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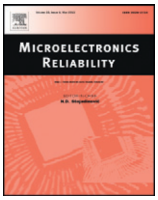

Finite element analysis of thermal and mechanical stresses due to the grain anisotropy of polycrystalline β-Sn

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ABSTRACT

In order to investigate the stress and strain distributions caused by the grain anisotropy of polycrystalline β-Sn, a finite-element (FE) analysis was conducted using a polycrystalline model that considers the effect of grain anisotropy on the elastic and plastic properties. Even in the case of thermal free expansion with a temperature change of 75 °C, plastic strains can be generated locally in polycrystalline β-Sn. This might be due to the high anisotropy of the thermal expansion coefficient and the low yield strength of β-Sn. It was found that both in-phase and out-of-phase thermal stresses can be present in the polycrystalline β-Sn simultaneously. The highest stress and strain appeared in the grains whose orientation is relatively different from those of neighboring grains, near the grain boundaries. This might cause the formation of a grain boundary void in the Pb-free solder. Comparing the strain distribution due to the thermal expansion coefficient anisotropy and the Young's modulus anisotropy, it was determined that the maximum value of the plastic strain due to the thermal expansion coefficient anisotropy is approximately 10% higher than that due to the anisotropy of Young's modulus, and the high strain areas are also different in the two cases. The thermo-mechanical fatigue life of β-Sn might be shorter than that estimated using the isothermal low cycle fatigue life at the same level as the macroscopic strain and could not be estimated by the previous method.

1. Introduction

The use of Pb-free solders has dramatically increased in the electronics industry in recent years to avoid the environmental and health issues related to the toxicity of Pb in Sn-Pb solders. However, the thermal stress generated in these solders can cause thermal expansion and contraction of electronic and mechanical components. In particular, thermo-mechanical fatigue (TMF) failure can occur in the solder joints in electronic devices because of constant temperature cycling. Even though this is a well-known effect, the information available regarding the TMF characteristics of Pb-free solders is not complete. Therefore, it is essential to evaluate the TMF lives of Pb-free solders to ensure the reliability of these electronics. The TMF lives of many kinds of materials can be estimated using an empirical correlation between the TMF life and the isothermal low cycle fatigue (LCF) life [1]. Isothermal LCF lives can be determined in many kinds of materials by the Coffin-Manson model [2,3], as

$$\Delta\varepsilon_p \cdot {N_f}^{\alpha} = C \qquad (1)$$

where $\Delta\varepsilon_p$ is the plastic strain range, N_f is the number of cycles to failure, and α and C are material constants.

There have been several studies on the TMF and LCF characteristics of various Pb-free solders [4–10]. Table 1 lists the Coffin-Manson model results of Pb-free solders reported in previous studies [4–7,9, 10]. Ima [4] conducted temperature cycle tests using an imitation sample of an electronic device with a Sn-3.0Ag-0.5Cu solder joint. Zhu et al. [5] conducted LCF tests under 343 K and 393 K using a shear-lap joint solder consisting of Sn-3.0Ag-0.5Cu. Mustafa et al. [6] performed LCF tests using an Iosipescu shear specimen of Sn-1.0Ag-0.5Cu, and investigated the effects of aging on the cyclic shear stress-strain and the fatigue behavior of Pb-free solders. Kanchanomai et al. [7] conducted LCF tests at 293 K using a tension-compression specimen with a center diameter of 6 mm and a varying composition of Sn-3.5Ag, Sn-3.0Ag-0.5Cu, Sn-3.0Ag-0.5Cu, Sn-3.0Ag-0.5Cu-1Bi, and Sn-3.0Ag-0.5Cu-3Bi. Moreover, they also investigated the effect of frequency on the LCF behavior of the Pb-free solder Sn-3.5Ag [8]. Pang et al. [9] conducted LCF tests using a tension-compression specimen with a center diameter of 3 mm and concentrations of Sn-3.8Ag-0.7Cu and Sn-0.7Cu under 298 K and 398 K. Kariya et al. [10] conducted LCF tests at 298 K using a tension-compression specimen with a center diameter of 10 mm and compositions of Sn-3.5Ag, Sn-3.5Ag-2Bi, Sn-3.5Ag-5Bi, and Sn-3.5Ag-10Bi. As

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Table 1
Coffin-Manson model of Pb-free solders reported in previous studies [4–7,9,10].

	Material	Specimen	Test condition	Coffin-Manson model
Ima (2013) [4]	Sn-3.0Ag-0.5Cu	Imitation sample of electronic device	Thermal cycle test 1. 233– 378 K 2. 263– 378 K 3. 243– 358 K	$\Delta\varepsilon_p \cdot N_f^{0.649} = 0.587$
Zhu et al. (2014) [5]	Sn-3.0Ag-0.5Cu	Shear lap test specimen	Low cycle fatigue at 1. 343 K 2. 393 K	1. $\Delta\varepsilon_p \cdot N_f^{0.8493} = 1.0454$ (343 K) 2. $\Delta\varepsilon_p \cdot N_f^{0.9424} = 1.0160$ (393 K)
Mustafa et al. (2016) [6]	Sn-1.0Ag-0.5Cu	Shear test specimen	Low cycle fatigue	$\Delta\gamma_p \cdot N_f^{0.5413} = 0.2516$
Kanchanomai et al. (2002) [7]	1. Sn-3.5Ag 2. Sn-3Ag0.5Cu 3. Sn-3Ag-0.5Cu-1Bi 4. Sn-3Ag0.5Cu-3Bi	Tension-compression test specimen (minimum diameter: ϕ6 mm)	Low cycle fatigue at 293 K, 0.1 Hz, and $R = -1$	1. $\Delta\varepsilon_p \cdot N_f^{0.93} = 21.9$ 2. $\Delta\varepsilon_p \cdot N_f^{0.73} = 3.7$ 3. $\Delta\varepsilon_p \cdot N_f^{1.14} = 57$ 4. $\Delta\varepsilon_p \cdot N_f^{0.96} = 5.7$
Pang et al. (2004) [9]	Sn-3.8Ag-0.7Cu	Tension-compression test specimen (minimum diameter: ϕ3 mm)	Low cycle fatigue at 1. 298 K and 1 Hz 2. 2. 398 K and 10^{-3} Hz	$\Delta\varepsilon_p \cdot N_f^{0.913} = 26.3$ (298 K, 1 Hz) $\Delta\varepsilon_p \cdot N_f^{0.853} = 9.2$ (398 K, 10^{-3} Hz)
	Sn-0.7Cu			$\Delta\varepsilon_p \cdot N_f^{0.973} = 21.27$ (298 K, 1 Hz) $\Delta\varepsilon_p \cdot N_f^{0.719} = 1.98$ (398 K, 10^{-3} Hz)
Kariya et al. (1998) [10]	1. Sn-3.5Ag 2. Sn-3.5Ag-2Bi 3. Sn-3.5Ag-5Bi 4. Sn-3.5Ag-10Bi	Tension-compression test specimen (minimum diameter: ϕ10 mm)	Low cycle fatigue at 298 K, $\Delta\varepsilon = 0.3\%$– 3%, and strain rate 5×10^{-3}/s	1. $\Delta\varepsilon_p \cdot N_f^{0.50} = 0.90$ 2. $\Delta\varepsilon_p \cdot N_f^{0.55} = 0.47$ 3. $\Delta\varepsilon_p \cdot N_f^{0.60} = 0.22$ 4. $\Delta\varepsilon_p \cdot N_f^{0.54} = 0.06$

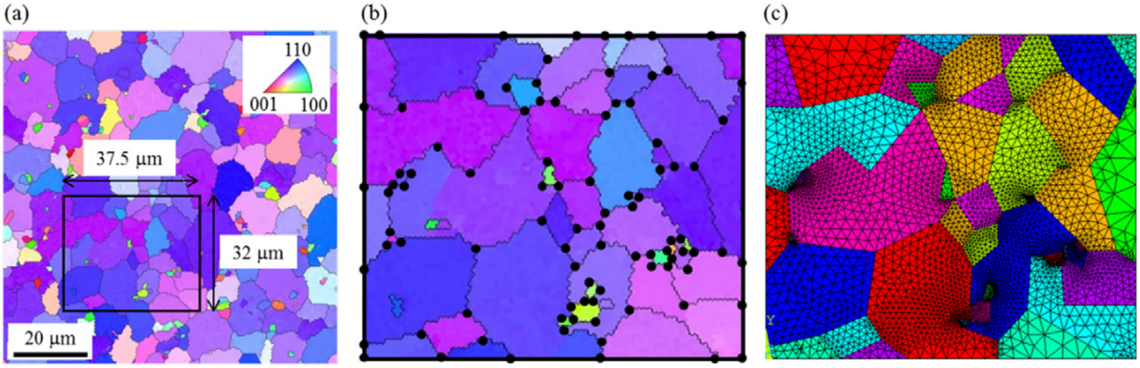

Fig. 1. Modeling procedure: (a) IPF map of tin; (b) modeling area of the IPF map (presented as a black box in (a)); and (c) FE model and mesh.

listed in Table 1, the TMF and LCF characteristics of the Pb-free solders can be affected by the addition of certain elements, temperature, aging, load frequency, and size, making the TMF analysis of these solders rather complicated. Therefore, it is important to clarify the characteristics of the main phase of these solders to investigate the effect of several factors on the TMF characteristics.

In this work, we focused on the characteristics of β-Sn, which is the main phase of Pb-free solders, to evaluate the TMF and LCF lives and to clarify the fracture mechanisms of Pb-free solders. Although β-Sn has a body-centered-tetragonal (BCT) structure, which leads to anisotropy on the elastic and plastic behaviors, there are only few studies focused on the distribution of stress and strain due to the grain anisotropy of polycrystalline β-Sn [11–17].

Thermal stress distribution due to grain anisotropy in a Pb-free solder alloy has been investigated by means of finite element (FE) simulation, using an anisotropic elastic model [11–13] and an anisotropic elastic-viscoplastic model [14]. Mechanical stress distributions due to grain anisotropy in a Pb-free solder alloy were also investigated by FE simulation using an elastic-plastic anisotropic model [15–17]. However, to our knowledge, the difference of the distributions between thermal and mechanical stresses has not been investigated in detail.

In order to investigate these distributions, a FE analysis was conducted during this study, using a polycrystalline model that considers the effects of grain anisotropy on the elastic and plastic properties of the material. On the basis of the analysis results, the characteristics of TMF and LCF lives of β-Sn were discussed.

Table 2
FE-analysis conditions.

	Thermal strain	Mechanical strain	Constraint
Condition A	75 K temperature rise and descent (298 K ≥ 373 K) (298 K ≥ 223 K)	–	No
Condition B	75 K temperature rise and descent (298 K ≥ 373 K) (298 K ≥ 223 K)	–	Yes
Condition C	–	Compressive and tensile strain: 1.65×10^{-3}	–