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# A new creep–fatigue life model of lead-free solder joint

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ABSTRACT

Life prediction plays an important role in reliability design of electronic product. Solder joint failure is one of the most common failure modes for electronic packaging structure. Current creep–fatigue life models of solder joints are unable to distinguish the creep damage and fatigue damage. In this work, a new creep–fatigue life model was proposed for solder joint tested under high strain rate, where the creep damage was based on Monkman–Grant equation and the fatigue damage was evaluated employing the Coffin–Manson model. Then, linear damage rule was utilized to build the new model. Creep test, fatigue test and creep–fatigue test were conducted respectively in order to determine the parameter in the new model. At last, the experimental result was compared with the predicted result, which shows that the calculation life meets well with the experimental life under high strain rate.

## 1. Introduction

Solder joints in electronic device play a significant role because it not only provides the electronic interconnection but also ensures the mechanical reliability. With the development of electronic device, the size of solder joints becomes smaller and smaller, which made the solder joint reliability more challenged, for the size has a significant effect on its property [1–3]. Generally, solder joint failure is attributed to the effect of fatigue–creep interaction [4]. Nowadays, many life prediction models have been reported. Low-cycle fatigue life model was firstly used to evaluate the solder joint life, such as Coffin–Manson model [5,6]. However, the model only just considers the plastic strain, which made this method inaccurate. Although plastic strain was replaced by inelastic strain in Coffin–Manson model, it did not distinguish each contribution of fatigue and creep. Some workers [7–9] modified it through adding a frequency parameter. Knecht and Fox [10] indicated that creep strain is the main reason for solder failure and proposed a model based on the creep strain range. Furthermore, Syed [11] divided the creep strain into two parts, the strain deduced by the sliding of solder matrix and that by the grain boundary sliding. Moreover, models based on energy were also reported [12,13]. Nevertheless, whether the variable in life prediction model is plastic strain range, creep strain range or energy, it did not distinguish the contribution of fatigue and creep to failure quantitatively. Hence, some models simultaneously considering the fatigue and creep damage have been proposed. Tsukada [14] employed the strain range partitioning method to evaluate the fatigue life of Sn63Pb37 solder alloy. Similarly, Kariya [15] used this model to lead-free solders. Besides, energy partitioning approach was also used by Dasgupta [16] to predict the solder life. Although fatigue and creep damage were considered simultaneously for these models, it is difficult to get the corresponding strain range or strain energy density component.

Hence, in this work, a new creep–fatigue life model for solder joint was proposed with simultaneously considering the fatigue and creep damage.

## 2. New prediction model

Generally, plastic strain for fatigue damage is time-independent, whereas the creep strain is time-dependent. Therefore, the creep effect is suppressed when the loading rate is high for creep–fatigue cyclic loading test. Some workers indicated that time-independent mechanical property of solder could be obtained when the strain rate exceeding $2 \times 10^{-2}\ \mathrm{s}^{-1}$ [17,18]. Correspondingly, for a certain creep–fatigue cyclic loading waveform with high strain rate, as shown in Fig. 1(a), the creep damage is mainly accumulated during the holding stage, whereas fatigue damage is concentrated in the stress/strain ramp stage. So, the creep–fatigue loading condition could be decoupled as a single fatigue loading test and a stress relaxation or creep test, as shown in Fig. 1(b) and (c). Then, the fatigue damage and creep damage could be evaluated employing the Coffin–Manson model and Monkman–Grant equation, respectively. At last, linear damage rule was used to build the new model. The flowchart is illustrated in Fig. 1.

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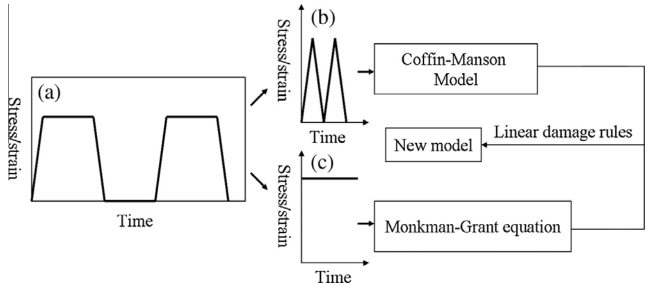

**Fig. 1.** Flowchart of the new proposed model.

The Coffin–Manson model is widely used to predict fatigue life, which is described as Eq. (1):

$$\Delta\gamma_p \cdot N_f^{\alpha} = \theta \tag{1}$$

where $\Delta\gamma_p$ is the plastic strain range, $N_f$ is the fatigue life, $\alpha$ represents the fatigue ductility exponent, and $\theta$ is the fatigue ductility coefficient. Here, it is supposed that the failure process of solder joint is uniform and the fatigue damage accumulated during one cycle could be expressed by the reciprocal of fatigue life, which is shown as Eq. (2):

$$D_f = 1/N_f = \left(\frac{\theta}{\Delta\gamma_p}\right)^{-1/\alpha} \tag{2}$$

where $D_f$ is the fatigue damage of one cycle. On the other hand, Monkman–Grant equation is widely used to evaluate the creep life of solder [19]. Equation is listed as Eq. (3):

$$\dot{\varepsilon}_s^m \cdot t_c = C \tag{3}$$

where $\dot{\varepsilon}_s$ is the stable creep deformation rate, $t_c$ is the creep rupture life, $m$ is exponent and $C$ is the constant depends on the material. Similarly, creep damage accumulated in unit time can be expressed by the reciprocal of creep life, which is shown as Eq. (4):

$$D_c = \frac{1}{t_c} = \frac{\dot{\varepsilon}_s^m}{C} \tag{4}$$

Accordingly, creep damage in one creep–fatigue loading cycle equal to the product of the creep damage in unit time and the creep time, which is listed as Eq. (5):

$$D_C = \frac{\Delta t}{t_c} = \frac{\Delta t \cdot \dot{\varepsilon}_s^m}{C} \tag{5}$$

where $\Delta t$ is the creep time. Total damage accumulated during one creep–fatigue loading cycle equal to the sum of fatigue damage and creep damage based on the Miner's linear damage rule [20]. It should be noted that although there are some shortcomings of this method such as it cannot reflect the loading order problem, however, it was also widely used for its simplicity. Furthermore, some modified models were suggested for example the double linear damage rule which will be discussed in this research. Generally, failure takes place when the total damage approaches 1. Hence, the creep–fatigue life model could be built as Eq. (6) shows based on Miner's linear damage rule:

$$N_F = \frac{1}{D_f + D_C} = \frac{1}{\left(\theta/\Delta\gamma_p\right)^{-1/\alpha} + \frac{\Delta t \cdot \dot{\varepsilon}_s^m}{C}} \tag{6}$$

where $N_F$ is the creep–fatigue cyclic life.

## 3. Experimental procedure

A shear-lap solder joint was fabricated in order to mimic the shear condition experienced by the actual solder joint, as shown in Fig. 2. Sn3.0Ag0.5Cu (96.5 wt.% Sn, 3.0 wt.% Ag, and 0.5 wt.% Cu) solder was employed in this research because it is considered as the most promising candidate for tin–lead solders [21]. The detailed fabrication process of solder joint is listed in our previous research [22].

In order to determine the parameters in Eq. (6), three types of tests were conducted. The first was fatigue test with a triangle waveform under room temperature, as shown in Fig. 3(a). Four frequencies (1 Hz, 2 Hz, 5 Hz, and 10 Hz) and four strain range (2%, 4%, 6% and 8%) were employed. Parameter $\alpha$ and $\theta$ in Eq. (1) could be achieved utilizing the linear fitting method. Then creep tests were performed under four temperatures (298 K, 348 K, 398 K, and 423 K) and four stress level (10 MPa, 15 MPa, 20 MPa, and 25 MPa), as shown in Fig. 3(b). At last, creep–fatigue tests were performed with a trapezoid waveform of three holding times (2 s, 5 s, and 10 s) and two strain range (3%, 4%) in order to prove the accuracy of the new model. The waveform is illustrated in Fig. 3(c). The test temperature is 348 K and 398 K. Three strain rates ($5 \times 10^{-3}\ \mathrm{s}^{-1}$, $4 \times 10^{-2}\ \mathrm{s}^{-1}$, $8 \times 10^{-2}\ \mathrm{s}^{-1}$) were selected which represent the low and high strain rates. All samples were tested to completely rupture and the time or cycle was defined as the life.

## 4. Results and discussions

Fig. 4 shows fatigue test result under room temperature, where the relationship between the fatigue life and plastic strain range are plotted under a ln-ln scale. It can be seen that the fatigue life and plastic strain range keep well linear relationship. The slowest strain rate is $4 \times 10^{-2}\ \mathrm{s}^{-1}$ for condition 1 Hz and 2% strain range. As described above, the creep property is suppressed under this strain rate. Hence, the solder joint failure was mainly induced by the fatigue damage. Parameters in Eq. (1) are calculated through averaging the parameter value obtained from different frequency fatigue tests and equation could be described as follows:

$$\Delta\gamma_p N_f^{0.42} = 0.76 \tag{7}$$

The parameter in Coffin–Manson model obtained in this research is little smaller than that obtained under other test conditions [9]. This is consistent with the high fatigue resistance of solder joint under low temperature or high frequency.

Parameters in Eq. (3) have been calculated in our another previous research [23] and Eq. (5) can be listed as follows:

$$D_C = \frac{\Delta t \cdot \dot{\varepsilon}_s^{0.78}}{0.50} \tag{8}$$

Based on Eqs. (7) and (8), Eq. (6) can be expressed as follows:

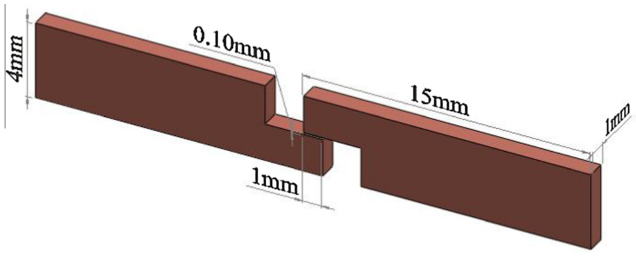

**Fig. 2.** Schematic diagram of shear-lap solder joint.