Thermal Cycling Analysis of Flip-Chip Solder Joint Reliability

John H. L. Pang, D. Y. R. Chong, and T. H. Low

***Abstract*—The reliability concern in flip-chip-on-board (FCOB) technology is the high thermal mismatch deformation between the silicon die and the printed circuit board that results in large solder joint stresses and strains causing fatigue failure. *Accelerated thermal cycling* (ATC) test is one of the reliability tests performed to evaluate the fatigue strength of the solder interconnects. Finite element analysis (FEA) was employed to simulate thermal cycling loading for solder joint reliability in electronic assemblies. This study investigates different methods of implementing thermal cycling analysis, namely using the "*dwell creep*" and "*full creep*" methods based on a phenomenological approach to modeling time independent plastic and time dependent creep deformations. There are significant differences between the "*dwell creep*" and "*full creep*" analysis results for the flip chip solder joint strain responses and the predicted fatigue life. Comparison was made with a rate dependent viscoplastic analysis approach. Investigations on thermal cycling analysis of the *temperature range,* (ΔT) effects on the predicted fatigue lives of solder joints are reported.**

***Index Terms*—Fatigue, flip-chip, reliability, solder joint, thermal cycling.**

I. Introduction

THE TREND of electronic products today is moving toward further miniaturization and improved performance. The continuous drive toward high density and low profile integrated circuit (IC) packaging has led to the growing application of flip-chip-on-board (FCOB) assemblies. In a FCOB assembly, the silicon die is directly attached to the FR4, printed circuit board (PCB) with 63%Sn–37%Pb eutectic solder joints. The epoxy underfill encapsulant fills the space between the silicon die and PCB giving reinforcement for the solder joints as shown in Fig. 1.

Thermal mismatch deformations arise due to differences in the coefficient of thermal expansion (CTE) between the assembly materials and high solder joint stresses and strains are generated. Low cost solder bumped FCOB assembly process employ eutectic 63%Sn–37%Pb solder joints which melts at $T_m = 456$ K (183 °C), where T_m, is the melting temperature. Reliability tests are necessary to assess the performance of the solder joints subjected to *accelerated thermal cycling* (ATC) tests where the solder joints are subjected to a homologous temperature of 0.5 to 0.87 T_m for a test temperature range of -55 °C to $+125$ °C. Hence, creep deformation plays an important role in the failure of flip chip solder joints. The low cycle fatigue failure response of the solder joints is a creep-fatigue mechanism which involves crack initiation and crack growth until complete rupture of the solder connection.

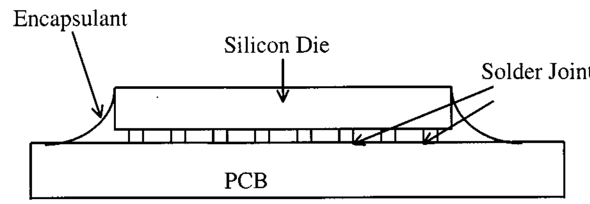

Fig. 1. Solder-bumped flip-chip-on-board assembly.

Finite element analysis (FEA) is widely used in the electronic packaging industry for modeling the physics of failure in solder joints subjected to thermal cycling test condition. In FEA simulation of thermal cycling analysis, the initial temperature or stress free state temperature is often modeled at room temperature (25 °C), or at the underfill encapsulant cure temperature. For example, Pang and Chong [3] used room temperature at 25 °C as the initial stress free state temperature, while Michealides and Sitaraman [4] and Pang *et al.* [5] assumed a stress free state of 140 °C at the curing temperature of the underfill epoxy. A more practical assumption would be to choose the stress free state at the melting point temperature of 183 °C. The stress free state temperature chosen for the analysis may have an effect on the solder joint strain response but this is not within the scope of this study. In this study, two issues on thermal cycling analysis will be addressed.

Firstly, two different approaches of modeling thermal cycling analysis were investigated. For example, Pang *et al.* [1]–[3] employed a phenomenological approach by modeling time independent plasticity and time dependent creep deformations separately and is simply called an elastic-plastic-creep analysis. Pang *et al.* [1] classified the elastic-plastic-creep analysis method into the "*full creep*" and the "*dwell creep*" methods of analysis. The "*full creep*" method of analysis models creep deformations during the temperature ramps and is expected to result in different equivalent plastic and creep strain range components compared to the "*dwell creep*" method which omits creep behavior during the temperature ramps. An alternative approach is to employ a physical state variable constitutive model for rate dependent viscoplastic analysis of solder as reported by Darveaux [6].

Secondly, a study on the effects of different temperature ranges, ΔT, with different maximum $(T_{\max})$ and minimum $(T_{\min})$ temperature limits were analyzed for five different thermal cycling test conditions. This study provide a numerical

Manuscript received February 1, 2001; revised June 22, 2001. This paper was recommended for publication by Editor A. Bar-Cohen upon evaluation of the reviewers' comments.

The authors are with the Centre for Advanced Numerical Engineering Simulations (CANES), School of Mechanical and Production Engineering, Nanyang Technological University, Singapore 639798 (e-mail: mhlpang@ntu.edu.sg).

Publisher Item Identifier S 1521-3331(01)08932-2.

1521–3331/01$10.00 © 2001 IEEE

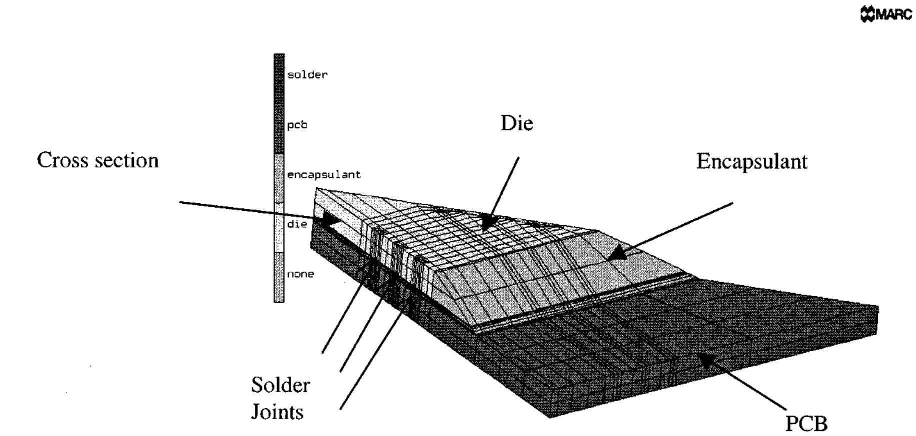

Fig. 2. FEA model of the FCOB assembly (3-D-1/8th model).

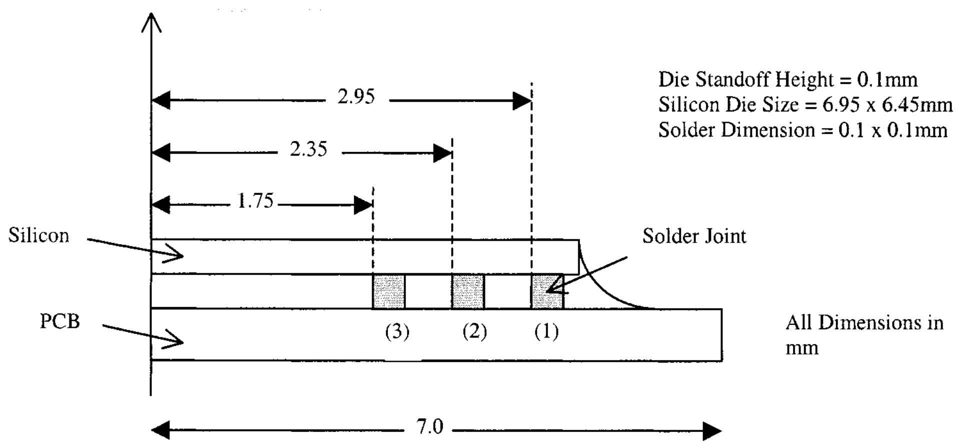

Fig. 3. Dimensions of the FCOB assembly section.

analysis basis for correlating different thermal cycling test conditions. For a higher $T_{\max}$ and a larger ΔT, creep deformation is expected to be more important. The "*full creep*" method of analysis is expected to show the competing effects of plastic strain and creep strain range in the solder joint for a small ΔT (of 25 °C to 75 °C) to a large ΔT (of −55 °C to +125 °C). A comparison between the elastic-plastic-creep analysis to the viscoplastic analysis results will be made.

II. Elastic-Plastic-Creep Analysis Method

A. FCOB Assembly and Material Properties

A three-dimensional (3-D) FEA model of the FCOB assembly was created as shown in Fig. 2. Due to its symmetry, only one-eighth of the FCOB assembly was modeled using a 3-D-1/8th FEA symmetry model along the two symmetry planes. The solder joints along the two symmetry planes of the FCOB assembly were modeled. The dimensions of the FCOB cross section, is shown in Fig. 3 where both the silicon die and PCB have a thickness of 0.5 mm.

The elastic properties of all materials at room temperature are considered to be homogenous and are given in Table I. The solder joints were modeled with elasto-plastic and creep material properties while the other parts of the FCOB assembly remain elastic. The *MARC* nonlinear FE program [7] was used to implement the *full creep* and *dwell creep* methods of analysis.

TABLE I
Elastic Material Properties of the FCOB Assembly

FCOB Materials	Elastic Modulus (MPa)	CTE (ppm/°C)	Poisson's Ratio
Silicon Die	131000	2.8	0.3
Solder	30674	21	0.35
Encapsulant	6900	29	0.3
FR-4 (substrate)	22000	18	0.28

The solder was assumed to exhibit elastic perfectly plastic behavior after yielding. The Elastic modulus and yield stress of solder [1] was assumed to be temperature dependent given by

$$E(T) = 75\,970 - 152T \text{ (N/mm}^2\text{)} \quad (1)$$

$$\sigma y(T) = 49.2 - 0.097T \text{ (N/mm}^2\text{)} \quad (2)$$

where temperature, T, in both (1) and (2) is in Kelvin.

The creep constitutive law for solder was taken from Darveaux's paper [8]

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

$$G = 28\,388 - 56T \text{ (N/mm}^2\text{)} \quad (4)$$

where

$\dot{\varepsilon}_c$ equivalent creep strain rate (s^{-1});
σ equivalent von Mises stress (N/mm^2);
G temperature dependent shear modulus (N/mm^2);

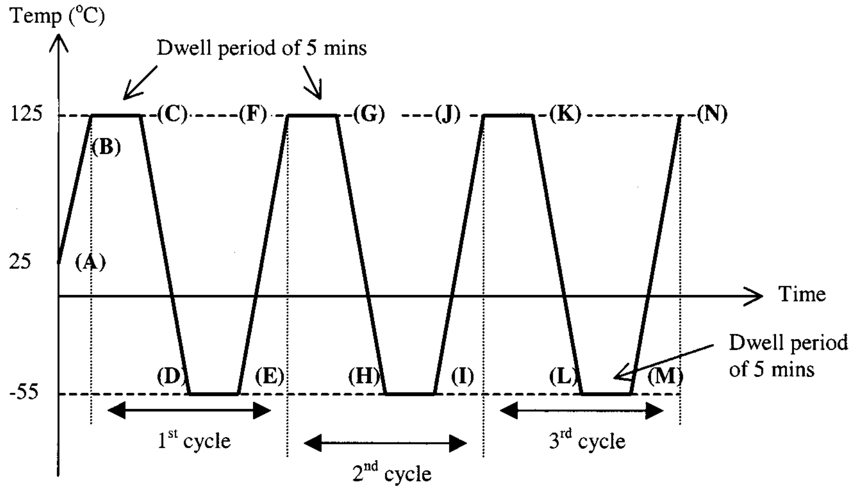

Fig. 4. Simulation of three temperature cycles.

T	absolute temperature (kelvin);
C_1	16.7 (K/s/N/mm^2)—a constant;
α	866; stress level at which power law dependence breaks down;
n	3.3; stress exponent for dislocation glide-controlled kinetics;
Q	0.548 (eV); activation energy for creep deformation process;
k	8.617×10^{-5} (eV/K); Boltzmann's constant.

B. Modeling and Simulation of Thermal Cycling Analysis

The temperature profile is shown in Fig. 4 and it specifies the temperature range of -55 °C $(T_{\min})$ to $+$ 125 °C $(T_{\max})$. The FEA model is subjected to incremental steps of temperature change steps with elastic-plastic analysis and time steps with creep analysis. The start or stress free state of the thermal loading is 25 °C, at room temperature and three cycles of temperature loading were simulated. The ramp rate is 50 °C/min and the dwell period is 5 min with a cyclic frequency of approximately 10^{-3} Hz. The ramp rates and dwell time are significant parameters for thermal cycling analysis and has influence on the extent of solder creep and stress relaxation process during the ramp up and down periods. Pang and Chong [3] have earlier shown that at slower ramp rates, more creep exposure occurs at the ramp up and down period. Shiratori and Yu [9] have determined that creep deformation is significant during the earlier part of the dwell period and diminishes when stress relaxation occurs. Thus, longer dwell time is not necessary and a dwell time of 5 minutes is sufficient for solder stress to relax to a lower level where creep strain accumulation is no longer significant.

The two methods of analysis for the "*dwell creep*" and "*full creep*" methods are illustrated in Figs. 5 and 6, respectively.

1) "Dwell Creep" Method of Analysis: For the "*dwell creep*" method time independent *elastic-plastic* analysis was implemented during temperature ramp up and down periods by temperature change steps. During the dwell period, creep analysis for 5 min was implemented for the dwell periods at the maximum and minimum temperature limits of the loading cycle (125 °C and -55 °C).

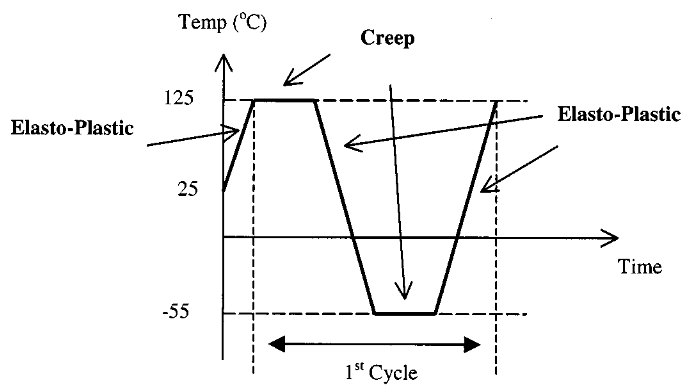

Fig. 5. Temperature profile for the "*Dwell Creep*" method.

2) "Full Creep" Method of Analysis: In the "*full creep*" method of analysis, alternate increments of time independent elastic-plastic and time dependent creep analysis were implemented during temperature ramp up and down periods by alternating between a small temperature step for elastic-plastic analysis and then a time step for creep analysis. During the dwell periods, only creep analysis was applied. This method of analysis gives a more realistic simulation of the temperature cycling loading, because as temperature changes, creep deformation of solder accumulates throughout the thermal cycle. The temperature ramps (up and down) were modeled with temperature change increments of 5 °C. At each 5 °C increment, elastic-plastic analysis was implemented and this is then followed by creep analysis for 6 s. The temperature and time steps will alternate during the ramps. In this manner, creep deformation is being considered during the temperature ramp up and down periods with a ramp rate of 50 °C/min. For both the "*dwell creep*" and "*full creep*" methods, three cycles of temperature loading was simulated. Outputs of the equivalent plastic and creep strain ranges from the FEA simulations were applied to fatigue life prediction models to estimate the fatigue life cycles to failure.

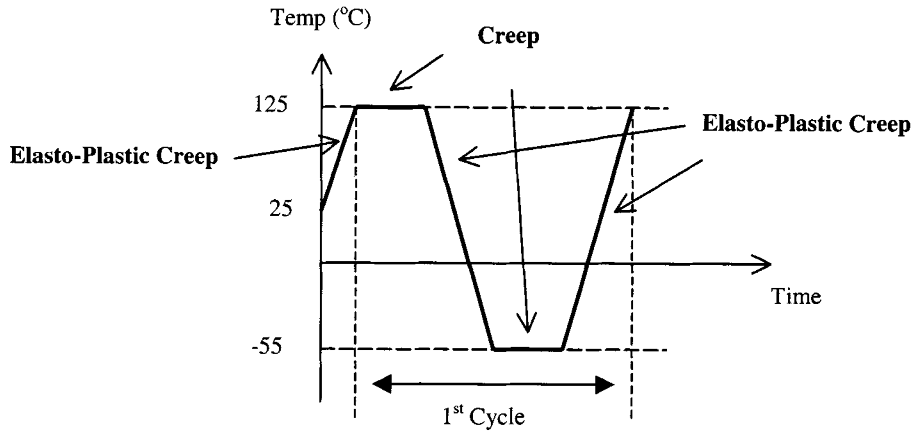

Fig. 6. Temperature profile for the "*Full Creep*" method.

C. Fatigue Life Prediction Models For Solder

During thermal cycling loading the FCOB assembly materials with different CTE properties for silicon, solder, epoxy and FR4-PCB, generates thermally induced stresses and strains in the FCOB assembly and solder joints. The interface region of the solder joint to the silicon die and the PCB are regions of high strain concentration and exhibit severe inelastic strains accumulated over each thermal cycle. Solder joint fatigue failure occurs at these locations due to cyclic plastic and creep strain damage leading to crack initiation and propagation to failure. The solder joint is subjected to a complex state of multi-axial stress strain response during thermal cycling and the equivalent stress-strain concept is required to represent the multiaxial state of stress and strains in the solder joints.

The yield condition for solder follow the von Mises yield criterion and the *equivalent stress* and *equivalent strain* components are given by

$$\sigma^e = \frac{1}{\sqrt{2}} \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]^{1/2} \quad (5)$$

$$\varepsilon^e = \frac{\sqrt{2}}{3} \left[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2 \right]^{1/2} \quad (6)$$

where the principal stresses and strains are derived from the normal and shear stress strain components. The relationships of the effective shear stress and shear strain to the equivalent stress and strain is given by

$$\tau^e = \frac{1}{\sqrt{3}} \sigma^e \quad (7)$$

and,

$$\gamma^e = \sqrt{3}\varepsilon^e. \quad (8)$$

These relationships may be employed to convert equivalent stress and strain values to effective shear stress and strain values for application in solder fatigue life prediction models.

The computation of the fatigue life cycles to failure for the solder joints employs failure parameters like the equivalent plastic and creep strain ranges per cycle computed from the FEA results. The low cycle fatigue life prediction models used for this study is given below.

Solomon [10] reported low-cycle fatigue relations for various isothermal temperatures and the expression at -50 °C is given below

$$N_p = [1.36 / \Delta\gamma_p]^{(1/0.5)}. \quad (9)$$

This model was developed from isothermal low cycle fatigue test data and the equation given here is for the case when the plastic shear strain range is dominant (at -50 °C where the creep effects can be neglected).

Knecht and Fox [11] developed a model based on the creep strain range approach

$$N_C = 8.9 / \Delta\gamma_c. \quad (10)$$

This model assumes that matrix creep deformation is dominant in the solder joints and the fatigue life during thermal cycling is related to the creep shear strain range per cycle. Pang *et al.* [1] proposed that the plastic and creep shear strain based fatigue models given in equations (9) and (10) can be combined to give a *Creep–Fatigue* life prediction model based on a Miners' rule approach. The creep–fatigue interaction model gives the resultant fatigue life (N_T) by

$$N_T = [(1/N_P) + (1/N_C)]^{-1}. \quad (11)$$

III. RESULTS FOR DWELL CREEP AND FULL CREEP METHODS

The FCOB model was analyzed using the "*dwell creep*" and "*full creep*" thermal cycling simulations. The highest solder joint strain regions were found to be at the corners of the outermost solder joint. The equivalent stress versus equivalent strain components for plastic and creep strain for the "*dwell creep*" and "*full creep*" analysis results are given in Figs. 7 and 8, respectively. From Fig. 7, no equivalent plastic strain was accumulated during the dwell periods. Some differences were observed in the plots of equivalent creep strain for the "*dwell creep*" and "*full creep*" methods given in Fig. 8 [12].

For the "*dwell creep*" method, creep strain was noted in the high temperature dwell periods only ("b"–"c," "f"–"g," and "j"–"k"). For the "*full creep*" case, where creep analysis was implemented for the ramp up and down periods, the equivalent

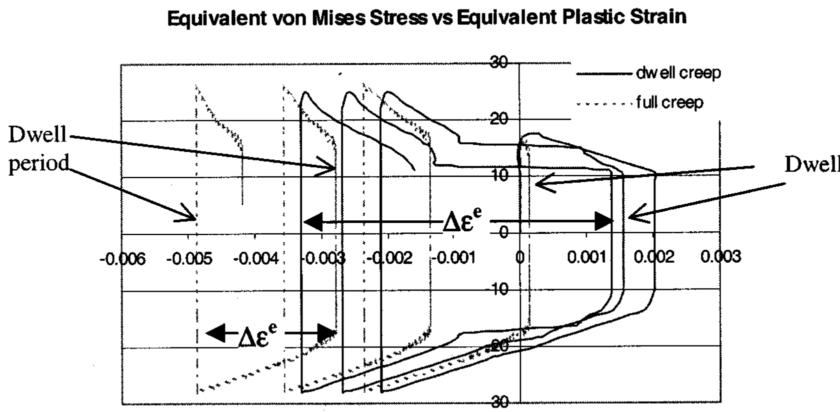

Fig. 7. Equivalent stress versus equivalent plastic strain plot.

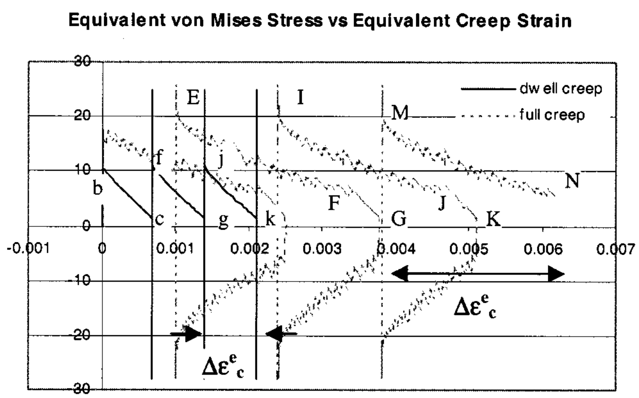

Fig. 8. Equivalent stress versus equivalent creep strain plot.

creep strain range increases with increase in temperature. It can be seen that the building up of creep strain range in ramp up periods ("E"–"F," "I"–"J" and "M"–"N") is actually much greater than the high temperature dwell periods. This shows that creep implementation is important and should not be ignored in the ramp up and down periods.

The equivalent stress versus equivalent plastic strain curves for both the "*dwell creep*" and "*full creep*" analysis methods show ratcheting effects but the equivalent strain range has stabilized as the size of the loops for three cycles remains fairly constant. As for the equivalent stress versus creep strain curves, ratcheting effect is more significant for the *full creep* method but the equivalent creep strain range per cycle is fairly stable. Therefore, the strain range ($\Delta\varepsilon_p^e$ and $\Delta\varepsilon_c^e$) of the third cycle can be used as failure parameters to predict the solder joints' fatigue life. Table II gives the various equivalent strain ranges of the third cycle for the "*dwell creep*" and "*full creep*" methods. The equivalent shear strain ranges ($\Delta\gamma_p^e$, $\Delta\gamma_c^e$) were computed by (8).

With the two methods of implementing thermal cycling analysis, the "*dwell creep*" analysis has generated higher plastic strain range with the equivalent plastic strain of 0.47%, higher than the "*full creep*" analysis result of 0.21%. On the other hand, creep strain ranges are higher in the "*full creep*" analysis. The equivalent creep strain range generated by the "*full creep*" analysis was 0.24% per cycle, very much higher than the "*dwell creep*" analysis result of 0.07%. The various failure parameters,

TABLE II
COMPONENTS OF EQUIVALENT AND SHEAR STRAIN RANGES

Method	$\Delta\varepsilon^e_p$	$\Delta\varepsilon^e_c$		$\Delta\gamma^e_p$	$\Delta\gamma^e_c$
Dwell Creep	0.0047	0.0007		0.0081	0.0011
Full Creep	0.0021	0.0024		0.0036	0.0041

TABLE III
PREDICTED FATIGUE LIVES OF FCOB SOLDER JOINT

Method	Solomon's Model [9]	Knecht/Fox Model [10]	Creep-Fatigue Model [1]
Dwell Creep	28268	7760	6089
Full Creep	138378	2149	2117

$\Delta\gamma_p^e$ and $\Delta\gamma_c^e$ were applied to the solder fatigue models to estimate the number of cycles to failure for the flip-chip solder joints. Table III gives the predicted fatigue lives of the FCOB solder joint using the different fatigue models.

Solomon's model hence predicts higher fatigue life, in particular for the "*full creep*" method. The Knecht/Fox model and the resultant Creep–Fatigue model showed that implementation of the creep deformation reduced the predicted fatigue life significantly and the difference between the "*dwell creep*" to the "*full creep*" analysis results is a factor of approximately three times for the Creep–Fatigue model. It was noted in Pang *et al.* [5], that the FCOB assemblies survived 1200 cycles (of −55 °C to +125 °C thermal shock test) with no failures before the test was discontinued. The "*full creep*" analysis method using the Creep–Fatigue model [1] gave more conservative results than the "*dwell creep*" method.

It is clearly shown that implementation of creep analysis during ramp up and down periods is necessary and has reduced the predicted fatigue life of the solder joints greatly. Hence, the "*dwell creep*" method predicts fatigue lives that are much longer than the "*full creep*" method and the later is highly recommended for thermal cycling analysis.

IV. VISCOPLASTIC ANALYSIS METHOD

The "*full creep*" analysis breaks down the non linear deformation process of the solder into time independent plastic strain and time dependent creep strain in a phenomenological manner. Alternatively, the non linear deformations of solder can be modeled using a rate dependent viscoplastic model for

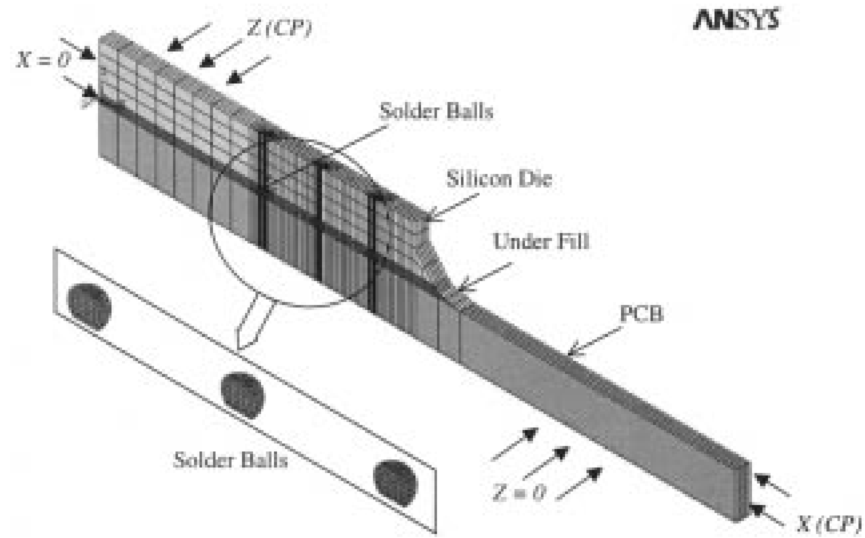

Fig. 9. Three-dimensional slice model of FCOB assembly for viscoplastic analysis.

example in the ANSYS program [13]. ANSYS has an option for viscoplastic analysis using the Anand's viscoplastic model to describe the rate-dependent material behavior with the large strain solid, VISCO107 element, for three-dimensional large strain solid. The basic features of the Anand model is that there is no explicit yield surface, rather the instantaneous response of the material is dependent on its current state. Secondly, a single scalar internal variable "s," called the deformation resistance, is used to represent the resistance to inelastic flow of the material. Anand's model is expressed by a flow and three evolution equations

$$\frac{d\varepsilon_p}{dt} = A\left[\sinh\left(\frac{\xi\sigma}{s}\right)\right]^{1/m} e^{(-Q)/kT} \tag{12}$$

$$\frac{ds}{dt} = \left\{h_o\left(|B|\right)^a \frac{B}{|B|}\right\}\frac{d\varepsilon_p}{dt} \tag{13}$$

$$B = 1 - \frac{s}{s^*} \tag{14}$$

$$s^* = s^\wedge\left(\frac{1}{A}\,\frac{d\varepsilon_p}{dt}e^{Q/kT}\right)^n. \tag{15}$$

Darveaux [14] reported solder life prediction model based on the plastic work dissipated in crack initiation and crack growth to failure. The model utilizes finite element analysis to calculate the plastic work per unit volume (i.e., inelastic strain energy density) accumulated per cycle. The plastic work is then used in a solder joint fatigue model to calculate the number of cycles to initiate a crack, and the number of cycles to propagate the crack through a solder joint. Darveaux's model [14] for crack initiation and crack growth are given by equations (16) and (17), respectively.

$$N_o = K_1 \Delta W^{K_2} \tag{16}$$

$$\frac{da}{dN} = K_3 \Delta W^{K_4} \tag{17}$$

where K_1, K_2, K_3, and K_4 are constants for a slice 3-D model. The plastic work, $\Delta W_{\rm ave}$ (in psi) is averaged across the elements along the solder joint interface where the crack propagates

$$\Delta W_{\rm ave} = \frac{\sum \Delta W \cdot V}{\sum V}. \tag{18}$$

The fatigue life was calculated using

$$\alpha = N_o + \frac{a}{\frac{da}{dN}} \tag{19}$$

where a is the solder joint diameter at the interface with the copper pad.

A comparative study was conducted for viscoplastic analysis using Darveaux's approach [14]. Fig. 9 shows a 3-D slice model of the flip chip geometry, together with its boundary conditions, subjected to the same temperature profile of -55 °C to $+125$ °C and also for two smaller temperature ranges. The temperature ramps (up and down) were modeled with increments of 10 °C and with dwell periods of 5 min. Two cycles were modeled so that the difference in the plastic work density between two cycles can be calculated. The boundary condition known as coupling (CP) was implemented in this 3-D slice model to implement generalized plain strain condition on the coupled surfaces. The constants used in the Anand's model were taken from Darveaux's paper [14] and they are $C1 = 1800$ psi, $C2 = 9400\ (1/K)$, $C3 = 4.0E6$ s^{-1}, $C4 = 1.5$, $C5 = 0.303$, $C6 = 2.0E5$, $C7 = 2.0E3$, $C8 = 0.07$ and $C9 = 1.3$, respectively. The fatigue model constants are $K_1 = 22\,400$ cycles/psi, $K_2 = -1.52$, $K_3 = 5.86 \times 10^{-7}$ in/cycle/psi, $K_4 = 0.98$, respectively. The plastic work density per cycle and the fatigue life predicted is shown in Table IV.

V. Temperature Range (ΔT) Effects

The purpose of this study is to quantify the effects of different temperature range, ΔT, using the "*full creep*" analysis method to compute the stress and strain behavior and to predict the fatigue lives for the solder joint. Five different temperature range (ΔT) conditions were investigated as specified in

TABLE IV
PREDICTED FATIGUE LIVES USING DARVEAUX'S MODEL [14]

Loading Profiles	Plastic Work Density (Psi)	Life Cycles by Darveaux's model
–55°C to +125°C	23.28	494
0°C to +100°C	10.44	1308
+25°C to +75°C	4.19	4283

TABLE V
DIFFERENT TEMPERATURE RANGE, ΔT CONDITIONS

Condition	Max. Temp Tmax (°C)	Min. Temp Tmin (°C)	ΔT (°C)	$\Delta\varepsilon^c_p$ %	$\Delta\varepsilon^c_c$ %	N_f, Life cycles by Creep-Fatigue [1]
A	25	75	50	0.087	0.057	8918
B	0	100	100	0.079	0.087	5871
C	25	125	100	0.042	0.117	4388
D	-25	100	125	0.132	0.250	3658
E*	-55	125	180	0.250	0.255	1975

* Typical ATC reliability test, ΔT, used for FCOB solder joint reliability tests.

TABLE VI
SCALE FACTOR FOR DIFFERENT ΔT CONDITIONS

Method	A (25 to 75°C)	B (0 to 100°C)	C (25 to 125°C)	D (-25 to 100°C)	E (-55 to 125°C)
Creep-Fatigue Model [1]	4.51	2.97	2.22	1.85	1.00
Darveaux's Model[14]	8.67	2.64	-	-	1.00

Table V. Condition B and C have the same temperature range, ΔT, but with different temperature limits, where the effect of mean temperature (T_{mean}) was investigated. The accumulated equivalent creep strain ranges experienced by the solder joint increases with increase in ΔT, resulting in a decrease in the predicted fatigue lives.

Fatigue lives estimated by the Creep–Fatigue model showed that with a higher ΔT, a lower fatigue life was predicted. This is due to higher creep strain range per cycle computed with increase in ΔT. For the case with the same ΔT, but with a higher maximum temperature (condition C versus B), a shorter fatigue life was obtained. Creep exposure is greater for the higher temperature limits of 25 °C to 125 °C compared to 0 °C to 100 °C, giving larger creep strain range per cycle. This section also provides a comparison of the FEA modeling results for the viscoplastic analysis method obtained for three different temperature ranges, ΔT, (conditions A, B, and E). The results can be scaled from one ΔT condition to a particular ΔT condition by a Scale Factor. Scale Factors for the predicted fatigue lives estimated by the Creep–Fatigue [1] and Darveaux's model [14] are normalized by the result for condition E, (i.e., -55 °C to 125 °C) as shown in Table VI. For the case of 0 °C to 100 °C normalized with -55 °C to 125 °C, the scale factor for "*full creep*" analysis is 2.97 compared to 2.69 for the viscoplastic analysis case with fairly good agreement. However, for the case of 25 °C to 75 °C normalized with -55 °C to 125 °C, the scale factor for "*full creep*" analysis is 4.51 compared to 8.67 for the viscoplastic analysis case. It was noted that the viscoplastic analysis predicted more conservative fatigue life of 4283 cycles compared to 8918 cycles for the "*full creep*" analysis case, when applied to predict the fatigue life at the smallest temperature range of 25 °C to 75 °C (Condition A).

With the Scale Factor obtained in Table VI from FEA simulations, the reliability performance of the solder joints for smaller temperature range conditions such as 25 °C to 75 °C or 0 °C to 100 °C could be estimated prior to conducting these extensive tests. These scale factors also provide useful information on the feasible of the testing time needed. For example, Conditions A to D will take very much longer to test and these scale factors give some indication of the test cycles to failure and hence the estimated test duration. These scale factors are inherently geometry or package dependent, but it fulfills its purpose for scaling the fatigue life for different temperature ranges for reliability assessments of a specific package.

VI. CONCLUSION

This paper has provided useful applications of employing finite element modeling and simulation techniques for thermal cycling analysis and fatigue life prediction of flip-chip solder joint reliability results. The study shows that the "*dwell creep*" method of analysis can predict fatigue lives that are about three times longer than the "*full creep*" analysis method. Hence, the "*full creep*" analysis method is recommended as it gives conservative results. A viscoplastic analysis using a 3-D slice model and Darveaux's model for solder joint fatigue life prediction gave even more conservative fatigue life compared to the "*full creep*" analysis result. Scale factors have been proposed for correlating flip chip solder joint fatigue life from an accelerated thermal cycling test condition with a larger temperature range (condition E) to smaller temperature ranges (conditions A to D).

REFERENCES

[1] J. H. L. Pang, C. W. Seetoh, and Z. P. Wang, "CBGA solder joint reliability evaluation based on elastic plastic creep analysis," *ASME, J. Electron. Packag.*, Sept. 2000.

[2] H. L. J. Pang, Y. T. Kowk, and C. W. SeeToh, "Temperature cycling fatigue analysis of fine pitch solder joints," *Adv. Electron. Packag.*, vol. 19, 1997.

[3] J. H. L. Pang and Y. R. Chong, "FEA modeling of FCOB assembly solder joint reliability," in *Proc. 3rd Int. Conf. Micro Mater. (MicroMat'00)*, Berlin, Germany, Apr. 17–19, 2000.

[4] S. Michealides and S. K. Sitaraman, "Effect of material and geometry parameters on the thermo-mechanical reliability of flip-chip assemblies," in *Proc. IEEE InterSoc. Conf. Thermal Phenom.*, 1998.

[5] J. H. L. Pang, T. I. Tan, Y. R. Chong, G. Y. Lim, and C. L. Wong, "Analysis of underfill encapsulation curing deformations on flip chip on board (FCOB) package reliability," *J. Electron. Manufact.*, vol. 8, no. 3/4, pp. 181–191, Sept./Dec. 1998.

[6] R. Darveaux, "Solder joint fatigue life model," in *Proc. TMS Annu. Meeting*, 1997, pp. 213–218.

[7] MARC Analysis Research Corporation, "MARC User Manual," Tech. Rep., 2000.

[8] R. Darveaux and K. Banerji, "Constitutive relations for tin-based solder joints," *IEEE Trans. Comp., Hybrids, Manufact. Technol.*, vol. 15, pp. 1013–1024, Dec. 1992.

[9] M. Shiratori and Q. Yu, "Life assessment of solder joint," *Adv. Electron. Packag.*, vol. 2, 1997.

[10] H. D. Solomon, "Fatigue of 60/40 Solder," *IEEE Trans. Comp., Hybrids, Manufact. Technol.*, vol. CHMT-9, Dec. 1986.

[11] S. Knecht and L. Fox, "Integrated matrix creep: Application to accelerated testing and lifetime prediction," in *Solder Joint Reliability: Theory in Application*, J. H. Lau, Ed. New York: Van Nostrand Reinhold, 1991, ch. 16.

[12] X. Q. Shi, H. L. J. Pang, W. Zhou, and Z. P. Wang, "Low cycle fatigue analysis of temperature and frequency effects in eutectic solder alloy," *Int. J. Fatigue*, vol. 22, no. 3, pp. 217–228, 2000.

[13] ANSYS, Inc., "ANSYS Users Manual," Tech. Rep., 2000.

[14] R. Darveaux, "Effect of simulation methodology on solder joint crack growth correlation," in *Proc. 50th IEEE Electron. Comp. Technol. Conf. (ECTC'00)*, Las Vegas, NV, 2000.

John H. L. Pang received the B.S. degree (with honors) and the Ph.D. degree from the University of Strathclyde, U.K., in 1985 and 1989, respectively.

He is an Associate Professor in the School of Mechanical and Production Engineering, Nanyang Technological University, Singapore. He is Program Manager for the Integrity, Reliability and Failure Modeling Research Program, Center of Advanced Numerical Engineering Simulation (CANES). His research interests are in the areas of design-for-reliability in advanced electronic packaging, nonlinear finite element analysis, solder joint reliability, fracture, and fatigue mechanics of materials.

D. Y. R. Chong received the B.S. degree (with honors) in mechanical and production engineering and the M.Eng. degree from Nanyang Technological University (NTU), in 1998 and 2000, respectively.

His research work is on the study of solder joint reliability using finite element modeling and simulation techniques. He is currently with Motorola, Singapore.

T. H. Low received the B.S. degree (with honors) in mechanical and production engineering from Nanyang Technological University (NTU), Singapore, in 2001

His research interest is in finite element modeling and simulation methods.