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High temperature rupture of Sn-Pb-0.05RE solder alloy[①]

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Abstract: Specimens of Sn-Pb-0.05RE solder alloy were tested to failure under two different stress states, uniaxial tension using smooth bar specimens and triaxial tension using notched bar specimens. The tests were conducted at a temperature of 125 ℃, far above 0.5 melting temperature of Sn-Pb-0.05RE solder alloy, which leads to a distinctive creep deformation. Rupture times were compared for uniaxial and triaxial stress states with respect to multiaxial stress parameters that are directly related to physical fracture mechanisms. The success of the parameters was judged according to how well the stress parameters correlate with the time to rupture. The results show that the Mises effective stress is the stress factor which dominates the creep rupture of Sn-Pb-0.05RE solder alloy. It further suggests that the cavity nucleation on a grain boundary plays an important role in the creep rupture process of Sn-Pb-0.05RE solder alloy.

Key words: Sn-Pb-0.05RE solder alloy; creep rupture; stress factor; multiaxial stress
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1 INTRODUCTION

Reliability of solder joints under the standard thermal cycling (- 55 ~ 125 ℃) in surface mount technology (SMT) microelectronics packaging is a great concern to packaging design engineers[1~3]. Essentially the failure of solder joints results from the failure of solder alloys, which are used as the interconnection material. Due to their low melting temperature, solder alloys experience the high homologous temperatures (e.g., 0.65 for the Sn-Pb eutectic solder at room temperature), and a time, temperature and stress-dependent deformation is caused in the solder material. It is well known that the most harmful mechanism that leads to the failure of soldered joints is the creep deformation.

Most investigations of creep rupture of Sn-Pb solder alloys have been performed with specimens tested under uniaxial tension, but they do not provide sufficient information to predict cavity growth and creep rupture under multiaxial stress states. Moreover, the soldered joints are subjected to multiaxial stress state under service conditions. Therefore, it is necessary to perform the creep tests of solder alloys under the multiaxial stress conditions in order to better describe and predict the mechanical behavior of soldered joints. The bending and torsion are examples of loading conditions that can cause multiaxial stresses in smooth components. Notches and other geometric irregularities of engineering components can also produce multiaxial stresses when the loading condition is purely uniaxial.

In this work, creep rupture tests of smooth and notched specimens are performed to analyze the rupture law of Sn-Pb-0.05RE solder alloy under the multiaxial stress conditions.

2 THEORETICAL ANALYSIS

Hayburst and Leckie[4~6] and their colleagues[7] studied the effects of multiaxiality on creep rupture and used the principles of damage mechanics[8,9] to describe these effects. They showed that for smooth round bar subjected to uniaxial tension, the rupture lifetime at a given temperature can be expressed as

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$$t_f = M\sigma^{-x} \quad (1)$$

where σ is the uniaxial stress, M and x are parameters that characterize the evolution of damage at the temperature in question. But Eqn. (1) can't correctly predict creep rupture of notched round bars, in order to do that, Eqn. (1) must be generalized to allow other components of the multiaxial stress state to enter the equation. Considering the maximum principal stress σ_1, the Mises effective stress σ_e, and hydrostatic tension stress σ_H all contribute to creep rupture, under the multiaxial stress state Eqn. (1) becomes

$$t_f = M(\alpha\sigma_1 + \beta J_1 + \gamma J_2) \quad (2)$$

where J_1 is the first stress invariant defined by

$$J_1 = \sigma_1 + \sigma_2 + \sigma_3 = 3\sigma_H \quad (3)$$

J_2 is the second stress invariant defined by

$$J_2 = \frac{1}{\sqrt{2}}[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_3 - \sigma_2)^2]^{1/2} = \sigma_e \quad (4)$$

The coefficients of α, β and γ describe the relative contributions of the different multiaxial stress components to the rupture life. In order to make Eqn. (2) to be consistent with Eqn. (1), for the case of uniaxial tension the coefficients must be chosen so that $\alpha + \beta + \gamma = 1$. Then for the case of the uniaxial tension, Eqn. (2) is reduced to Eqn. (1).

Hayburst and Leckie[6] reviewed the multiaxial creep rupture data for several metals and found that the maximum principal stress, σ_1, the Mises effective stress, σ_e, are much more important than the hydrostatic stress, σ_H, in determining creep rupture. Thus let $\beta = 0$ in Eqn. (3) as an approximation and rewrite the equation as

$$t_f = M[\alpha\sigma_1 + (1 - \alpha)\sigma_e]^{-x} \quad (5)$$

Considering the physical basis of Eqn. (5) from the point of view of metal physics, it is well known that the diffusive growth of intergranular cavities is driven by the tensile stresses acting on the grain boundaries. It is reasonable to assume that this component of the stress plays a central role in creep rupture. In addition, the nucleation of cavities is driven by shear stresses. This suggests that the effective stress should be included in Eqn. (5).

3 EXPERIMENTAL

3.1 Experimental material

The material used in this investigation was Sn60Pb40 + 0.05% RE solder alloy, which was made by adding the master alloy Sn-RE and Pb-RE into SnPb solder alloy. An SEM micrograph of etched material prior to creep testing is shown in Fig. 1.

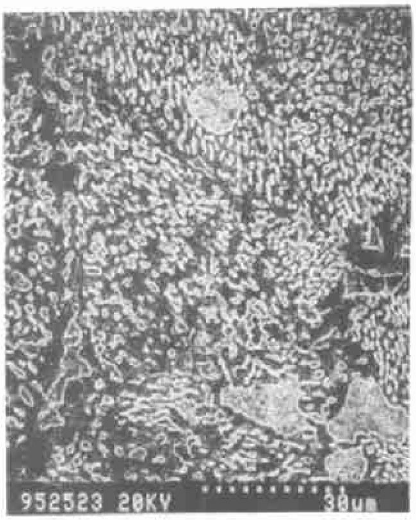

Fig. 1 Typical solder microstructure of a untested specimen

3.2 Design of notched bars

The design of notched bars should follow the below basic principles:

(1) the stress gradients in the notch region are acceptably small;

(2) the complex states of stress can be generated;

(3) the size of the volume over which the stress and strain rate remain approximately uniform is sufficiently large to permit metallographic examination.

According to the principles above, the design of notch was the same as the Hayburst circular notch bars[10], the specimen geometry is shown in Fig. 2. The finite element calculations from Ref. [7] give out the relation of the maximum principal stress and the Mises effective

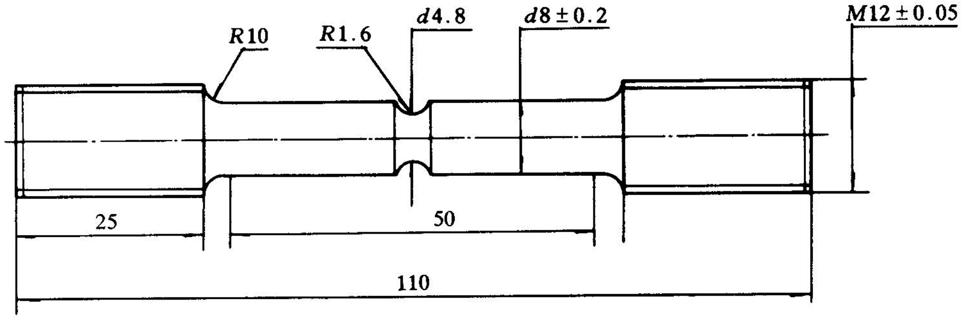

Fig.2 Notched specimen used for multiaxial creep test (unit: mm)

stress as follows:

$$\sigma_1/\sigma_e = 1.49 \qquad (6)$$

3.3 Experimental procedure

All creep tests were performed in MTS 880 testing systems. The temperature variation was less than 1 ℃ and the load precision was within 0.2%. The test conditions and results are shown in Table 1.

4 RESULTS AND DISCUSSION

Fig.3 shows that the multiaxial creep rupture data of notched specimens and creep rupture data of unnotched specimens. In this figure, two different stress parameters, the Mises effective stress and the maximum principal stress are plotted against the logarithm of the rupture time. In Fig.3(a) the data for uniaxial tension are distinguished from those for the notched bar experiments by different symbols. Evidently, the maximum principal stress doesn't correlate well with the time to rupture. By contrast, the Mises effective stress brings all of the creep rupture data into a single curve. Based on Eqn.(1) and Eqn.(5) this showed that the Mises effective stress was the stress factor which dominates the creep rupture of Sn-Pb-0.05RE alloy.

From Table 1 it can be seen that the rupture time of notched specimens is ten times longer than that of the unnotched specimens for the same load, the reason may be explained as that because the maximum Mises effective stress carried by notched specimen is smaller than that of the unnotched specimen.

5 CONCLUSION

Creep rupture data analysis shows that the Mises effective stress is the stress factor which dominates creep rupture of Sn-Pb-0.05RE solder alloys, and it can be used to describe creep fracture of Sn-Pb-0.05RE solder alloys under multiaxial stress conditions. It also indicates that the creep cavity nucleation plays an important role in the creep rupture process of Sn-Pb-0.05RE solder alloys. Creep tests showed that the rupture time of notched specimens is ten times longer

Table 1 Creep test conditions and results of Sn-Pb-0.05RE

Specimen No.	Specimen shape	Load /N	Initial stress /MPa	Maximum principal stress /MPa	Mises effective stress /MPa	Average rupture time/h
1	Unnotched	550	68.6	68.6	68.6	0.237
2	Unnotched	470	58.8	58.8	58.8	0.335
3	Unnotched	390	49.0	49.0	49.0	0.420
4	Unnotched	314	39.2	39.2	39.2	0.651
5	Notched	225	78.0	78.0	52.3	2.095
6	Notched	200	69.3	69.3	46.6	2.403
7	Notched	150	52.0	52.0	34.9	8.384

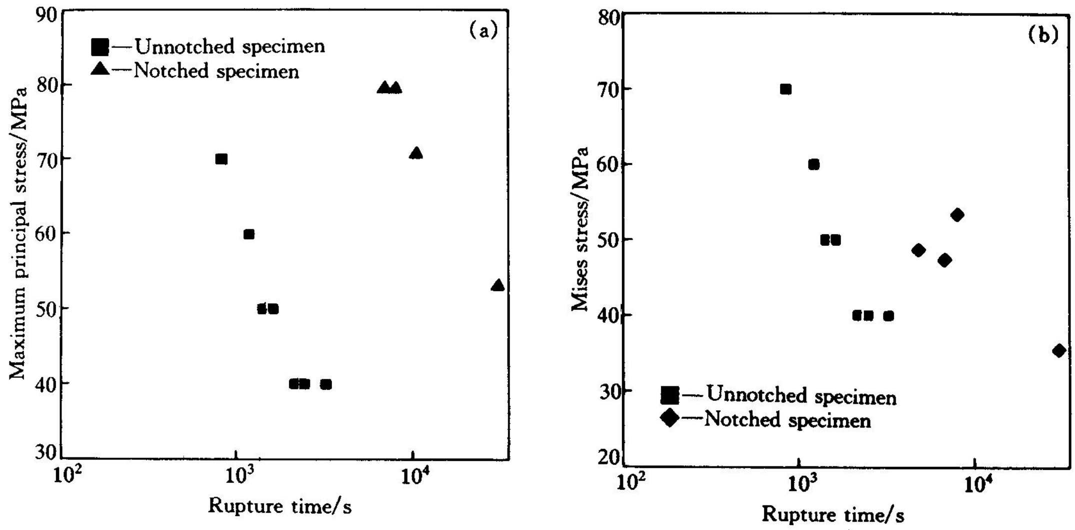

Fig.3 Creep rupture data for Sn-Pb-0.05RE alloy plotted as maximum principal stress(a) and Mises effective stress (b) vs logarithm of rupture time

than that of unnotched specimens for the same load. It is because the maximum Mises effective stress carried by notched specimens is smaller than that of smooth specimen.

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