



Viscoplastic creep and microstructure evolution of Sn-based lead-free solders at low strain



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ABSTRACT

In this study, the viscoplastic creep behaviors of the Sn-4Ag/Cu, Sn-3Cu/Cu and Sn-58Bi/Cu solder joints under shear stress were in-situ observed, and the evolutions in microstructure of the solders were characterized by in-situ EBSD. The results reveal that the creep strain of the Sn-Cu and Sn-Ag solders increase linearly with increasing time. Deformation of the Sn-Cu solder concentrates in some parallel shear bands, while deformation of the Sn-Ag solder is relatively uniform, and the deformation concentration along the joint interface is not obvious for the two solders. The strain concentration around the fine Ag₃Sn particles in the Sn-Ag solder is not obvious, while the strain concentration around the large Cu₆Sn₅ grain in the Sn-Cu solder is serious and result in fracture of the Cu₆Sn₅ grain. Dynamic high-temperature recovery occurs in the Sn-Ag and Sn-Cu solders, result in grain boundary migration, polygonization and formation of a few low-angle grain boundaries. The Sn-Bi solder deforms through grain boundary sliding and phase boundary sliding, the strain increase exponentially with increasing time, and its grain structure is stable during the deformation process.

1. Introduction

Soldering in microelectronic package not only provides the electronic connection, but also ensures the mechanical reliability of the joints, which makes the mechanical property of the solder joints one of the major concerns for the integrity of the electronic connection [1]. Therefore, understandings on deformation mechanisms of the solders are of great importance for evaluating the reliability of the solder joints. In the electronic components, the primary strain subjected by the solder joints is resulted from the difference in the coefficients of thermal expansion (CTE). Since the strain is induced by rise and decline of temperature, while the temperature usually changes slowly, the solder joints deform at a low strain rate, and the strain is also very low [2]. The deformation of the solder joints usually concentrates in the solder since the substrate materials and the intermetallic compounds (IMC) have much higher yield strength than the solder. Besides, because the melting temperature and yield strength of the solders are very low, the solders creep through a viscoplastic mechanism when it is deformed at a low strain rate even at room temperature, and dynamic microstructure evolution occur during the deformation process [3,4].

Thus far many studies on creep behaviors of the solders have been reported, the creep stress exponents and activation energies of a series of Sn-based solders were obtained, and creep mechanisms of the solders

are proposed [5–10]. However, most of these studies focus on the creep curves, parameters and equations, while little attention has been paid to the deformation morphologies and the microstructure evolution during the deformation process. Besides, the strain chosen in most of the studies is quite high, while the strain suffered by the solder joints in the electronic components is usually very low [11]. As both the strain and the strain rate are very low, it is necessary to reveal the deformation mechanisms of the solders at low strain and low strain rate.

The discussions above indicate that a comprehensive, intuitionistic understanding on deformation mechanisms of the lead-free solders at low strain and low strain rate is required. Therefore, the creep behaviors of a series of Pb-free solders were investigated in this study. The Scanning Electronic Microscope (SEM) equipped with in-situ tensile stage and Electronic Back-scattered Diffraction (EBSD) system was used to conduct the experiments, which allows visualized observation on morphology of the solder and characterization of the microstructure evolution. The employed specimens are small in scale (1 × 1 mm), in order to make them more like the solder joints in the electronic components. By analyzing the deformation morphologies and the EBSD maps, new understandings on deformation mechanisms of the solders at low strain and low strain rate are provided. Furthermore, it is expected that this research may provide a new approach to reveal the dynamic deformation and microstructure evolution behaviors of the solder.

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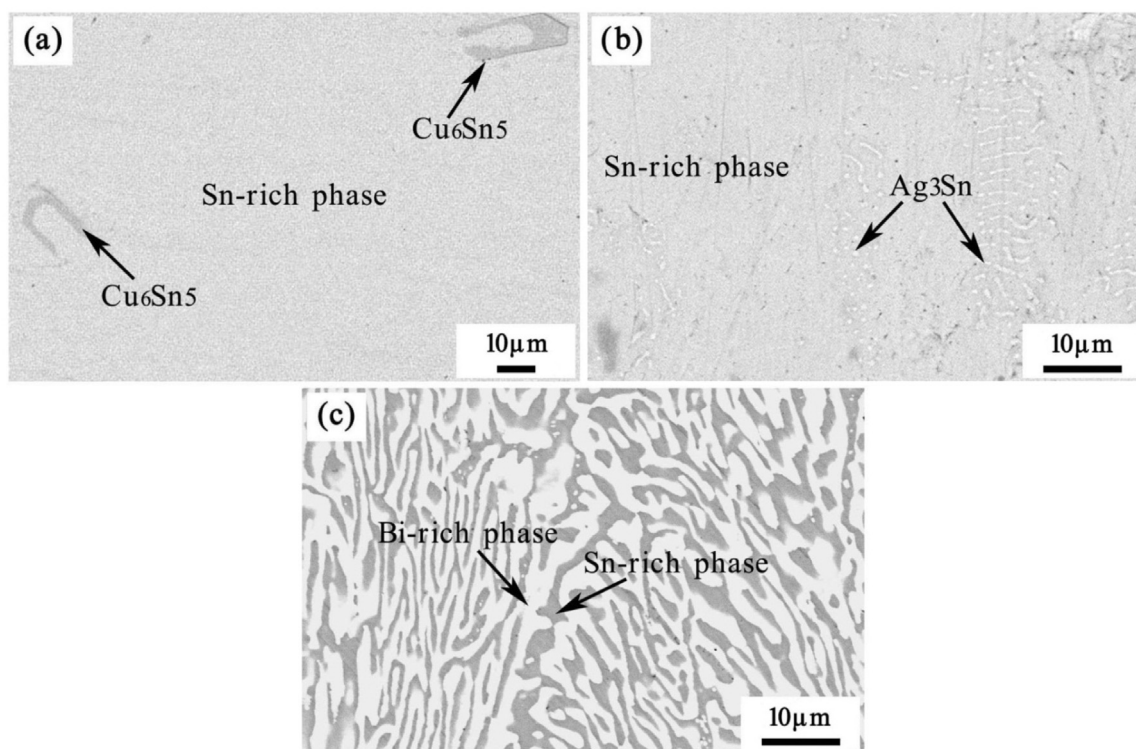


Fig. 1. Back scattered electron images of the (a) Sn-3Cu, (b) Sn-4Ag and (c) Sn-58Bi solders.

2. Experimental procedure

The Sn-4 wt%Ag/Cu, Sn-3 wt%Cu/Cu and Sn-58 wt%Bi/Cu solder joints were chosen as examples in this study. The solders were prepared by smelting high-purity Sn, Ag, Cu and Bi metals in vacuum, and the substrate is cold-drawn oxygen-free Cu rods with a yield strength of about 300 MPa. Since the Cu substrate has much higher yield strength than the solders, it only exhibits very slight elastic deformation under the shear loading. The Cu rod was firstly spark cut into small blocks with a step at one end, then the surfaces at the ends were ground and electrolytically polished, a flux was dispersed on the polished area, and the solder sheets were sandwiched between the two Cu blocks. The prepared samples were put in an oven with a certain temperature, kept for 3 min after melting of the solder and then cooled in air. The soldering temperature of the Sn-4Ag, Sn-3Cu and Sn-58Bi solder joints are 260 °C, 260 °C and 200 °C, respectively. After that, the samples were sliced into shear specimens by spark cutting, and their side surfaces were ground and mechanically polished for observation. The back scattered electron images of the Sn-3Cu, Sn-4Ag and Sn-58Bi solders are shown in Fig. 1. It can be found that the Sn-3Cu solder is composed by Sn matrix and some large Cu_6Sn_5 IMC grains, the Sn-4Ag is composed by Sn matrix and thin Ag_3Sn particles, and the eutectic Sn-Bi solder has a fine lamellar structure of Sn-rich phase and Bi-rich phase. The shape, dimension of the test specimens and the loading direction are illustrated in Fig. 2(a).

The shear creep tests were carried out by a Gatan MTEST2000ES Tensile Stage equipped on the LEO Super35 SEM, and the creep stresses were chosen according to some early publications [4,12]. The specimens were loaded to and held at the chosen stresses, makes the solder joints deform at a very low strain rate. Each group of the solder joints were deformed at a few stresses. During the deformation process, the dynamic strain and time data were recorded, and the deformation morphologies of the specimens were in-situ observed. The full views of the solder joints were observed firstly to show the macroscopic damage, then deformation morphologies of some local regions were tracked. It should be noticed that the image was not rotated during the

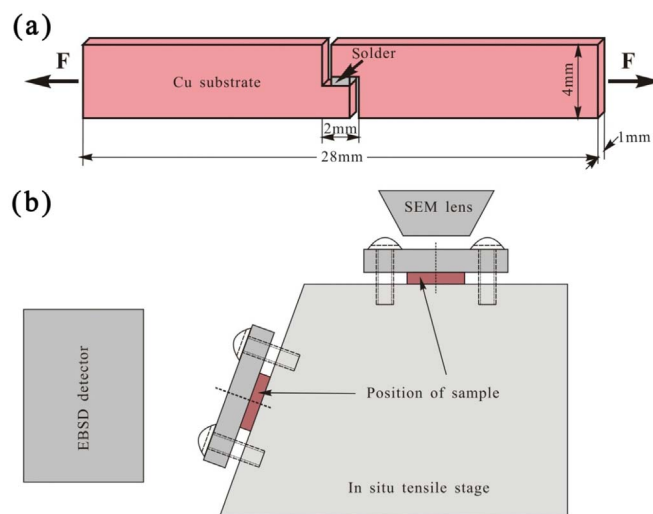


Fig. 2. Illustrations on (a) shape and dimension of testing specimens and (b) position of samples in the stage.

experiment, to make sure that the deformation direction of all images are the same. When the strain increased to a certain value, the stress was decreased to zero and the EBSD data of the solder were collected and analyzed by a HKL Channel software version 5 (HKL Technology, Hobro, DK). All the experiments were conducted at 25 °C in vacuum. Illustrations on the in-situ characterizations are exhibited in Fig. 2(b).

3. Experimental results

3.1. Viscoplastic creep strain-duration curves

Fig. 3 presents the creep strain-duration curves of the three solder joints, with the creep stresses labelled on the figure. The strain is calculated by firstly subtracting the elastic displacement of Cu from the

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