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Applying viscoplastic constitutive models to predict ratcheting behavior of sintered nanosilver lap-shear joint

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ABSTRACT

A series of displacement-controlled tests were conducted for sintered nanosilver lap-shear joints at different loading rates and temperatures. The relationship between force and displacement was studied. It was found that higher loading rate or lower temperature caused higher stress–strain response of the sintered nanosilver joint. Force-controlled cyclic tests were also performed at different mean forces, force amplitudes, dwell time at peak force, and temperatures. The mean force, the force amplitude, and the temperature played key roles in the shear ratcheting strain accumulation. The ratcheting strain rate could be enhanced with increasing the dwell time at peak force as well. A viscoplastic constitutive model based on Ohno–Wang and Armstrong–Fedrick (OW–AF) non-linear kinematic hardening rule, and Anand model were separately embedded in ABAQUS to simulate the shear and the ratcheting behavior of the sintered nanosilver joint. It was concluded that OW–AF model could predict the ratcheting behavior of the sintered nanosilver joint better than Anand model, especially at high temperatures.

1. Introduction

With the development of many high-temperature power electronic packaged devices (Sabbah et al., 2012; Steger, 2012; Streubel et al., 2002), such as high-power InGaN blue-light-emitting diodes, automotive and aeronautic applications, it is necessary to provide related electrical and structural interconnection materials with high qualities. However, traditional interconnection materials, such as solder alloys and conductive adhesives, could not meet those demands opportunely. Therefore, it is seriously required to find a novel and suitable interconnection material to solve those problems. Sintered silver paste has the potential to be the one with many high performances, such as high melting point, high electrical/thermal conductivity and excellent mechanical reliability (Bai and Lu, 2006; Franco et al., 1984; Wang et al., 2007).

Lu et al. (2004) introduced a low-temperature sintering method for nanoscale silver paste, and improved the sintering process in the subsequent works (Bai et al., 2006; Wang et al., 2007). Meanwhile, Chen et al. (2008, 2012) and Mei et al. (2012a,b, 2011a,b) conducted quantities of researches on sintered nanosilver, including elastic modulus, thermal residual stress, electrochemical migration, thermal impedance, and mechanical behaviors. They pointed out that ratcheting strain of this material becomes larger as increasing mean stress and stress amplitude or decreasing loading rate. More importantly, ratcheting deformation occurred in components will accelerate damage accumulation and eventually reduce the components fatigue life (Chen et al., 2005b; Date et al., 2008; Rider et al., 1995). Therefore, some investigations on ratcheting and fatigue behaviors have been carried out in specific materials: magnesium alloy (Lin et al., 2011a, 2013),

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copper (Kwofie, 2006), SS304 steel (Kang et al., 2006), 42CrMo steel (Kang et al., 2009), 316FR stainless steel (Date et al., 2008), epoxy polymer (Tao and Xia, 2007) and conductive adhesive (Gao et al., 2003; Lin et al., 2011b). In particular, to study ratcheting and fatigue behaviors of low-temperature sintered nano-scale silver paste, Wang et al. (2010) have conducted the ratcheting tests of nanosilver films at different temperatures, and the effect of mean stress, stress amplitude, temperature, peak stress holding time, and loading history on the ratcheting response of films were considered and analyzed. It was demonstrated that ratcheting strain increases significantly with the increasing temperature and peak stress holding time, and that the fatigue failure of sintered nanosilver films is dominated by ratcheting response especially at the high temperature and the long peak stress holding time. Regrettably, most of works concerning the nanosilver paste were performed just for sintered nanosilver film rather than sintered nanosilver joint for power electronics packaging (Chen et al., 2008; Wang et al., 2010). Recently, Li et al. (2013, 2012) studied mechanical properties of sintered nanosilver lap-shear joints in monotonic shear and cyclic ratcheting tests. They found that ratcheting behavior of sintered nanosilver plays an essential role on fatigue life of the joints. Therefore, it is important to present a reliable method to consider the ratcheting behavior of sintered nanosilver joint.

Finite element method (FEM) is extensively implemented to simulate deformation and failure behavior of materials and structures in electronic packaging. To make simulations more acceptable and accurate, an applicable constitutive model should be provided at the first place. Anand model (Anand, 1985; Brown et al., 1989) was widely used to predict strain–stress relationship of solders. Wilde et al. (2000) used Anand model to represent the inelastic deformation behavior for a Pb-rich solder 92.5Pb5Sn2.5Ag. Subsequently, material parameters for the Anand model of four different Sn–Pb solders were determined by Cheng et al. (2000), and they applied the Anand model into finite element simulation of stress/strain responses in solder joints for chip component, thin quad flat pack and flip-chip assembly. Chen et al. (2005a) and Wang et al. (2001) applied an improved Anand model to describe the inelastic stress–strain relationship of eutectic Sn–3.5Ag solder. Bai et al. (2009) modified Anand model to predict the uniaxial tensile properties of Sn–0.7Cu solder and Sn–3Ag–0.5Cu solder. Yu et al. (2009) applied Anand model to describe sintered nanosilver film, they found that the model over predicted the cyclic ratcheting strain when loading loops were more than several cycles at high temperatures. Since Anand model does not have explicit loading and unloading criterion, and it employs only one single scalar as an internal variable to describe the inelastic deformation of materials (Chen et al., 2005a), it is difficult to apply Anand model to predict the complex stress–strain response of the materials precisely, especially when the cyclic inelastic strain accumulation needs to be taken into account.

However, Ohno–Wang and Armstrong–Fedrick (OW–AF) constitutive model (Abdel-Karim and Ohno, 2000) had been adopted to simulate the evolution of cyclic accumulated plastic strain for different materials by a few scholars (Kang, 2002, 2004; Kang et al., 2004; Kang and Kan, 2007; Ohno and Abdel-Karim, 2000). Ohno and Abdel-Karim (2000) applied this constitutive model successfully to simulate the ratcheting experiments (Mizuno et al., 1999) of 316FR steel at room temperature. Kang (2004) developed a similar viscoplastic model with OW–AF to simulate ratcheting of cyclically stable material U71Mn rail steel and achieved good results. Afterwards, Kang and Kan (2007) used three kinds of constitutive models to describe time-dependent ratcheting by using the OW–AF kinematic hardening rule (Abdel-Karim and Ohno, 2000). Nakane et al. (2008) used OW–AF kinematic and isotropic hardening model to describe the cyclic plasticity of OFHC (Oxygen-free high thermal conductivity) copper substrate of solder-bonded elastic and elastoplastic layers, and pointed out that cyclic hardening of OFHC-Cu played an important role in the cyclic growth of deflection.

In this paper, a series of displacement-controlled tests and cyclic force-controlled tests were conducted on sintered nanosilver lap-shear joints at different loading rates and temperatures. The relationships between force and displacement were obtained. A viscoplastic constitutive model based on OW–AF non-linear kinematic hardening rule was implemented in ABAQUS by an UMAT subroutine. A two-dimensional (2-D) finite element model was established to simulate the inelastic deformation of sintered nanosilver lap-shear joint under cyclic loadings. The comparison of predicted ratcheting deformation between OW–AF model and Anand model were also discussed in the text.

2. Experimental procedure

The nanosilver paste in the study was provided by NBE LLC. (Blacksburg, VA) (LLC). It is with 80 wt.% silver nanoparticles, which are mixed with organic components such as alcohol, terpilenol by ultrasonic wave shaking or mechanical shaking. The lap-shear joints were put onto a heating block and sintered as the profile shown in Fig. 1.

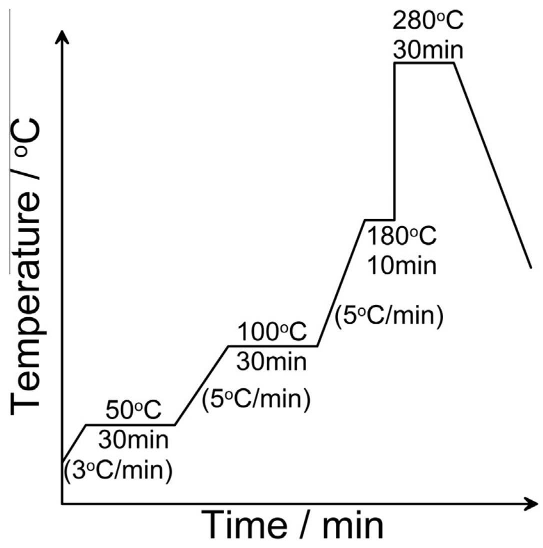

Fig. 1. Sintering profile of nanosilver paste.