Sensitivity study on material properties for the fatigue life prediction of solder joints under cyclic thermal loading

Shi-Wei Ricky Lee
Department of Mechanical Engineering, The Hong Kong University of Science and Technology, Kowloon, Hong Kong
Xiaowu Zhang
Department of Mechanical Engineering, The Hong Kong University of Science and Technology, Kowloon, Hong Kong

A computational study is presented in this paper to investigate the effect of variation in material properties on the fatigue life prediction of solder joints subjected to cyclic thermal loading. The package under investigation was a plastic quad flat pack (PQFP) with gull-wing leads. A commercial finite element code, ABAQUS, was employed to perform a two-dimensional plane stress analysis. While all other constituents of the PQFP assembly were assumed to be linear elastic, the solder joint was considered to be elastic-viscoplastic. The creep model was adopted from Norton's equation and was implemented in the finite element analysis via a user-defined subroutine. The maximum creep strain was evaluated and incorporated into the modified Coffin-Manson equation to estimate the life cycles under thermal fatigue. It was found that the variation in material properties could have a significant influence on the fatigue life prediction of solder joints.

Introduction

Owing to the demands for lost-cost and high-volume mass production, surface mount technology (SMT) has become the major assembly method in electronics industries. For surface-mounted components, the solder joint is not only the passage of electrical signal and power, but also the mechanical support to hold the component in position on the printed circuit board (PCB). Since the dimension of solder joints is usually very small and the solder materials are susceptible to low cycle fatigue, the reliability of solder joints is a main concern in SMT. It is well known that the dominant fatigue loading for electronics in service is thermal cycling (Lau, 1991). Many studies have been performed in the past to investigate the reliability of solder joints under thermal fatigue loading (Dasgupta *et al*., 1983; Engelmaier, 1983; Pao, 1992). In particular, most studies used computational analysis, since experimental work is rather difficult and very time consuming. However, it has been noted in the literature that various studies used different properties for the modeling of the same solder material. In some instances, the difference in a certain material property could be more than 50 per cent! This discrepancy only makes for further confusion and renders the reliability study "unreliable".

The present study aims to investigate the effect of variation in material properties on the fatigue life prediction of solder joints under thermal cyclic loading. The solder is considered an elastic-viscoplastic material while all other constituents of the package are assumed to be linear elastic. A steady state creep model based on Norton's law is adopted for the constitutive relation in solder joints. The finite element code, ABAQUS, is used in the present study. The maximum creep strain in solder joints under cyclic thermal loading is obtained from the computational analysis. The fatigue life is evaluated by the modified Coffin-Manson equation. The material property variables under investigation include Young's Modulus, the coefficient of thermal expansion (CTE), and the activation energy of solder. It is found that the variation in material properties may lead to very different results in fatigue life prediction. The findings of the present study should be helpful for other researchers when it comes to choosing the solder material properties for their future solder joint reliability modeling.

Finite element model

The package under investigation in the present study is a plastic quad flat pack (PQFP) with gull-wing leads as shown in Figure 1. The body size of the PQFP is $40 \times 40 \times 3.9$mm; the pin-count is 304 and the lead pitch is 0.5mm. The package is assembled and joined to a 1.58mm thick printed circuit board (PCB) by eutectic solder (63Sn/37Pb). To avoid tedious calculation and excessive computing resources, a two-dimensional analysis is performed in this study. A commercial finite element code, ABAQUS, is employed for modeling. The PQFP assembly is modeled by eight-node plane stress elements as illustrated in Figure 2. Owing to symmetry in geometry, only half of the assembly is simulated.

In general, the PQFP assembly consists of four constituents, namely, the PQFP body, the gull-wing lead, the FR-4 PCB, and the solder joint. For simplicity, instead of modeling all detailed structures inside the package, the PQFP body in the present model is considered as an effective material of all compositions. Since the lead is rather long and compliant, by St Venant's principle, the stress state

Figure 1
The PQFP under investigation

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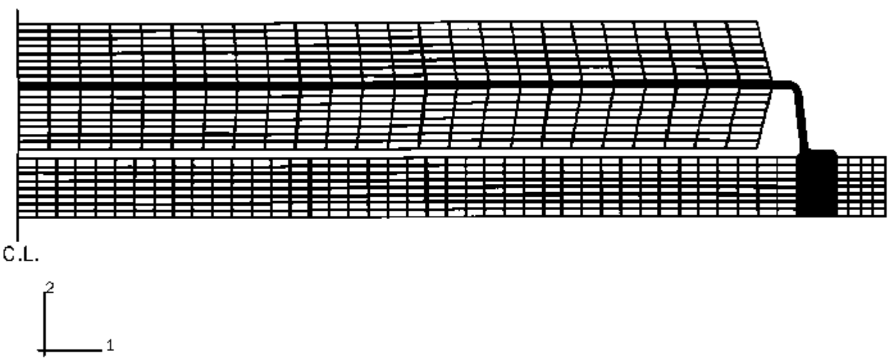
Figure 2
Mesh configuration of the finite element model for PQFP assembly



in the solder joint will not be affected by the aforementioned simplification. All constituents of the PQFP assembly except the solder are assumed to be linear elastic. The material properties are adopted from Gavila *et al*. (1994) and are given in Table I.

It has been identified that the solder joint is a material with substantial thermal creep behavior (Darveaux and Banerji, 1992). Therefore, unlike the other constituents, the solder joint is considered to be elastic-viscoplastic in this study. The viscoplastic response adopted in this paper is a steady state creep based on Norton's law (Pao *et al*., 1992). The constitutive equation can be written as

$$\frac{d\gamma_c}{dt} = B^* \exp\left(\frac{-Q}{\kappa T}\right)\tau^n \qquad (1)$$

where γ_c is shear creep strain; τ is shear stress; T is absolute temperature; κ is the Boltzmann constant (8.63×10^{-5}eV/°K); Q is activation energy; and n and B^* are material constants which can be determined from creep hysteresis response. Equation (1) can be incorporated into the finite element analysis via a user-defined subroutine.

Stress analysis and life estimation

After the establishment of the aforementioned finite element model, cyclic thermal loading is applied to the PQFP assembly. A typical creep strain contour of the solder joint is presented in Figure 3. The temperature profile of thermal loading is given in Figure 4. It is found that the maximum value occurs at the leading edge of the toe base. Figures 5 and 6 show the equivalent creep strain and stress at the toe base over time, respectively, within a single cycle. The accumulation of creep strain and stress relaxation due to creep can be clearly observed. These two figures can be correlated and then form a creep hysteresis loop. Figure 7 shows the result of three thermal cycles. Note that the creep hysteresis loop has become steady after the first cycle.

The purpose of stress analysis for solder joints is to estimate the fatigue life under cyclic thermal loading. A widely adopted life prediction model is the modified Coffin-Manson equation which can be written as:

$$N_f = \theta(\Delta\gamma)^\eta \qquad (2)$$

Table I
Material properties of the constituents of PQFP assembly

Material	*E*(GPa)	Poisson's ratio	CTE (ppm/°C)
PQFP body	14	0.23	22
Lead (Cu)	121	0.35	17
FR-4 PCB	22	0.24	15

Source: Govila *et al.* (1994)

Figure 3
Equivalent creep strain contour in the solder joint

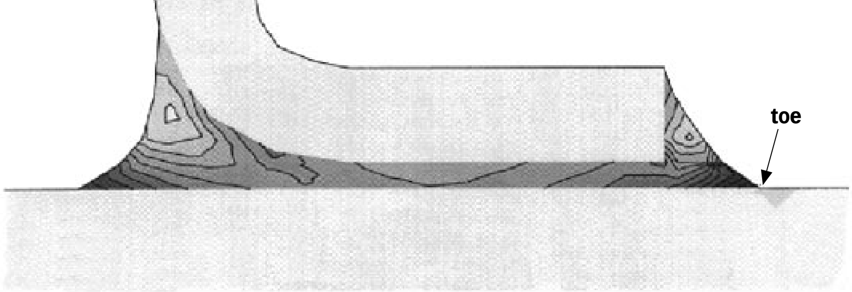


Figure 4
Temperature profile of thermal loading (single cycle)

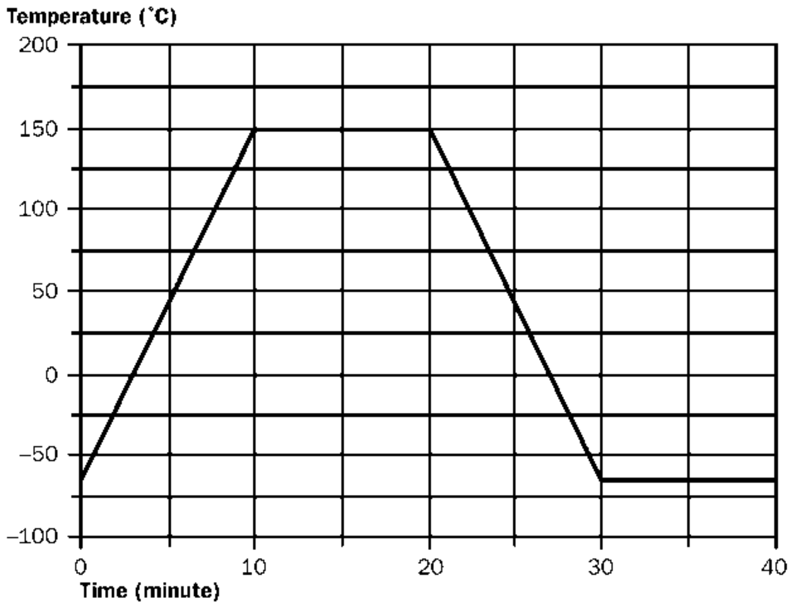
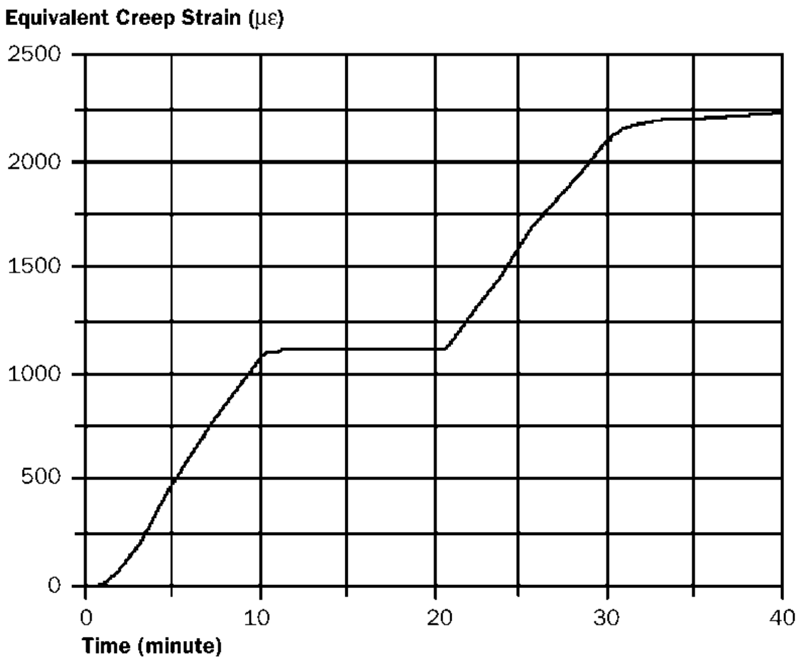


Figure 5
Equivalent creep strain in one thermal cycle over time



where N_f is the number of cycles to failure; $\Delta\gamma$ is the shear strain range; θ and η are material constants. The values of the last two quantities for 63Sn/37Pb have been determined as $\theta = 1.2928$ and $\eta = -1.96$, respectively (Solomon, 1986). It should be noted that, in the original Coffin-Manson equation, the shear strain range is plastic strain. However, since the current solder joint is elastic-viscoplastic, the shear strain range in equation (2) is replaced by the maximum shear creep strain obtained from the finite element analysis.

Effect of variation in material properties

It is essential for computational modeling to have accurate material properties as input; otherwise, the results of a reliability analysis could become very unreliable. However, it is still quite difficult to achieve unified material properties for solder joint modeling. This situation may be attributed to the lack of standards for solder material characterization and the difference between bulk and in-situ material properties. Therefore, a study is needed to estimate the possible error of analysis due to the variation in material properties.

Figure 6
Von Mises stress in one thermal cycle over time

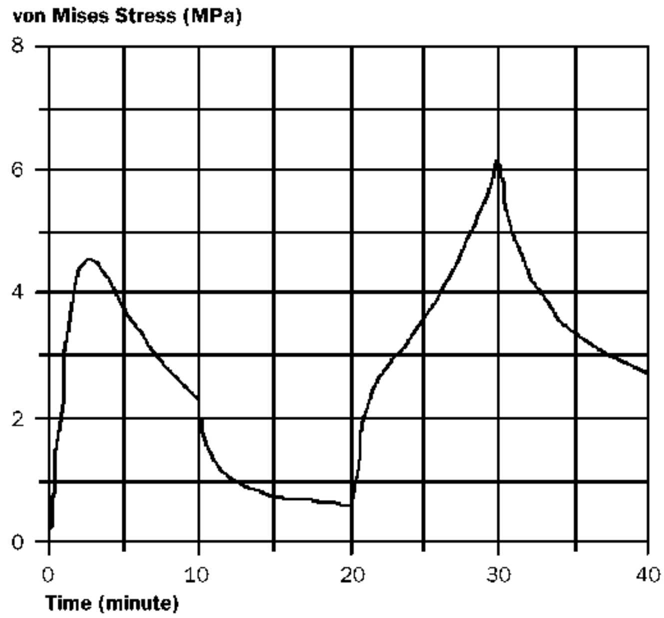
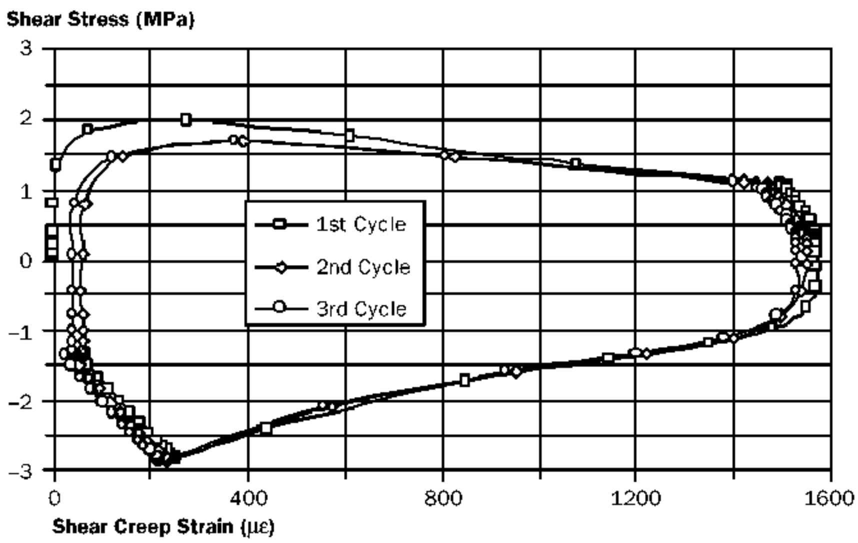


Figure 7
Creep hysteresis loop for three thermal cycles



The objective of this paper is to perform a sensitivity study on material properties for the fatigue life prediction of solder joints under cyclic thermal loading. The material properties under investigation include Young's Modulus, CTE, and the activation energy of the solder joint. Different values of the aforementioned quantities have been reported in various studies. In this paper, a base case of solder material properties is chosen as given in Table II (Pao *et al*., 1994). The results of thermal fatigue life estimation, by finite element analysis and equation (2), with variation in material properties noted in the literature, are presented in Figures 8-10.

In Figure 8, it can be seen that the influence on life estimation is limited when Young's Modulus of solder is

Table II
Material properties of 63Sn/37Pb for the base case study

E(GPa)	Poisson's ratio	CTE (ppm/°C)	*Q*(eV)	*B**(1/MPa^n)	*n*
30.2	0.4	21.1	0.49	0.205	5.25

Source: Pao *et al.* (1994)

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Figure 8
Effect of variation in Young's Modulus on fatigue life estimation

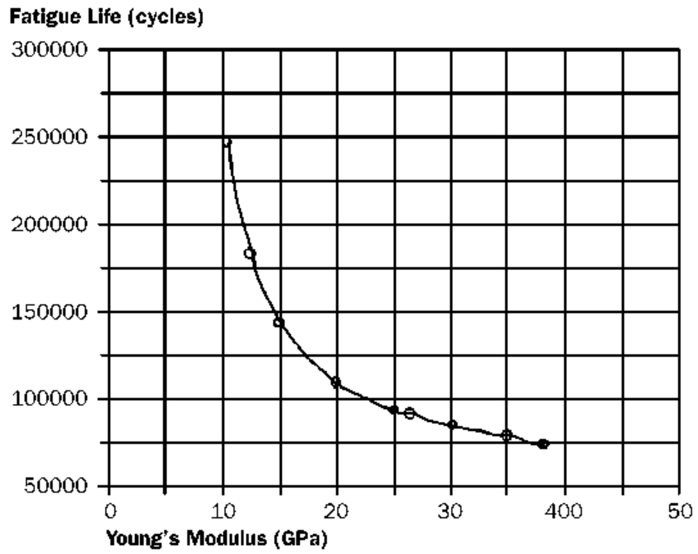
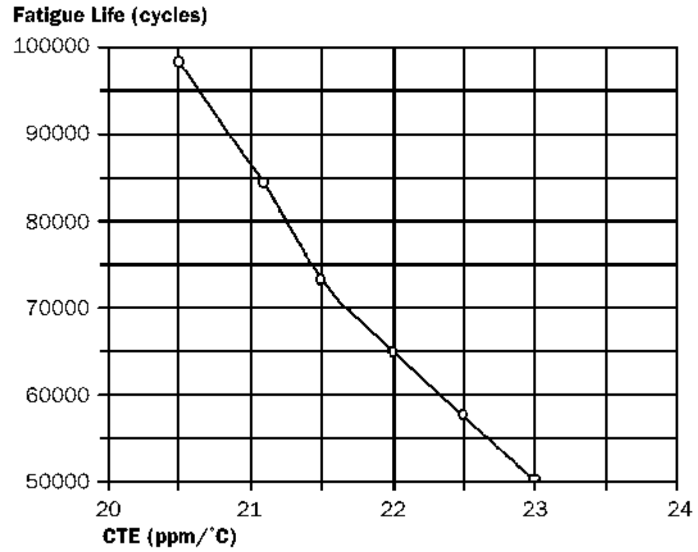


Figure 9
Effect of variation in CTE on fatigue life estimation



within 25-38GPa. However, if this quantity is below 20GPa, the discrepancy in life cycles is quite substantial and the trend is highly nonlinear. The effect of the CTE is shown in Figure 9.

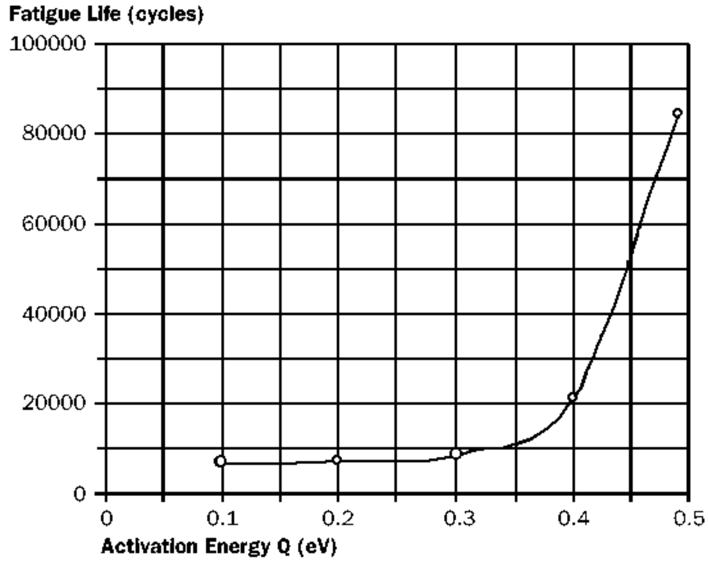
Since the range of variation given in the literature is not significant, it seems that the influence of CTE on fatigue life prediction is not as strong as Young's Modulus. Moreover, the trend is rather linear in behavior. Figure 10 illustrates the effect of activation energy. The result indicates that life cycles are insensitive to the value of activation energy if Q is less than 0.4eV. However, if Q goes beyond 0.4eV, there will be a large discrepancy in fatigue life prediction.

An additional analysis with Q = 0.6eV was also performed. The estimated life cycles are one order of magnitude higher than the base case (Q = 0.49eV). Therefore, it seems that the activation energy of the solder material has the greatest influence on the estimation of thermal fatigue life.

Concluding remarks

A series of computational analyses was performed to study the effect of the variation in solder material properties on the estimation of fatigue life for solder joints under cyclic thermal loading. A PQFP assembly was investigated as an illustration. The stress analysis was carried out by 2D finite element modeling with an elastic-viscoplastic constitutive relation for the solder joint. The maximum creep shear strain together with the modified Coffin-Manson equation was used to estimate the fatigue life cycles. It was observed that Young's Modulus of solder in various ranges of value may have different degrees of influence on life prediction. The effect of CTE does not seem as significant as Young's Modulus due to the limited range of variation. However, the life cycles were found to be very sensitive to the activation energy of solder when Q is beyond a certain value. Therefore, it is essential to ensure that activation energy is accurate when carrying out a computational analysis with steady state creep constitutive models for the prediction of thermal fatigue life.

Figure 10
Effect of variation in activation energy on fatigue life estimation



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