Study on Linear and Nonlinear Coupling Damage Model of BGA Solder Joint

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Abstract. Due to the complex and changeable environment in space, the ball grid array (BGA) has become one of the most important form of the electronic package in aerospace industry. As the main factors which affect the reliability of electronic products, temperature and vibration will lead to creep and fatigue respectively. Based on the damage mechanism, taking SnAgCu solder joints as the research object, the relationship between the resistance and the damage index are established by using the micro-conductive model of resistance. The mathematical model between stress cycle and damage value is established by damage mechanics. Then, the linear and nonlinear interaction models are established to simulate the initial and mature damage of solder joints respectively based on the principle of area interference. Finally, Monte Carlo method is used to simulate the growth of the crack, concluding that it’s suitable for the linear model when the damage index is less than 0.155 and the nonlinear model is suitable when the damage index is more than 0.155.

1. Introduction

The stress in space is complex and diverse, which makes the ball grid array (BGA) be wildly used in rockets and satellites. The reliability of BGA also become more important than before. In the aspects of physics of failure (PoF), the failure of BGA can be regard as the crack or tiny-hole in the joints. Up to now, the damage caused by thermal stress, vibratory stress and other stresses alone has been studied widely [1]. However, the solder joints are often exposed to the thermal stress, vibratory stress and voltage stress at the same time during service. This coupling effect caused by different physical stresses will affect the failure mechanism and failure mode of the joints, making the failure of joints more complex.

The life prediction of solder joint under multiphysical interaction is usually inaccurate up to now [2]. On the one hand, there is no universal interaction model included all kinds of stresses, on the other hand, the stress in model can’t fit the actual situation well. Because the BGA solder joints are mainly subject to thermal stress and vibratory stress during mission profile [3,4]. This paper will explore models to describe the damage of BGA based on damage mechanics, then explore the probabilistic failure models of BGA caused by creep and fatigue. Finally, the using situations of the linear model and nonlinear model will be simulated by Monte-Carlo sampling.
2. Damage model of creep and fatigue of BGA

2.1 Damage
Damage is the fundamental cause of deterioration of the material's mechanical properties, which eventually reduces the stiffness, strength or toughness of the material and reduces the life of the devices. The solder joints are often subject to the combined action of multiphysical stresses at the same time, causing internal damage of the solder joints, reducing the macroscopic mechanical properties, and shortening the remaining life ultimately [5]. Due to the micro-size and high-dense arrangement of solder joints, it is impossible to reflect the actual damage inside the solder joints by measuring the change of mechanical properties of the solder joints. Therefore, the resistance of solder joints is used to characterize the damage. The simplified model of the solder joint is shown below in Figure. 1 [6,7].

![Figure 1. Simplified damage model of BGA joint](image)

The current can’t pass the damage area due to the atomic separation at the crack, so the resistance could get increased. No matter the low frequency or high frequency, the damage can be measured as the increase of resistance. According to the damage mechanics [8], the relationship between damage and resistance can be represented as:

\[
D = 1 - \frac{R_0}{R_t}
\]

(1)

Where \( R_0 \) is the primary resistance of the solder joint, \( R_t \) is the resistance after the crack occurs.

2.2 Creep failure mechanism of BGA solder joints
Creep refers to the phenomenon that the material produces the deformation after the temperature reach or exceed the 1/3 of the melting temperature. The melting temperature of solder joint is around 200℃, so when the components heat up, creep deformation occurs in BGA solder joints during long service. The tensile stress produces after each cycle of temperature, the creep deformation will accumulate until the failure. In theory of energy, the creep damage of solder joint increases with the increase of dissipated inelastic strain energy, and eventually leads to creep failure [9,10].

In theory of continuum damage mechanics, based on the dissipative function put forward by Lemaitre [4], the relationship between creep damage \( D_c \) and the cycle of temperature \( N_c \) can be deduced as:

\[
D_c = 1 - \left( 1 - \frac{n_c}{n_c^*} \right)^\beta
\]

\[
n_c = \sqrt{\frac{2ES_0}{\gamma_u}} \left( \frac{\omega_{acc}}{\omega_0} \right)^{-1}
\]

(2)

(3)

Where \( \beta \) is the index of creep, \( n_c \) is the upper limit of temperature cycle, \( E \) is the modulus of elasticity, \( S_0 \) is the constant related to the dissipation.

2.3 Fatigue failure mechanism of BGA solder joints
Fatigue refers to the accumulation of damage after stress cycles. Under the stress cycles, the fatigue crack will initiate, expand and destruct [11]. As for electronic component, the fatigue usually comes from the vibration of devices. Taking the cycle hardening into account, the relationship between fatigue damage \( D_c \) and the cycle of stress \( N_c \) can be deduced as:
\[ D_f = 1 - \left( 1 - \frac{N_f}{n_f} \right)^\gamma \] (4)

\[ n_f = \frac{2k'\varepsilon_S\gamma}{\sigma_a} \left( \frac{2k'}{\sigma_a} \right)^{\frac{1}{n' - 1}} \] (5)

Where \( \gamma \) is the parameter of fatigue, \( n_f \) is the upper limit of stress cycle, \( K' \) is the cycle strengthening factor, \( n' \) is the cyclic hardening index.

3. Coupling mechanism of creep and fatigue

The coupling mechanism can be defined as two kinds of form: the linear coupling and the nonlinear coupling. In engineering, the linear coupling is wildly used for it’s easy to calculate [12]. But the total damage is not the sum of creep and fatigue actually. There is an overlap of damage area when the two damages meet.

3.1 Linear coupling

In the early time of the crack, there is no interaction between the creep damage and the fatigue damage because of the tiny area of damage. So there is no overlap area of the two damage area, and the total damage of the creep-fatigue coupling is \( S_D = S_c + S_f \), the damage can be regard as the sum of the creep damage and the fatigue damage:

\[ D = \frac{S_D}{S} = D_c + D_f \] (6)

Both of the thermal stress and stress exist in the mission profile, so regard the cycle of the temperature and vibration are same: \( N_c = N_f = N \), combined with the (2)(4), the relationship between damage \( D \) and cycle \( N \) can be deduced as:

\[ D = 2 - \left( 1 - \frac{N}{\beta\sqrt{2\varepsilon_S\gamma(\omega)\rho^{-1}}} \right)^\beta - \left( 1 - \frac{N}{\frac{2k'\varepsilon_S\gamma(2k')}{\sigma_a}^{\frac{1}{n' - 1}}} \right)^\gamma \] (7)

3.2 Nonlinear coupling

When arrive the mid-age of the damage, the damage area of creep and fatigue start to overlap. So the total area of damage is:

\[ S_D = S_c + S_f(S - S_c) \]

The damage can be deduced as:

\[ D = \frac{S_D}{S} = D_c + D_f - D_cD_f \]

This nonlinear coupling model suggest that the damage area can be calculated as the sum of creep area and fatigue area, and subtract the common area of these two. The model can be reshaped as:

\[ D = 1 - (1 - D_c)(1 - D_f) \] (8)

Same to 3.1, combined with (2)(4), the relationship between damage \( D \) and cycle \( N \) can be deduced as:

\[ D = 1 - \left[ \frac{N}{\beta\sqrt{2\varepsilon_S\gamma(\omega)\rho^{-1}}} \right]^\beta - \left[ \frac{N}{\frac{2k'\varepsilon_S\gamma(2k')}{\sigma_a}^{\frac{1}{n' - 1}}} \right]^\gamma \] (9)
3.3 Environmental experiment and solving of parameters

The progress of experiment and result data are referred from [11]. The parameters in (7) and (9) can be solved by the data from the experiment, which constituted by marble frame, invar alloy, aluminum alloy, and BGA joint. The thermal expansivity of invar alloy resembles the silicon chips’, and the thermal expansivity of aluminum alloy resembles the FR4 substrates.

The cycles of temperature profile and the vibration profile loads in same steps. The temperature ranges from -40°C to 125°C, and the stress range from -40MPa to 40MPa. The hold time of max and min in each cycle is 15min, and the resistance are tested for each 15 cycles after back to room temperature. The model of the experiment is shown in Figure. 2.

![Figure 2. Life test of BGA joint](image)

According the method in [12], the parameters in \( n_f \) and \( n_c \) can be deduced. Taking these parameters into (2) and (4), the creep damage and the fatigue damage can be calculated by (10) and (11). The Figure. 3 shows the model is consistent with the experimental data mostly [13].

\[
D_c = 1 - \left(1 - \frac{N_c}{605.57}\right)^{0.2029} \\
D_f = 1 - \left(1 - \frac{N_f}{387.82}\right)^{0.2383}
\]

(10)

(11)

![Figure 3. Simplified damage model of BGA](image)

4. Simulation of sampling and result

Combined the (12) (13) with the result in formula (6) (8), the linear model \( D_l \) and nonlinear model \( D_n \) can be deduced as follow:

\[
D_l = 2 - \left[1 - \frac{N}{605.57}\right]^{0.2029} - \left[1 - \frac{N}{387.82}\right]^{0.2383}
\]

(12)
\[ D_n = 1 - \left[ \frac{1}{1 - \left( 1 - N^605.57 \right)^{0.2029} \left( 1 - N^387.82 \right)^{0.2383}} \right] \]  

(13)

From the micro perspective, these two crack show up at random locations. The point of creep and the point fatigue can hardly meet in the initial time of crack, which can be considered as linear coupling. As time goes by, the crack would get growth and the overlap of damage area occurs, after the overlap, the damage can be considered as nonlinear coupling. The cycle of environmental stress where the linear comes to an end and the nonlinear gets start can be deduced as:

\[ N_0 = D_l^{-1}(D_0) \]  

(14)

The boundary between the linear model \( D_l \) and nonlinear model \( D_n \) depends on the initial location and the speed of growth. The closer they are, the earlier they overlap. According to the law of large number, the conclusion will get convergence with the increase of the simulation times. The mechanism can be simplified as Figure. 4.

**Figure 4.** The extension of crack

Monte Carlo method is an efficient way to solve this problem. In each simulation cycle, assuming that there are only one creep crack and one crack point when the damage occurs and their location of the creep crack and damage crack are both random variables. With the environment stresses load on, the cracks extend along by their own speed [14]. When the two damage area overlaps, the simulation stops, returns the \( D_0 \) and starts the next cycle. The program flowchart and the simulation result are shown in Figure. 5.

After 1000 times of simulation, the mean of \( D_0 \) converges to 0.155. And the load cycle \( N_0 = 143 \) can be get from formula (16). The result of Mont Carlo simulation and then damage curve are shown in Figure. 6 and Figure. 7:

**Figure 5.** Program flowchart of simulation

**Figure 6.** Simulation result

**Figure 7.** Comparison of models
5. Conclusion

Probabilistically, there is hardly overlap between the creep damage area and the fatigue damage area at the initial time of the crack, and the total damage can be calculated by: \( D = D_c + D_f \). As the stresses go on, the damage area get larger until the overlap occurs, and the damage can be calculated by: \( D = D_c + D_f - D_cD_f \). According to the results of simulation. The \( D=0.155 \) can be regarded as the boundary of linear model and nonlinear model. So when the proportion of damage area is lower than 0.155, the coupling can be regarded as linear model, and when the proportion of damage area is higher than 0.155, the coupling can be regarded as nonlinear model. The life of BGA made of other materials can be calculated by this method too.

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