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Correlation between thermal fatigue and thermal anisotropy in a Pb-free solder alloy

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Abstract

Intrinsic thermal fatigue in a mechanically unconstrained Pb-free, Sn-rich Sn–3.8Ag–0.7Cu alloy has been investigated under cyclic thermal loading between 293 K and 353 K. Fatigue damage is shown to occur preferentially along high angle grain boundaries. From a combination of orientation imaging microscopy and finite element modelling it appears that this fatigue damage and stresses resulting from the thermal anisotropy of Sn are highly correlated.

Keywords: Fatigue; Electron backscattering diffraction (EBSD); Misorientation; Grain boundaries; Microstructure

1. Introduction

The replacement of Sn–Pb solders due to environmental and health concerns has given an impetus to the development of Pb-free solder alloys [1].

Some potential Sn–Ag, Sn–Bi, Sn–Zn, Sn–Cu binary eutectic and Sn–Ag–Cu, Sn–Ag–Bi, Sn–Zn–Bi ternary eutectic alloys have been developed as substitutes for Sn–Pb alloys [2–4]. Recently, industry has focused its interest on eutectic Sn–Ag–Cu (SAC) because of its comparatively low melting temperature, the competitive price, and good mechanical properties [5]. SAC is the main subject of this paper.

Any alloy used for solder interconnections is exposed to thermo-mechanical fatigue (TMF) during service as a result from thermal cycling caused by normal use. The thermal cycling induces mechanical loads because of mismatches in coefficients of thermal expansion (CTEs). These mechanical loads on the solder alloy originate on a *macroscopic scale* from the thermal expansion mismatch between e.g., a chip and a printed circuit board and on a *microscopic scale due* to differences in CTEs between the various phases in the solder itself [6]. A further interesting cause for thermo-mechanical loads in Sn-rich alloys on a microscopic scale is the intrinsic anisotropy of Sn. Sn has a body-centered tetragonal structure with lattice parameters of $a = b = 0.5632$ nm and $c = 0.3182$ nm at 25 °C, which is highly anisotropic with c/a ratio of 0.546 [7]. At 30 °C, the coefficients of thermal expansion in the principal directions are $\alpha_{[1\,0\,0]} = \alpha_{[0\,1\,0]} = 16.5 \times 10^{-6}\,°C^{-1}$ and $\alpha_{[0\,0\,1]} = 32.4 \times 10^{-6}\,°C^{-1}$; at high temperatures, the values change substantially, for example at 130 °C: $\alpha_{[1\,0\,0]} = \alpha_{[0\,1\,0]} = 20.2 \times 10^{-6}\,°C^{-1}$ and $\alpha_{[001]} = 41.2 \times 10^{-6}\,°C^{-1}$ [7]. Sn is also markedly anisotropic in its elastic behavior. The following values for the elastic moduli [8–10]: $c11 = 73.5$, 83.91, 86.0; $c12 = 23.4$, 48.70, 35.0; $c13 = 28.0$, 28.10, 30.0; $c33 = 87.0$, 96.65, 133.0; $c44 = 22.0$, 17.54, 49.0; $c66 = 22.65$, 7.41, 53.0 (all values in GPa) show this anisotropic behavior.

It has recently been reported that this anisotropy in thermal expansion and elastic properties of Sn may induce significant stresses at Sn-grain boundaries during

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thermal cycling [11]. Also, work on thermo-mechanical fatigue in bulk Sn-rich solders has shown [12,13] that damage may occur by sliding or separation of grain boundaries.

In this paper we study the role of the intrinsic anisotropy of Sn on the thermal fatigue damage in more detail, combining experimental results (orientation imaging microscopy, OIM) and numerical calculations (Finite Element Modelling, FEM). The aim is to investigate whether a correlation between microscopic damage evolution and thermally induced stresses indeed occurs in an otherwise mechanically unconstrained solder alloy.

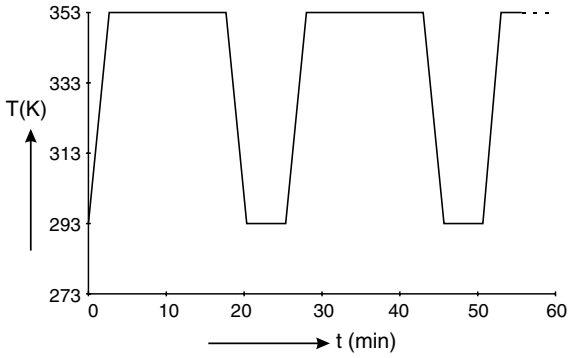

Fig. 1. Thermal cycling profile.

2. Experimental techniques

Bulk SAC solder specimens were prepared from commercial solder alloy Sn-96L-NS (Balverzinn, Germany). The alloy was sealed in a cylindrical quartz ampoule of 1 cm diameter and 5 cm length under a vacuum of 10^{-4} Pa. The ampoules were superheated to 50 °C above the eutectic temperature in a furnace at a heating rate of 10 °C/min and held for about 5 min. To ensure the homogeneity of the alloy, the ampoules were carefully shaken before quenching it with liquid nitrogen (LN2) to −196 °C. The purpose of using LN2 was to obtain bulk specimens with a fine microstructure representative of a solder interconnection used in microelectronics. The samples were then with a cutting blade impregnated with diamond sectioned into 1 cm pieces sectioned into 1 cm pieces. The bulk solder specimen was cylindrical, with diameter 10 mm and height 4 mm. All specimens for microscopic examination were prepared following a standard metallographic technique. The alloy was thermally cycled within the temperature range 293–353 K with 5 min hold at low temperature and 15 min hold at high temperature and with a ramp rate of 30 °C/min following the temperature profile as shown in Fig. 1 using a heating–cooling stage (LINKAM LTS-350) with a temperature accuracy of 1 °C for 1000 cycles.

Liquid nitrogen (LN2) was purged into the stage to attain sub-zero temperatures. Polarization microscopy was used for characterization of the microstructure on the plane section of specimens before and after thermal cycling. Backscattered electron (BSE) images (FEI Sirion HR-SEM) were taken from selected areas on the plane section of samples before and after thermal cycling to evaluate the microscopic deformation mechanisms.

Orientation imaging microscopy (TSL OIM detector) was performed to obtain local orientation information by collecting electron backscattering diffraction (EBSD) patterns. A 30 kV beam with a current intensity of about 8 nA was used. Crystallographic orientation data was collected from an area of $4 \times 10\ \text{mm}^2$ within the cross-section of the specimen before thermal cycling. After thermal cycling, OIM maps were collected from the same area.

3. Results and discussion

3.1. Damage evolution

Fig. 2 shows polarization micrographs of the as-solidified bulk SAC alloy, and the same specimen after the

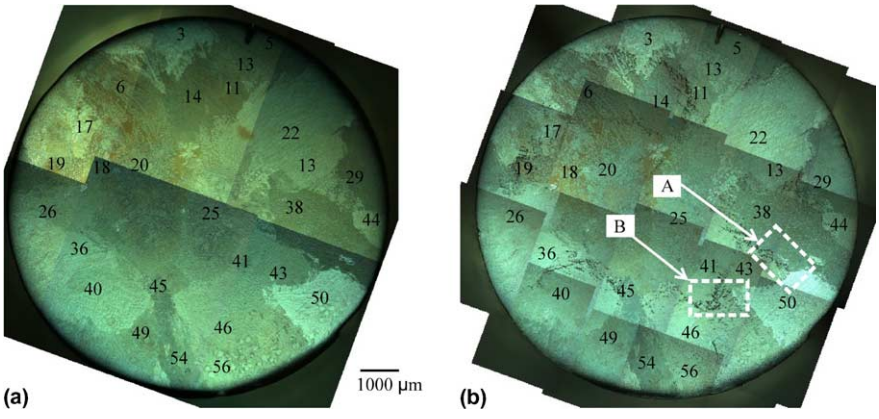

Fig. 2. Optical micrographs (a) before and (b) after thermal cycling within the temperature range 293–353 K for 1000 cycles.