Numerical Simulation of Fatigue Crack Growth in Microelectronics Solder Joints

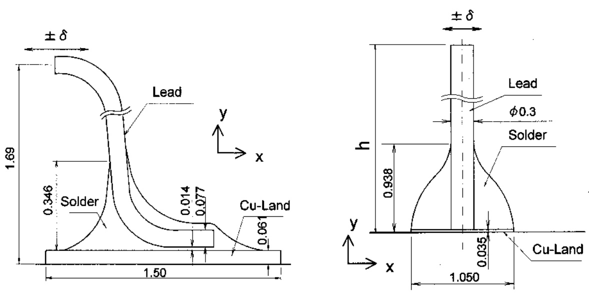
K. Kaminishi[1], M. Iino[2], H. Bessho[2], M. Taneda[3]

Abstract: An FEA (finite element analysis) program employing a new scheme for crack growth analysis is developed and a prediction method for crack growth life is proposed. The FEA program consists of the subroutines for the automatic element re-generation using the Delaunay Triangulation technique, the element configuration in the near-tip region being provided by a super-element, elasto-inelastic stress analyses, prediction of crack extension path and calculation of fatigue life. The FEA results show that crack extension rate and path are controlled by a maximum opening stress range, $\Delta\sigma_{\theta\max}$, at a small radial distance of $r = d$, where d is chosen to be a grain diameter's distance, 3.5 μm, in solder material. The experimentally obtained crack extension rate is found to be related to $\Delta\sigma_{\theta\max}$ in FEA as $da/dN = \beta[\Delta\sigma_{\theta\max} - \gamma]^{\alpha}$, where $\alpha = 2.0$, $\beta = 4.5 \times 10^{-9}$ mm^5/N^2 and $\gamma = 98$ MPa are determined for all test conditions. The calculated values of crack extension life by the FEA using the above equation are in good agreement with the experimental ones and are independent of the joint types.

keyword: solder joints, life prediction, low cycle fatigue, finite element method

1 Introduction

From a viewpoint of reliability assessment of the microelectronics solder joints, it is important to predict the fatigue life of the joints, which should help in improving package design accuracy and efficiency. The fatigue life of solder joints may be divided into the crack initiation and extension lives. As to crack initiation life, many formulae based on the Coffin-Manson's law or the modified Coffin-Manson's law have been proposed [Mukai, Kawakami, Endo, and Takahashi (1991); Lau, Rice, and Erasmus (1992); Busso, Kitano, and Kumazawa (1994); Shiratori and Qiang (1996)]. By applying the strain range partitioning approach and a linear cumulative damage concept, and using material-dependent parameters, the authors also have proposed a fatigue life prediction formula on eutectic (63Sn - 37Pb) and low melting-point (37Sn - 45Pb - 18Bi) solders, expressing the number of cycles to failure as a function of cyclic frequency and equivalent inelastic strain range, which can be understood to successfully incorporate a creep damage effect [Taneda and Kaminishi (1992)]. However, little is known about crack growth behavior of the solder joints used in surface mount technology.



(a) Gullwing type (b) Butt type

Figure 1 : Geometry of test models

In this work, a finite element program employing a new scheme for crack growth analysis is developed, and finite element analyses (FEA) of fatigue crack growth in microelectronics solder joints are carried out by this program. The calculated results are compared with the experimental ones to examine the feasibility of crack growth life prediction by the FEA.

2 Model and material

The configuration and dimension of solder joint models used in this study are shown in Fig. 1. The lead wire is made of 42 Alloy, and the substrate of glass epoxy resin. In this simulation, perfect rigidity of the substrate is assumed, and the presence of a copper coated layer is disregarded because of its negligibly small thickness as compared to the substrate thickness. The bottom of the solder fillet is constrained in the x- and y-directions. The reciprocating displacements with a constant amplitude dare given in the x-direction at the top of the

Table 1 : Mechanical properties used for numerical simulation

Material	Young's modulus (GPa)	Yield stress (MPa)	Poisson's Ratio
Solder	35.0	13.4	0.3
Lead	137.2	392.0	0.3

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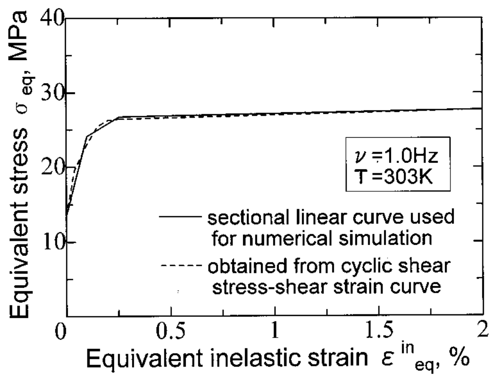


Figure 2 : Equivalent stress-strain curve

lead wire as shown in Fig. 1. To take into consideration the plasticity and creep effect, the inelastic constitutive equation of Perzyna type [Perzyna (1971)] is employed. The parameters of this equation are determined from the cyclic stress-strain curves obtained from fatigue test data for 63Sn - 37Pb eutectic solder [Taneda and Kaminishi (1992)]. An example of cyclic stress-strain curves of the solder material is given in Fig. 2. Mechanical properties used in the numerical simulation are given in Tab. 1.

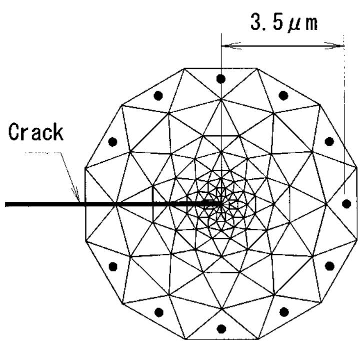


Figure 3 : Super-element embedded in the near crack-tip region

3 Crack path prediction

A finite element program employing a new scheme for crack growth analysis is developed and a prediction method of crack growth path is proposed. The FEA program consists of subroutines for the automatic element re-generation using Delaunay Triangulation technique [Sloan and Houlsby (1984)], the element configuration in the near-tip region being provided by a super-element which can be rotated in conformity with the direction of crack growth as demonstrated in Fig. 3, elasto-inelastic stress analyses, prediction of crack extension path and calculation of fatigue life. In Fig. 3, the bold line indicates a crack having proceeded from the left up to a current crack tip. The crack can shift its direction in accordance with the adopted fracture criterion. Fig. 4 illustrates an initial finite element meshing which embeds the super-element. A crack 10 μm long is introduced as an initial crack at the location of numerically obtained maximum equivalent inelastic strain range.

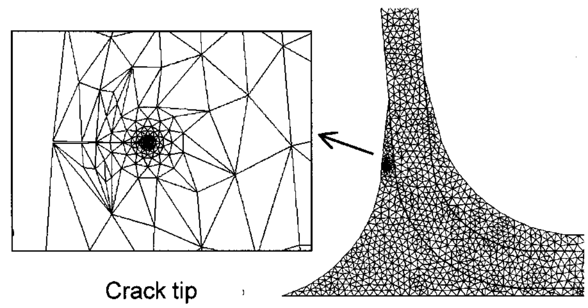


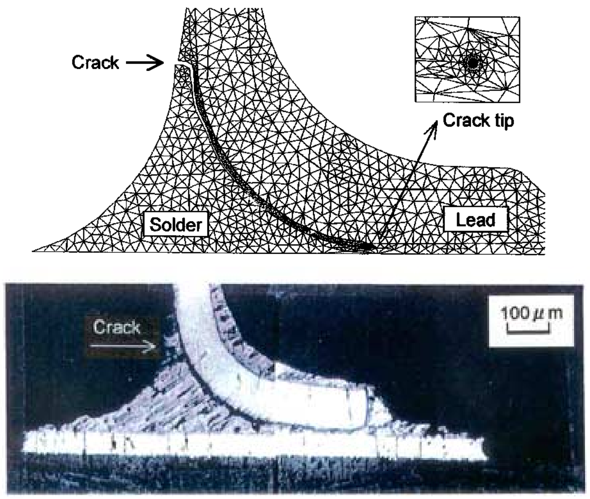
Figure 4 : Initial finite element meshing

In the process of crack growth it is found that general yielding proceeds in solder fillets. Here the linear fracture mechanics representation would be inappropriate to use stress fields at the crack tip to determine crack extension path. It is assumed in this instance that crack extends in the direction of maximum $\Delta\sigma_\theta$ at a small radial distance of $r = d$, where d is chosen to be a grain diameter's distance, 3.5 μm, in solder material. See Iino, Kaminishi, and Taneda (1997) for general discussions including maximum tangential stress (MTS) criteria and the present assumption.

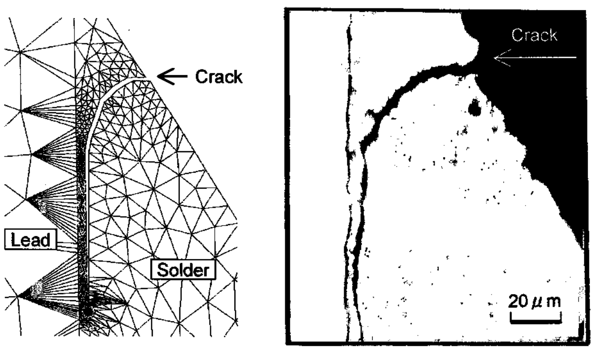
The crack paths determined by FEA are demonstrated in Fig. 5 (a) and (b) for Gullwing type and butt joint, respectively. The crack extended changing in direction in the upper position of the solder fillet, travelling along the vicinity of the solder-lead interface after it approached the interface. The simulated crack growth path is in good agreement with the experimentally observed one independently of the joint type. It would be reasonable to suppose that the crack extension path in microelectronics solder joint can be predicted by using the present FEA program.

4 Crack growth life

Let us now attempt to extend this simulation to the prediction of crack growth life. Fig. 6 plots the computed $(\Delta\sigma_\theta)_{CT}$ against crack length for test conditions indicated in the figure, where $(\Delta\sigma_\theta)_{CT}$ denotes the maximum $\Delta\sigma_\theta$ at $r = 3.5$ μm. It is characteristic of this plot that $(\Delta\sigma_\theta)_{CT}$ decreases monotonously as crack length exceeds 0.1 mm and this tendency is similar to the experimentally obtained relationship between crack extension rate and crack length. In Fig. 7 crack



(a) Gullwing type



(b) Butt type

Figure 5 : Comparison of simulated crack growth with experiment

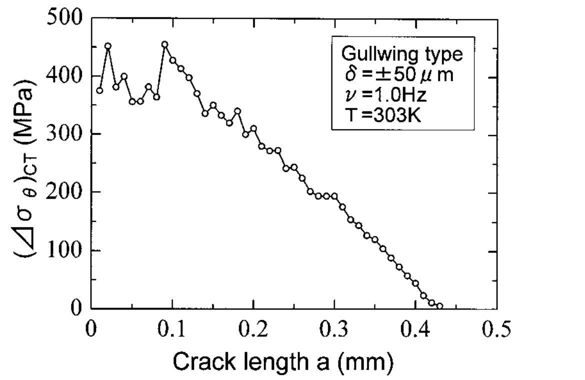


Figure 6 : Plot of computed maximum tangential stress range against observed crack length

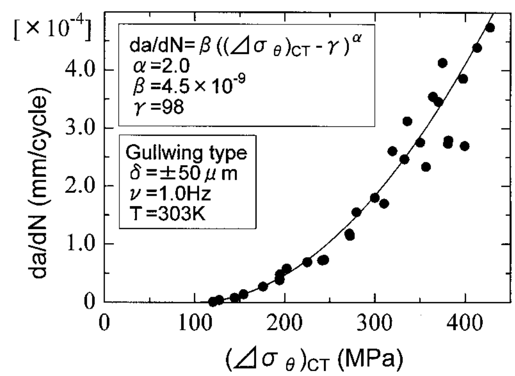


Figure 7 : Plot of experimentally determined crack growth rate against maximum tangential stress range

growth rate, da/dN, is plotted against $(\Delta\sigma_\theta)_{CT}$ which describes crack growth rate as a function of $(\Delta\sigma_\theta)_{CT}$ of the form;

$$da/dN = \beta\,[(\Delta\sigma_\theta)_{CT} - \gamma]^\alpha, \quad (1)$$

where $\alpha = 2.0$, $\beta = 4.5 \times 10^{-9}\ mm^5/N^2$ and $\gamma = 98\ MPa$.

In the FEA the same super-element is embedded in the near crack-tip region to avoid the effect of mesh density on the results. It is considered that α, β and γ in the above equation would be regarded as material constants being independent of the applied displacement amplitude, δ, and joint type, provided that the same super-element is used in the FEA. For this reason, fatigue crack growth life can be predicted by integrating Eq. 1. Crack length-to-number of cycles relations obtained by numerical integration of Eq. 1 based on the FEA are compared with experimental ones for Gullwing type joints in Fig. 8. As seen from the figure the numerical simulated curves are in agreement with experimentally observed fatigue crack growth behavior. The same observation applies to the case of butt joint as shown in Fig. 9. In spite of the difference in joint type, the numerical result is in a fair agreement with the experimental one. These comparison would suggest validity of the present FEA for the prediction of fatigue crack growth life of the solder joint.

5 Conclusions

An FEA program employing a new scheme for crack growth analysis was developed, by which fatigue crack growth in microelectronics solder joints were numerically analyzed. The FEA results show that crack extension rate and path are controlled by a maximum opening stress range, $\Delta\sigma_{\theta\max}$, at a small radial distance of $r = d$, where d is chosen to be a grain diameter's distance, 3.5 μm, in solder material.

Experimentally obtained crack extension rate is found to be related to $\Delta\sigma_{\theta\max}$ by

$$da/dN = \beta\,[\Delta\sigma_{\theta\max} - \gamma]^\alpha,$$

where $\alpha = 2.0$, $\beta = 4.5 \times 10^{-9}\ mm^5/N^2$ and $\gamma = 98\ MPa$ are

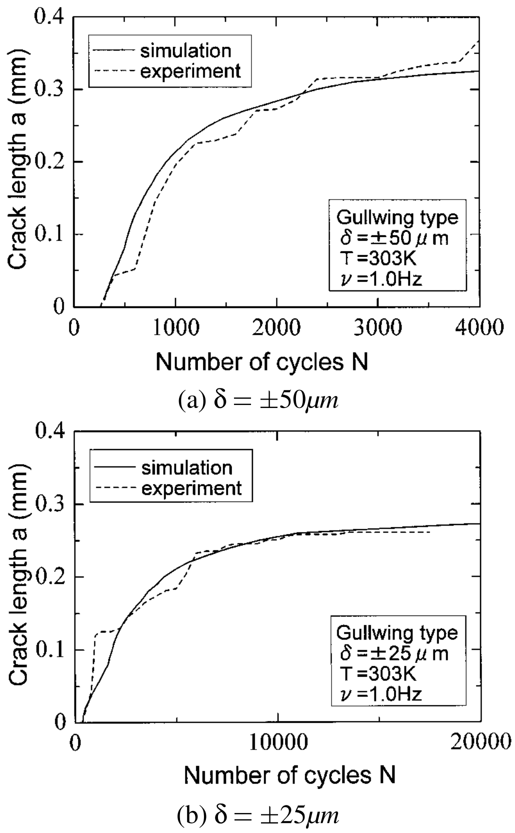


Figure 8 : Relationship between crack length and number of cycles (Gullwing type)

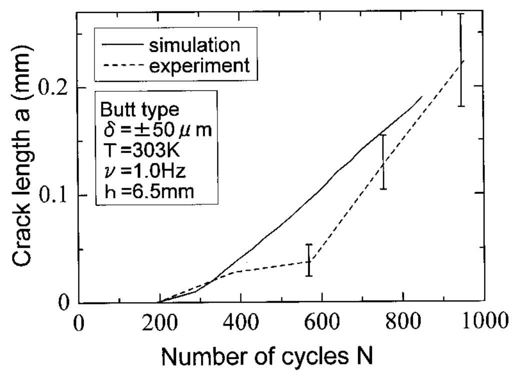


Figure 9 : Relationship between crack length and number of cycles (Butt type)

determined independently of the test conditions. Conclusively it is shown that experimentally observed fatigue crack extension path and life can be predicted by numerically integrating the above equation.

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