A NOVEL ACCELERATION-FACTOR EQUATION FOR PACKAGING-SOLDER JOINT RELIABILITY ASSESSMENT AT DIFFERENT THERMAL CYCLIC LOADING RATES

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ABSTRACT

Acceleration-factor (AF) equations have been developed to rapidly predict product lifetime, and the most widely used equation is Norris-Landzberg (N-L) equation. In recent years, some researchers have found that the current AF equation does not accurately predict the experimental results for thermal cyclic loading at high ramp rates; indeed, it may yield the opposite results, due to the changing effect of the solder strain rate at different ramp rates. Modifying the current AF equation to better assess product reliability has thus become an important task for researchers.

In this study, a novel AF equation was developed from a wafer level chip-scale package (WLCSP) under different thermal cyclic loadings. The frequency term used in the N-L equation was replaced with a new term in the proposed AF equation to distinguish between the effects of ramp rate and dwell time under thermal cyclic loading conditions. Proposed AF equation showed a high level of correlation with the simulation and test results for various thermal cyclic loadings. In addition, the proposed AF equation was validated by confirming the consistency of its results with experimental data on a range of packages and thermal-cycling profiles reported in the literature.

Keywords: AF equation, Ramp rate, Creep, Strain rate.

1. INTRODUCTION

The Norris-Landzberg (N-L) acceleration factor (AF) equation [1] (Eq. (1)) was initially established for use with SnPb eutectic solder. Therefore, the equation does not accommodate the effect of the solder strain rate, which is a much more important material property of lead-free (SnAg(Cu)) solder [2] than of SnPb eutectic solder. As shown in Fig. 1, lead-free solder has a higher elastic modulus than SnPb eutectic solder, and its strain rate increases with temperature. Therefore, during solder deformation under thermal cyclic loading, the effect of stress is greater for lead-free solder than for SnPb eutectic solder.

$$\mathrm{AF}=\frac{N_{field}}{N_{test}}=\left(\frac{\Delta T_{test}}{\Delta T_{field}}\right)^{1.9}\left(\frac{f_{field}}{f_{test}}\right)^{1/3}\exp\left(\frac{1414}{T_{field}^{MAX}}-\frac{1414}{T_{test}^{MAX}}\right), \tag{1}$$

where AF is the acceleration factor, N is the fatigue life cycle, ΔT is the difference between the maximum and minimum temperature of the thermal load, f is the frequency of thermal loading, and T^{MAX} is the maximum operating temperature (K). The subscripts "test" and "field" represent the acceleration-test environment and the product-service environment, respectively.

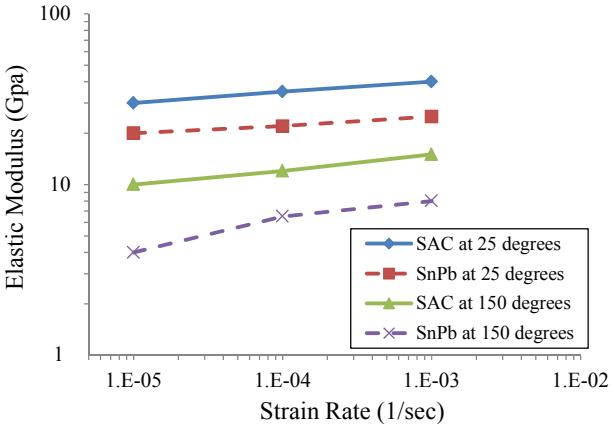


Fig. 1 Elastic modulus vs. strain rate for SnPb and SAC solder [2].

Salmela [3] extends the N-L AF equation by adding a correction term to accommodate the available test results for lead-free solder. Dauksher [4] uses the solder

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DOI : 10.1017/jmech.2016.30
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https://doi.org/10.1017/jmech.2016.30 Published online by Cambridge University Press

creep effect to revise the frequency term in the N-L AF equation and refit the equation's parameters. The contribution of dwell time is treated separately within the frequency term to accommodate the creep effect, but the ramp rate is still not considered. Lee *et al*. [5] confirm that solder joints have a shorter lifetime at higher ramp rates, *i.e.*, larger AF values are obtained in tests than in simulations. However, the above equations all produce smaller AF values than those obtained experimentally, because they do not take the effect of ramp rate into account. Clech [6] proposes a new acceleration-factor equation, based on the parameter of incremental energy density, which accommodates the effects of the strain rate of the solder material at different thermal cycling ramp rates. This equation accurately reflects the experimental outcome of a shorter lifetime at a higher ramp rate. However, as calculating the incremental energy density using the finite element method (FEM) is time consuming, Clech's equation does not offer the advantage of rapid assessment.

To better represent the relationship between the ramp rate effect and solder strain rate behavior in the AF equation, the FEM [7] is used in the current study to calculate the energy density corresponding to the amount of physical damage at different thermal cyclic loadings. The FEM is used to build a wafer level chip scale package (WLCSP) (Fig. 2) with lead-free solder joints, which is measured under various ramp rates and dwell times at temperatures ranging from –40 to 125°C. The objectives are to determine how the strain rate influences the fatigue life of solder joints, and to develop a novel AF equation with a modified frequency term. The new term distinguishes between the effects of ramp rate and dwell time during thermal cyclic loading, and the whole equation retains the advantage of rapid reliability assessment. The results of the FEM correlate well with the experimental results, and the simulation results are also consistent with the test data reported in studies of other package types.

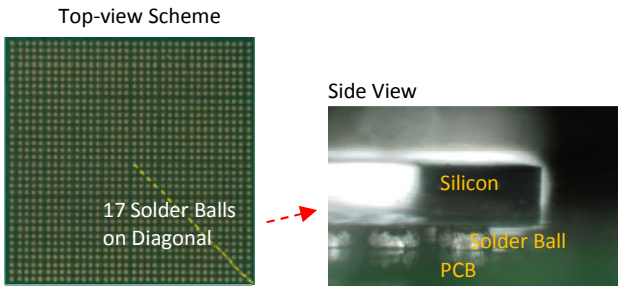


Fig. 2 WLCSP scheme (14mm × 14mm).



Fig. 3 WLCSP on PCB in an ESPEC TCC-150 thermal-cycling chamber.

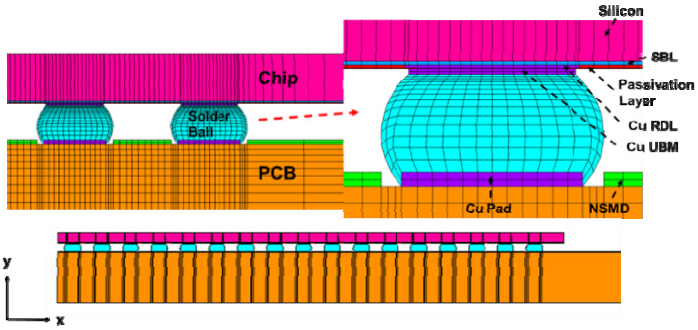


Fig. 4 Symmetrical FEM model of the WLCSP structure.

2. EFFECTS OF THE WLCSP RAMP RATE AND STRAIN RATE

To create the WLCSP, a silicon chip is directly mounted on a printed circuit board (PCB), as shown in Fig. 2. As the WLCSP is subjected to cyclic temperature loading (Fig. 3), large solder-ball deformation may result from a mismatch in the coefficient of thermal expansion (CTE) between the silicon chip and the PCB. The accumulation of cyclic strain on the packaging-solder joints eventually results in fatigue failure. In this section, the solder creep behavior and fatigue failure are investigated to evaluate WLCSP reliability as a basis for the development of a new AF equation.

2.1 Finite Element Modeling and Lifetime Model

A 14mm × 14mm solder ball type WLCSP with a 34 × 34 full array is used in the study, and a finite element model of the WLCSP is built as shown in Fig. 4. The diagonal line shown in Fig. 2 [8] is used to establish a half-size symmetrical model of the WLCSP comprising a silicon chip, a stress-buffer layer (SBL), a passivation layer, solder balls, a solder mask, copper pads, and a PCB. The material properties of the WLCSP are listed in Table 1, and Table 2 presents the material properties of the solder. The solder is assumed to have viscoelastic material properties [9,10], and its creep behavior is described by the Garofalo-Arrhenius steady-state creep model as a function of temperature and stress. The parameters developed by Clech [11] are used to examine the effects of ramp rate and strain rate.

An empirical energy-based lifetime equation is used to assess the effects of the solder strain rate and thermal cycle ramp rate on the solder fatigue life, as shown in Eqs. (2) and (3) below.

$$N_0 = K_1(\Delta W_{inelastic})^{K_2}, \quad \frac{da}{dN} = K_3(\Delta W_{inelastic})^{K_4}, \qquad (2)$$

https://doi.org/10.1017/jmech.2016.30 Published online by Cambridge University Press

Table 1 Material properties of the WLCSP.

Material	Young's modulus (GPa)	Poisson's ratio	CTE (ppm)
Silicon	112	0.28	2.62
SBL/passivation layer	2	0.33	55
Copper	68.9	0.34	16.7
Solder mask	6.87	0.35	19
PCB	18.3	0.19	16

Table 2 96.5 Sn/3.5 Ag solder material properties.

SnAg material properties		
Temp. (°C)	Young's modulus (GPa)	Yield stress (MPa)
–40	55.3	44.1
–20	54.0	42.2
40	49.9	32.7
80	46.9	26.2
125	43.4	20.5
Creep equation		
$\dot{\varepsilon}_{cr} = C_1\left[\sinh(C_2\sigma)\right]^{C_3}\exp\left(\frac{-C_4}{T}\right)$		
C_1	C_2	C_3	C_4
23.17	0.051	5.04	5004

In Eq. (2), N_0 is the initial fatigue crack cycle, a is the characteristic length, and $\Delta W_{inelasticis}$ the incremental inelastic energy density. $K_1 = 13.77$, $K_2 = -1.64$, $K_3 = 1.708 \times 10^{-3}$, and $K_4 = 1.04$, based on the WLCSP [12]. In sum, the fatigue life is calculated as follows:

$$N_\alpha = N_0 + \frac{a}{\frac{da}{dN}}, \tag{3}$$

where a is defined as 2.40×10^{-4}m, based on the length of the Cu under bump metallurgy.

2.2 Validation of Effects of the Ramp Rate and Strain Rate

The effect of the solder strain rate is assessed under three thermal cyclic loading conditions between –40 and 125°C at various ramp rates, with a constant dwell time of 10min. Together, the simulation results and test results shown in Table 3 illustrate the effects of the strain rate at different thermal cycling ramp rates. The change in incremental creep strain with the ramp rate is insignificant, but the strain energy density significantly increases with the ramp rate. In addition, the fatigue-life predictions drawn from the energy-based lifetime equation consistently agree well with the test data.

These results indicate that the energy density, described in Eq. (4), is an appropriate index of the solder fatigue life when considering the effects of strain rate at different thermal cycling ramp rates. Equation (4) and the results of the simulation suggest that the increase in strain energy density is mainly due to a change in stress caused by the solder's strain-rate properties. As illustrated in the von Mises stress curve in Fig. 5, stress increases as ramp rate increases.

Table 3 Simulation and test results for solder ball fatigue life.

Ramp rate (°C/min)	Ramp time (sec)	Dwell time (sec)	Incremental energy density	Incremental creep strain	Fatigue life cycle (simulation)	Fatigue life cycle (test)
33	300	600	0.728	0.289	218	204
16.5	600		0.668	0.287	240	246
11	900		0.635	0.287	253	288

$$W = \int_0^{\varepsilon} \sigma d\varepsilon, \tag{4}$$

where W is the strain energy density, σ denotes the von Mises stress, and ε is the equivalent strain.

3. NEW AF EQUATION WITH THE RAMP-RATE EFFECT

Similar to the findings reported in the literature [5], our WLCSP test data, presented in Table 3, indicate the necessity of revising the N-L AF equation to incorporate the effect of the ramp rate. Unlike Clech's [6] equation, the AF equation proposed in this study is a modified version of the N-L equation, with a new frequency term. It thus retains the advantage of rapid assessment.

3.1 New AF Equation Based on WLCSP

During thermal cyclic loading, the dwell time and ramp time have opposite effects on the solder fatigue life cycle due to the material properties of the solder. The life cycle shortens with either an increase in dwell time or a decrease in ramp time. However, as the frequency term used in the N-L equation (Eq. (1)) is related to the total thermal cyclic loading time, *i.e.*, the sum of the ramp time and the dwell time, no distinction is made in this equation between the effects of the ramp time and dwell time on the life cycle. Therefore, a novel AF equation, Eq. (5), is developed in this study to accommodate the distinct effects of the ramp and dwell time as well as the concept of total cycle time. The frequency term used in Eq. (1) is replaced in Eq. (5) with two separate factors, one reflecting the ramp time and the other the dwell time. This modification clearly decouples the effect of the ramp rate (related to the solder strain rate) from that of the dwell time (related to solder creep behavior), but retains the concept of total cycle time. The applicability of the proposed equation in extreme cases is demonstrated in the section on validation.

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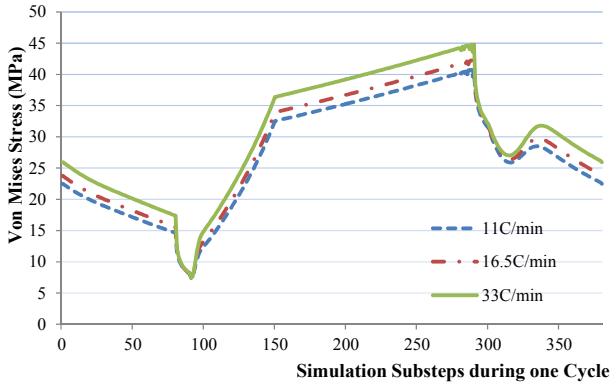


Fig. 5 Von Mises stress for various ramp rates.

$$\mathrm{AF}=\frac{N_{field}}{N_{test}}=\left(\frac{\Delta T_{test}}{\Delta T_{field}}\right)^{1.9}\left(\frac{t_{ramp,field}^{a}+t_{dwell,test}^{b}}{t_{ramp,test}^{a}+t_{dwell,field}^{b}}\right)\exp\left(\frac{1414}{T_{field}^{MAX}}-\frac{1414}{T_{test}^{MAX}}\right), \quad (5)$$

where t_{ramp} is the ramp time (sec) and t_{dwell} is the dwell time (sec) during one cycle. The subscripts "test" and "field" represent the acceleration-test environment and the product-service environment, respectively. The values of a and b can be derived from test data or previous simulation results. The difference between a and b will be addressed in a future study.

The selected WLCSP test data reported in Table 4 are used to determine either the dwell-time factor or the ramp-time factor, which can be used for curve fitting to obtain the values of a and b. The value obtained for a is 0.667 and that for b is 0.638. The corresponding new term is shown in Eq. (6).

$$\mathrm{AF}=\frac{N_{field}}{N_{test}}=\left(\frac{t_{ramp,field}^{0.667}+t_{dwell,test}^{0.638}}{t_{ramp,test}^{0.667}+t_{dwell,field}^{0.638}}\right) \quad (6)$$

The same split-test design is used to determine the values of a and b by curve fitting simulation data (Table 5). The values obtained are 0.239 and 0.199, respectively. The corresponding new term is shown in Eq. (7).

$$\mathrm{AF}=\frac{N_{field}}{N_{test}}=\left(\frac{t_{ramp,field}^{0.239}+t_{dwell,test}^{0.199}}{t_{ramp,test}^{0.239}+t_{dwell,field}^{0.199}}\right) \quad (7)$$

The differences in the values of a and b between Eqs. (6) and (7) arise from the selection of data for the curve fitting. Equation (6) is based on test data, and Eq. (7) is based on simulation data. Factors such as variation in operating temperature, ramp time, and dwell time are uncertain under test conditions, and differ from case to case. The influence of these uncertainties is demonstrated in the next section, in which the proposed AF equation is validated using test data obtained for different packages. In contrast, these uncertainties are excluded during the simulation process; only pure solder thermal-mechanical creep and strain-rate behavior are considered, as shown in Eq. (7). In addition, a remarkable agreement between the lifetime prediction derived from the simulation results and that derived from AF Eq. (7) is observed, as illustrated in Table 6. The lifetime prediction drawn from the revised equation is almost the same as the result of the energy-based lifetime equation used in the simulation. Therefore, the proposed AF equation can probably be used to simplify the simulation process. As only a few simulation steps are necessary to establish the bases for the AF calculation, the simulation time is considerably reduced.

Table 4 Three sets of experimental data used in curve fitting to determine a and b in Eq. (5).

Ramp rate (°C/min)	Dwell time (sec)	Ramp time (sec)	Fatigue cycle (cycle)
11	600	900	288
16.5	300	600	293
16.5	600	600	246

Table 5 Three sets of simulation data used in the curve fitting to determine a and b in Eq. (5).

Ramp rate (°C/min)	Dwell time (sec)	Ramp time (sec)	Fatigue cycle (cycle)
11	600	900	253
16.5	300	600	254
16.5	600	600	240

3.2 Validation with Test Data and Different Package Types

In addition to the WLCSP used in this paper, various package types reported in the literature, such as ball grid array (BGA) packages and other chip-scale packages (CSPs), are used to validate the proposed AF equation. It is clear from Table 7 that the first version (based on experimental data) of the new AF equation, Eq. (6), accurately predicts the fatigue life cycle of the WLCSP used in this paper, but is not consistent with all of the test data reported in the literature. In some cases, the error is as high as 200%. This inaccuracy is due to variation in the uncertainties of the test process from case to case. However, the lifetime predictions drawn from the second version (based on simulation data) of the new AF equation, Eq. (7), are consistent with the test data, with error values within 10%. Equation (7) even predicts the extreme case of a zero dwell time. The validation results are shown in Table 8. Therefore, the new AF term used in Eq. (7), with a and b coefficients derived by simulation, is the recommended means of estimating the test uncertainties from case to case.

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Table 6 Solder ball fatigue life: Simulation results and AF results.

Ramp time (sec)	Dwell time (sec)	Fatigue life cycle (simulation)	AF Eq. (7)	
			AF	Fatigue life cycle (AF)
900	300	268	1.12	269
600		254	1.05	254
300		231	0.97	232
900	600	253	1.05	254
600		240	1 (Base)	240
300		218	0.91	219
900	900	246	1.02	245
600		232	0.97	232
300		211	0.88	211

Table 7 Solder ball fatigue life: Test data and results of AF Eq. (6).

Package type	Temp. range (°C)	Dwell time (sec)	Ramp time (sec)	Life cycle (test)	AF Eq. (6)		
					AF	Life cycle	Error (%)
Ceramic BGA (CBGA) [13]	0 ~ 100	450	450	1286	2.11	2103	64%
		3,150		997	1	997	–
CBGA [14]	0 ~ 100	600	600	1040	4.89	3182	206%
		21,000		651	1	651	–
BGA [15,16]	0 ~ 100	600	900	1040	5.06	3293	217%
		21,000	600	651	1	651	–
CSP [14]	0 ~ 100	600	600	1025	1.96	1542	50%
		3,600		787	1	787	–
CSP [17]	–40 ~ 125	0	1237.5	7381	2.08	10648	44%
			412.5	5117	1	5117	–
WLCSP (this study)	–40 ~ 125	300	600	295	1.191	293	1%
		600	900	288	1.171	288	0%
			600	246	1	246	–
			300	204	0.796	196	4%

Table 8 Solder ball fatigue life: Test data and results of AF Eq. (7).

Package type	Temp. range (^{o}C)	Dwell time (sec)	Ramp time (sec)	Life cycle (test)	AF Eq. (7)		
					AF	Life cycle	Error (%)
Ceramic BGA (CBGA) [13]	0 ~ 100	450	450	1286	1.204	1201	7%
		3,150		997	1	997	–
CBGA [14]	0 ~ 100	600	600	1040	1.442	939	10%
		21,000		651	1	651	–
BGA [15,16]	0 ~ 100	600	900	1040	1.5	977	6%
		21,000	600	651	1	651	–
CSP [14]	0 ~ 100	600	600	1025	1.184	932	9%
		3,600		787	1	787	–
CSP [17]	–40 ~ 125	0	1237.5	7381	1.3	6653	10%
			412.5	5117	1	5117	–
WLCSP (this study)	–40 ~ 125	300	600	295	1.06	260	12%
		600	900	288	1.06	260	10%
			600	246	1	246	–
			300	204	0.913	225	10%

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4. CONCLUSIONS

In this study, a novel AF equation is established to decouple the dwell time from the ramp time, based on the results of a strain energy density simulation using a WLCSP. The frequency term used in the N-L equation is modified to give a new term that accurately reflects the solder strain rate and creep effects at different thermal cyclic loading rates. The results of the proposed AF equation are highly consistent with the results of simulations for various ramp rates and dwell times, and with data obtained in tests. The proposed AF equation accurately predicts not only the results of experiments but also those of simulations. The equation is further validated by confirming the consistency of its results with test data reported in studies of other package types. The error is consistently within 10%, indicating the wide applicability of the equation. The proposed AF equation thus offers useful guidance for microelectronics reliability lifetime assessment.

In addition, the simulation results suggest that strain energy density is the best index of the accumulated damage caused by the effects of strain rate at different ramp rates. The effect of the strain rate is observed from stress and strain changes during thermal cyclic loading.

ACKNOWLEDGEMENTS

The authors would like to thank the National Science Council for supporting this research (NSC102-2221-E-007-038-MY3).

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(Manuscript received November 23, 2015, accepted for publication January 13, 2016.)

https://doi.org/10.1017/jmech.2016.30 Published online by Cambridge University Press