Modeling Constitutive Model Effect on Reliability of Lead-Free Solder Joints

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Abstract

This paper will focus on the study of solder constitutive model effect on solder joint fatigue life prediction. Two loading conditions are considered, namely thermal cycling and cyclic bending. In this study, four different solder constitutive models including elastic-plastic (EP), elastic-creep (Creep), elastic-plastic-creep (EPC) and viscoplastic Anand's (Anand) models are implemented in FE modeling and simulation for comparison. Two cases involving in Plastic-Ball-Grid-Array (PBGA) assembly subjected to thermal cycling and Very-thin-Quad-Flat-No-lead (VQFN) assembly subjected to cyclic bending are selected for investigating solder constitutive model effect on solder fatigue life and stress-strain behavior. Fatigue life prediction shows that the Creep, EPC and Anand models result in consistent fatigue life for PBGA assembly. When using EPC model, the creep deformation is dominant for PBGA assembly. For cyclic bending study for VQFN assembly, the significant different simulation result can be found when using different constitutive models. Results show that EP and EPC model can lead to similar result and accumulated strain energy density per cycle is easier to converge, while Creep model is equivalent to Anand's model which result in lower strain energy density value for high temperature bending. The thermal cycling fatigue test data for PBGA is also presented for validating FE simulation results.

1. Introduction

For microelectronic assembly, it is known that solder joint, when subjected to cyclic loading such as thermal cycling/shock and cyclic bending, is prone to fatigue failure. Typically it takes half a year to perform board level thermal cycling test in order to evaluate a new package. This long turnaround time is sometimes unaffordable due to the tight time-to-market schedule. Finite element modeling and simulation is a powerful tool for quick prediction of solder joint fatigue life based on simulation results and existing solder fatigue models. However, accurate life prediction can be affected by many factors such as material properties, FE models, solder constitutive models, and solder fatigue models [1]. Solder constitutive model is one of the important factors that affect solder stress-strain behavior in FE simulation. Therefore, the selection of constitutive model for solder joints is very critical in order to simulate correct solder stress-strain behavior under different loadings.

Solder creep behavior is temperature and time dependent, and is an important characteristic at high homologous temperature, say 0.4 T_m and above. Creep deformation can be developed in any stress level for solder alloy [2]. Time independent plastic strain will only become significant at stress levels above $\tau/G = 10^{-3}$. The time-independent plastic strain and time-dependent creep strain is difficult to separate in higher stress level. In order to study the constitutive behavior using a state variable visco-plastic approach, the creep and plastic strain can be combined into inelastic strain. One commonly used visco-plastic model for solder is the Anand model [3-4]. It is assumed in creep model that all inelastic strain developed is due to creep deformation, which can give more accurate result when slow mechanical or thermomechanical load cycles are simulated. In visco-plastic model, plastic strain and creep strain cannot be separated distinctly and they are unified as plastic strain or inelastic strain. However, elastic-plastic-creep (EPC) model is realized by combining time independent elastic-plastic model and time dependent creep model [5]. Plastic strain and creep strain are separated distinctly and their summation is called total inelastic strain. In this paper, different constitutive model effects on solder stress-strain behavior and solder joint fatigue life will be presented.

As the electronic assembly becomes smaller and smaller which induce more significant geometry mismatch among different parts in packaging and more and more I/Os are used, the finite element modeling using traditional full 3D model will become more difficult with using large element size which require high-performance computing resource. Therefore, the global-local modeling technique, or called submodeling, is a good choice for board-level simulation in reliability analysis for electronic assembly [6]. The volume-averaging method is typically used in parameter extraction from simulation results for solder fatigue life prediction to reduce the stress concentration effect [7]. Strain-based and energy-based solder fatigue models are commonly used for solder joint fatigue under mechanical and thermomechanical loadings. Reference [1] showed that the energy-based fatigue model resulted in accurate and reasonable fatigue life prediction compared to strain-based fatigue model. In this paper, the energy-based fatigue model is used. In addition, thermal cycling and cyclic bending experimental data are also presented for numerical result validation.

2. Constitutive Models for Sn-Ag-Cu Solder

The time- and temp-dependent deformation behavior of solder includes single creep equations with power-laws or hyperbolic sine functions [8], elastic-plastic and elastic-plastic-creep models [9].

Elastic-Plastic-Creep Model: The solder is modeled as an elastic-plastic-creep material with temperature and strain rate dependent Young modulus and yield stress material properties expressed by following equations [6]:

$$E(T,\dot{\varepsilon})=(-0.0005T+6.4625)\log\dot{\varepsilon}+(-0.2512T+71.123)\ (GPa) \quad (1)$$

$$\sigma(T,\dot{\varepsilon})=(-0.1362T+67.54)(\dot{\varepsilon})^{(0.000559T+0.0675)}\ (MPa) \quad (2)$$

where T has unit of degree ^{o}C; strain rate for thermal cycling was usually correspond to 10^{-4}1/s.

The solder is assumed to exhibit elastic, bilinear kinematic hardening plastic behavior after yield. The creep behavior of solder is modeled using hyperbolic sine creep equation [10]:

$$\dot{\varepsilon}_c = C_1\frac{G}{T}\left[\sinh\left(\alpha\frac{\sigma}{G}\right)\right]^n \exp\left[\frac{-Q}{kT}\right] \quad (3)$$

This equation is then re-written into equation (4) in the required format of input for implicit creep model in ANSYS [11]. The constants *C1, C2, C3* and *C4* for Sn-3.8Ag-0.7Cu are given in Table 1.

$$\dot{\varepsilon}_c = C_1[\sinh(C_2\sigma)]^{C3}\exp^{-C4/T} \quad (4)$$

The elastic-plastic-creep (EPC) model for solder can be realized in ANSYS using combined model of bilinear kinematic hardening plasticity with implicit creep.

Table 1 Constants for Sn-3.8Ag-0.7Cu solder [10]

C1	C2	C3	C4
3.2e4	0.037	5.1	6524.7

Anand Model: Anand model is a commonly used viscoplastic model for solder [6]. The Anand model was used for large, isotropic, viscoplastic deformations. There are two basic features in this model. First, this model needs no explicit yield condition and no loading/unloading criterion. Second, this model employs a single scalar as an internal variable, the deformation resistance *s*, to represent the averaged isotropic resistance to plastic flow. The Anand model is broken down into a flow equation, and three evolution equations:

Flow equation

$$\dot{\varepsilon}_p = A\left[\sinh\left(\frac{\xi\sigma}{s}\right)\right]^{1/m}\exp\left(\frac{-Q}{kT}\right) \quad (5)$$

Evolution equations

$$\dot{s}=\left\{h_0(|B|)^a\frac{B}{|B|}\right\}\dot{\varepsilon}_p \quad (6)$$

$$B=1-\frac{s}{s^*} \quad (7)$$

$$s^*=s^{\wedge}\left[\frac{\dot{\varepsilon}_p}{A}\exp\left(\frac{Q}{kT}\right)\right]^n \quad (8)$$

Nine constants in the above Anand model, *A*, *Q/k*, ξ, *m*, $\hat{s}$, *n*, h_0, *a*, s_0, can be determined from the experimental data, such as creep tests and constant strain rate tensile tests [12].

In addition, elastic-creep model (Creep) is considered creep effect on solder material and all inelastic deformation is induced by creep phenomena. For the slow rate loading and lower stress level case, it is reasonable and accurate to just considering creep effect. Another model is elastic-plastic (EP) model. In EP model, the inelastic deformation is induced by plastic behavior without considering creep effect, which is reasonable when mechanical loading such as bending with shorter cyclic time is encountered. Four models mentioned above are commonly used for solder joints when subjected to thermomechanical or mechanical load. However, how these models affect the solder joint stress-strain behavior and life prediction have not been fully discussed from existing literatures, especially for Pb-free solder reliability issue, so Creep model, EP model, Anand model and EPC model are compared and discussed systematically in this study using them as the solder constitutive model for PBGA assembly subjected to thermal cycling and VQFN subjected to bending loading.

3. Thermal Cycling Reliability Test and FEA Analysis for PBGA Assembly

Reliability Test and Analysis: The test specimen is shown in Fig.1. PBGA316 component with pitch of 1.27mm, solder ball stand-off height of 0.58mm and die length of 7.6mm are mounted on the FR4 PCB using Sn-3.8Ag-0.7Cu lead-free solder joints whose distribution is also shown in Fig.1. Six specimens were tested under thermal cycling condition. Thermal Cycling (TC) tests for PBGA specimen were conducted in a three-zone temperature cycling chamber. Thermal cycling loading followed JEDEC Standard [13] with –40^{o}C /125^{o}C temperature range. The test started from room temperature, then ramp up to maximum temperature of 125^{o}C at which dwell time of 15 minutes is used, after that temperature ramp down to minimum temperature of –40^{o}C with dwell time of 15 minutes. The TC loading has cycle time of 60 minutes. The solder joints are connected via daisy chain and used for in-situ resistance monitoring using data logger. Only one daisy chain connects all the solder joints for each PBGA component as shown in Fig.1. Failure of the solder joint is defined when the resistance value is larger than 300Ω. The mean-time-to-failure (MTTF) based on Weibull plot is about 2742 cycles. The failure mode shows the solder fatigue failure with failure site closed to IMC layer on package side.

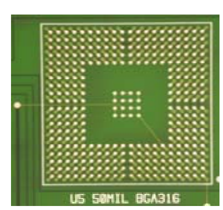

Fig. 1 PBGA layout and solder distribution pattern.

Fatigue Life Prediction Methodology: Low cycle fatigue model is frequently used to predict fatigue life of solder subjected to thermal cycling loading. Morrow's energy-based model is a commonly used low cycle fatigue model [10]:

$$N_f^n W_p = A \quad (9)$$

The fatigue ductility coefficient, A, and the fatigue exponent, n, can be obtained from fatigue test data analysis. In thermal cycling test, temperature changes from –40^{o}C to 125^{o}C with 1 hour per cycle. The isothermal fatigue test condition is required closing to thermal cycling test. The highest temperature and strain rate in thermal cycling test have significant effect on solder joint fatigue failure. According above condition, the isothermal fatigue test condition is selected as at temperature of 125^{o}C with frequency of 0.001Hz. The material constants n, and A for Sn-3.8Ag-0.7Cu solder are 0.897, and 311.7MPa, respectively [10]. Plastic work density or plastic strain energy density accumulated per cycle, W_p, can be extracted from FEA results. The volume-averaged method was commonly used for plastic work density calculation:

$$\Delta W_{ave} = \frac{\sum \Delta W \bullet V}{\sum V} \quad (10)$$

It can be seen from Eq. (10) that the averaged plastic strain energy density is sensitive to elements selected for volume averaging. The accumulated plastic strain energy density is larger on solder/component interface than on solder/PCB interface based on simulation result. Three averaging volumes at solder/component interface were selected for fatigue life prediction study by Che et al. [7] and the result shows that solder fatigue life based on outermost ring elements has a good agreement with test result. Therefore, in following solder joint fatigue life prediction, the outermost ring elements would be selected as averaged-volume.

The global-local modeling technique was used in FE simulation and the 3D quarter global model was used due to symmetry as shown in Fig.2. Temperature dependent material properties were implemented for solder, die, and copper pad. Orthotropic elastic material properties were used for FR-4 PCB [14]. From global model result, the critical solder joint could be determined as shown in Fig.3 and then submodel was created based on this critical solder joint. It can be seen from Fig.3 that the critical solder joint for the PBGA component is the solder ball close to the silicon die corner.

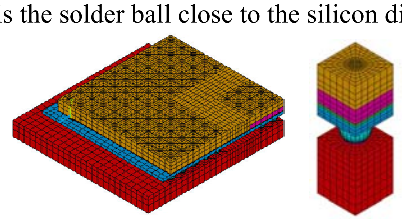

Fig. 2 FEA global model and submodel.

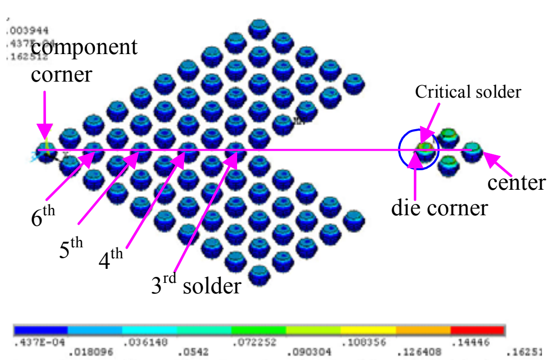

Fig. 3 Plastic work density distribution on solder joint.

Effect of Constitutive Models on Solder Fatigue Life: In this study, elastic-plastic (EP), elastic-plastic-creep (EPC), elastic-creep (Creep) and viscoplastic (Anand) constitutive models for Sn-3.8Ag-0.7Cu discussed above were used in FEA simulation for PBGA assembly, respectively. For solder joint plastic behavior, the temperature dependent yield stress can be calculated using Eq. (2) and listed in Table 2.

Table 2 Temperature dependent yield stress of solder.

Temperature (^{o}C)	-40	25	50	125
Yield stress (MPa)	45.8	22.7	18.4	12.4

Based on outermost ring element volume-averaged result, accumulated strain energy densities per cycle were extracted from FEA results for different solder constitutive models as shown in Fig.4. It can be seen from Fig.4 that the energy density obtained from EPC model, Creep model and Anand model have consistent values. In EPC model, total inelastic strain energy was separated into two parts: creep part and plastic part. It can be seen from Fig.4 that the creep part is dominant (EPC creep) in total inelastic energy density value (EPC total) when using EPC model for PBGA solder joint.

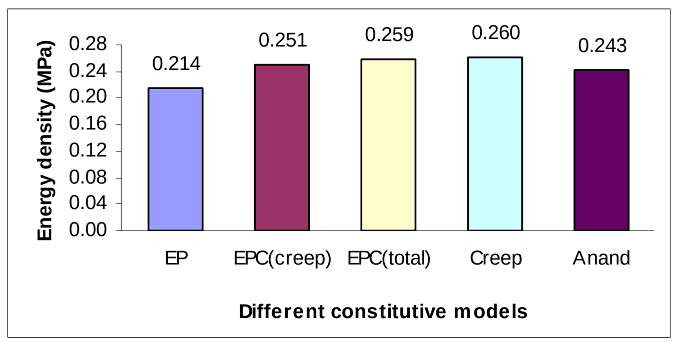

Fig. 4 Strain energy density accumulation per cycle for different constitutive models.

In Anand model, plastic and creep strain energy density cannot be separated and they were unified as inelastic strain energy density. In Creep model, time-dependent creep behavior was considered and it can be developed in any stress level. In EP model, time-independent plastic behavior was considered but time-dependent creep behavior was not considered. Therefore, the energy density calculated from EP model is lower than that from the other models. These phenomena can also be illuminated from Fig.5 where the strain energy density was extracted from central node of solder/component interface. The data curve for EP model shows some flat lines without strain energy density increase during temperature dwell period, while strain energy density from the other models exhibit slight increase during temperature dwell due to creep behavior consideration. Therefore, EP model is not suitable in thermal cycling simulation for solder material because it cannot account for creep behavior in temperature dwell time. The creep and EPC models result in similar strain energy density.

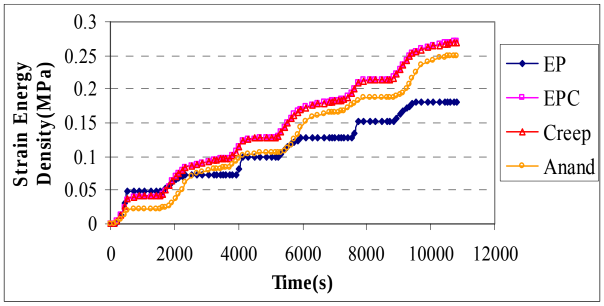

Fig. 5 Strain energy density history for different constitutive models.

Fatigue life calculation was conducted by substituting energy density value of Fig.4 into fatigue model of Eq. (9). The fatigue life prediction based on different constitutive model results was shown in Fig.6. Compared with testing result, the EPC, Creep and Anand models lead to more accurate fatigue life prediction than EP model. The EP model overestimates the solder fatigue life because the creep effect on temperature dwell and ramp up is not considered. Therefore, EPC, Creep and Anand models are consistent and reasonable for solder fatigue life prediction using FEA modeling and simulation for thermal cycling.

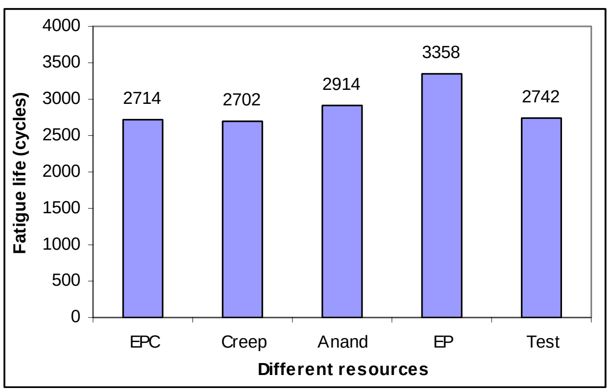

Fig. 6 Fatigue life based on different constitutive models.

4. Cyclic Four-Point Bend Test and FEA Analysis for VQFN Assembly

Bend Test and Analysis: Correlation between three-point bend and four-point bend has been developed by Che and Pang [15, 16] considering components in four-point bend test subjected to the same bending moment value as components in three-point bend. The VQFN assembly with SnAgCu solder was selected for cyclic four-point bend test in this study. The specimen size and layout as shown in Fig.7 follows JEDEC standards [17, 18]. VQFN package of 7mm×7mm×0.8mm was mounted on the FR-4 PCB with size of 132mm×77mm×1mm by 48 SnAgCu solder joints with 0.1mm thickness. Daisy chain loop was designed for each VQFN component and the failure event was detected when resistance of daisy chain loop is greater than 300Ω. Constant bending moment can be obtained between load head in four-point bend test so that all the samples within the load span are subjected to the same stress level, which significantly increase the sample size. From literature review, no bend tests at high temperature, say, 125°C, were reported [19, 20]. In this study, four-point bend tests were conducted at room temperature and high temperature of 125°C to investigate temperature effect on bending fatigue failure. The test results showed that the cycle to failure increases significantly with displacement ranges decreasing for both bend tests at 25°C and at125°C. The acceleration factor of cycle to failure due to high temperature effect is higher than that due to room temperature effect [16]. It was shown by failure mode analysis using cross-section and microscopy that failure mode exhibits solder fatigue failure.

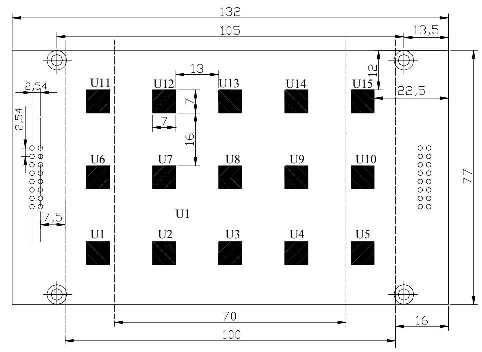

Fig.7 Layout of VQFN specimen.

FEA Analysis for Bending Test: FEA modeling for bend fatigue tests were conducted at 25°C and 125°C to investigate the solder constitutive model and bending temperature effects on stress strain behavior of solder joint. Submodeling technique as shown in Fig.8 was used for board-level FEA simulation. Corner solder joints of VQFN package were prone to failure and submodel was created based on corner solder joint accordingly. The difference between bend simulations at 25°C and 125°C is that some material properties used in high temperature bend simulation are temperature-dependent [15] and before applying bending load, temperature ramp up from 25°C to 125°C was simulated.

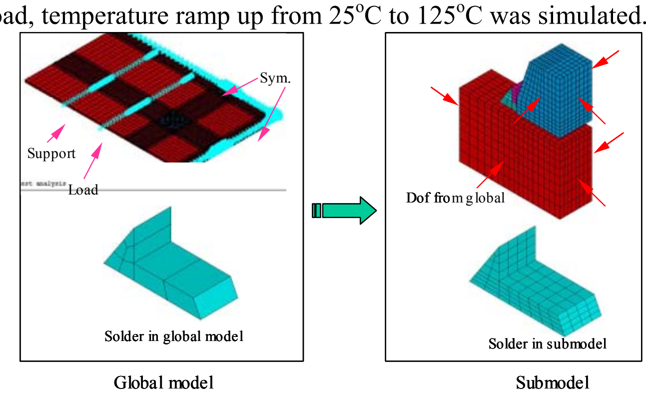

Fig. 8 Quarter FEA global model and submodel.

The top and bottom solder joint interface layers as shown in Fig.9 were selected for volume-averaged strain energy density calculation. The simulation result shows that the accumulated strain energy density on bottom layer is much higher than that on top layer for both bending simulations at 25°C and 125°C due to PCB bending deflection effect. Therefore, the subsequent analyses focus on bottom layer volume-averaged result.

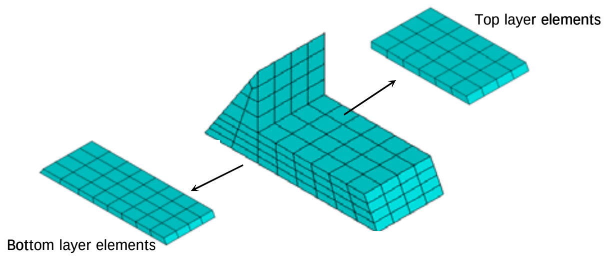

Fig. 9 Solder joint mesh and averaging volumes.

The result comparison between bending simulation at 25°C and at 125°C with the same maximum displacement of 2.16mm and Anand model for solder is shown in Fig.10. Usually, 10 to 15 simulation cycles are needed to obtain converged results for bending load with 1Hz frequency when using Anand model [19]. It is found from Fig.10 that convergence of 5% difference between two continue cycles was obtained after 15 cycles for both room temperature bend and high temperature bend FEA simulation. However, for EPC model the converged result can be obtained after 4 or 5 simulation cycles as shown in Fig.11. It also can be seen from Fig.10 that the strain energy density accumulation in high temperature bending simulation is higher than that in room temperature case, which indicates that higher temperature accelerates bending fatigue failure of solder joint compared to room temperature.

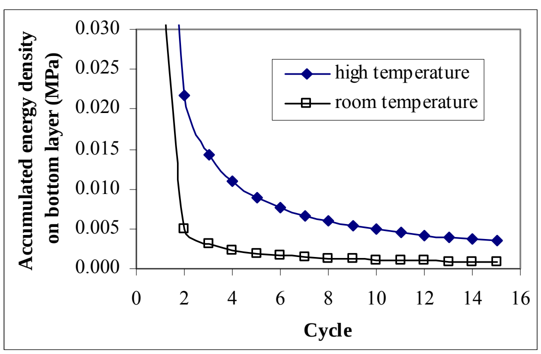

Fig. 10 Energy density accumulation per cycle for bending simulation with 2.16mm deflection and Anand model.

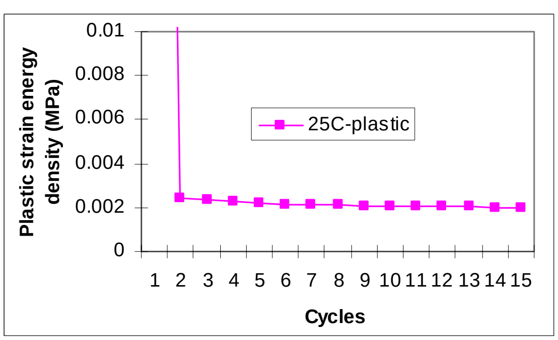

Fig. 11 Energy density for bending simulation at 25°C with 2.16mm deflection and EPC model.

Generally, mechanical loading is much faster than thermal cycling loading with cycle time from several minutes to hours. It was shown from above thermal cycling simulation result that Anand model, Creep model and EPC model result in consistent results due to slow strain rate in thermal cycling. In this study, all four different solder constitutive models mentioned above were also used for mechanical bending simulation to investigate the constitutive model effect on solder behavior under fast bending loading. Figs.12 and 13 show the FEA result comparison using different solder constitutive models in room and high temperature bend simulations, respectively. For room temperature case, EPC model and Anand model lead to consistent results after convergence and EP model results in lower energy density due to low-level plastic behavior at room temperature. However, for high temperature case, EPC model and EP model lead to consistent results based on the fact that the plastic part is dominant compared to creep part because for such large plastic deformation case, the plastic strain suppresses the creep development. The Anand model and Creep model result in similar lower energy density and the result convergence is slow because creep cannot fully develop in shorter cyclic period of bending. Therefore, for high temperature FEA bending simulation, the Anand model and Creep model are not suitable model based on result analysis and physical explanation. For both room temperature and high temperature bending simulations, EPC is a suitable model with faster convergence and reasonable result compared to others.

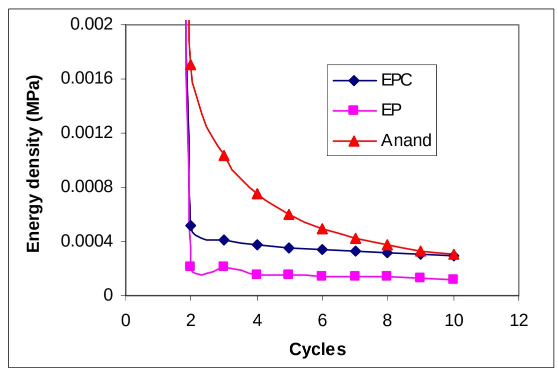

Fig. 12 Energy density accumulation per cycle for bending simulation with 1.5mm deflection and 25°C.

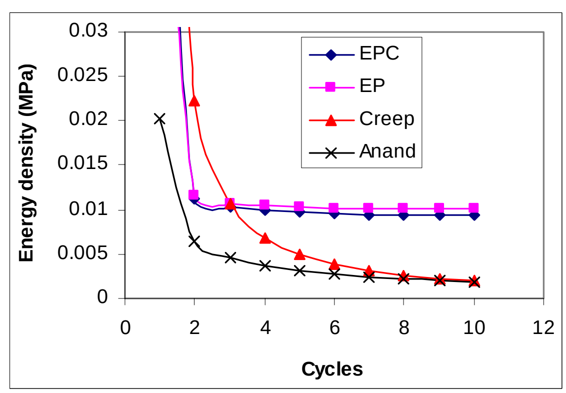

Fig. 13 Energy density accumulation per cycle for bending simulation with 1.5mm deflection and 125°C.

Usually, the EPC model was used for cyclic loading simulation from slow loading rate (thermal cycling) to fast loading rate (mechanical bending), while the Anand model is only suitable for slow loading rate, such as thermal cycling.

5. Conclusions

In this study, four different solder constitutive models including elastic-plastic (EP), elastic-creep (Creep), elastic-plastic-creep (EPC) and viscoplastic Anand's (Anand) models are implemented in FEA modeling and simulation to investigate solder constitutive model effect on solder fatigue life and stress-strain response considering two cases involving in PBGA subjected to thermal cycling and VQFN assembly subjected to cyclic bending. Fatigue life prediction shows that the Creep, EPC and Anand's models result in consistent fatigue life for PBGA assembly. When using EPC model, plastic strain is very small compared to creep strain for PBGA assembly. The EP model is not suitable in FEA simulation for thermal cycling because creep behavior cannot be considered.

For cyclic bending study for VQFN assembly, accumulated energy density per cycle at 125^{o}C is more than that at 25^{o}C significantly, which indicates that higher temperature accelerates bending fatigue failure of solder. The significant different simulation result can be found when using different constitutive models. The EPC model and EP model can lead to reasonable result and accumulated strain energy density per cycle is easier to converge for high temperature bending case. For room temperature, the EPC model also can lead to reasonable result compared to other models.

Therefore, for thermal cycling simulation, Creep, EPC and Anand models can be used as solder constitutive model. The EPC model is suitable for cyclic bending simulation, while the Creep and Anand model are not reasonable for cyclic bend with high frequency of 1 Hz because creep cannot develop at fast loading rate, therefore is not a great concern.

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