Prediction of Thermal Fatigue Life of Lead-Free BGA Solder Joints by Finite Element Analysis

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This study was focused on the numerical prediction of the thermal fatigue life of a μ BGA (Micro Ball Grid Array) solder joint. Numerical method was performed to predict three-dimensional finite element analysis with various solder alloys such as Sn-37 mass%Pb, Sn-3.5 mass%Ag, Sn-3.5 mass%Ag-0.7 mass%Cu and Sn-3.5 mass%Ag-3 mass%In-0.5 mass%Bi during a given thermal cycling. Strain values, which were obtained by the result of mechanical fatigue tests for solder alloys, were used to predict the solder joint fatigue life using the Coffin-Manson equation. The numerical results showed that Sn-3.5 mass%Ag with the 50 degree ball shape geometry had the longest thermal fatigue life in low cycle fatigue. Also a practical correlation for the prediction of the thermal fatigue life was suggested by using the dimensionless variable γ .

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1. Introduction

Rapid developments in the mobile communication equipments and the modern electronic devices require high performance, miniaturization, and lightweight. And the packaging technology for their electronic devices has been developed from the QFP (Quad Flat Package) and BGA (Ball Grid Array) toward the CSP (Chip Scale Package)¹⁻³ and Flip Chip.⁴ Technical developments in this area are very important to achieve improved designs.

μ BGA (Micro Ball Grid Array), a kind of CSP, used in small electronic equipments such as mobile phones have a ball size of 0.3 ~ 0.35 mm and a fine pitch of 0.5 ~ 0.75 mm. As compared with the common BGAs, μ BGA has more complex structure and higher chip size ratio in package. Therefore a proper estimation method for the thermal fatigue life of the μ BGA is required for the micro solder joint design. Since the most widely used Sn-Pb solder alloys are restricted to be used for the electronic equipments due to environmental problems, study on the Pb-free solders is an important research topic.

In this paper, studies on the life estimation of the μ BGA solder joint with Pb-free solders as well as Sn-37Pb were performed. To study the effect of solder shape on the life, we analyzed three different shapes for four different solder alloys using the FEA (Finite Element Analysis). Stress and strain results obtained from FEA were used to predict the thermal fatigue life through the Coffin-Manson fatigue life estimation equation and Kariya *et al*'s data.^{5,6} Finally, We are suggesting a new equation for thermal fatigue life using the dimensionless variable γ which is a function of ΔT and T_M , etc.

2. Numerical Simulation by FEA

To assess a long term reliability of the μ BGA solder joint, the most important criterion is the failure by thermal fatigue. This is observed as the result of the thermal expansion of each component caused by the heating up and cooling down of the

Fig. 1 Schematic diagram of μ BGA and solder ball.

chip or by the thermal change of the circumstance. As the result, a thermal stress is concentrated on the micro-joining interface continuously and the solder joint will cause the thermal fatigue fracture at last. At that time, the difference of total CTE (Coefficient of Thermal Expansion) for PCB and package should be considered regarding thermal displacement caused by the thermal change.

Usually the thermal fatigue failure occurs in the upper part of the solder joint as shown in Fig. 1. Because the solder joint has low yield stress and results easily in an unrecoverable plastic deformation, its material characteristics is independent of the time.

The Coffin-Manson equation⁷⁾ and the modified Coffin-Manson equations^{8,9)} are used frequently in order to observe the relationship between equivalent plastic strain and fatigue life. It is given by

$$\Delta \epsilon_p^* N_f^\alpha = C. \quad (1)$$

For the thermal stress analysis of the solder joint, the FEA by ANSYS Version 5.51 was used. And the solder joint between $6 \times 8 \mu$ BGA and PCB was considered. Since the module was assumed to be symmetric, a quarter of the whole part was selected for the modeling. Considering the influences in stress and life, the model was simplified with 6 different mate-

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Fig. 2 Finite element model of μ BGA (a) whole system, (b) solder joint.

Fig. 3 Correlation of yielding stress with temperature.^{10,11)}

materials which were Si chip, Encapsulant, Cu pad, Polyimide film, Nubbin (Low modulus elastomer material) and FR-4 PCB. Figure 1 shows the schematic diagram of μ BGA and Fig. 2 shows the μ BGA after modeling.

From thermal fatigue experiments we frequently observe a solder joint as shown in the Fig. 2(b) where the fatigue failure is caused by the stress concentration. For FEA modeling, 8 node thermal, structural and viscosity elements were used. All materials except solder alloys were assumed to be isotropic, linear elastic and bi-linear kinematics hardening at yielding stress as shown in Fig. 3.^{10,11)} The relationship between the yielding stress and temperature was assumed to be inverse-linear.

Table 1^{6,11)} represents the fatigue constant of different solder alloys. Displacement in the axial direction at a quarter cutting surface was constrained by the boundary condition.

Table 1 Fatigue constant of four different solder alloys.^{6,11)}

	Sn-37Pb	Sn-3.5Ag	Sn-3.5Ag-0.7Cu	Sn-3.5Ag-3In-0.5Bi
C	0.24	0.9	0.46	0.60
α	0.49	0.5	0.43	0.51

Fig. 4 Temperature profile of thermal cycling test.^{12,13)}

For load conditions, thermal cycles like Fig. 4^{12,13)} were set to have a uniform temperature distribution at all nodes by time for simplicity. Reference temperature for determining the thermal expansion was set to 293 K. And three whole cycles in Fig. 4 were applied in order to get a stable strain hysteresis loop due to the non-linearity of the solder and to minimize the transient ratcheting and shakedown effects.

3. Results and Discussions

Computed average elastic-plastic strain is listed in Table 2. Results showed that the plastic strain was increased in the order as Sn-37Pb < Sn-3.5Ag-3In-0.5Bi < Sn-3.5Ag-0.7Cu < Sn-3.5Ag at the lower temperature range, but at the higher temperature range, the tendency changed to be Sn-37Pb < Sn-3.5Ag-0.7Cu < Sn-3.5Ag-3In-0.5Bi < Sn-3.5Ag. Elastic deformation was relatively small as compared to the plastic deformation except for the temperature range of 233–373 K. This means it is rational to consider only the plastic deformation for estimation of the thermal fatigue life. The inelastic strain, which depends on the frequency, can be classified into plastic and creep strain; Since the results^{6,8,14)} of thermal fatigue life are mainly dependent on the plastic and creep strain, creep strain need be applied especially when the strain rate is under 0.025 Hz. But, when the strain rate is over 0.25 Hz, the plastic strain need be taken into account for the solder joint. Namely, in case that the total strain rate is larger than the maximum creep strain, the plastic strain plays the major role in solder joint deformation. Therefore, in this study, it was assumed that the inelastic strain occurred in the solder joint was only due to the plastic strain.

Plastic strains for different temperatures and materials were used to estimate the thermal fatigue life, to see the effect of temperature and solder alloys on the fatigue. In this case the elastic strain was ignored to see only the effect of low cycle fatigue due to the plastic strain. Logarithm representation of the result is shown in Fig. 5.

From Fig. 5, it is observed that the thermal fatigue life is

Table 2 Elastic-plastic strain of solder joint.

	$T_{\text{cycle}}(K)$		Sn-37Pb	Sn-3.5Ag	Sn-3.5Ag-0.7Cu	Sn-3.5Ag-3In-0.5Bi
$\Delta\epsilon_{el}$	293–373		0.000592	0.000267	0.000347	0.000303
	253	30°	0.000799	0.000248	0.000427	0.000317
	~	50°	0.000599	0.000209	0.000321	0.000257
	373	70°	0.000718	0.000332	0.000372	0.000383
	233–393		0.000915	0.000381	0.000489	0.000483
$\Delta\epsilon_{pl}$	293–373		0.001466	0.003626	0.003713	0.000848
	253	30°	0.003957	0.007859	0.008242	0.004778
	~	50°	0.003030	0.004945	0.004996	0.002363
	373	70°	0.007546	0.008768	0.008377	0.005347
	233–393		0.006745	0.015806	0.014786	0.014668

Fig. 5 Log-log graph of ΔT vs N_f . Fig. 6 Log-log graph of γ vs N_f .

almost linear for four different solder alloys and their temperature. Thermal fatigue life of four different solder alloys show an increasing order as Sn-3.5Ag-3In-0.5Bi > Sn-3.5Ag-0.7Cu > Sn-3.5Ag > Sn-37Pb at low temperature range and Sn-3.5Ag > Sn-3.5Ag-0.7Cu > Sn-37Pb > Sn-3.5Ag-3In-0.5Bi at high temperature range. As the amplitude of temperature was increased Sn-3.5Ag showed the longest fatigue life while Sn-Ag-In-Bi showed the shortest life. This can be interpreted that the properties^{1,2,15)} of In and Bi, which has high stiffness at low temperature between 383–413 K but has low stiffness at higher temperatures, results in this phenomenon.

Figure 5 shows the relationship between temperature and number of cycles to failure in solder joint. It is possible to observe linearity of thermal fatigue life in solder joint. However, due to the temperature change and the average temperature of thermal cycling on the thermal fatigue life, temperature change and average temperature cannot be simply ignored. So another dimensionless variable γ defined in eq. (2) was considered to account for the effects of melting point, the average temperature and standard ambient temperature.

$$\gamma = (\Delta T^* T_{\text{mean}}) / (1/2^* T_M^* T_0) \quad (2)$$

where

$\Delta T(K)$: Temperature range,

$T_{\text{mean}}(K)$: Average temperature,

$T_M(K)$: Melting point,

$T_0(K)$: Standard ambient temperature

Figure 6 shows relationship between number of cycles to failure life expressed in $\log N_f$ and dimensionless variable $\log \gamma$.

Table 3 Calculated fatigue constant of four different solder alloys.

	Sn-37Pb	Sn-3.5Ag	Sn-3.5Ag-0.7Cu	Sn-3.5Ag-3In-0.5Bi
$\log A$	2.492	2.774	2.565	1.716
β	-4.967	-4.660	-5.561	-8.887

The tendency of thermal fatigue life of solder joint for different operational conditions and melting points can be understood by Fig. 6. The following eqs. (3) and (4) and Table 3 can be derived from the data shown in Fig. 6.

$$N_f = 10^{\log A + \beta \log \gamma} \quad (3)$$

$$N_f = A^* (\gamma)^\beta \quad (4)$$

where

N_f : number of cycles to failure (thermal fatigue life).

A : calculated fatigue material constant,

β : calculated fatigue material exponent

Thermal fatigue life obtained for different temperatures and dimensionless variable γ are presented in Table 4. Figure 7 shows number of cycles to failure data obtained by using γ and FEA. As shown in the Fig. 7, the result obtained from γ is well matched with FEA result.

The eq. (2) can be used to understand the physical meaning of γ , which used for the thermal fatigue life estimation. In case that all variables are set to be constant, the γ is increasing as $1/2T_M$ decreases or T_{mean} increases. On the other hand, we may observe that the γ variable increases as the ΔT increases with the others fixed.

At the same time, when the solder temperature is increased, the plastic deformation rate becomes larger. And also the re-

Table 4 γ and number of cycles to failure of four different solder alloys.

$T(K)$	Sn-37Pb		Sn-3.5Ag		Sn-3.5Ag-0.7Cu		Sn-3.5Ag-3In-0.5Bi	
	γ	N_f	γ	N_f	γ	N_f	γ	N_f
293-373	0.399	29782	0.368	62682	0.371	91140	0.371	349119
273-373	0.562	5433	0.519	12627	0.523	13502	0.523	16507
253-393	0.750	1295	0.692	3304	0.698	2712	0.698	1269

Fig. 7 Thermal fatigue life with γ vs FEA.

gion affected by the high temperature fracture behavior becomes wider during the total temperature cycling.

On the other hand, as the ΔT is decreased, γ is decreased also. Though there are some differences according to the material and its mean temperature, the ratio of the elastic deformation to the total deformation generated on the concerned part becomes larger. Therefore, the influence of elastic deformation can not be ignored in estimating the fatigue life.

However, fatigue fracture, which is generated by elastic or elastic-plastic deformation for most materials, lies in the domain of high cycle fatigue. And the thermal fatigue life by high cycle fatigue becomes larger as compared to that by low cycle fatigue, which is the main topic in this paper. In other words the γ can be considered as an important parameter in determining how severe the environment of solder application is.

Applying this parameter for the materials considered in this study and comparing with the computed results, it is found that the solder alloys with larger γ such as the Sn-37Pb have longer fatigue life as compared to the Sn-Ag solder alloys that have shorter γ at the same temperature level. And also within the temperature range between 293 and 373 K where γ is very small, the effect of the elastic deformation can't be ignored. These results coincide with the conclusion we have already made in the earlier discussion.

However eq. (3) can't be used for estimating the thermal fatigue life when the temperature is low enough where the elastic strain cannot be ignored. In this case, the combined effects of low and high cycle fatigue should be used for the life estimation.

By examining the relation between the thermal fatigue life and the shape of solder joint using the data in Table 2, it is found that the longest life was obtained when the solder ball was formed 50 degree angle with a line perpendicular to the package base. When the upper part of solder joint, where stress concentration usually occurs, became more concave than 50 degree angle, the stress was well distributed. Also

effect of the solder shape on life was more evident for solders of light material. Since the effect of the solder shape on the fatigue life is very significant, a more systematic research on practical life for different solder shape is required.

The results obtained by FEA can be used for the selection of optimum solder type and shape, which assures an acceptable thermal fatigue life at various operation conditions. And there are also used for estimating approximate life of μ BGA. But in this research, effects of micro crack at bonded interface due to the metallurgical structure change caused during the process and operation conditions were not considered. Effect of the creep deformation which was not well understood for some materials was also ignored. Therefore, the result obtained from this research may directly apply to the solder alloys at a certain temperature range where elastic strain cannot be ignored. To find more reliable thermal fatigue life estimation, extensive experiments at various conditions should be followed to interpret the effects of shape and material on life.

4. Conclusions

The thermal fatigue life of μ BGA joint using different solder alloys and various shapes were investigated by FEA. The conclusions of this research are summarized as followings.

(1) The thermal fatigue life equation is derived using the dimensionless variable γ obtained from ΔT , T_m , T_{mean} for life estimation of μ BGA. In addition, the results with γ show a good agreement with the FEA results.

(2) It is found that Sn-3.5Ag solder alloys showed better thermal fatigue life than Sn-37Pb over the whole temperature range considered. At low temperature range from 293 to 373 K, Sn-3.5Ag-3In-0.5Bi shows the best fatigue life. And in the temperature range from 233 to 393 K, the Sn-3.5Ag shows in a relatively better fatigue life.

(3) The longest fatigue life can be obtained when the shape of solder joint makes 50 degree angle to a line perpendicular to package base. This means that the thermal fatigue life of solder joint depends on the local shape of the joint where fracture occurs. And it is also observed that the rate of fracture depends on compositions of the solder alloys.

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