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Multiscale modeling of the anisotropic transient creep response of heterogeneous single crystal SnAgCu solder

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ABSTRACT

The lack of statistical homogeneity in functional SnAgCu (SAC) solder joints due to their coarse grained microstructure, in conjunction with the severe anisotropy exhibited by single crystal Sn, renders each joint unique in terms of mechanical behavior. A mechanistic multi-scale modeling framework is proposed in this study to predict the influence of composition and microstructure on the anisotropic transient creep response of single crystal SnAgCu (SAC) solder. Tier I consist of single-crystal eutectic Sn–Ag alloy, with nanoscale Ag_3Sn particles embedded in a single-crystal Sn matrix. Tier II consists of single crystal SAC solder which is composed of Sn dendrites surrounded by the eutectic Sn–Ag phase of Tier I. The Tier I anisotropic transient creep model is based on dislocation mechanics. The Tier II model uses the results of Tier I as an input and is based on anisotropic composite micro-mechanics.

In Tier I, creep deformation is governed by dislocation impediment and recovery at nanoscale Ag_3Sn particles, with recovery being the rate controlling mechanism. Dislocation climb and dislocation detachment at the Ag_3Sn particles are proposed to be the competing rate controlling recovery mechanisms. Line tension and mobility of dislocations in dominant slip systems of single crystal Sn are estimated based on the elastic crystal anisotropy of body centered tetragonal (BCT) Sn. The anisotropic transient creep rate of the eutectic Sn–Ag phase of Tier I is then modeled using above inputs and the evolving dislocation density calculated for dominant glide systems during the transient stage of creep. The dominant slip systems are determined based on the dislocation mobility and on the orientation angle between the crystal principal axes and the loading direction. The creep response of the eutectic phase (from Tier 1) is combined with the creep response of Sn lobes at Tier 2, using the anisotropic Mori-Tanaka homogenization theory, to obtain the transient creep response of a SAC305 single crystal along global specimen directions. This model has been calibrated using experimentally obtained transient creep response of a SAC305 single crystal specimen. The above multiscale calibrated model is then used to predict (i) the transient creep response of another SAC305 single crystal specimen and (ii) the effect of orientation (by changing one of the Euler angles) on the transient creep response of SAC305 single crystal. The grain orientation of above two SAC single crystal specimens (with respect to loading direction) were identified with orientation image mapping and then utilized in the model to estimate the resolved shear stress along the dominant slip directions. Parametric studies have also been conducted to predict the

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effects of the volume fraction, aspect ratio, and orientation of ellipsoidal Sn inclusions on the anisotropic transient creep response of SAC single crystals.

1. Introduction

The hypo-eutectic SnAgCu (SAC) alloys chosen to replace eutectic Sn–Pb contain approximately 97 weight percent of Sn, and display very different physical and mechanical behavior than the well characterized Sn–Pb system (Donald and Henderson, 2004; Dudek et al., 2003; Lehman et al., 2004; Kinyanjui and Lehman, 2005; Shawkret Ahat, 2001; Subramanian and Lee, 2004; Syed, 2004; Telang et al., 2004). The nature of solidification in SAC alloys often leads to solder joints comprised of very large, highly anisotropic Sn grains (Lehman et al., 2004; Kinyanjui and Lehman, 2005; Telang et al., 2004). Thus, the microstructure of most functional SAC solder joints is coarse-grained with 1–6 grains in the joint. Because the thermomechanical properties of Sn exhibit large anisotropy, the thermomechanical response of SAC solder joints depends greatly on the size and orientation of the few Sn grains (Donald and Henderson, 2004; Dudek et al., 2003; Lee et al., 2002; Lehman et al., 2004; Matin et al., 2005; Rayne and Chandrasekhar, 1960; Kinyanjui and Lehman, 2005; Shawkret Ahat, 2001; Subramanian and Lee, 2004; Syed, 2004; Telang and Bieler, 2005a,b; Telang et al., 2006, 2004). The lack of statistical homogeneity in these microscale SAC joints due to its coarse grained microstructure, in conjunction with the severe anisotropy exhibited by single crystal Sn, renders each joint unique in terms of anisotropic mechanical behavior (Bieler et al., 2006; Chu and Li, 1980; Park et al., 2007; Sylvestre and Blander, 2008; Telang et al., 2003; Weertman, 1957; Yang and Li, 2006). There is significant evidence in the literature that micron-scale high-Sn SAC solder joints exhibit significant piece to piece variability in their mechanical response under identical load conditions in the as-fabricated state (Arfaei et al., 2008; Borgesen et al., 2007; Donald and Henderson, 2004; Park et al., 2007; Sylvestre and Blander, 2008). For example, the steady state creep strain rate of a SAC solder reported by several authors can be seen to vary by orders of magnitude when tested at similar stress levels (refer to Fig. 1).

Creep measurements conducted on microscale SAC305 solder specimens in a study conducted by Cuddalorepatta et al. (2010) also show significant piece-to-piece variability in the creep behavior of identical test specimens tested under the same loading conditions (refer to Fig. 2). Primary creep strains observed for four specimens tested at the same shear stress level (20 MPa) at room temperature varies considerably. Microstructural analysis of these microscale SAC305 solder specimens revealed (Cuddalorepatta et al., 2010) that in spite of using consistent fabrication protocols, these specimens exhibit a non-repeatable coarse-grained Sn microstructure similar to that seen in SAC joints in functional microelectronics (refer to c-axis grain orientation maps of a PBGA joint in Fig. 3). In order to understand the effects of anisotropic Sn properties and of grain orientation on the variability of creep response of these SAC solder interconnects, a multiscale modeling approach is proposed where the microstructure can be classified into five distinct length scales, as shown in Fig. 4 and discussed below.

Tier 4 represents the geometry of the solder joint itself and the architecture of the interfaces with the component and PWB (including the interfacial metallization and IMC layers) because this geometry governs the complex evolving boundary conditions imposed on the solder joint. In this study, the structure of interest at Tier 4 is not a functional electronic assembly but rather a modified Iosipescu lap shear specimen (Iosipescu, 1967) used for mechanical characterization. The next lower length scale (Tier 3) is the grain scale microstructure, typically consisting of one or several anisotropic Sn grains, either

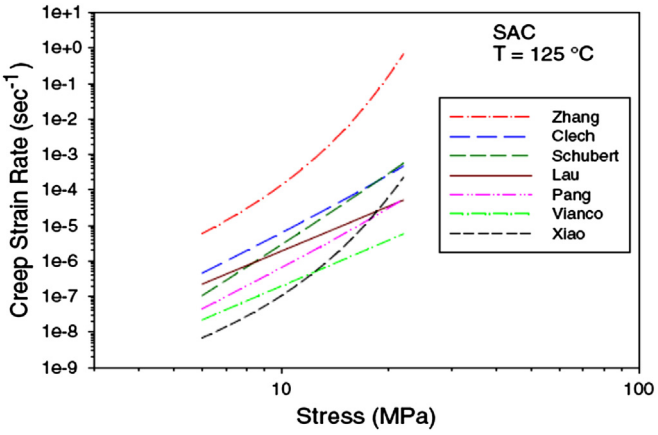

Fig. 1. (3–4) orders of magnitude variability observed in steady state secondary creep strain rates in SAC305 solder alloy tested at 125 °C (Ma and Suhling, 2009).