma} = A \left( \frac{\alpha b}{RT} \right) \left( \frac{\bar{b}}{d} \right)^p \left( \frac{\tau}{G} \right)^n \left[ D_0 \exp \left( \frac{-Q}{RT} \right) \right] \quad (1)
\]

where \( \dot{\gamma} \) is creep strain rate, \( A \) is a material constant, \( G \) is the shear modulus, \( b \) is burger’s vector, \( k \) is Boltzmann’s constant, \( T \) is absolute temperature, \( d \) is the grain size, \( \tau \) is the applied shear stress, \( n \) is the stress exponent, \( p \) is the grain size exponent, \( D_0 \) is the diffusion coefficient, \( Q \) is the activation energy for creep process, \( R \) is universal gas constant, and \( T \) is the absolute temperature.
A unified constitutive model, called Anand model, which was proposed by Anand [1985] and Brown et al. [1989] given by:

\[
\dot{\varepsilon}_{\text{in}} = A \left[ \sinh \left( \frac{\xi \sigma}{s} \right) \right]^{\frac{1}{m}} \exp \left( -\frac{q}{RT} \right) \quad (2)
\]

where \( \dot{\varepsilon}_{\text{in}} \) is the inelastic strain rate, \( \xi \) is a multiplier of stress, \( \sigma \) is the applied stress, \( s \) is a single scalar as an internal variable to represent the averaged isotropic resistance to plastic flow, and \( m \) is the strain rate sensitivity of stress.

For the steady-state creep approximation, Anand model is simplified to the hyperbolic sine creep form resulting in the following steady state creep equation;

\[
\dot{\gamma} = A (\sinh \beta \tau)^n \exp \left( -\frac{q}{RT} \right) \quad (3)
\]

where \( n \) is \( 1/m \), and \( \beta \) is a multiplier of hyperbolic sine law which is obtained from curve fitting to experimental data by using linear and non-linear least square regression. This functional form Eq. (3) is provided by ABAQUS, and used by many electronic packaging mechanics researchers, [6-10].

Pan [1991] proposed modifying Anand model with grain size effect for the eutectic Pb/Sn alloy. Model C has an additional grain size term, as well as all other original terms.

\[
\dot{\gamma} = A (\sinh \beta \tau)^n (d)^{-p} \exp \left( -\frac{q}{RT} \right) \quad (4)
\]
Darveaux and Banerji [1991] proposed a creep function given by equation (5). This model is very similar to model B. However, the shear modulus is a function of temperature. Therefore, the analysis results obtained by models B and D are different.

\[
Model D \quad \dot{\gamma} = A \left( \frac{G}{T} \right) \left( \sinh \beta \frac{\tau}{G} \right)^n \exp \left( -\frac{q}{RT} \right) \quad (5)
\]

Shi et al. [2003] proposed a creep model given by:

\[
Model E \quad \dot{\gamma} = A_1 \left( \frac{\tau}{G} \right)^{n_1} \exp \left( -\frac{q_1}{RT} \right) + A_2 \left( \frac{\tau}{G} \right)^{n_2} \exp \left( -\frac{q_2}{RT} \right) \quad (6).
\]

This model assumes that there are two regimes of steady-state creep, and each regime has a power law dependence of strain rate on stress. Based on their own experimental results, the same researchers also proposed the model F, Eq. (7):

\[
Model F \quad \dot{\gamma} = A_1 \left( \frac{G}{T} \right) \left( \sinh \beta \frac{\tau}{G} \right)^{n_1} \exp \left( -\frac{q_1}{RT} \right) + A_2 \left( \frac{G}{T} \right) \left( \sinh \beta \frac{\tau}{G} \right)^{n_2} \exp \left( -\frac{q_2}{RT} \right) \quad (7),
\]

for the creep deformation of the solder alloys at different temperatures over a wide stress range. In model F the first term is for low temperature dislocation-glide controlled creep, while the second term is for high temperature dislocation-climb controlled creep.

It is well known that, solder alloy properties are highly temperature dependent. Therefore, we propose to modify Anand model to account for shear modulus temperature dependency and grain size with the following models;
\[ \dot{\gamma} = A \left( \sinh \frac{\beta x}{G} \right)^n \exp \left( -\frac{Q}{RT} \right) \quad (8) \]

\[ \dot{\gamma} = A \left( \frac{b}{d} \right)^p \left( \sinh \frac{\beta y}{G} \right)^n \exp \left( -\frac{Q}{RT} \right) \quad (9) \]

Model I uses the hyperbolic sine term instead of power law used in Dorn equation which is given by model A. We can observe the effect of \((Gb/kT)\) on the creep model by comparing model H with model I.

\[ \dot{\gamma} = A \left( \frac{Gb}{kT} \right) \left( \frac{b}{d} \right)^p \left( \sinh \frac{\beta y}{G} \right)^n \exp \left( -\frac{Q}{RT} \right) \quad (10) \]

**COMPARISON OF VARIOUS SOLDER ALLOY CREEP MODELS**

First, the creep models discussed above are compared against test data reported by Shi et al. [2] on eutectic 63Sn/37Pb solder alloy, which actual chemical composition was as follows; 63.200 Sn, 36.773 Pb, 0.006 Sb, 0.002 Cu, 0.004 Bi, 0.001 Zn, 0.002 Fe, 0.001 Al, 0.010 As, and 0.001 Cd. Constants, parameters, shear modulus \(G\), and the grain size are given in Table 1. [1, 2]

Non-linear least square regression is applied to obtain the creep equation’s parameters, \(A\) and \(\beta\) by using log-scale strain rate. Parameters of models E and F are determined by trial and error due to the complex representation. To estimate accuracy of models, mean squared error (MSE) is calculated and revealed on Table 2 for all creep models. The results show that models D, F, G, H, and I have much less error than others. Even though model F performs very well in representing the test data, it is omitted due to the difficulty of acquiring material parameters for two regimes. Model D is not considered because the difference between models D and I is the grain size term only. The effect of grain size term is studied by comparing models G and H. For the reason, we focus on models G, H and I among the models introduced above.
Figure 4. presents fitting of creep models discussed above to experimental data. In Figure 4, a., models G and H represent the viscoplastic behavior well due to the normalized stress term, \((\tau/G)\). In spite of some discrepancy with test data at temperature 25°C and 75°C, model I yields the best overall results for the entire regime.

Shi et al. [2003] test data does not provide the effect of grain size on creep behavior, because the experiment was done for a single grain size of, \(d = 30 \, \mu m\). Models G and H yield the same results, when grain size is ignored. In order to study the influence of grain size, models G and H is compared using on Kashyap and Murty [3] test data, where grain size information is provided. Results presented in Figure 5 and 6 indicate that the grain size term is essential in the creep constitutive model. One interesting observation is that the stress exponent factor \(n\) increases from 1.67 to 2.3 when grain size is accounted for. It shows that the stress exponent factor, \(n\), also depends on the grain size.

Table 1. Constants, parameters, and properties in the creep models G, H, and I

<table>
<thead>
<tr>
<th>Creep data</th>
<th>(A_G)</th>
<th>(A_H)</th>
<th>(A_I)</th>
<th>(G) (GPa)</th>
<th>(Q) (J/mol)</th>
<th>(\beta_G)</th>
<th>(\beta_H)</th>
<th>(\beta_I)</th>
<th>(n)</th>
<th>(d(\mu m))</th>
<th>(p)</th>
<th>(b(\text{nm}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shi et al. [2]</td>
<td>412.4</td>
<td>2.91E+17</td>
<td>4.47E-4</td>
<td>24.78-0.040T</td>
<td>52800</td>
<td>2124</td>
<td>2124</td>
<td>2068</td>
<td>3.3</td>
<td>30</td>
<td>3</td>
<td>0.337</td>
</tr>
<tr>
<td>Kashyap and Murty [3]</td>
<td>2.16E+3</td>
<td>1.69E+18</td>
<td>2.80E+3</td>
<td>24.28-0.029T</td>
<td>44700</td>
<td>1479</td>
<td>1479</td>
<td>1281</td>
<td>1.67</td>
<td>9.7</td>
<td>2.3</td>
<td>3.34</td>
</tr>
</tbody>
</table>

Table 2. Mean Squared Error (MSE) for all models by using test data of Shi et al. [2]

<table>
<thead>
<tr>
<th>Model</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSE</td>
<td>1.46</td>
<td>0.659</td>
<td>0.659</td>
<td>0.128</td>
<td>0.520</td>
<td>0.105</td>
<td>0.179</td>
<td>0.179</td>
<td>0.128</td>
</tr>
</tbody>
</table>
Figure 4. Representation of Experimental Data for each model

a. Creep models G and H

b. Creep model I
Figure 5. Creep model G for different grain sizes

a. Model G on Grain size = 9.7 μm

b. Model G on Grain size = 28.4 μm
Figure 6. Creep model H for different grain sizes
Figure 7. Creep model I for different grain sizes

a. Model I on Grain size = 9.7 μm

b. Model I on Grain size = 28.4 μm
FINITE ELEMENT ANALYSIS WITH DIFFERENT CREEP MODELS

In order to study the effect of creep model on a cycling loading finite element analysis, the models G, H, and I were implemented in a finite element program, ABAQUS, with a user defined subroutine. An example given in Lau and Pao [4] was repeated. An electronic packaging solder joint modeled with a four-node plane strain element is subjected into the displacement controlled pure shear test. The imposed thermal cycle has a range of -25°C to 125°C with a rate of 30°C/h and a two-hour hold time. Shear strain has the maximum value, 0.01, at minimum temperature and zero at maximum temperature. The material employed in this simulation is a eutectic 63Sn /37Pb solder alloy. In this simulation, elastic and viscoplastic properties are considered, and the material properties and details of simulation are given in [4], hence, for the sake of brevity, the details of the analysis are not repeated in here.

Figure 8 shows that maximum shear stress obtained by model I is about 16% smaller than that of models G and H. It indicates that the choice of viscoplastic model may be responsible for differences in maximum stress values observed in FEA.

![Shear Stress versus Time Graph](image)
CONCLUSIONS

Most commonly used solder alloy creep models have been studied. To judge the performance of these models they are compared against the same test data. From this study, the following conclusions can be made

1) Hyperbolic sine model provides a better representation on the entire stress regime compared to power law for solder alloys.

2) Creep laws with $\tau/G$ term in general yield better results than those of stress term only represented by shear stress, $\tau$.

3) Grain size term plays an important role in the creep model and it cannot be ignored.

Creep laws given by models G, H and I were the most successful in fitting the experimental data. However, model G does not have the grain size term. Even though the models H and I yield the similar results for the entire regime, model I yields the better results for eutectic 63Sn/37Pb solder alloy.

This study is performed by using only two experimental data sets, and only uses a eutectic 63Sn/37Pb solder alloy. Therefore, the reliability of creep models requires more similar studies before implementing in finite element analysis codes. This is something seriously overlooked in
engineering practice and research projects, where commercial FEA code implemented creep models are regularly used for solder alloys, without any experimental verification.

When the strain-controlled cycling pure shear test was simulated by using ABAQUS, the difference of maximum shear stress between models H and I is about 16 percentage of maximum shear stress. This result shows that the choice of creep model may make the critical difference in numerical analysis results, even if two models yield the similar results for same stress-strain rate data.

Based on this comparative study, we propose the following creep law for the eutectic solder alloys.

\[
\dot{\gamma} = A \left( \frac{Gb}{kT} \right) \left( \frac{b}{d} \right)^p \left( \sinh \beta \frac{\tau}{G} \right)^n \exp \left( -\frac{Q}{RT} \right)
\]  

(10)

ACKNOWLEDGMENTS

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REFERENCES


