A review of typical thermal fatigue failure models for solder joints of electronic components

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Abstract. For electronic components, cyclic plastic strain makes it easier to accumulate fatigue damage than elastic strain. When the solder joints undertake thermal expansion or cold contraction, different thermal strain of the electronic component and its corresponding substrate is caused by the different coefficient of thermal expansion of the electronic component and its corresponding substrate, leading to the phenomenon of stress concentration. So repeatedly, cracks began to sprout and gradually extend [1]. In this paper, the typical thermal fatigue failure models of solder joints of electronic components are classified and the methods of obtaining the parameters in the model are summarized based on domestic and foreign literature research.

1. Introduction
Relevant record data indicates that the performance, service life and reliability of electronic products are greatly influenced by temperature. Because among the environmental factors that cause the failure of airborne electronic equipment, there are 45% of the failure caused by the temperature factor. In recent years, with the development of fault physics technology, reliability test based on fault physics is more and more popular, which is used to evaluate fatigue life of electronic products. Statistics show that 70% of the electronic components failure is caused by the failure of packaging and assembly and that in electronic packaging and assembly failure, solder joint failure is the main reason [2]. So this paper focuses on the research and summary of the typical thermal fatigue failure models of solder joints of electronic components.

2. Classification of thermal fatigue failure models of solder joints of electronic components
A lot of researches on the thermal fatigue failure of solder joints have been carried out, and the thermal fatigue life model of solder joints is generally classified as shown in Fig.1 [3,4]:
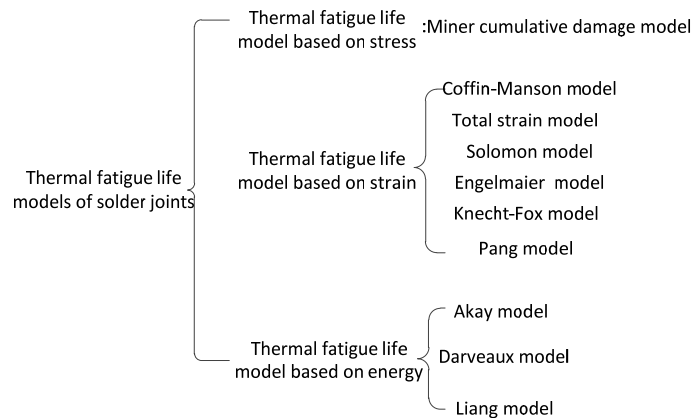
Fig. 1   Thermal fatigue life model of solder joints

2.1 Thermal fatigue life model based on stress
The application of this model is mainly due to the condition that electronic packaging devices are under thermal cycling load. Every time thermal cyclic loading will cause damage of products, and when the cumulative amount of damage exceeds the limit value of product or material, it will cause failure of the product. This model is called cumulative damage model.

In many linear damage accumulation theories, Palmgren-Miner theory is more typical, which is also referred to as Miner theory [5]. This theory has been widely used in engineering because it is very simple [6]. There are also some nonlinear cumulative deterministic theories, where many parameters need to be corrected by a large number of experimental data, leading to that its accuracy is not higher than the Miner theory. Miner theory also has its own shortcomings: it is assumed that the load state of the product and the load order don't affect the damage accumulation.

2.2 Thermal fatigue life model based on strain
In the thermal fatigue model based on strain, the strain is composed of three parts :
$$\triangle\gamma=\gamma_e+\gamma_p+\gamma_c \qquad\qquad （1）$$
γ_e—Elastic strain，which is obtained from formula calculation or finite element analysis or test;
γ_p—Plastic strain，which is obtained from formula calculation or finite element analysis or test;
γ_c—Creep strain，which is obtained from formula calculation or finite element analysis or test.
Those strain will exist at the same time in most cases, so it is not easy to distinguish strictly.
Thermal fatigue life model based on strain has the following categories:
•   Coffin-Manson model
•   Total strain model
•   Solomon model
•   Engelmaier model
The Coffin-Manson model is mainly used to calculate the low cycle fatigue life and its application is very wide. The expression is as follows:
$$\frac{\Delta\varepsilon_P}{2}=\varepsilon_f(2N_f)^c \qquad\qquad （2）$$
N_f—Number of failure cycles;
ε_P—Amplitude of plastic strain, which could be obtained from formula calculation or finite element analysis;
ε_f—Fatigue ductility coefficient, which could be obtained from 《Dictionary of materials》；
^{c}—Fatigue ductility exponent, which could be obtained from formula calculation.
The total strain model combines Coffin-Manson model and Basquin equation effectively, not only considering the effect of elastic strain on fatigue life, and considering the influence of plastic strain [7]. The expression is as follows:

$$\frac{\Delta\varepsilon}{2}=\frac{\sigma_f}{E}(2N_f)^b+\varepsilon_f(2N_f)^c \qquad\qquad (3)$$

$\Delta\varepsilon$—Strain range, which could be obtained from formula calculation or finite element analysis;

E—Elastic modulus of solder joints, which could be obtained from 《Dictionary of materials》;

σ_f—Fatigue strength coefficient; which could be obtained from 《Dictionary of materials》;

b—Fatigue strength exponent, which could be obtained by experiment;

ε_f and c—as mentioned before.

Solomon model only considers the effect of plastic shear strain on the fatigue life of solder joint [8]:

$$\Delta\gamma_P N_P^\alpha=\theta \qquad\qquad (4)$$

$\Delta\gamma_P$—Plastic shear strain, which could be obtained from formula calculation or finite element analysis;

N_P—Number of failure cycles;

θ—The reciprocal of fatigue ductility coefficient, which could be obtained from formula calculation;

α—Material constant, which could be obtained from 《Dictionary of materials》.

After the Solomon model was proposed, many scholars has focused on the model and used it to the QFP package, receiving good results. However, the Solomon model didn't consider the influence of creep strain on the fatigue life of solider joint. As a result of this, the actual application is limited.

Engelmaier model, an improved version of Coffin-Manson model, takes the thermal cycle frequency, temperature effect and elastic-plastic strain into account. As a result of this, the actual application is popular. The expression is as follows:

$$N_f=\frac{1}{2}\left(\frac{\Delta\gamma}{2\varepsilon_f}\right)^{\frac{1}{c}} \qquad\qquad (5)$$

N_f—Fatigue life;

ε_f—Fatigue ductility coefficient, and $\varepsilon_f=0.325$ for the eutectic solder;

c, reflecting the temperature stress, is determined by:

$$c=-0.442-0.0006T_{sj}+0.0147\left(1+\frac{360}{t_H}\right) \qquad\qquad (6)$$

T_{sj}—Average temperature, obtained from formula calculation;

t_H—Time of duration of high temperature;

$\Delta\gamma$—The total shear strain range, which could be obtained from formula calculation or finite element analysis.

The fatigue model based on creep, proposed by Knecht and Fox, is relatively simple:

$$N_f=\frac{C}{\Delta\gamma_{mc}} \qquad\qquad (7)$$

$$\gamma_{mc}=\int C_0\left(\frac{\tau}{\tau_0}\right)^{nMC} dt \qquad\qquad (8)$$

γ_{mc}—The shear strain caused by matrix creep, which could be obtained from formula calculation or finite element analysis;

nMC, C_0, τ_0—material parameter, which could be obtained by experiment.

Some researchers think we should combine the matrix creep and grain boundary sliding to fully consider the influence of the two parts on solder joint life, and then they put forward the new model [9]:

$$N_f=\left(0.022D_{gbs}+0.063D_{mc}\right)^{-1} \qquad\qquad (9)$$

In this model, D_{gbs}, the creep caused by grain boundary sliding, and D_{mc}, the matrix creep, are fully considered [10]. In addition, Syed has done a lot of research and experiments based on TSOP package,

and given the conclusion: when the rate of temperature change increases gradually and the whole package stiffness changes, the creep mechanism has a gradual transition from grain boundary sliding to the matrix creep.

Pang proposed a new life model based on the plastic strain model from Solomon and the creep fatigue model from Knecht-Fox organically, including plastic strain and creep strain, as shown in Eq. 10:

$$\frac{1}{N_f}=\frac{1}{N_p}+\frac{1}{N_c} \tag{10}$$

N_p—The fatigue life of Solomon model;

N_c—The fatigue life of Knecht-Fox model.

Based on this model, Pang predicted the life of FCOA and CBGA package and compared with the expected results of other models, finally he was in support of the use of this model.

2.3 Thermal fatigue life model based on energy

This model considers hysteresis energy and stress-strain based on volume weighted average [5]. After Akay considered the total strain energy, he proposed new fatigue model, as follows:

$$N_f=\left(\frac{\Delta W_{total}}{W_0}\right)^{\frac{1}{k}} \tag{11}$$

N_f—Cycle number of failure;

ΔW_{total}—Total strain energy, which is obtained from formula calculation or finite element analysis;

k—fatigue quotient, from available experimental data.

Based on the above model, Akay took the pin package structure as the test object and ultimately determined the constant value: $k = -0.6342$，$W_0 = 0.1573$, but he did not further study the fatigue life of solder joints.

Taking into account the crack propagation and the plastic dissipation for crack propagation, a new fatigue model is proposed by Darveaux. The implementation of this model is as follows: Firstly, the finite element method is used to calculate the accumulated plastic work of per cycle. The accumulated plastic work is then used to calculate the number of cycles the solder joint experiences before the internal crack initiation of the solder joint and the number of cycles the solder joint experiences during the diffusion of the crack inside the solder joint. And then by adding the two results, the fatigue life can be obtained. The Darveaux model uses formula Eq.12 and Eq.13 to calculate the number.

$$N_0=k_1\Delta W^{K_2} \tag{12}$$

$$\frac{da}{dN}=K_3\Delta W^{K_4} \tag{13}$$

k_1，K_2，K_3，K_4—material constant.

For the internal work of the solder joints, we calculate the solution according to the average value, such as formula Eq. 14:

$$\Delta W=\frac{\sum_i \Delta W_i V_i}{\sum_i V_i} \tag{14}$$

Then the fatigue life of solder joints is calculated according to formula Eq. 15:

$$\alpha=N_0+\frac{\alpha}{da/dN} \tag{15}$$

Liang proposed another fatigue model based on energy, as shown in the following. The model takes into account the influence of the geometric size of solder joints and the elastic creep analysis.

$$N_f=C(W_{ss})^{-m} \tag{16}$$

W_{ss}—Energy density under the hysteresis loop of stress and strain, determined based on hysteresis loop;

C，m—Material constant.

3. Summary

At home and abroad, the statistical data shows that about 52% of the airborne electronic equipment faults is caused by environmental factors, of which the temperature factor accounts for about 42% of the faults, the vibration factor accounts for 27%, and the humidity factor accounts for 19%. Therefore, the environmental stress, which affects the reliability of avionics equipment, is temperature, vibration and humidity in turn. So it is necessary to evaluate the fatigue life of electronic products. In recent years, with the development of fault physics technology, it is more popular to evaluate the fatigue life of electronic products by using the reliability test based on fault physics. The method ,temperature fatigue life of electronic products obtained by Fault Analysis of physical, need to understand the characteristics of electronic products and the typical thermal fatigue failure model. This article gives an investigation and summary of typical thermal fatigue models of solder joint of the electronic components and has certain engineering significance.

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