Experimental and Numerical Verification of Fatigue Life Estimation for Solder Bumps*

Minoru MUKAI**, Hiroyuki TAKAHASHI**,
Takashi KAWAKAMI**, Kuniaki TAKAHASHI***,
Ken IWASAKI****, Kikuo KISHIMOTO*****
and Toshikazu SHIBUYA*****

Fatigue life estimation of solder bumps is one of the most critical technologies for the development of ball grid array packages. In this study, mechanical fatigue tests were carried out using Sn63-Pb37 solder bump specimens. The cracks were initiated along the entire circumference in the vicinity of the interface. The fatigue life estimation of the solder bumps was performed based on the elastic-creep finite element method (FEM) analysis. It was clear that the strain concentration region coincides with the crack initiation site. The estimation result for the crack initiation was in good agreement with the experimental results. The results reconfirmed that it was desirable to employ the equivalent creep strain range occurring at a distance of 50 μm from the singularity point. The life ratio, which provides the quantitative correlation between the crack initiation and the ultimate fracture, was determined from the experimental results. The number of cycles to the fatal failure can be roughly estimated by multiplying the analytical estimation results for the crack initiation by this life ratio. This simple estimation of fatal failure may well be of practical use in actual ball grid array (BGA) design for thermal load conditions.

Key Words: Fatigue, Life Prediction, Structural Analysis, Solder Bump, Electronic Device, Elastic-Creep Behavior

1. Introduction

Devices such as LSI packages and chip components are soldered directly onto the surface of the printed circuit board (PCB) using surface mount

technology. Solder joints connect the devices mechanically as well as electronically to the PCB. Devices mounted on the PCB are subject to temperature variations arising as a result of the power switching on/off operations and changes in ambient temperature. Because of the differences in thermal expansion coefficients of the various materials on the PCB, thermal stresses arise during thermal cycling. Since the solder material is mechanically the most ductile part, low cycle fatigue cracking may occur in the solder joints. Consequently, fatigue life prediction of solder joints has become one of the most important areas of research in the development of reliable electronic components. Hence, many studies have been conducted concerning fatigue life estimation for solder joints⁽¹⁾⁻⁽³⁾.

In previous papers, the authors proposed an estimation method for fatigue life of Sn63-Pb37 solder joints using a simple elastic-creep model, which consists of a linear spring element and Norton's creep law⁽⁴⁾⁻⁽¹⁰⁾. In these studies, the elastic-creep model

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** Research and Development Center, Toshiba Corporation, 1 Komukai Toshiba-cho, Saiwai-ku, Kawasaki 212-8582, Japan. E-mail: minoru.mukai@toshiba.co.jp

*** Digital Media Network Company, Toshiba Corporation, 2-9 Suehiro-cho, Ome-city, Tokyo 198-8710, Japan

**** Semiconductor Company, Toshiba Corporation, 1 Komukai Toshiba-cho, Saiwai-ku, Kawasaki 212-8582, Japan

***** Department of Mechanical and Intelligent Systems Eng., Tokyo Institute of Technology, 2-12-1 Ohokayama, Meguro-ku, Tokyo 152-8552, Japan

Fig. 1 Ball grid array package

Fig. 2 Solder bump specimen

was applied to the solder joints of a quad flat package (QFP) and a pin grid array package (PGA). The results revealed the advantage of this method. Recently, the ball grid array package (BGA, Fig. 1) has been widely adopted. In the estimation of the fatigue life of BGA solder bumps, owing to the crack initiation in the vicinity of the interface, it is essential to take account of the effects of stress-strain singularity. For this reason, the accurate fatigue life estimation of BGA is more complicated than that of other packages (for example, QFP and PGA). In the present study, mechanical fatigue tests were carried out using solder bump specimens, and stress analyses using the elastic-creep model were carried out. Fatigue life estimation for solder bump corners subjected to stress-strain singularity was verified, based on the assumption that the evaluation point is located at some distance from the singularity point. A simple estimation method for fatal failure was proposed based on the life ratio, which provides the quantitative correlation between crack initiation and fatal failure.

2. Mechanical Fatigue Tests

An Sn63-Pb37 solder bump specimen is illustrated in Fig. 2. The ceramic boards were soldered together with solder balls placed between them, and they were left for more than three months after soldering. The shape of the solder bumps agreed well with that of the actual BGA. Since the boards used in this experiment were made of ceramic, their stiffness was markedly greater than that of the bumps. Figure 3 shows the mechanical fatigue test equipment developed in this study. This equipment was used to apply force to the solder bumps, with load conditions that simulate the thermal expansion mismatch between the BGA and

Fig. 3 Mechanical fatigue test equipment

Fig. 4 Number of cycles vs. Maximum load range

PCB. The upper board was gripped by a special chuck and moved through a displacement reducer by a linear actuator controlled by the output signals from a displacement sensor. The specimens were subjected to displacement-controlled loading conditions with a triangular waveform. The values of the relative displacement range, ΔX , were fixed at 7 to 14 μm . Since the strain rate due to thermal loading is small in the actual solder joints of electronic packages, the frequency of the waveform was maintained in the range of 0.003 to 0.005 Hz.

Figure 4 shows the maximum load range determined by the load transducer. Fatal failure occurred after a monotonic load drop with an increasing number of cycles. In order to uniformly handle results of the shear-type fatigue tests involving friction of the fracture surface, the number of cycles to fatal failure was defined as 75% of the load drop. Fatal failure life defined is indirectly related to the increase in electrical resistance, because it may induce electronic failure when solder joints are subjected to tensile force caused by mechanical and thermal loads. Figure 5 shows the fracture surface of a solder bump. The observation results suggested that the fracture surfaces were mainly of the intergranular creep type. Figure 6(a) and (b) show the fracture surface after 150 cycles and 300 cycles respectively, of fatigue tests

Fig. 5 Fracture surface of solder bump

(a) After 150 cycles

(b) After 300 cycles

Fig. 6 Fracture surface of solder bump

under the condition of $\Delta X = 12 \mu\text{m}$. The load drop values for 150 cycles and 300 cycles were 16% and 40%, respectively. Cracks were observed along the entire circumference in the vicinity of the interface. Macroscopic cracks with depths of about $50 \mu\text{m}$ and $100 \mu\text{m}$ were observed in the vicinity of the interface after 150 cycles and 300 cycles, respectively.

3. Solder Bump Analyses

3.1 Analytical procedures

The solder bump model of the specimen is illus-

Table 1 Material properties of Sn63-Pb37 solder

Young's modulus (MPa)		2.00×10^4
Poisson's ratio		0.39
$\epsilon_c = A \sigma^n$	A (1MPa/hr)	1.975×10^{-8}
	n	4.7
Thermal expansion coefficient ($^{\circ}\text{C}$)		2.47×10^{-5}

Fig. 7 FEM model

trated in Fig. 7. A half section of the solder bump was considered due to the symmetry of the geometry. The ceramic boards were not modeled, because their deformation behavior was negligible. Quadratic brick elements were used over the entire region, with fine elements generated around the corner of the bump to obtain details of the stress-strain singularity. The relative displacement range, ΔX , was applied to the upper surface of the bump in the direction indicated by the arrow in Fig. 7. Constructing a suitable material model of the Sn63-Pb37 solder is the most important issue for stress analysis. Since solder materials are alloys with low melting points, their creep behavior is significant even at room temperature. The authors have previously proposed a simple elastic-creep model to express the deformation behavior of Sn63-Pb37 solder, and have also used this model in the present study. The elastic and creep properties of Sn63-Pb37 solder at typical temperatures are listed in Table 1⁽⁴⁾. Experimental results for Sn63-Pb37 solder materials have shown that an elastic-creep model is adequate for characterizing the creep behavior of materials in the low strain rate range.

3.2 Estimation of crack initiation

The authors have previously carried out low cycle fatigue tests using thin-walled cylindrical specimens⁽⁶⁾. The results showed that the effects of temperature and waveform on the Coffin-Manson plot were small. The following Coffin-Manson equation has been obtained to estimate thermal fatigue life:

$$N_f = 0.146(\Delta\epsilon_{in})^{-1.94} \quad (1)$$

where N_f is the number of cycles to failure and $\Delta\epsilon_{in}$ is the inelastic strain range. In this study, this Coffin-Manson equation was employed for the estimation of

Fig. 8 Distribution of equivalent creep strain range

Fig. 9 Distribution of equivalent creep strain range around singularity point ($\Delta X = 12 \mu\text{m}$)

crack initiation.

The distributions of the equivalent creep strain are shown in Fig. 8. It is clear that the strain concentration region coincides with the crack initiation site along the entire circumference in the vicinity of the interface. Figure 9 shows the relationship between the equivalent creep strain range and the distance from the singularity point in the direction of the strain concentration. Because of the effects of strain singularity at the corner of the solder bump, a quantitative estimation of the number of cycles required for crack initiation based on the maximum value of the equivalent creep strain range is not significant. In order to avoid the singularity problem of numerical analysis, the authors have proposed a practical method employing the equivalent creep strain range, which occurs at some distance from the singularity point⁽⁷⁾. Considering of the grain size of the solder material ($\sim 20 \mu\text{m}$),

Fig. 10 Equivalent creep strain range at evaluation point

Fig. 11 Solder bump model with initial cracks

it has been assumed that the estimation point is located at a distance of $50 \mu\text{m}$ from the singularity point on the surface of the bump. This depth corresponds to several times of the grain size. Figure 10 shows the equivalent creep strain range at the evaluation point. In the case of $\Delta X = 12 \mu\text{m}$, values of 0.026 and 0.033 were obtained at sites A and B, respectively. Owing to the scatter in the shapes of bump corners, the small difference in these values for the strain range is insignificant for fatigue life estimation. From an averaged value of the equivalent creep strain range, the number of cycles to crack initiation was estimated to be 140 cycles. Since macroscopic cracks with depths of about $50 \mu\text{m}$ were observed after 150 cycles of fatigue tests, this estimated result is considered to be satisfactory.

Because the crack observation by destructive testing is not suitable for evaluating innumerable results, the number of cycles to crack initiation was defined based on the load drop for sake of convenience. This load drop phenomenon during the fatigue tests occurred due to a decrease in stiffness caused by crack initiation and cyclic softening behavior of the solder material. The load drop caused by the decrease in stiffness with crack initiation was assessed using a FEM model with cracks. Figure 11 shows the FEM model with cracks, which were $50 \mu\text{m}$ in depth along the entire circumference. The results of FEM analysis under the same conditions showed that the maximum load range decreased by 11% due to initial

Fig. 12 Low cycle fatigue life of bulk specimen

cracks. The load drop caused by the cyclic softening behavior of the solder material was assessed using the experimental results of the low cycle fatigue behavior of the bulk specimen. Figure 12 shows the low cycle fatigue life obtained using the thin-walled cylindrical specimens, and is plotted versus total shear strain range. In addition to the N_f (25% load drop), the numbers of cycles to 5% and 10% load drop are also plotted. In the case of this bump specimen, the value of the averaged total shear strain range, $\Delta\gamma_t$, could be obtained by the displacement range, ΔX , and the bump height. Referring to Fig. 12, the load drop caused by the cyclic softening behavior could be evaluated to be 7% using the total shear strain range, $\Delta\gamma_t$, and the estimated fatigue life, N_f (for example, $\Delta X = 12 \mu\text{m} \Rightarrow \Delta\gamma_t = 0.03$ and $N_f = 140$). As shown in the following equation, the number of cycles to crack initiation was defined by a 17% load drop, which was obtained from the load drop caused by the decrease in stiffness with crack initiation and the cyclic softening behavior of the solder material.

$$1 - (1 - L_{d1}) \cdot (1 - L_{d2}) \approx 0.17 \quad (2)$$

where L_{d1} ($=0.11$) is the value of load drop caused by the decrease in stiffness with crack initiation and L_{d2} ($=0.07$) is the value of load drop caused by the cyclic softening behavior of the solder material.

Figure 13 shows the number of cycles plotted by the definition described above, and the estimation results obtained by FEM analysis. Although there are variations in the experimental results of the number of cycles required for crack initiation because of the scatter from the bumps, this estimation agrees well with the experimental results. Consequently, the estimation of crack initiation using the equivalent creep strain range occurring at the above evaluation point is satisfactory for the reliability design of BGA solder bumps.

Fig. 13 Fatigue life estimation

Fig. 14 Results of mechanical fatigue tests for solder bumps

3.3 Simple estimation method for fatal failure

In this study, a simple estimation method for determining fatal failure has been proposed. Figure 14 shows the number of cycles for crack initiation (N_f : 17% load drop) and fatal failure (N_{ff} : 75% load drop). This figure indicates that the two distributions are generally parallel, and the life ratio, N_{ff}/N_f , which provides the quantitative correlation between crack initiation and fatal failure, was 4 to 6. The number of cycles to fatal failure can be roughly estimated by multiplying the analytical estimated results for crack initiation by this life ratio. To investigate the applicability of the present method to actual BGA design, the general trend of the life ratio under thermal loads of field conditions was studied as described below. In the case of mechanical fatigue tests, which simulate only the global mismatch (thermal expansion mismatch between the BGA and PCB), the cracks were initiated along the entire circumference in the vicinity of the interface. In the case of the thermal loads under field conditions, however, the cracks are frequently observed to form in one direction on the circumference, because thermal loads

partly involve thermal expansion mismatch between the bump and BGA or PCB. This trend suggests that the life ratio under thermal loads, N_{ff}/N_f , may be greater than that under mechanical loads. Consequently, in the case of the load conditions markedly subjected by the global mismatch, this approach may lead to conservative estimates under many thermal loads in field conditions.

4. Conclusions

Mechanical fatigue tests were carried out using Sn63-Pb37 solder bump specimens. Cracks were observed along the entire circumference in the vicinity of the interface. The observed results suggested that the fracture surfaces were mainly of the intergranular creep type. Fatigue life estimation of the solder bumps was performed based on elastic-creep FEM analysis. It was clear that the strain concentration region coincided with the crack initiation site in the vicinity of the interface. The estimated results of the number of cycles required for crack initiation agreed well with the experimental results. The results reconfirmed that it is desirable to employ the equivalent creep strain range occurring at a distance of 50 μm from the singularity point. Consequently, the estimation of crack initiation using the equivalent creep strain range occurring at the above point is satisfactory for the reliability design of BGA solder bumps. The relationship between the number of cycles for crack initiation and fatal failure was examined. In the case of the bump size used in the present study, the two distributions were generally parallel, and the life ratio, N_{ff}/N_f , which provides the quantitative correlation between crack initiation and fatal failure, was 4 to 6. The number of cycles to fatal failure can be roughly estimated by multiplying the analytical estimation results for crack initiation by this life ratio. In the case of the load conditions markedly subjected by the global mismatch (thermal expansion mismatch between the BGA and PCB), the number of cycles to fatal failure under thermal loads in field conditions may be similarly estimated using this approach. In the range of engineering applications, this simple estimation of fatal failure may be satisfactory in practical use.

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