Mechanical characterization of an Au-Ge solder alloy for high temperature electronic devices

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Abstract

This paper presents a description of the mechanical behaviour of an Au-Ge solder under various loading conditions as well as an elastoviscoplastic modelling. In order to achieve the modelling task, the solder is subjected to a set of shear, creep and fatigue loadings in order to determine the behaviour dependence to the temperature and displacement rate and which could be useful to evaluate the degradation of the material. These tests are realized under a wide range of temperatures, loads and displacement rates for modelling purposes. Then, a unified viscoplastic model is applied to predict correctly the material mechanical responses. The model is correlated with the experimental data

1 Introduction

The need of more reliable power modules in extreme temperature and high power environment is leading to the investigation of new range of soldering materials with more important thermomechanical and electrical characteristics. The choice of the solder is generally made with respect to the thermal and mechanical conditions as well as the chemical compatibility with underlying components in order to avoid the formation of voids or weak intermetallic compounds in the interfaces. There are many ways to ensure good bonding between module elements and the most interesting one is that which permits to reach the goal under low elaboration temperature. So, it's a great challenge to achieve a highly resistant joint without use of severe technical conditions and efforts. Among promising techniques, paste silver sintering [1,2] and solid state diffusion bonding (SSDB) are now cited as substitutes for solders reflow process. Particularly, solid state diffusion bonding [3,4] is used for silver and gold based alloys such as Au-Sn and Au-Ge solders. It consists on a first reflowing step where the solder melts to form a primary joint between thick Au metalized components [5], then an annealing step to diffuse the binary entity on the metallization and minimize its proportion on the joint. Thus, we can obtain a solid solution with much higher melting temperature and good thermomechanical aspects. For this purpose, and as a first part of our extended work, we present next a mechanical characterization of an Au-Ge solder which may be used in SSDB technique. The Au-Ge eutectic solder has good thermal properties and a melting temperature of 356°C.

2 Shear Behavior and modelling of the Au-Ge solder

2.1 Experimental procedure

Cyclic displacement controlled tests are performed at 25°C, 200°C and 300°C under various displacement rates 10^{-2}, 10^{-3} and 10^{-4}mm/s. Creep tests are also achieved at 25°C, 200°C and 300°C with imposed Load of 100 N and 200 N. The shear specimen considered consists of two soldered copper plates with a thickness of 3 mm as shown in figure 1. The plates are soldered using Au-Ge preform whose dimensions are 3×2×0.2 mm. The specimen was obtained using a reflow process of the Au-Ge solder in alternated nitrogen-vacuum atmosphere to improve wetting quality and prevent oxidation. This specimen is then mounted on an Electroforce® machine test as shown in figure 2, which is rated up to 450 N and can perform precision materials tests including tension/compression loading, fatigue and dynamic material characterization.

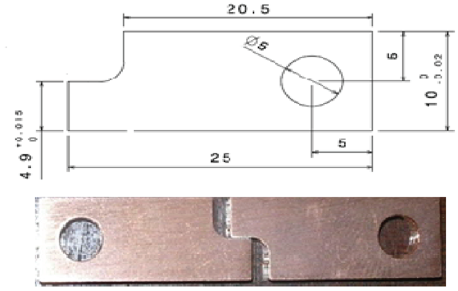

Figure 1 Single shear joint specimen

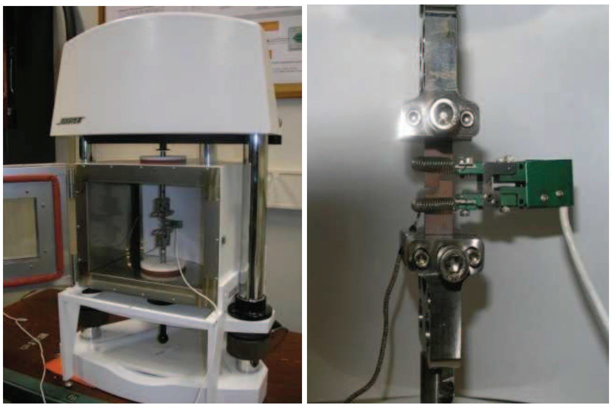

Figure 2 Test machine (left) and specimen mounting (right)

The apparatus is equipped with a furnace which can reach temperatures up to 300°C. Displacements are measured by mean of an axial extensometer as shown in figure 2.

2.2 Thermoviscoplastic modelling of the solder

At extreme temperature i.e. 300°C, Au-Ge solder exhibit high strain rate sensitivity due to the activated creep mechanisms in the materials. The solder is also subjected to thermal stressing due to the thermal expansions of the underlying materials especially in case of DBC copper plates. The interaction of plasticity and creep leads to the use of unified viscoplastic models which not separate the two phenomena and considers that they are issued from the same time-dependent deformation [6]. So, inspite of the formulation complexity of these models, they can accurately reproduce a realistic behaviour of the material under complex loading conditions. In this framework, a McDowell's unified thermoviscoplastic model [7] is used for the modelling task.

2.2.1 Formulation of the model

McDowell's viscoplastic model contains a set of constitutive equations: (1) a flow law which represents the material deformation and the viscosity effects and (2) the evolution equations which describe the associated physical microstructural aspects using a set of state variables. In this case, α_{ij} represents the kinematic hardening variable and R is the isotropic hardening variable. The flow law or the evolution of the inelastic strain rate is expressed as follows

$$\dot{\varepsilon}_{ij}^{in} = \frac{3}{2} A\Theta F\left(\varsigma, D, \eta\right) \frac{s_{ij} - \alpha_{ij}}{J_2\left(\sigma_{ij} - \alpha_{ij}\right)} \qquad (1)$$

As we can see, the flow law depends on a diffusivity parameter Θ and a Zener-Hollowman function F whose expression is fixed generally within the stress and temperature levels [8]. McDowell proposed an exponential term to take into account viscosity effects

$$F = \varsigma^N \exp\left(B\varsigma^{N+1}\right) \qquad (2)$$

Where

$$\varsigma = \frac{J_2\left(\sigma_{ij} - \alpha_{ij}\right) - R}{\left(1-\eta\right) D} \qquad (3)$$

The factor η represents the sensibility partition of the strain rate and mainly varies between 0 and 1. D is an isotropic resistance which is usually constant for solder alloys or proportional to the yield stress for copper $\left(D = A_0 R\right)$. N is a temperature-dependent parameter. A and A_0 are temperature-independent material parameters.

The diffusivity parameter depends on the temperature level

$$\begin{cases} \Theta = \exp\left(-\dfrac{Q}{kT}\right) & \text{for } T \geq \dfrac{T_m}{2} \\ \Theta = \exp\left(-\dfrac{2Q}{kT_m}\left\{\ln\left(\dfrac{T_m}{2T}\right)+1\right\}\right) & \text{for } T \leq \dfrac{T_m}{2} \end{cases} \qquad (4)$$

T_m is the melting temperature, Q is the activation energy, and k is the Boltzmann's constant. $\langle . \rangle$ is defined as $\langle g \rangle = g$ if $g \geq 0$ else $\langle g \rangle = 0$.

Microstructural changes such as dislocation motion, interaction between dislocations and isotropic defects repartition are described by two variables which are R and α_{ij} Kinematic hardening variable α_{ij} is divided into two other variables α_{ij}^s and α_{ij}^* taking into account the displacement rate of disclocations. In the isothermal case, we can write

$$\dot{\alpha}_{ij}^s = Cb\dot{\varepsilon}_{ij}^{in} - C\alpha_{ij}^s \left\|\dot{\varepsilon}_{ij}^{in}\right\| - Cb\Omega^s\Theta\alpha_{ij}^s \qquad (5)$$

$$\dot{\alpha}_{ij}^* = H^*\dot{\varepsilon}_{ij}^{in} - H^*\Omega^*\Theta\alpha_{ij}^* \qquad (6)$$

In the other hand, a variable χ constitute a coupling variable between isotropic and kinematic hardening effects i.e. the contribution of R^{iso} and b^{iso} following

$$\dot{R}^{iso} = \sqrt{\frac{3}{2}}\left(1-\omega\right)\dot{\chi} \qquad (7)$$

$$\dot{b}^{iso} = \omega\dot{\chi} \qquad (8)$$

$$\dot{\chi} = \mu'\left(\bar{\chi} - \chi\right)\left\|\dot{\varepsilon}_{ij}^{in}\right\| - \mu\bar{\chi}\Omega^{\chi}\Theta \qquad (9)$$

The variable χ saturates to $\bar{\chi}$ and its evolution equation includes dynamic and static thermal recovery terms such as those of α_{ij}^s and α_{ij}^*

C, H^*, b^0, R^0, μ' and $\bar{\chi}$ are temperature-dependent parameters.

The thermal static recovery terms are expressed in the following forms:

$$\Omega^s = C^s\left(\alpha_{ij}^s\alpha_{ij}^s\right)^{M^s/2}, \qquad (10)$$

$$\Omega^* = C^*\left(\alpha_{ij}^*\alpha_{ij}^*\right)^{M^*/2}, \qquad (11)$$

$$\Omega^{\chi} = C^{\chi}\left(\alpha_{ij}^{\chi}\alpha_{ij}^{\chi}\right)^{M^{\chi}/2} \qquad (12)$$

The yield stress R and the kinematic hardening saturation b are written respectively as $R = R^0\left(T\right) + R^{iso}$ and $b = b^0\left(T\right) + b^{iso}$

R^0 is the initial yield stress. H^*, C^s, M^s, C^*, M^*, C^χ and M^χ are material parameters.

2.2.2 Integration and implementation of the constitutive equations

As for the most popular unified viscoplastic models, McDowell's model is formulated using a set of strongly coupled, first order differential equations which is hard to solve without advanced integration schemes. McDowell used a semi-implicit integration scheme combined with a Newton-Raphson iteration procedure [9] to solve the model equations. In the semi-implicit scheme, the effective cumulated inelastic strain increment Δp is updated in implicit way contrarily to the stress and the other state variables. Moreover, an automatic stepping procedure is introduced in order to improve the solution computation. Let's see that all the equations of the model may be written in the form $\dot{y}_{ij} = f\left(y_{ij}, t\right)$. So, the incremental solution of each variable is written as

$$y_{ij}^{t+dt} = y_{ij}^t + \Delta y_{ij}^t = y_{ij}^t + \Delta t \dot{y}_t \tag{13}$$

The aim is to minimize the error function F expressed as

$$F\left(\sigma, \alpha, R\right) = \Delta p - \Delta t \sqrt{\left(\dot{\varepsilon}_{ij}^{in}\right)^{t+dt} : \left(\dot{\varepsilon}_{ij}^{in}\right)^{t+dt}} \tag{14}$$

Where $\left(\dot{\varepsilon}_{ij}^{in}\right)^{t+dt}$ depends on the stress and state variables which are updated at $t + \Delta t$.

The value of Δp is updated for the next iteration $k+1$ only when the quantity $\left|\dfrac{\Delta p^k - \Delta p^{k+1}}{\Delta p^{k+1}}\right|$ is greater than a given tolerance ε^{tol} fixed to 10^{-4} in our case. The update of Δp is then computed using the following equation

$$\Delta p^{k+1} = \Delta p^k - \frac{F\left(\Delta p, \sigma_{ij}, \alpha_{ij}, R\right)}{F'\left(\Delta p, \sigma_{ij}, \alpha_{ij}, R\right)} \tag{15}$$

Otherwise, Δp is retained for the next step as well as the corresponding stress and state variables for the iteration $k+1$. Algorithm developments as well as the tangent tensor computation are detailed elsewhere [9]. Once integrated, the McDowell's model is implemented as subroutine UMAT in the finite element code ABAQUS. The solver used in the finite element computation is an asymmetric one with a full Newton-Raphson iteration scheme.

2.2.3 Material parameters identification

An identification algorithm was performed using Python scripting based on the Least Square minimization procedure. This algorithm was combined to UMAT subroutine to identify the model parameters with respect to the finite element model showed on the figure 3.

Copper plates are considered as an elastoplastic material modeled with a combined hardening elastoplastic Chaboche model. Elastic modulus and Poisson ratio of Au-Ge are taken respectively as E (MPa) = 70495 - 51.9 T (°C) and $\nu = 0.32$.

For the finite element modeling, we consider the following geometry in figure 3 as the used model for the parameters identification and results extraction

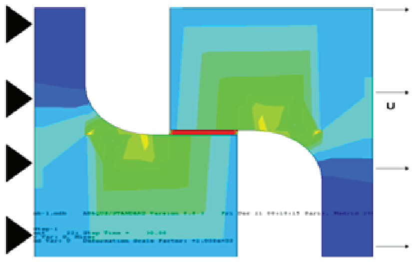

Figure 3 Finite element model for the identification procedure

McDowell model contains only six temperature-dependent coefficients i.e. E, ν, C, H^*, b^0, R^0, μ' and $\overline{\chi}$. All the temperature dependent parameters may be expressed as functions of temperature as for the Young's modulus E.

The identified material parameters of the Au-Ge solder alloy are given in the table 1 for McDowell's model

McDowell's Model parameters			
Temperature	25°C	200°C	300°C
n	3.1	-	-
A	5000	-	-
B	0.002	-	-
C	1744	1626	955
$D(MPa)$	3.2	-	-
$H^*(MPa)$	125	161	177
w	1	-	-
C^s	0.0	-	-
$C^*(MPa/s)$	150	-	-
M^s	1	-	-
M^*	1	-	-
$Q(J/mol)$	48000	-	-
$R^0(MPa)$	15	10.5	9.6
$b^0(MPa)$	16.9	11.3	10.9
$\overline{\chi}$	250	121	86
μ'	17.3	20.7	20.7

Table 1 Optimized model parameters for Au-Ge solder

For the rate sensitivity viewpoint, and following experimental data shown in figure 4 and 5, the material appears to be unaffected by displacement rate variation and shows no sensitivity to loading rate at ambient temperature and 200°C. The material reaches in all cases a load value of approximately 200N for a fixed displacement level at about 0.02 mm.

Following the results presented in figures 6, 7 and 8, for the uniaxial shear tests, the soldered assembly shows a cyclic hardening at least for the first cycle of loading. Also, Bauschinger effect is apparent which indicates kinematic hardening domination.

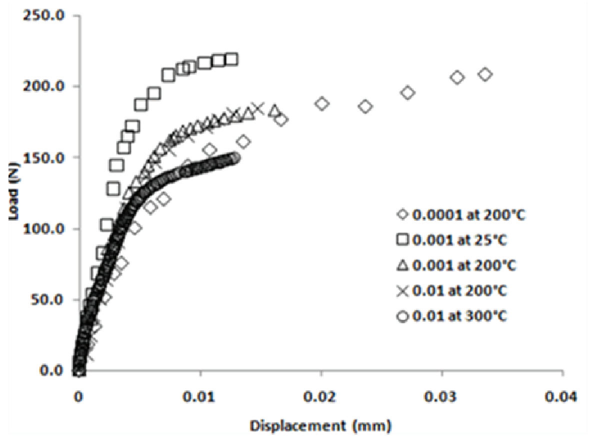

Figure 4 Uniaxial shear tests at various temperatures and strain rates

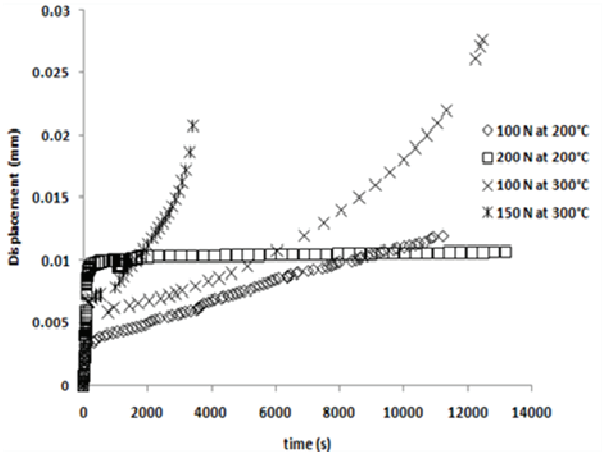

Figure 5 Creep tests at various temperatures and Loads

Good correlation is also recorded between experimental data and numerical simulations obtained by finite element computations especially for the cyclic shear tests which indicate acceptable set of identified model parameters. The modeling task may be extended using thermomechanical fatigue and ratcheting tests to improve numerical and identification results. A damage model is also suitable for lifetime estimation of the solder material.

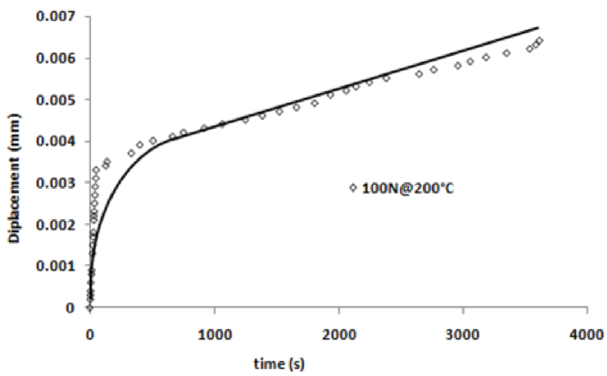

Figure 6 Creep tests at 200°C and 100 N

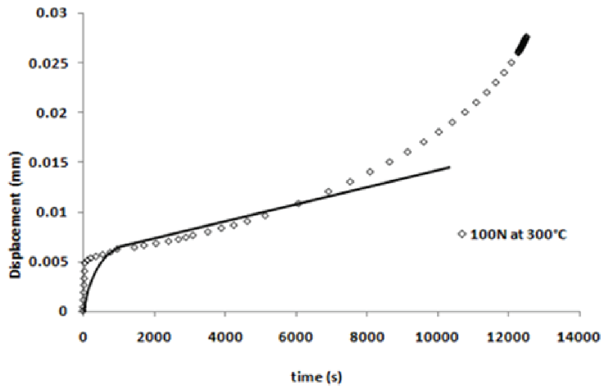

Figure 7 Creep tests at 300°C and 100 N

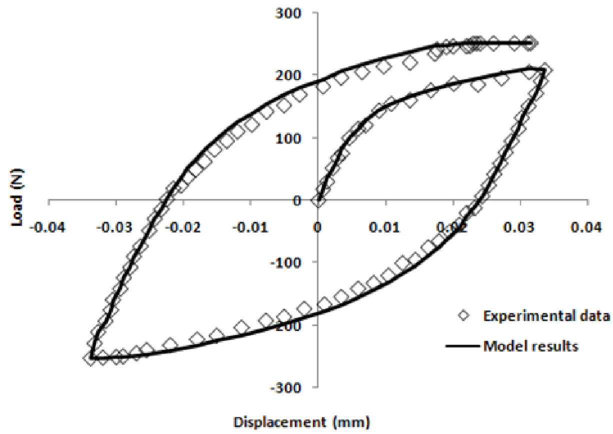

Figure 8 Cyclic shear tests at 25°C and 10^{-3} mm/s

3 Conclusion

A set of experimental tests are conducted to characterize the thermoviscoplastic behaviour of Au-Ge solder material. The data is the used to identify the McDowell's unified viscoplastic model which is successfully implemented in Abaqus using semi-implicit integration algorithm. There was good agreement between numerical results from finite element simulations and tests results. That's indicates the efficiency of the identified model and thus it will be useful for more complex cases of loading.

4 Literature

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