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ARTICLE

Reliability of SnAgCuFe Solder Joints in WLCSP30 Device

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Abstract: Anand constitutive model of SnAgCuFe solder joints was studied, and 9 parameters were determined based on tensile testing. And the model was incorporated in finite element code for analyzing the stress-strain response of SnAgCuFe solder joints in WLCSP30 device. The results indicate that the maximum stress concentrates on the top surface of corner solder joints, and the stress-strain of SnAgCuFe solder joints is lower than that of SnAgCu solder joints. Based on the fatigue life model, the addition of Fe can enhance the fatigue life of SnAgCu solder joints. Therefore, the SnAgCuFe solders can replace the traditional SnPb to be used in electronic packaging.

Key words: Anand model; solder joints; stress-strain; fatigue life

Semiconductor industries are striving to find viable alternatives to lead-based solder in order to meet world-wide regulatory requirements (human health and environment) on the restrictions on the use of lead (Pb: toxic)[1,2]. Among these lead-free solders, SnAgCu solder has been proposed by lots of researchers[3-5] to replace the traditional SnPb alloys in electronic industry because of its relatively low melting temperature compared to the SnAg binary eutectic alloy, and better solderability and mechanical properties compared with the SnCu binary eutectic solder. However, there are some drawbacks for the SnAgCu solders, e.g., brittle phase in the matrix, and lower thermal fatigue behavior.

In order to improve the properties of SnAgCu solder, an alloying method was used to modify the alloys. The fourth elements can be added into SnAgCu solder. The rare earth Ce was selected by L. Zhang[6], and it was observed that 0.03%Ce can enhance the fatigue life of SnAgCu solder joints. K. S. Kim[7] found that fourth elements (Fe, Ni, Co, Mn, Ti) can refine the microstructures of SnAgCu solders, and all quaternary bulk alloys exhibited similar or slightly larger tensile strengths. X. Y. Liu[8] demonstrated that with the addition of Fe particles, the tensile strength and the hardness of SnAgCu solder joints can be improved significantly. Y. W. Wang[9] proved that minor Fe, Co and Ni can reduce the Cu3Sn thickness of SnAgCu/Cu solder joints, and the strength was also enhanced. The addition of Al nanoparticles into SnAgCu solder joints improved the wettability, mechanical properties, fatigue life of solder joints, refined the microstructures, and inhibited the IMC layer growth[10-12]. For the series of new SnAgCu base lead-free solders, the reliability should be studied before the application in electronic industry.

In the present paper, the reliability of Sn3.8Ag0.7Cu0.8Fe solder was researched based on finite element simulation. The parameters of SnAgCuFe solders were determined based on tensile testing, and combing with the finite element code the stress-strain response was analyzed. The fatigue life was computed to analyze the reliability of solder joints.

1 Determination of Parameters

For the finite element simulation of solder joints in electronic components, the constitutive mode is needed to represent the nonlinear stress-strain response. Until now, there are many types of constitutive relations based on the creep strain, plastics strain, and von Mises stress. Among these constitutive models, Anand model was proposed to describe the inelastic deformation of lead-free solders, the physical mechanisms such as temperature sensitivity, strain hardening, strain rate sensitivity, strain rate and temperature history effects should be taken into account.

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The following functional form for the flow equation of Anand model was selected to exactly accommodate the strain rate dependence on the stress at constant structure[13]:

$$\dot{\varepsilon}_{\mathrm{p}} = A\exp\left(-\frac{Q}{RT}\right)\left[\sinh\left(\xi\frac{\sigma}{s}\right)\right]^{1/m} \tag{1}$$

where $\dot{\varepsilon}_{\mathrm{p}}$ is the inelastic strain rate, A is the pre-exponential factor, Q is the activation energy, R is the gas constant, T is the absolute temperature, ξ is the multiplier of stress, σ is the applied stress, s is a single scalar as an internal variable to represent the averaged isotropic resistance to plastic flow, and m is the strain rate sensitivity of stress.

The evolution equation is represented as

$$\dot{s} = \left[h_0\left|1-\frac{s}{s^*}\right|^{a}\operatorname{sign}\left(1-\frac{s}{s^*}\right)\right]\dot{\varepsilon}_{\mathrm{p}} \tag{2}$$

where $a>1$.

$$s^* = \hat{s}\left[\frac{\dot{\varepsilon}_{\mathrm{p}}}{A}\exp\left(\frac{Q}{RT}\right)\right]^{n} \tag{3}$$

where h_0 is the hardening/softening constant, s^* is the saturation value of S, a is the strain rate sensitivity of hardening/softening, $\hat{s}$ is the coefficient for the saturation deformation resistance, and n is the strain rate sensitivity for the saturation value of deformation resistance.

Based on the tensile testing, the nine parameters of Anand model can be determined. In our previous work[14], the experimental parameter of uniaxial tensile tests, and the standard calculation procedure were described in detail. Therefore, the experimental procedure can be omitted in this paper. The nine parameters determined based on the fitting of experimental data are shown in Table 1. Moreover the parameters[15] of SnPb solders are also shown in Table 1, and the data will used for the comparison analysis of finite element simulation. Fig.1 shows the experimental data and Anand data, and good agreement can be seen between experimental data and predicted data using Anand model.

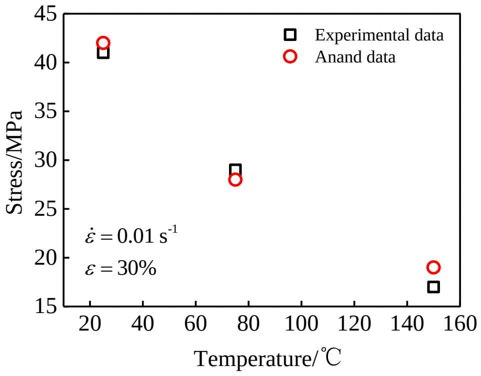

Fig.1 Stress data of solders

2 Finite Element Simulation

A 1/4 symmetry model of the WLCSP 30 device was used to predict the stress-strain response. SOLID186 elements were employed for meshing all the materials except solder joints, and VISCO107 for solder joints. The finite element mode of 1/4 WLCSP device is shown in Fig.2.

Table 1 Nine parameters of solders

Materials parameters	SnAgCuFe	SnAgCu	SnPb
A/s^{-1}	23765	24300	6220
Q/R/K^{-1}	8311	8710	6526
$\hat{S}$/MPa	59.1	65.3	36.86
h_0/MPa	3844.7	3541.2	60599
ξ	5.4	5.8	3.33
m	0.15	0.183	0.27
n	0.0181	0.019	0.022
a	2.5	1.9	1.7811
s_0/MPa	37.3	39.5	3.1522

According to MIL-STD-883 specification[16], thermal cycle loading was selected to be imposed on the WLCSP30 assembly. It was performed at temperatures ranging from 218 K to 398 K, with dwell time at all peak temperature 15 min, the rates of descend and ascend temperature 15 K/min. Ten cycles were used to simulate the stress-strain response of SnAgCu and SnAgCuFe solder joints.

Fig.3 shows the Von Mises stress of solder joints in WLCSP30 device. The critical solder joints (most vulnerable to fatigue cracking) of the WLCSP are determined by plotting the contour of the stress. The critical solder joints are in the corner of the array, the largest stress area is the top-surface of the corner solder joints near the chip, and the area is then defined as the key location that is the easiest to be failed under thermal cycles. In Zhao's experiments[17], the fatigue crack path was found in the solder joints and along a thin layer of solder connecting to the chip, which demonstrated that the crack happened in the largest stress area. The stress distribution is not uniform, and there is no essential difference in the stress distribution between the SnAgCu and SnAgCuFe solder joints, while only the stress value differs.

Fig.4 plots the Von Mises stress of SnAgCu and SnAgCuFe solder joints in WLCSP30 devices. It is evident that the level of stress in the SnAgCuFe solder joints is lower than that of

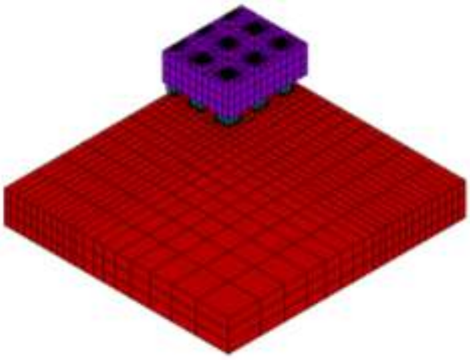

Fig.2 Finite element model of WLCSP30

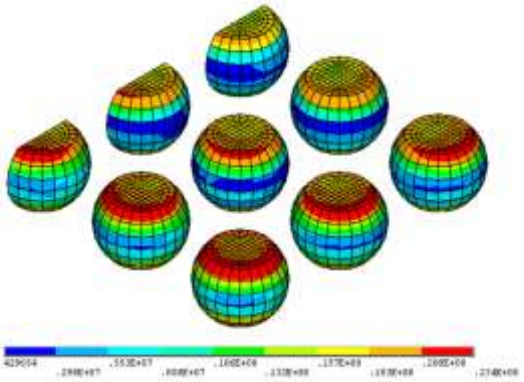

Fig.3 Von Mises stress of solder joints

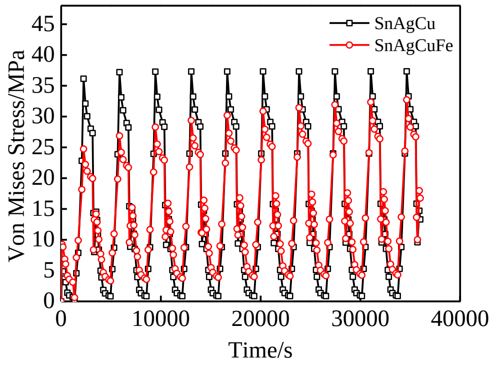

Fig.4 Von Mises stress of SnAgCu/SnAgCuFe

the SnAgCu solder joint during the whole process. And the relaxation phenomena and hysteresis performance during the ramp-up of temperature can be observed in all the solder joints. The similar phenomena can be found in SnAgCu, SnAg and SnPb solder joints of PLCC devices[18].

For the finite element simulation, it is important to study response for multiple cycles until the stress-strain become stable. Fig.5 shows the von Mises strain curves of SnAgCu and SnAgCuFe solder joints in WLCSP devices during ten cycles. It can be found that the von Mises strain is quite stabilized after the second cycle for the two kinds of solder joints, both increase steadily for the ten cycles, and the von Mises strain of SnAgCu solder joints is higher than that of SnAgCuFe solder joints.

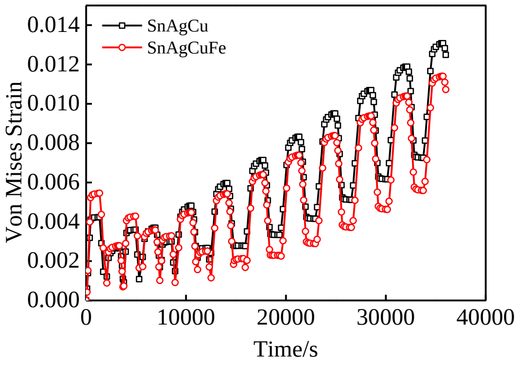

Fig.5 Von Mises strain of SnAgCu/SnAgCuFe

The strain of solder joints can be used to calculate the fatigue life based on the fatigue life model. The von Mises strain-von and Mises stress for the tenth cycle is shown in Fig.6, and the hysteresis loops of X-components of plastic strain and stress at the most critical locations of the solder joints are plotted in Fig.7. SnAgCu solder joints exhibit a larger amount of ratcheting than the SnAgCuFe solder joints. Strain ratcheting refers to the progressive increase in the mean strain in each successive cycle, which further proves the superiority of SnAgCuFe with smaller stress and strain.

3 Fatigue Life Prediction

For the fatigue life calculation of solder joints, the plastic strain range can be used to compute the fatigue life of SnAgCuFe, SnAgCu and SnPb solder joints. The Engelmaier modified fatigue prediction equation can be written as Eq.(4).

$$N_{\mathrm{f}}=\frac{1}{2}\left(\frac{\Delta\gamma}{2\varepsilon_{\mathrm{f}}'}\right)^{1/c} \tag{4}$$

where N_{f} is the fatigue life, $\Delta\gamma$ is the inelastic shear strain range per cycle calculated using finite element simulation, $\varepsilon_{\mathrm{f}}'$ is the fatigue ductility coefficient which is taken as $2\varepsilon_{\mathrm{f}}'=0.514$, c is the fatigue ductility exponent which is

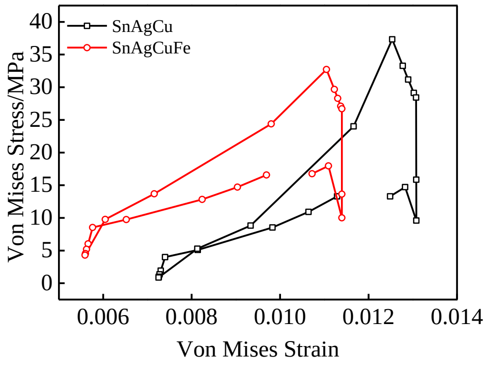

Fig.6 Von Mises stress-von Mises strain curve

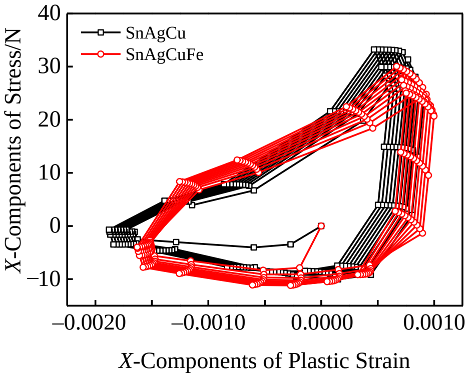

Fig.7 Stress-strain curves of SnAgCu/SnAgCuFe

approximately –0.5708 for SnAgCu base solder joints[19].

The fatigue life of SnAgCuFe solder joints in WLCSP30 device is 2800 cycles, 2510 cycles for SnAgCu solder joints, and 2350 cycles for SnPb solder joints. The results show that the fatigue life of SnAgCuFe is 11.6% higher than that of SnAgCu solder joints, which demonstrate that the Fe addition can improve the reliability of SnAgCu solder joints, and can replace the traditional SnPb solder to be used in electronic industry.

4 Conclusions

1) The nine parameters of Anand constitutive model for SnAgCuFe solders are determined using tensile testing, and the model is used in the finite element simulation.

2) Based on finite element analysis, it is demonstrated that SnAgCuFe solder joints shows higher fatigue life than SnAgCu and SnPb solder joints.

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WLCSP30 器件 SnAgCuFe 焊点可靠性研究

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摘　要：研究 SnAgCuFe 焊点的本构方程，采用拉伸测试拟合本构模型的 9 个参数。基于有限元模拟应用 Anand 模型分析 WLCSP30 器件 SnAgCuFe 焊点的应力-应变响应。结果表明，器件最大应力集中在拐角焊点上表面，SnAgCuFe 焊点应力值明显小于 SnAgCu 焊点。基于疲劳寿命预测模型，证实微量的 Fe 可以显著提高 SnAgCu 焊点疲劳寿命，因此 SnAgCuFe 可以替代传统的 SnPb 应用于电子封装。

关键词：Anand 模型；焊点；应力-应变；疲劳寿命

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