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Improving the Solder Joint Reliability Prediction Accuracy for Quad Flat No Lead Packages

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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Short Research Article

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ABSTRACT

This paper discusses the modeling approach used in improving the solder joint reliability prediction for Quad Flat No Lead (QFN) packages. A new power equation fatigue prediction model was developed based on the accumulated creep strain energy density from FEA (finite element analysis) simulation and the corresponding actual experimental result in terms of solder characteristic life of different QFN packages. The new curve fitted fatigue life correlation equation was then used in the solder joint reliability modeling together with the use of a hyperbolic sine constitutive model for lead-free solder. The model prediction using the new curve fitted equation was compared with the result from using the equation previously published. Based on the results, the new curve-fitted life prediction equation was able to improve the accuracy of solder life prediction. This study shows that solder joint reliability prediction could be improved by developing a prediction model based on actual data and consistent FEA modeling considerations in terms of methodology, material model and properties.

Keywords: Solder joint reliability; thermomechanical modeling; fatigue correlation model; finite element analysis; QFN.

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1. INTRODUCTION

Prediction of solder joint life under thermal cycling on board (TCoB) conditions is important in microelectronics packaging. Actual thermal cycling takes considerable time and resources especially when evaluating several package designs. Modeling using finite element analysis (FEA) technique has then become popular in assessing solder joint reliability before an actual package is manufactured. It can be used to select the best package design and materials from several available options. There are solder constitutive models and fatigue life prediction models developed from empirical data to predict solder joint life. However, these models may not produce accurate results when used in other packages or conditions other than the specific case it has been developed for. For instance, solder fatigue life correlation model for Ball Grid Array (BGA) packages would result in significant discrepancy in predicted solder life when used for Quad Flat No Lead (QFN) packages as revealed in a previous study involving lead-free solder material [1].

Evaluation of solder joint reliability is commonly done with thermal cycling conditions for a semiconductor package mounted on printed circuit board (PCB). In this case, the reliability of the solder joint connection between the package and the PCB is assessed when subjected to alternating cold and hot temperatures. Under thermal cycling, the solder joint is subjected to higher levels of stress that could then result in solder crack because of the differences in the coefficient of thermal expansion (CTE) of the materials.

For applications requiring better dissipation of heat generated in the integrated circuit (IC) die, leadframe-based packages are commonly used because of its superior thermal performance compared to laminate substrate-based packages. Among the leadframe-based packages available in the semiconductor industry, QFN is one of the most popular. When this QFN is mounted on PCB as shown in Fig. 1, the exposed die pad of the leadframe acts as a heatsink for removing heat from the die. A solder joint material establishes electrical and mechanical connections between the IC package and the PCB. The solder joint connection of the leadframe die pad under the die to the PCB also serves as a thermal path for heat dissipation. In recent years, lead-free solder materials like SAC solder (SnAgCu) have been widely used to replace the lead-based solder materials due to regulations restricting the inclusion of lead in most consumer electronics.

In this study, the solder joint reliability of QFN packages using lead-free SAC solder was investigated. Using the SAC solder constitutive model and fatigue life prediction equation for QFN from existing literature [1], FEA modeling was conducted. However, the solder fatigue life predicted from modeling showed some significant deviations from actual results. Hence, this study would explore the development of a new power equation fatigue prediction model for QFN based on the accumulated creep strain energy density from FEA simulation and the corresponding actual experimental result in terms of solder characteristic life of different QFN packages. Development of a new QFN solder fatigue correlation model was pursued with the goal of improving the solder joint reliability prediction.

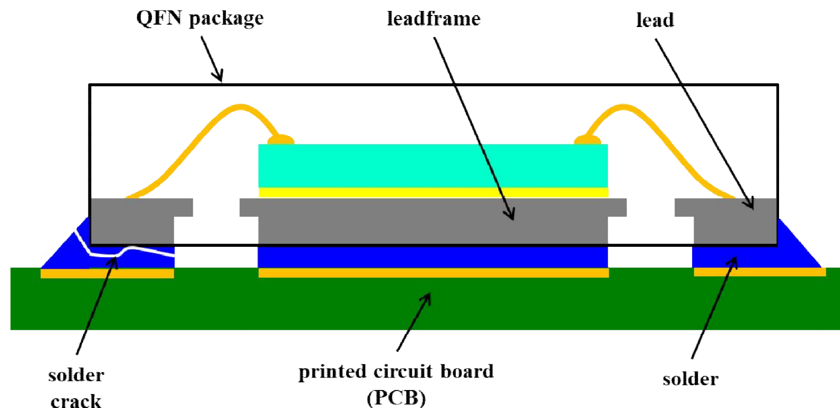

Fig. 1. QFN package soldered on PCB

2. SOLDER JOINT FATIGUE LIFE PREDICTION

Solder joint fatigue life prediction requires the solder constitutive model for the specific solder material being used to connect the package to the PCB. Aside from the solder constitutive model, a life prediction model is also needed to come up with the characteristic solder life in terms of the number of thermal cycles before joint failure happens.

2.1 Solder Material Constitutive Models

For a specific solder material, a constitutive model describes the physical properties or material responses to various loading conditions and provides the stress–strain relationship of the material. Four different material models including elastic-plastic (EP), elastic-creep (Creep), elastic-plastic-creep (EPC) and viscoplastic Anand's (Anand) models were considered in a modeling and simulation study to investigate the solder constitutive model effect on solder fatigue life and stress-strain response [2]. Based on fatigue life prediction, it was shown that Creep, EPC and Anand models are suitable for thermal cycling simulations. However, for SAC solders (e.g. SAC 305, SAC405, SAC396 and SAC387), the hyperbolic sine creep equation is commonly used to model the solder's temperature and time-dependent creep behavior. It is defined as [2,3]:

$$\dot{\varepsilon}_c = C_1 \frac{G}{T}\left[\sinh\left(\alpha \frac{\sigma}{G}\right)\right]^n \exp\left[\frac{-Q}{kT}\right] \quad (1)$$

Equation (1) can be simplified and rewritten as:

$$\dot{\varepsilon}_c = C_1 [\sinh(C_2\sigma)]^{C_3} \exp\left[\frac{-C_4}{T}\right] \quad (2)$$

where,
$\dot{\varepsilon}_c$ = creep strain rate
σ = applied stress
C_1, C_2, C_3, C_4 = material constants
T = absolute temperature in Kelvin

Equation (2) is also known as the Garofalo hyperbolic sine law [4] in which C_2 is obtained from curve fitting to experimental data by using linear and nonlinear least square regression and C_3 is the stress exponent which can be determined from creep deformation map. The material constant, C_4, is a function of the activation energy, Q, expressed in kJ/mol or eV and the Boltzmann's constant, k.

There are researchers [3,5-7] who have done characterization on the creep behavior of SAC solders. As shown in Table 1, different material constants are reported. The variations in the values of the viscoplastic creep model constants of these solder materials are mainly caused by differences in specimen geometry, testing methodology, and test conditions (varying temperature and stress levels) [8].

In ANSYS FEA software, the material constants (C_1, C_2, C_3 and C_4) are the required inputs to define the creep strain rate of the solder material considered. The constitutive model material constants adopted and implemented in the solder joint FEA modeling in this study were based on the results published by Pang et al [3].

2.2 Solder Fatigue Life Prediction Models

Solder fatigue life prediction also requires a correlation model that relates an FEA solder joint simulation output parameter to the solder life. The fatigue life prediction could either be based on strain or strain energy. However, it was shown in a previous study that the energy-based fatigue model resulted in accurate and reasonable fatigue life prediction compared to strain-based fatigue model [9,10]. To reduce the stress concentration effect, the volume-averaging method is typically used in parameter extraction from simulation results for solder fatigue life prediction [11]:

$$W_{cr} = \frac{\sum(W_{cri}\, V_i)}{\sum V_i} \quad (3)$$

Table 1. Material constants for SAC solder alloys

Solder Alloy	Reference	C_1 (1/s)	C_2 (1/MPa)	C_3	C_4 (K)
SAC387	Pang et al [3]	32000	0.037	5.1	6524.7
SAC387	Schubert et al [5]	277984	0.02447	6.41	6500
SAC396	Lau et al [6]	441000	0.005	4.2	5412
SAC305	Vianco [7]	2630	0.0453	5.0	6300

** SAC387 = Sn3.8Ag0.7Cu; SAC396 = Sn3.9Ag0.6Cu; SAC305 = Sn3.0Ag0.5Cu*

The volume-averaged accumulated strain energy density per cycle (W_{cr}) in equation (3) is implemented on the results in ANSYS software using a set of commands or script. Once the accumulated strain energy density per cycle is obtained from the model output, the characteristic life in terms of the number of thermal cycles, Nf (63.2% accumulative failure), can be calculated by using the fatigue life correlation model developed for a given solder material.

There are fatigue life correlation models published for solders and one of them is Schubert's correlation model for SnAgCu(SAC) solders [5] as defined in equation (4) below. This has been found to have good prediction accuracy for ball grid array (BGA) laminate-based packages with solder ball connection.

$$N_f = 345W_{cr}^{(-1.02)} \quad (4)$$

Another fatigue correlation model derived from curve fitting was reported by Syed [12,13] for BGA packages using SAC solder and is given in equation (5).

$$N_f = 674.08W_{cr}^{(-0.9229)} \quad (5)$$

Though Schubert's solder fatigue correlation model, defined in equation (4), is quite popular for BGA packages, a related study [1] has shown that it would not give a good solder fatigue life prediction when used with QFN packages. A different fatigue correlation model was developed that appears to work well with solder fatigue life prediction for QFNs. The curve fitted QFN prediction model is defined by equation (6).

$$N_f = 741.37W_{cr}^{(-0.3902)} \quad (6)$$

It can be observed that there are also variations in the solder fatigue life correlation equations for SAC solders as reported by different researchers. One source of these variations can be the differences in the modeling methodology to get the accumulated creep strain energy density per cycle from FEA simulation. In this study, the fatigue life prediction equation (6) for QFN was initially used. However, there were some significant deviations from actual results that prompted the development of a new fatigue life prediction equation using curve fitting with actual QFN data.

2.3 Solder Joint Reliability Simulation using FEA

The solder joint reliability simulation in this study was done using ANSYS FEA software. Linear elastic material properties were used for all the package materials and PCB except the solder material. The material properties of the SAC solder used are shown in Table 2. The model was using SOLID186 finite elements. The thermal cycling condition considered is shown in Fig. 2. As indicated, the temperature is from -40°C to 125°C. This thermal cycling profile follows the Jedec standard with 10 minutes dwell time and 5 minutes ramp time. This condition results in having the solder joint connection subjected to 2 thermal cycles per hour. Three thermal cycles were simulated since this is the number of cycles in which the accumulated strain energy density or plastic work accumulation is already stable, and the change becomes minimal [14].

The FEA model of the board-mounted QFN package investigated is shown in Fig. 3. Quarter symmetry finite element model was used to reduce the computation time. This is also valid since the package is symmetric in the X-axis as well as in the Y-axis. The solder joint connecting the package leads to the PCB has the solder fillet included since it is a critical joint and the model must be close as possible to the actual solder joint shape for accuracy of results.

As shown in Fig. 4, there are 4 layers of elements in the solder thickness direction. This number of layer elements was consistently maintained in all the simulations done. The top interface layer of the critical joint was used for calculating the volume-averaged accumulated strain energy density per cycle according to equation (3). The accumulated strain energy density obtained from this top interface layer was

Table 2. Material Properties of the SAC Solder [3] in the FEA Modeling

Solder Material	CTE (ppm/ °C)	Modulus (GPa)	Constitutive Model
SAC387 (Sn3.8Ag0.7Cu)	22	54.4@-40°C, 41.7@25°C, 36.8@50°C, 22.2@125°C	Hyperbolic sine model: C_1 = 32000, C_2 = 0.037, C_3 = 5.1, C_4 = 6524.7

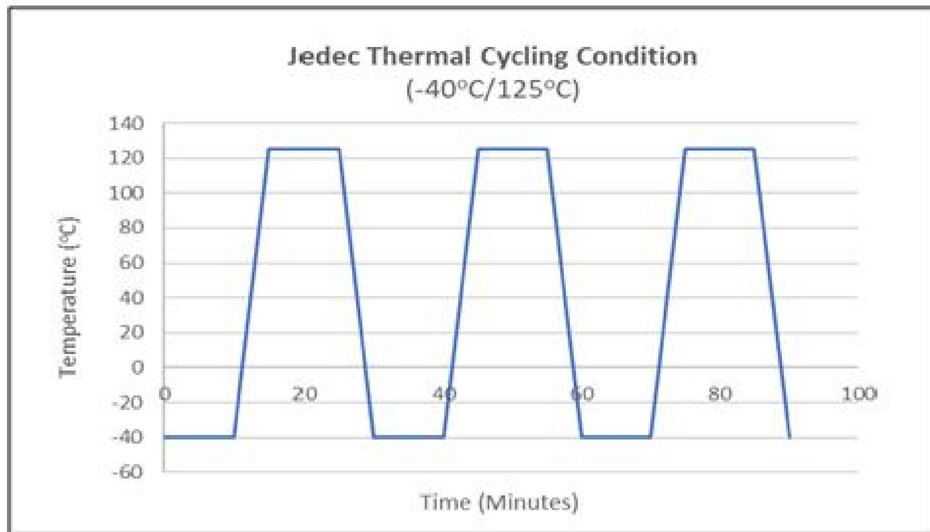

Fig. 2. Jedec thermal cycling (TC) profile

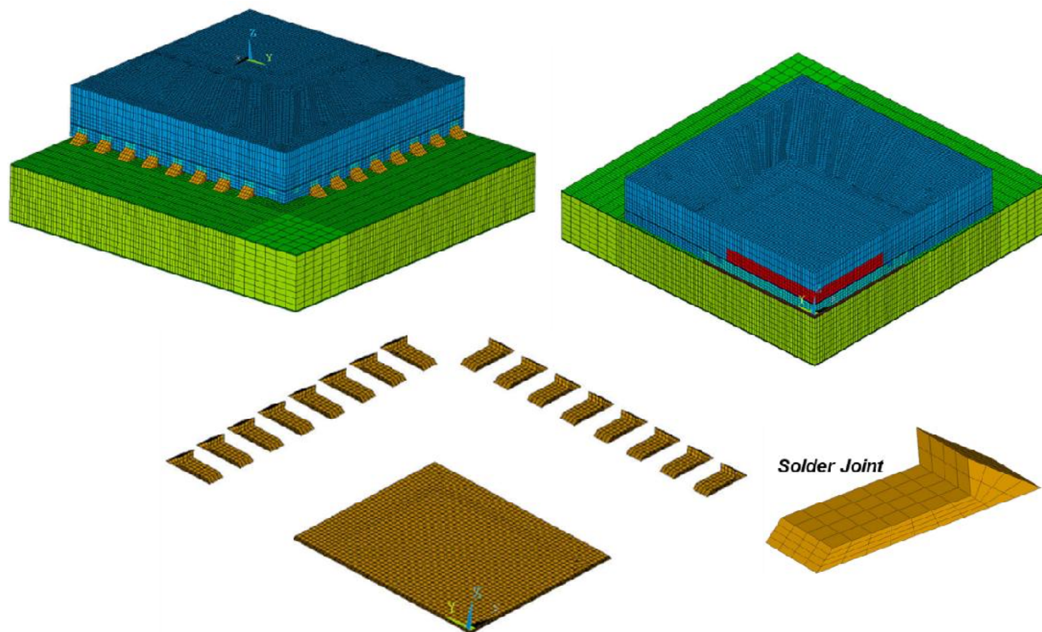

Fig. 3. Finite element model of the QFN package soldered on PCB

used in the fatigue life prediction. The characteristic solder life was calculated using equation (6), which is the fatigue life prediction model for QFN published in literature [1].

After the accumulated creep strain energy was obtained from the FEA outputs results, another set of simulation was also conducted with the other QFN packages that have actual solder joint life data available. The values of the accumulated creep strain energy density per cycle for each QFN package were then plotted versus the corresponding values of the actual solder life. Then curve fitting was performed to obtain a power equation that would define the solder fatigue life as a function of the accumulated creep strain energy density per cycle.

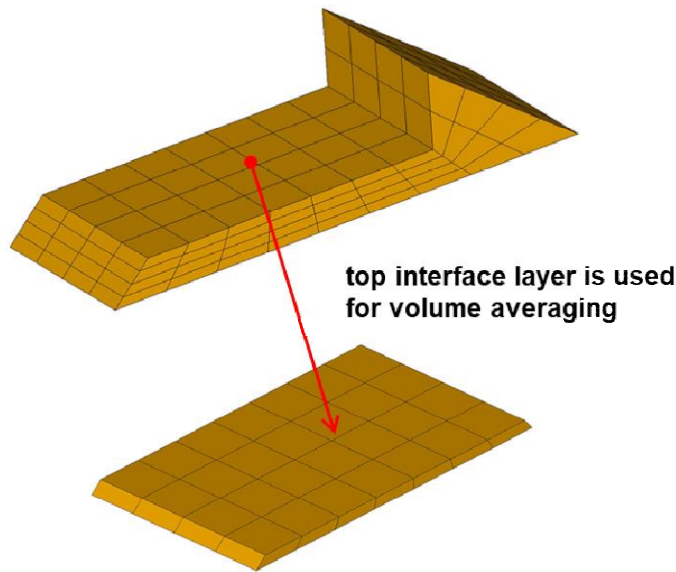

Fig. 4. Solder layer used in the strain energy density volume averaging

3. RESULTS AND DISCUSSION

The creep strain energy density contour plot after 3 thermal cycles is shown in Fig. 5. The modeling shows that the critical solder joint is located at the package corner and is the one expected to fail earlier than the other joints. The volume-averaging technique presented earlier was implemented to get the accumulated creep strain energy density per cycle for the top solder material interface layer. From the accumulated strain energy density per cycle obtained, the characteristic life was calculated using the published QFN solder fatigue life prediction model described previously. Fig. 6 shows the comparison between the predicted solder life using published QFN solder fatigue life model and the actual solder life data. Comparison shows some significant deviations from actual results. The solder life predictions are quite far from the actual data for QFN B, QFN C, QFN D, and QFN E. Only QFN A shows good agreement between the predicted value and the actual result. The predicted solder life values are generally much lower than the actual values. This implies that there is still a need to improve the solder life prediction by developing a new solder fatigue life correlation equation.

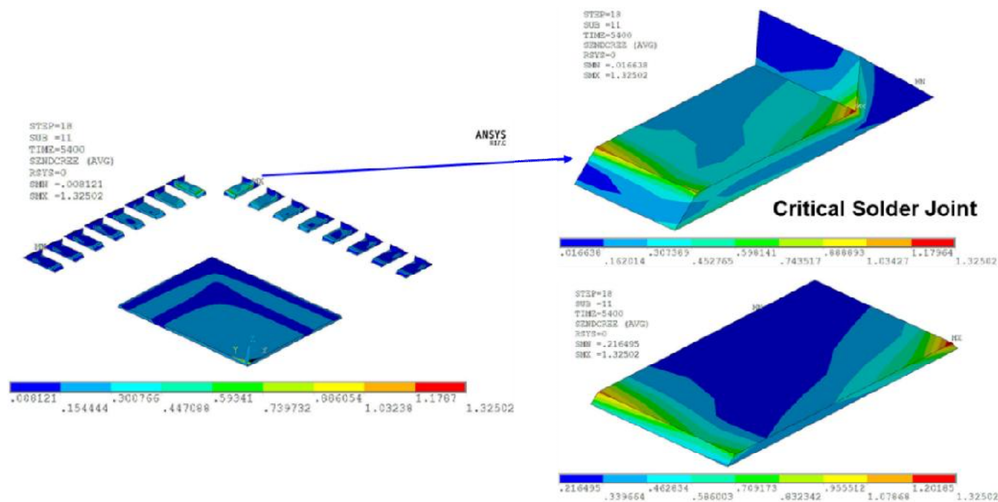

Fig. 5. Creep strain energy result of the solder joint after 3 thermal cycles

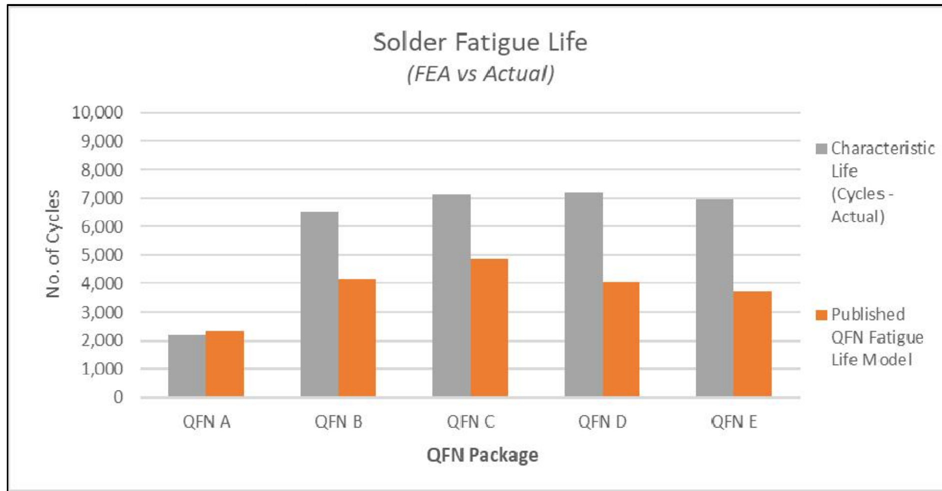

Fig. 6. Comparison of results using published fatigue life model vs actual solder life

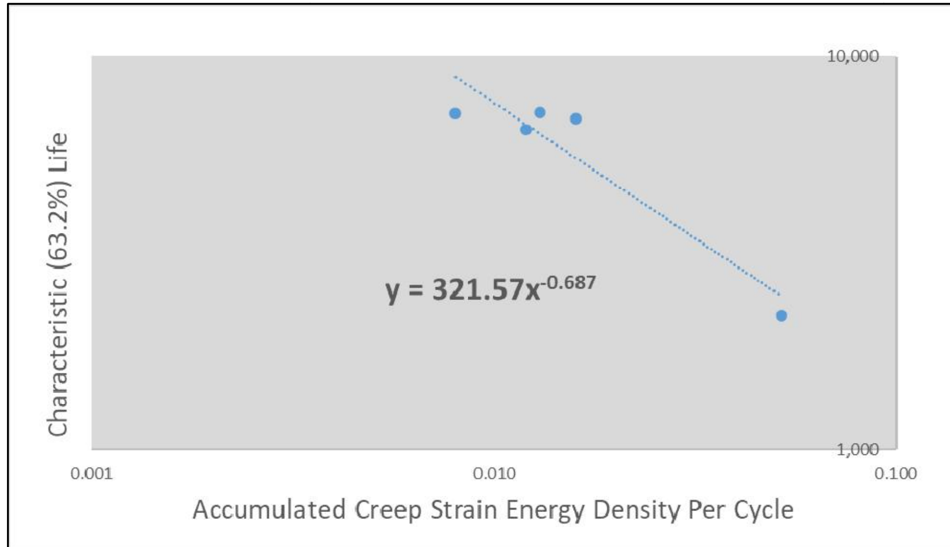

Fig. 7. New curve fitted QFN life prediction correlation model

Table 3. QFN Packages with Actual Solder Life

Package	*Accumulated creep strain energy density*	*Actual solder life (# of Cycles)*
QFN A	0.052	2191
QFN B	0.012	6522
QFN C	0.008	7144
QFN D	0.013	7184
QFN E	0.016	6937

Curve fitting was done with the actual solder joint characteristic life data in Table 3. After performing the curve fitting to obtain a power equation that would define the solder fatigue life as a function of the accumulated creep strain energy density per cycle obtained from FEA, the new curve fitted solder fatigue life correlation model is given in Fig. 7. The new QFN correlation model defined in equation (7) was then used to obtain new sets of predicted solder life for the QFN packages considered.

$$N_f = 321.57W_{cr}^{(-0.687)} \qquad (7)$$

With the new curve fitted fatigue life correlation equation, the predicted solder life is compared with the actual result as shown in Fig. 8.

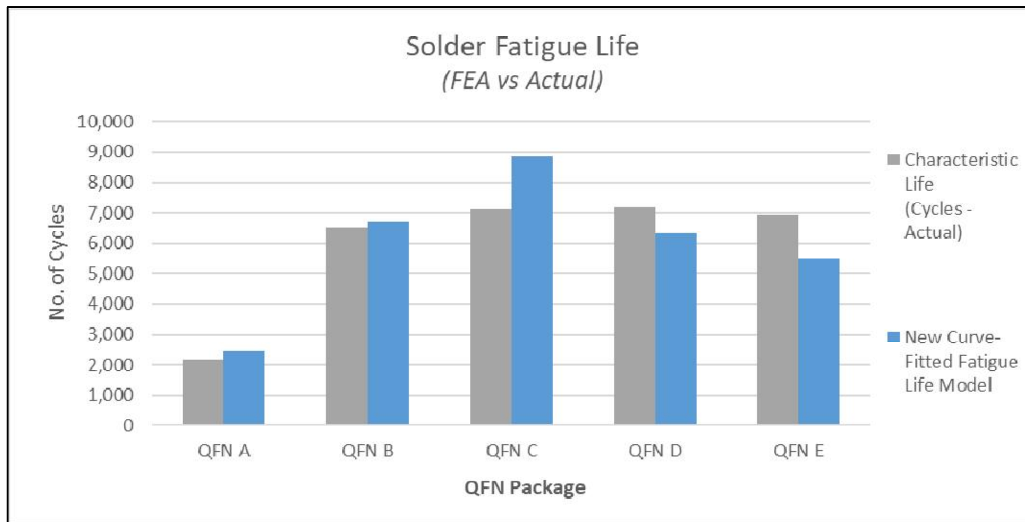

Fig. 8. Comparison of results using the new curve fitted fatigue life model with actual solder life

Comparison shows that the predicted solder life values are now in good agreement with the actual data. This indicates that solder life for QFN packages can be improved by developing fatigue correlation model based on actual solder life data. Consistency in the modeling methodology, solder constitutive model and other material properties used to come up with the correlation model is also necessary.

4. CONCLUSION

Based on this study, using published solder fatigue correlation models would not ensure accuracy in the solder life prediction in semiconductor packages. Those models may not produce accurate results when used in different packages, conditions or modeling considerations. Solder joint reliability prediction could be improved by developing a new solder fatigue life correlation equation using consistent modeling methodology, material model and properties. The fatigue life model is obtained by curve fitting the accumulated creep strain energy density per cycle and the corresponding solder life from actual thermal cycling evaluation. Further refinement of the QFN fatigue life correlation model developed in this study is planned as more QFN solder life data are available in the future.

DISCLAIMER

The products used for this research are common and predominantly used in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because there is no intent to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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