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Rapid communication

Effect of rare earth Ce on the fatigue life of SnAgCu solder joints in WLCSP device using FEM and experiments

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ABSTRACT

With the addition of 0.03 wt% rare earth Ce, in our previous works, the properties of SnAgCu solder were enhanced obviously. Based on the Garofalo–Arrhenius creep constitutive model, finite element method was used to simulate the stress–strain response during thermal cycle loading, and combined with the fatigue life prediction models, the fatigue life of SnAgCu/SnAgCuCe solder joints was calculated respectively, which can demonstrate the effect of the rare earth Ce on the fatigue life of SnAgCu solder joints. The results indicated that the maximum stress–strain can be found on the top surface of the corner solder joint, and the warpage of the PCB substrate occurred during thermal cycle loading. The trends obtained from modeling results have a good agreement with the experimental data reported in the literature for WLCSP devices. In addition, the stress–strain of SnAgCuCe solder joints is lower than that of SnAgCu solder joints. The thermal fatigue lives of solder joints calculated based on the creep model and creep strain energy density model show that the fatigue life of SnAgCuCe solder joints is higher than the SnAgCu solder joints. The fatigue life of SnAgCuCe solder joints can be enhanced significantly with the addition of Ce, is 30.2% higher than that of SnAgCu solder joints, which can be attributed to the $CeSn_3$ particles formed resisting the motion of dislocation; moreover, the refinement of microstructure and the IMC sizes also contribute to the enhancement of fatigue life, which elucidates that SnAgCuCe solder can be utilized in electronic industry with high reliability replacing the SnAgCu solder.

1. Introduction

Environmental regulations require lead-free solder alloys for interconnections between electronic components and printed wiring board (PCB). The European common market has introduced legislation to forbid lead-containing solder [1], so lead-free solders have become one of the key materials in the electronic industry. Among the series of lead-free alloys, SnAgCu has been proposed as the alternative for the traditional SnPb solder [2] because of its good soldering and wetting behavior on several substrate materials such as Cu, Ag, Au, Ni and respective alloys. However, there are still some drawbacks because SnAgCu solders need to be further investigated, e.g., the lower creep fatigue resistance of solder joints [3], and rapid formation of brittle intermetallic compound (IMC) layers at the solder and substrate interface [4].

With the addition of trace amount rare earth, the properties of lead-free solders can be improved obviously [5]. Until now, few literatures have been reported about the reliability of lead-free solder joints bearing rare earth in service. For the series of new lead-free solder containing rare earth elements, the research all was confined to the academic level, because no applications in real solder joint technology are found. Therefore, the application of lead-free solders bearing rare earth in the electron device should be studied further, and the reliability in service should be analyzed to demonstrate the practicability.

In our previous work, we found that Sn3.8Ag0.7Cu solders containing 0.03 wt% rare earth Ce showed ascendant properties and refined microstructures [6,7]. In this paper, the SnAgCuCe and SnAgCu solders were used to interconnect the WLCSP device and PCB substrate. Moreover, the finite element method was utilized to analyze the stress–strain response of solder joints during thermal cycle loading, combing the fatigue life prediction model to calculate the thermal fatigue life, and the experiments were carried out to explain the effect mechanism, which can demonstrate the effect of rare earth Ce on the fatigue performance of SnAgCu solder joints in a WLCSP device.

2. FEM model and materials properties

Solder joints reliability in electronic devices plays an important role during service. Nonlinear finite element simulation was conducted and the three-dimensional model was constructed for

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chip scale packages in the FE analysis due to the symmetry in geometry. The 1/2 3D finite element model of WLCSP 5 × 6 is shown in Fig. 1. The SOLID186 was selected to model the complex geometry, and the created model contained a total of 8466 elements. The solder joints arrays were refined with acceptable solution accuracy, as shown in Fig. 2. Because of the nonlinear deformation of lead-free solder joints (SnAgCu and SnAgCuCe), the fine elements were carried out in solder joints, and sparse elements for other materials. The symmetry plane was prescribed to have no displacement.

The 3D geometric model consists of a PCB substrate, chip, Cu pads and solder joints. Because the work temperature is so low, which has little affect on the chip, PCB substrate and Cu pads, these materials are assumed to be linear elastic with temperature dependent properties. The parameters of these materials are shown in Table 1.

It is well known that due to the higher homologous temperature ($>0.5T_m$, T_m is the absolute melting temperature.), the solder alloy shows a remarkable creep deformation even at room temperature [8]. And the Garofalo–Arrhenius creep model is often used to describe the creep behavior of lead-free solder joints during thermal cycle loading:

$$\frac{d\gamma}{dt}=C\left(\frac{G}{\theta}\right)\left[\sinh\left(\omega\frac{\tau}{G}\right)\right]^{n}\exp\left(-\frac{Q}{RT}\right)\ldots \qquad (1)$$

where γ is the creep shear strain, t is the time, C is a materials constant, G is the temperature-dependent shear modulus, T is the absolute temperature, ω defines the stress level, τ is the shear stress, n is the stress exponent, Q is the activation energy, and R is the Boltzmann constant.

Because the solder materials obey the von Mises criterion, the creep model can be expressed as follows:

$$\dot{\varepsilon}=C_1[\,\sinh(C_2\sigma)]^{C_3}\exp\left(-\frac{C_4}{T}\right) \qquad (2)$$

where C_1, C_2, C_3 and C_4 are the material parameters, σ is the equivalent stress, T is the absolute temperature, and $\dot{\varepsilon}$ is the equivalent creep strain rate. The four parameters of SnAgCu/SnAgCuCe solders have been determined by creep testing [9], and the four parameters are shown in Table 2.

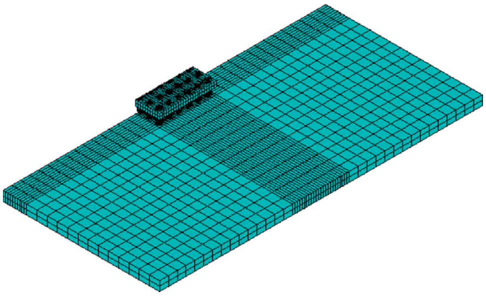

Fig. 1. 1/2 Finite element model of WLCSP 5 × 6.

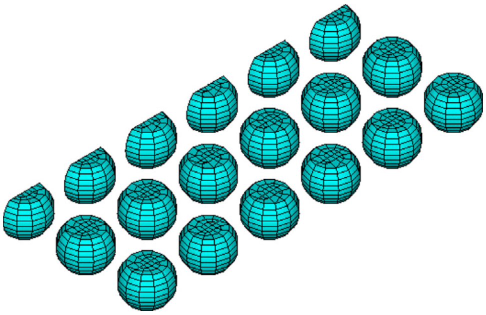

Fig. 2. Solder joints array.

Table 1
Parameters of materials.

Materials	Elastic modulus, E (MPa)	Poisson ratio, μ	CTE, α_l ($10^{-6}\,\mathrm{K}^{-1}$)
Chip	163,000	0.28	2.5
PCB	18,200	0.25	15
Cu pad	117,000	0.23	16.6
SnAgCu	39,000	0.35	25
SnAgCuCe	37,000	0.30	23

Table 2
Creep parameters of the Garofalo–Arrhenius model [9].

Solders	C_1 (1/s)	C_2 (1/MPa)	C_3	C_4 (K)
SnAgCu	325,000	0.05217	5.3	5800
SnAgCuCe	284,000	0.02432	6.1	6400

According to MIL-STD-883 specification [10], cycle temperature loading was selected to be imposed on the WLCSP device. It was performed at temperatures ranging from 218 K to 398 K and the reference temperature is 298 K, dwell time at all peak temperature is 15 min, and the rate of descend and ascend temperature are 12 K/min. The temperature loading profile is shown in Fig. 3; its initial temperature is 298 K, and it is assumed that in the finite element simulation no stress occurs at the temperature. For the thermal cycle loading, it was imperative to set a uniform temperature distribution at all nodes in the WLCSP device.

The SnAgCu and SnAgCuCe solders were prepared from the pure Sn, Sn–Cu alloy, Sn–Ag alloy, and Sn–Ce alloys. All the raw materials for SnAgCu and SnAgCuCe solders were melted in a ceramic crucible, and melted at 550 ± 1 °C for 40 min and the mechanical stirring was needed to homogenize the solder alloy. In order to protect the solder for oxidation during the melting process, KCl + LiCl (1.3:1) was used over the surface of liquid solder. Then the molten alloys were chilled and cast ingots in a mold and solidified by nominally air cooling. Cutting–remelting technology was used to produce WLCSP solder balls. With reflow soldering technology the WLCSP device was soldered on FR-4 substrate with Cu pads.

All samples were mechanically polished with 1 μm diamond paste for microstructural observation. The etching solution contained 93% methanol, 5% nitric acid, and 2% hydrochloric acid. The microstructure of these solders was examined by SEM, OM and TEM.

3. Results and discussion

Fig. 4 shows the displacement of the WLCSP assembly. An obvious uneven warpage can be found in the PCB substrate, which was caused by the constraints from the chip and PCB. Moreover, due to the warpage of the PCB substrate, the stress–strain response may be strong in the WLCSP assembly.

Fig. 5 shows the von Mises stress distribution of the solder joints array. For the solder joints array, the stress distribution is not uniform, and high stress region can be found between the chip and the solder joints. It is found that the largest stress concentrates in the outermost corner joint, namely the most critical solder joint. Moreover, the same solder joint that is located on the diagonal of the WLCSP assembly also shows stress concentration, and this solder joint is then defined as the key solder joint that is the easiest to analyze the solder joints′ reliability. There is no