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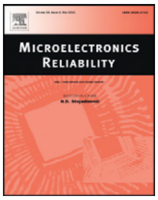

Characterization on acceleration-factor equation for packaging-solder joint reliability☆

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ABSTRACT

The well-known Norris-Landzberg acceleration factor (N-L AF) empirical equation was developed based on the accelerated thermal cycling (ATC) test. It has been widely used for many years to predict product lifetimes. However, some recent test results have shown the insufficiency of this equation when the ramp rates change. The AF equation predicts a longer lifetime when the ramp rate is higher, which contradicts the experimental test data. The reason for this discrepancy is that the N-L AF equation combines both ramp rate and dwell time factors in one frequency term. Thus, modifying the current AF equation to more precisely predict product lifetimes has become an important topic.

This study proposes a new AF equation to decouple the effects of the ramp rate and dwell time during an ATC test, replacing the frequency term used in the N-L equation with two new terms. One is related to the ramp rate for the strain rate effect, and the other is related to the dwell time for the creep effect of the packaging solder joint material. The new AF equation produces a good correlation between the simulation and test results for different package types discussed in the literature with various ramp rates and dwell times.

1. Introduction

The Norris-Landzberg (N-L) acceleration factor (AF) empirical equation in Eq. (1) was initially developed with SnPb eutectic solder material to provide a quick method for predicting product lifetime based on accelerated thermal cycling (ATC) test profiles and results [1]. Two factors of the ATC loading condition are used in the initial equation, operating temperature and frequency, which incorporate the ramp rate and dwell time through the concept of cycle time. According to this equation, a shorter cycle time, which is associated with a higher ramp rate, would result in a longer lifetime. This means that the effect of packaging solder strain rate is not considered in the equation, which is acceptable for SnPb eutectic solder material. However, the issue has become more critical, because of the widespread adoption of lead-free SnAg(Cu) solder in recent year and as Ma's research [2] indicated the lead-free SnAg(Cu) solder has relative higher stress caused by strain rate effect than eutectic solder.

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

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

Many researches shown the AF empirical equation should be modified to get more accurate prediction result, especially for various ramp rate loading conditions. Lall et al. [3] refit the parameters of N-L AF equation by principal component regression models (PCR) to incorporate the available test results from SnAgCu lead-free solder. Lee et al. [4] confirm that solder joints have a shorter test lifetime at higher ramp rates. Chaparala et al. [5] study similar effects on wafer level chip scale package (WLCSP) solder balls, and conclude that a fast ramp rate decreases their lifetime. Wu et al. [7] also show that a high solder strain rate during a fast ramp rate will induce more fatigue damage, resulting in shorter solder joint fatigue life. These studies indicate that a smaller AF value is required for higher ramp rates to reflect the shorter lifetime demonstrated in test results. However, the AF value calculated by Eq. (1) for higher ramp rate conditions produces a larger AF value, which means a longer lifetime. The reason for this discrepancy is that the effect of the solder strain rate at different ramp rates is not apparent for SnPb eutectic solder, and is not considered in Eq. (1). Clech and Syed [7,8] propose new AF equations, based on the parameter of incremental strain energy density, which is able to accommodate the effect of the solder strain rate at different thermal cycling ramp rates. The equations

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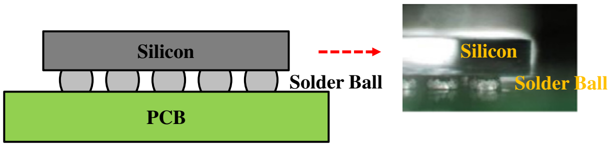

Fig. 1. WLCSP scheme and optical photo.

accurately reflect the experimental result of a shorter lifetime at a higher ramp rate. However, as calculating the strain energy density using finite element method (FEM) [9] simulation is quite time-consuming, their equations do not allow for rapid assessment, which was the advantage of the AF equation. To create an AF equation that is more convenient to use under various loading conditions, we propose a dimensionless equation related to the ramp rate and dwell time replaces the original frequency term, to accommodate the effects of the strain rate and the creep of solder material at different thermal cycling ramp rates.

In this study, an AF equation with two new terms is proposed to distinguish the effects of the ramp rate and dwell time during thermal cycling loading. A WLCSP in Fig. 1 assembled with SnAgCu lead-free solder joints is selected to characterize the effects of the ramp rate and dwell time in thermal cycling loading conditions ranging from −40 °C to 125 °C. FEM is used to calculate the energy density to better address the relationship between solder strain rate and the effect of ramp rate in the AF equation [6]. A new AF equation based on Eq. (1) with two new terms is proposed accordingly, and this equation retains the advantage of a quick reliability assessment. The AF results calculated by the new proposed equation match very well with test data and FEM simulation data in selected WLCSP, and show consistency with the test data in the literature on different package types.

2. WLCSP model validation and strain rate effect under different ramp rates

When a WLCSP mounted on a printed circuit board (PCB) is subjected to various thermal cycling ramp rates, the strain rate effect of the packaging solder joint influences the fatigue life time. In this section, the FEM simulation results indicate that strain energy density is a better index than strain for the accumulated damage caused by the strain rate at different ramp rates. In addition, the effect of the strain rate can be observed from strain and stress changes during thermal cycling loading.

3. WLCSP finite element model validation

The WLCSP package selected for this study, shown in Fig. 1, is a 200 μm silicon chip with solder balls directly mounted on 1 mm PCB board. The package is 14 mm × 14 mm with a 34 × 34 full solder ball grid array design, and the PCB design follows JESD22-B111 guidelines. A typical daisy chain design is integrated, going through the silicon chip, solder ball and PCB trace routing for in-situ monitoring of solder ball electrical continuity during thermal cycling loading. The FEM model for the WLCSP is shown in Fig. 2, a 1/2 symmetric model along a diagonal of the WLCSP. The model includes a silicon chip, a stress buffer layer (SBL), a passivation layer (PL), silicon pads, solder balls, PCB pads, a solder mask, and a PCB. Table 1 lists the material properties of the WLCSP structure, and the material properties of the solder balls are presented in Table 2. To describe the effects of solder strain rate and creep, the solder is assumed to have viscoplastic material properties [11,12], and creep behavior as described by the Garofalo-Arrhenius steady-state creep mode. This creep model in Eq. (2) is a function of stress and temperature that reflects the effects of creep and strain rate at various thermal loading profiles with different ramp times and dwell times. The parameters of SnAg lead-free solder developed by Clech [10] are used in this study. In terms of strain rate and creep, the mechanical behavior in different temperatures for both materials is similar [11].

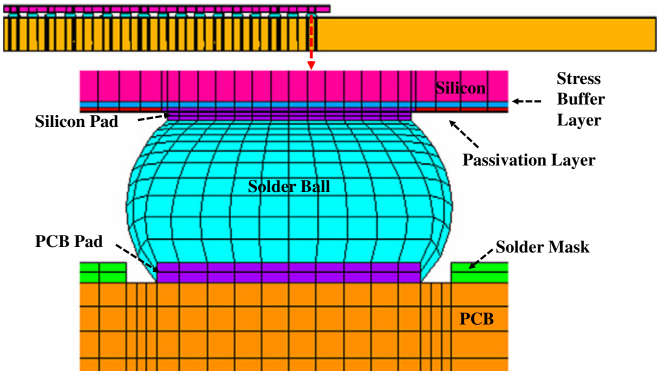

Fig. 2. FEM symmetric model of the WLCSP.

Table 1
Material properties of the WLCSP FEM.

Material	Young's modulus (GPa)	Poisson's ratio	CTE (ppm)
Silicon	150	0.28	2.62
SBL/PL	2	0.33	55
Copper	68.9	0.34	16.7
Solder (SnAg)	non-linear	0.4	22.4
Solder mask	6.87	0.35	19
PCB	18.3	0.19	16

$$\dot{\varepsilon} = A[\sinh(B\sigma)]^n e^{\frac{-Q}{RT}} \tag{2}$$

where A and B are material-related coefficients, σ is the applied stress, n is the stress exponent, R is Boltzmann's constant, T is the absolute temperature, and Q is activation energy.

To assess the solder fatigue life caused by the solder strain rate and creep behavior, an empirical energy-based lifetime equation is used, with parameters developed for WLCSP [5], as shown in Eqs. (3) and (4). The lifetime equation is based on incremental energy density and includes solder stress and strain to describe the amount of physical damage.

$$N_0 = 13.79(\Delta W)^{-1.64}$$
$$\frac{da}{dN} = 1.707 \times 10^{-6}(\Delta W)^{1.04} \tag{3}$$

Table 2
Material properties of 96.5 Sn/3.5 Ag solder.

SnAg material properties			
Temp. (°C)	Young's modulus (GPa)		Yield stress (MPa)
−40	55.3		42.2
−20	54.0		41.2
40	49.9		32.4
80	46.9		26.1
125	43.4		20.5
Creep equation			
$\dot{\varepsilon}_{cr} = C_1[\ ,\sinh(C_2\sigma)]^{C_3}\ ,\exp(\frac{-C_4}{T})$			
C1 (1/s)	C2 (MPa^{-1})	C3	C4 (kJ/mol)
23.17	0.0509	5.04	41.6