Microelectronics Reliability 80 (2018) 47–54

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Constitutive modelling on the whole-life uniaxial ratcheting behavior of sintered nano-scale silver paste at room and high temperatures

Gang Chen*, Xiaochen Zhao

School of Chemical Engineering and Technology, Tianjin University, Tianjin, China

ARTICLE INFO

Keywords:
Nano-silver paste
Whole-life ratcheting
Temperature-dependent
Damage-coupled
Visco-plasticity
Constitutive model

ABSTRACT

Uniaxial ratcheting and fatigue behaviors of low-temperature sintered nano-scale silver paste at both room and high temperatures were studied in the authors' previous work. The deterioration of sintered silver pastes under cyclic loading which manifest itself as decrease in elastic modulus is addressed by introducing a damage variable as represented by θ function. Then, the damage variable is coupled into a visco-plastic constitutive model, based on the Ohno-Wang and Armstrong-Frederick (OW-AF) nonlinear kinematic hardening rule. In addition, the temperature-dependent ratcheting behavior are also captured by incorporating the Arrhenius power-law model into the flow rule. The whole-life ratcheting behaviors of low-temperature sintered nano-scale silver paste are simulated and are in well agreement with experimental data.

1. Introduction

Nano-scale silver paste is a new, green thermal interface material, which has been the focus of research in recent years [1–11]. Researchers focused on the nano-scale silver paste, itself, and structure preparations, sintering processes, electrical and thermal conductivity, mechanical property and constitutive model. Lu et al. [2] introduced a low-temperature sintering method for nano-scale silver paste. The sintering temperature is less than 300 °C, and the nano-scale silver paste exhibits several excellent properties, such as high electrical and thermal conductivity, high operating temperature, etc. Moreover, Bai et al. [3,4] and Wang et al. [5] did significant work by proposing fairly mature sintering processes.

For materials or structures subjected to cyclic stress with non-zero mean stress, a cyclic accumulation of inelastic deformation will occur if the applied stress is high enough, which is termed as ratcheting behaviors. As nano-scale silver paste is subjected to cyclic mechanical and thermal loads, it will inevitably experience ratcheting behavior. Chen et al. [6,7] and Mei et al. [8,9] conducted research on sintered nano-scale silver film and focused on the mechanical behaviors. They demonstrated that ratcheting strain of nano-scale silver became larger as the mean stress and stress amplitude increased or loading rate decreased, and the elastic modulus and tensile strength decreased as the temperature increased. Moreover, sintered nano-scale silver, as a thermal interface material, serves to link chip and substrate, and to conduct electricity and heat. Therefore, many scholars studied the effects of attachment area, loading rates, and temperature on mechanical behavior of sintered nano-scale silver attachment. Bai et al. [4] conducted shear and heat cycling experiments on a low-temperature sintered silver die attached SiC power device assembly. Qi et al. [10] studied the mechanisms, observing that a larger interconnection area would cause a poor interconnection quality of the nano-scale silver joints in the industry. In addition, a relationship between shear strength and interconnection area of sintering joints with nano-scale silver paste was also observed. Tan et al. [11] carried out both load-controlled fatigue and dwell-fatigue tests at elevated temperatures to describe the high temperature mechanics of nano-silver sintered lap-shear joints, and found that creep was the dominant factor that resulted in failure acceleration and cyclic life reduction at 325 °C. However, creep played a less important role in the total deformation, when temperature decreases to 225 °C.

The unified visco-plastic constitutive model has been greatly developed in recent decades, ensuring the efficient description and prediction of ratcheting and fatigue behavior of sintered nano-scale silver using constitutive model and finite element analysis (FEA). Prager [12] proposed a linear kinematic hardening rule to predict strain hardening effect of materials. Unfortunately, the linear kinematic hardening model predicts a closed loop for cyclic loading. In order to describe the accumulated plastic strain, a well-known nonlinear kinematic hardening model was proposed by Armstrong and Frederick [13]. The nonlinear kinematic hardening rule, contains a “recall” term, incorporating fading memory effect of the strain path. In addition, the “recall” term in A-F kinematic hardening rule produces change in shapes between forward and reverse loading paths. Thus, the loop does

* Corresponding author.
E-mail address: agang@tju.edu.cn (G. Chen).

https://doi.org/10.1016/j.microrel.2017.11.010
Received 11 August 2017; Received in revised form 11 November 2017; Accepted 14 November 2017

not close and results in ratcheting behavior. On the basis of A-F kinematic hardening rule, many constitutive models were subsequently developed [14–30].

In order to describe the whole-life ratcheting deformation and precisely predict fatigue life, it is necessary to introduce a damage-coupled, temperature-dependent visco-plastic constitutive model. Chaboche [31–33] developed the framework and principle of continuum damage mechanics in the view of thermal mechanics, and energy was the main line during the derivative process. Yao et al. [34,35] and He et al. [36] proposed a visco-plastic model and performed FEA simulation to describe the evolution of damage and fracture behavior of solder materials. Yang et al. [37] proposed a damage-coupled unified visco-plastic constitutive model for the 63Sn–37Pb alloy used in solder joints. Kang et al. [38] proposed a damage-coupled visco-plastic cyclic constitutive model, based on the framework of unified visco-plasticity and continuum damage mechanics to describe the whole-life ratcheting deformation and predict the fatigue life of 42CrMo steel. In the proposed model, the damage consisted of both elastic and plastic damage, and failure modes were proposed to determine failure life. The damage-coupled model could predict whole-life ratcheting behavior and fatigue life. Shi et al. [39] introduced the sphericity of the voids as damage, which was coupled into the OW-AF model, to describe the whole-life ratcheting deformation of SAC305 lap-shear solder joints. The evolution of the voids was observed using X-ray CT technology, and it was found that the ratcheting behaviors of SAC305 were dominated by damage. As for the temperature-dependent behavior of materials, abundant of unified thermo-viscoplastic constitutive models had been developed [40–50]. Yu et al. [51] and Bai et al. [52] simulated the mechanical behaviors of electronic packing materials using a unified visco-plastic constitutive model at different temperatures.

In this study, a temperature-dependent and damage-coupled visco-plastic constitutive model is proposed to simulate the whole-life ratcheting and temperature-dependent behaviors of the sintered nano-scale silver paste. A damage variable represented the decrease of the unloading elastic modulus, and the evolution of damage was described by the θ function [53]. Damage was coupled into the visco-plastic constitutive model, and the Arrhenius power-law rule was introduced to modify the flow rule. Then, the model parameters were determined to simulate the whole-life ratcheting behavior of the sintered nano-scale silver paste. Finally, it is verified from a comparison of the experimental and simulation results, that the modified model can reasonably simulate the whole-life ratcheting behaviors of the sintered nano-scale silver paste.

2. Visco-plastic constitutive models

2.1. Visco-plastic constitutive model based on OW-AF rule

2.1.1. Main constitutive equations

The main constitutive equations of visco-plastic constitutive model have been widely used by many scholars [15–22]. It is supposed that the total strain can be decomposed into two parts: elastic strain and visco-plastic strain:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{\mathbf{e}} + \boldsymbol{\varepsilon}^{\mathbf{vp}} \tag{1}$$

where $\boldsymbol{\varepsilon}^{\mathbf{e}}$ and $\boldsymbol{\varepsilon}^{\mathbf{vp}}$ are elastic strain and visco-plastic strain tensor, respectively. The elastic strain portion obeys Hooke's law:

$$\boldsymbol{\varepsilon}^{\mathbf{e}} = [(1+\nu)/\mathrm{E}]\boldsymbol{\sigma} - (\nu/\mathrm{E})(tr\boldsymbol{\sigma})\mathbf{I} \tag{2}$$

where E and ν represent the elastic modulus and Poisson's ratio, $\boldsymbol{\sigma}$ denotes a stress tensor and $\mathbf{I}$ is a second-order unit tensor, tr is the trace.

The plastic flow rule can be stated as [22,25,54]:

$$\dot{\boldsymbol{\varepsilon}}^{\mathbf{vp}} = \sqrt{\frac{3}{2}}\left\langle \frac{\sigma_v}{K} \right\rangle^n \frac{\boldsymbol{s}-\boldsymbol{\alpha}}{||\boldsymbol{s}-\boldsymbol{\alpha}||} \tag{3}$$

where K and n are the visco material parameters, $\mathbf{s}$ and $\boldsymbol{\alpha}$ indicate the deviatoric parts of stress $\boldsymbol{\sigma}$ and back stress, respectively. The symbol < > denotes MaCauley's bracket, defining: $\langle x \rangle = \frac{x+|x|}{2}$, σ_v represents the overstress, and $\sigma_v = \sqrt{(3/2)(\boldsymbol{s}-\boldsymbol{\alpha}):(\boldsymbol{s}-\boldsymbol{\alpha})} - \sigma_y$. The von-Mises yield criterion dominates the yield criterion, which is defined as:

$$f(\sigma) = (3/2)(\boldsymbol{s}-\boldsymbol{\alpha}):(\boldsymbol{s}-\boldsymbol{\alpha}) - \sigma_y^2 \tag{4}$$

where σ_y is the size of the yield surface. The plastic flow law is defined as:

$$d\boldsymbol{\varepsilon}^{\mathbf{p}} = \mathrm{d}\lambda * (\partial f/\partial \boldsymbol{\sigma}) \tag{5}$$

where dλ is a plastic multiplier and can be obtained from the following equation:

$$\mathrm{d}\lambda = \langle \sigma_v/K \rangle^n \tag{6}$$

2.1.2. Non-linear kinematic hardening rule

The non-linear kinematic hardening rule was proposed by Abdel-Karim et al. [30]. The equations are displayed as follows:

$$\boldsymbol{\alpha} = \Sigma_{k=1}^{M}\boldsymbol{\alpha}^{(\boldsymbol{k})} = \Sigma_{k=1}^{M} r^{(k)}\mathbf{b}^{(\mathbf{k})} \tag{7}$$

$$\dot{\mathbf{b}}^{(\mathbf{k})} = \zeta^{(k)}\{(2/3)\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{p}} - [(1-\mu^{(k)})\boldsymbol{H}(f^{(k)}) + \mu^{(k)}]\dot{p}\boldsymbol{b}^{(\boldsymbol{k})}\} \tag{8}$$

where ξ_i, r_i and μ_i (i = 1,2,…,M) are material constants. r_i represent the saturation values of backstress components. $\mathbf{H}$ means the Heaviside step function: if $\boldsymbol{x} \geq 0$, $\mathbf{H}(x) = 1$; $\boldsymbol{x} < 0$, $\mathbf{H}(x) = 0$. ξ_i denotes the dynamic recovery multiplier.

2.2. Temperature-dependent and damage-coupled visco-plastic constitutive model

From the scholars' work, the ratcheting behaviors of the sintered nano-scale silver paste are temperature-dependent, and damage dominant fatigue failure. Thus, it is necessary to couple damage and temperature into the OW-AF model, which is on the basis of the damage mechanics concept [55,56]. The damage variable D was normally coupled into the constitutive model as 1/(1-D) to quantify the damage accumulation [38]. The damage variable coupled into the OW-AF model and main equations are outlined as follows:

$$f(\boldsymbol{\sigma}) = (3/2)(\boldsymbol{s}/(1-D)-\boldsymbol{\alpha}):(\boldsymbol{s}/(1-D)-\boldsymbol{\alpha}) - \sigma_y^2 = 0 \tag{9}$$

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{\mathbf{e}} + \boldsymbol{\varepsilon}^{\mathbf{p}} \tag{10}$$

$$\boldsymbol{\varepsilon}^{\mathbf{e}} = [(1+\nu)/\mathrm{E}]\boldsymbol{\sigma}/(1-D) - (\nu/\mathrm{E})(tr\boldsymbol{\sigma})/(1-D)\mathbf{I} \tag{11}$$

$$\boldsymbol{\varepsilon}^{\mathbf{p}} = d\lambda/(1-D) * (\partial f/\partial \boldsymbol{\sigma}) \tag{12}$$

$$d\lambda/(1-D) = \langle \sigma_v/K \rangle^n \tag{13}$$

$$\sigma_v = \sqrt{(3/2)(\boldsymbol{s}/(1-D)-\alpha):(\boldsymbol{s}/(1-D)-\boldsymbol{\alpha})} - \sigma_y \tag{14}$$

$$\boldsymbol{\alpha} = \Sigma_{k=1}^{M}\boldsymbol{\alpha}^{(\boldsymbol{k})} = \Sigma_{k=1}^{M} r^{(k)}\mathbf{b}^{(\mathbf{k})} \tag{15}$$

$$\dot{\mathbf{b}}^{(\mathbf{k})} = \zeta^{(k)}\{(2/3)(1-D)\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{p}} - [(1-\mu^{(k)})\boldsymbol{H}(f^{(k)}) + \mu^{(k)}]\dot{p}(1-\boldsymbol{D})\boldsymbol{b}^{(\boldsymbol{k})}\} \tag{16}$$

In this study, the damage-coupled constitutive model was proposed for predicting the ratcheting response of the sintered nano-scale silver paste precisely, especially for the whole-life ratcheting. It is noted that the evolution of backstress is independent of the evolution of damage. Thus, the parameters in kinematic hardening rule can be obtained from the experimental results without considering the effect of damage.

As for temperature-dependent stress-strain response, the Arrhenius power-law model was introduced into the flow rule to modify the stress-strain and ratcheting responses of the sintered nano-scale silver paste at a different temperature. The Arrhenius power-law model was set as: $A\exp\left(-\frac{Q}{RT}\right)$, where A denotes the pre-exponential factor and R is the gas constant, Q stands for the activation energy, T represents the