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Finite element simulation for mechanical response of surface mounted solder joints under different temperature cycling ①

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[Abstract] Nonlinear finite element simulation for mechanical response of surface mounted solder joint under different temperature cycling was carried out. Seven sets of parameters were used in order to evaluate the influence of temperature cycling profile parameters. The results show that temperature cycling history has significant effect on the stress response of the solder joint. Based on the concept of relative damage stress proposed by the authors, it is found that enough high temperature holding time is necessary for designing the temperature cycling profile in accelerated thermal fatigue test.

[Key words] finite element simulation; surface mounted solder joint; thermal cycling; mechanical response
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1 INTRODUCTION

Reliability of solder joints is critical to electronic assembly since they provide both mechanical and electrical connections, especially the thermal fatigue life of solder joints under environmental temperature cycling condition. Accelerated temperature cycling tests are commonly used for the evaluation of the reliability. Unfortunately, it is very difficult to get on-line stress information during temperature cycling test because of the minuteness of the assembly. Therefore, finite element simulation is widely used to analyze the mechanical response of solder joints[1].

In this study, the mechanical response of surface mounted solder joints under different temperature cycling loadings is analyzed and some suggestions are provided for the designing of accelerated thermal fatigue tests.

2 FINITE ELEMENT MODEL

The structure of the surface mounted solder joint used for accelerated thermal fatigue tests is shown in Fig. 1[2]. Ceramic substrate (Ni plated) was soldered with FR-4 board (Cu pad on it) by Sn60-Pb40 solder alloy and the dimension of the solder joint was 1 mm × 2 mm × 0.2 mm. The local enlargement of the solder joint in the corresponding two-dimensional finite element model of cross section at $Z = 0$ is shown in Fig. 2. The model is made of four-node plane stress elements with a total of 364 units and 418 nodes.

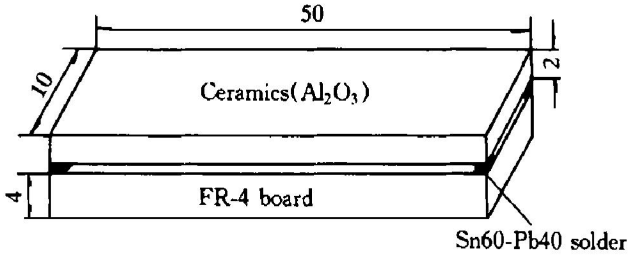

Fig. 1 Schematic diagram of surface mounted assembly

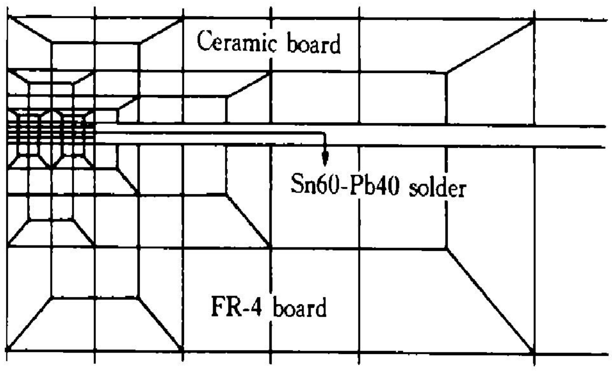

Fig. 2 Local enlargement of FEM mesh of solder joint

As to the constitutive relationship of the materials, ceramic and resin board are assumed to be linearly elastic according to the traditional treating method[1]. The solder alloy is considered viscoplastic body that both the creep and the plastic deformation

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are taken into account. Its stress—strain relationship is given by

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}^{e}_{ij} + \dot{\varepsilon}^{p}_{ij} + \dot{\varepsilon}^{c}_{ij} \quad (1)$$

where the total strain rate tensor $\dot{\varepsilon}_{ij}$ is the sum of the elastic strain rate tensor $\dot{\varepsilon}^{e}_{ij}$, the plastic strain rate tensor $\dot{\varepsilon}^{p}_{ij}$ and the creep strain rate tensor $\dot{\varepsilon}^{c}_{ij}$.

The definition of the elastic and plastic strain rate is the same as that usually used in nonlinear FEM calculation[2, 3]. The creep strain rate is defined as[4~6]

$$\dot{\varepsilon}^{c}_{ij} = B_1 D\left(\frac{\sigma_e}{E}\right)^3 + B_2 D\left(\frac{\sigma_e}{E}\right)^7 \quad (2)$$

where E is elastic module; $B_1 = 1.7 \times 10^{12}$; $B_2 = 8.9 \times 10^{24}$; $D = \exp(-5413/T)$; σ_e is Mises equivalent stress, $\sigma_e = \sqrt{3S_{ij}S_{ij}/2}$; the deviatoric stress tensor $S_{ij} = \sigma_{ij} - \delta_{ij}\sigma_{kk}/3$, σ_{ij} is the stress tensor and δ_{ij} is the Kroneker delta. The materials parameters used in FEM calculation are obtained from Ref. [3] and listed in Table 1.

Seven temperature cycling profiles were applied for analysis. The combined effects of the parameters, such as holding time, ramping rate and cycling temperature range on the mechanical response of solder joints were studied. Fig. 3 shows a typical temperature cycling profile while the detailed conditions of all are specified in Table 2.

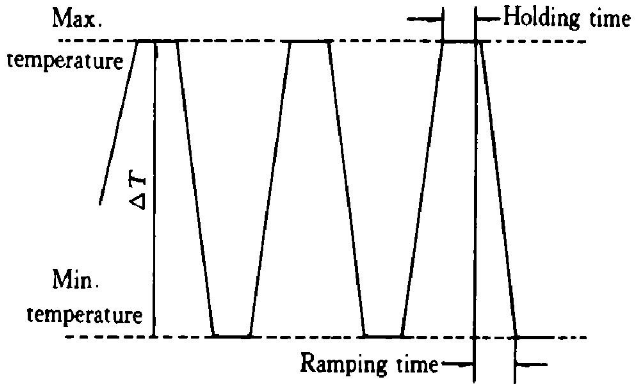

Fig. 3 Schematic diagram of temperature cycling profile and its parameters

Commercial nonlinear FEM program MARC 7.0© with pre- and post- processing program MENTAT 3.1© was used for numerical simulation. Eqn. (2) was combined with MARC main program by using self-defined subroutine CRPLAW.

Table 1 Materials parameters used in FEM calculation

Material	Temperature / K	Elastic modulus / MPa	Poisson ratio	Thermal expansion coefficient / (10^{-6} K^{-1})	Yield stress / MPa
Ceramics (Al_2O_3)		131000	0.3		
	293			5.4	
	316			6.6	
	349			7.4	
	411			8.5	
	473			9.2	
FR-4		22000	0.28	18.0	
Sn60Pb40 solder alloy	218	47966	0.3516	24.1	43.20
	238	46892	0.3540	24.6	37.51
	258	45779	0.3565	25.0	32.05
	278	44377	0.3600	25.2	29.86
	295	43251	0.3628	25.4	29.10
	323	41334	0.3650	26.1	22.96
	348	39445	0.3700	26.7	17.40
	373	36854	0.3774	27.3	12.31
	398	34568	0.3839	27.9	9.35

Table 2 Parameters of various temperature cycling profiles

Cycling profile	Max. temperature / K	Min. temperature / K	ΔT / K	Holding time / min	Ramping time / min	Ramping rate / (K·min^{-1})
1	398	218	180	15.0	15.0	12.0
2	398	218	180	7.5	7.5	24.0
3	398	218	180	5.0	5.0	36.0
4	398	218	180	3.0	3.0	60.0
5	373	223	150	15.0	15.0	10.0
6	373	253	120	15.0	15.0	8.0
7	373	273	100	15.0	15.0	6.7

3 RESULTS AND DISCUSSION

The Mises equivalent stress was commonly used for the analysis of mechanical response of the solder joints and the main application is to predict the possible crack initiation site or evaluate the reliability of different shapes of solder joints according to the maximum stress distribution[7,8]. Because interface void damage is the main failure mechanism for solder joints under thermal loading[9~11], it is very important to take into account of the stress triaxiality rather than the equivalent stress[12,13]. In this work, both the Mises equivalent stress and the stress triaxiality were considered for the analysis of the mechanical response of the surface mounted solder joint under temperature cycling.

3.1 Influence of ramping rate and holding time

Fig. 4 shows the effect of ramping rate and holding time on the response of the Mises equivalent stress and the stress triaxiality. It can be seen from Fig. 4 (a) that both ramping rate and holding time have little effect on the level of equivalent stress. The fundamental feature of the response is that maximum level of the equivalent stress occurs during the low temperature stage and minimum level during the high temperature stage.

On the other hand, as shown in Fig. 4(b), high level of stress triaxiality takes place during holding time, especially the high temperature holding time, and the value increases with increasing ramping rate.

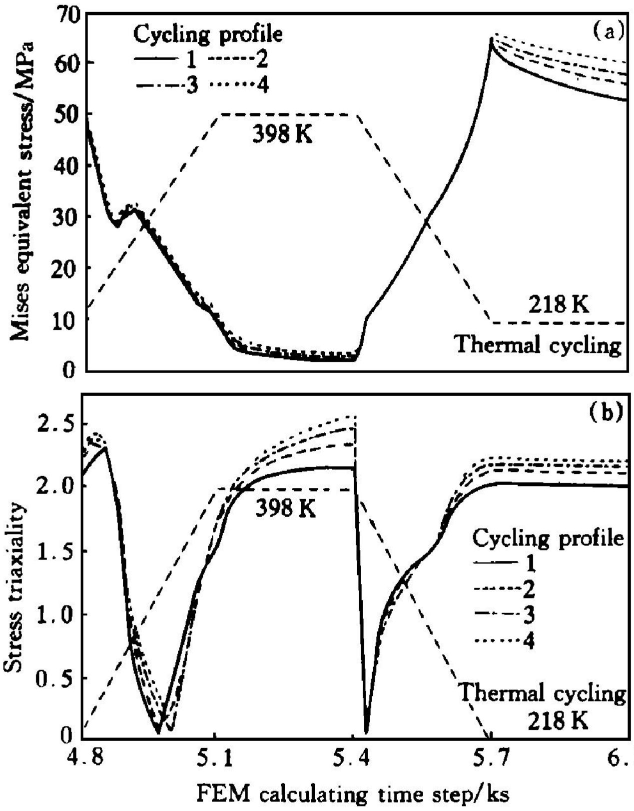

Fig. 4 Influence of ramping rate and holding time on stress response of solder joint under different cycling profiles
(a) —Mises equivalent stress; (b) —Stress triaxiality

3.2 Influence of temperature range

Fig. 5 shows the effect of temperature range on the response of the Mises equivalent stress and the stress triaxiality. In Fig. 5(a), both the maximum equivalent stress and its cycling range increase with increasing temperature range. On the other hand, although there is large differences of temperature range among the four kinds of profiles, the level of stress triaxiality response is almost the same, especially at the high temperature stage.

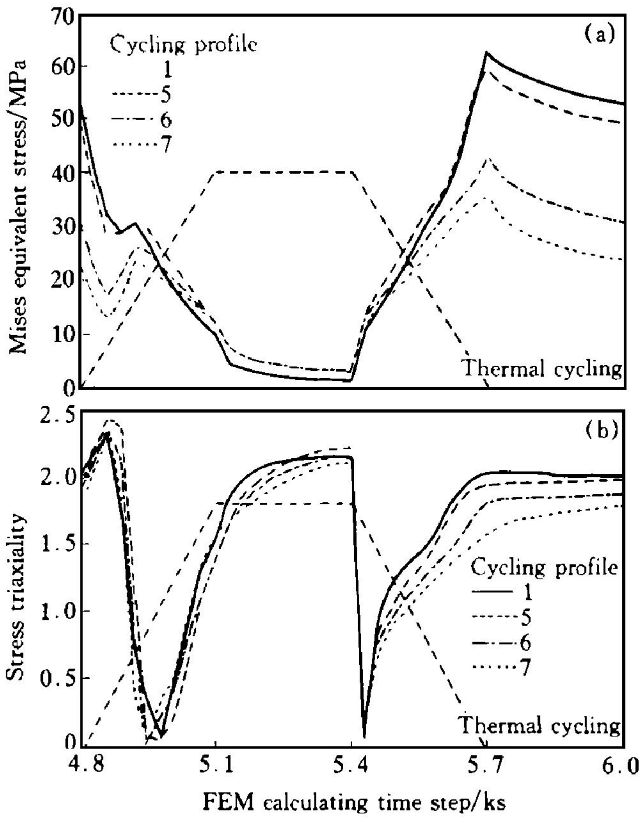

Fig. 5 Influence of temperature range on stress response of solder joint
(a) —Mises equivalent stress; (b) —Stress triaxiality

3.3 Discussion

From the view of damage mechanics, the Mises equivalent stress governs the plasticity, the stress triaxiality governs the void damage and both are important for the analysis of the failure process of solder joints. From Fig. 4 and Fig. 5, we can see that the response of the Mises equivalent stress and stress triaxiality under different temperature cycling profiles are quite different. The maximum level of Mises equivalent stress occurs at low temperature stage, while the maximum level of stress triaxiality occurs at high temperature stage. Therefore, in order to evaluate the stress response of solder joint under different temperature cycling, the authors propose a new mechanical concept, relative damage stress, σ^*, which is defined as

$$\sigma^* = \sigma_e R_\nu^{1/2} / \sigma_y(T) \tag{5}$$

$$R_\nu = \frac{2}{3}(1+\nu) + 3(1-2\nu)\left(\frac{\sigma_H}{\sigma_e}\right)^2 \tag{6}$$

where σ_y is the yield stress which is the function of temperature, σ_H is the hydrostatic stress, R_ν is a function of the stress triaxiality and the Poisson ratio ν. The new mechanical concept reflects the failure mechanism of solder joint and is suitable for direct comparison of the effect of different temperature stage during the whole cycling[13, 14].

Fig. 6 shows the comparison of the level of relative damage stress between cycle 1 and 6. The most important characteristics of the curves is that the maximum level of relative damage stress occurs at the high temperature time. That is to say, with the combination of the effect of the Mises equivalent stress, the stress triaxiality and the temperature relativity of the materials mechanical property, the high temperature holding time is the most important parameter for failure during the whole temperature cycling. As a result, enough high temperature holding time is necessary.

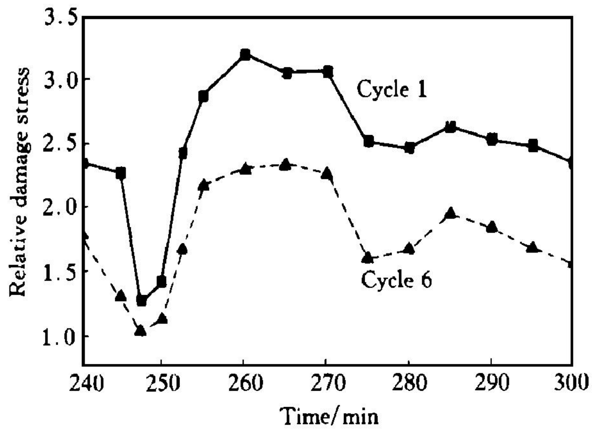

Fig. 6 Relative damage stress of solder joint under different cycling profiles

4 CONCLUSIONS

1) A new mechanical concept, relative damage stress, is proposed to evaluate the stress response of solder joint under different temperature cycling.

2) The calculated results indicate that enough high temperature holding time is necessary during the whole temperature cycling.

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