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Introductory invited paper

Coupling damage and reliability modeling for creep and fatigue of solder joint

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ABSTRACT

Solder joint often plays a crucial role in the normal operation of electronic equipment due to its unique material properties and harsh working condition, making it very important to carry out the accurate reliability analysis of solder joint. The low-cycle fatigue due to temperature cycling and the creep brought by continuous high temperature are two dominant failure modes of the solder joint. Current modeling methods for these two mechanisms mainly focus on failure process of each mechanism separately, with little consideration of the coupling relationship in the material properties. This paper introduces a coupling damage model considering both low-cycle fatigue and creep. The coupling relationship between these two failure mechanisms is investigated with the effects of creep strain rate on the ductility and the effects of damage on mechanical properties of solder joint. The analysis of the former mechanism concerns the fatigue parameter of Coffin-Manson model, while the latter one focuses on the applied stress increasing with the accumulation of damage. Further, considering that creep degradation rate would increase once the cumulative damage reaches a trigger threshold, a generalized cumulative damage model is developed. Based on this assumption, a reliability model for solder joint considering the uncertainty of model parameters is then proposed. Finally, a case study of a lead-free solder joint is given to validate this method.

1. Introduction

Solder joints provide both electrical connection and mechanical support for electronic devices [1,2]. Due to the thermal expansion mismatch between the electronic components and printed circuit boards (PCBs), the solder joints burden alternating strains in large magnitude [3,4]. The service temperature for solder joints usually locates in the high homologous temperature, which is higher than 0.5 T_m (T_m is the absolute melting temperature), thus the creep strain would have existed during the hold period [5]. It can be considered that the failure of solder joints occurs due to creep-fatigue combined effect.

Investigation into the creep-fatigue of solder joints can be traced back to the 1980s and was greatly based on experience of the aviation and the energy field. The most common approach is that the creep fatigue failure can be assumed as low cycle fatigue failure. The low cycle fatigue model can be classified by the plastic strain range and inelastic strain energy density used to characterize the fatigue damage process [6]. For the plastic strain range, the most representative model is Coffin-Manson fatigue model [7] and for the latter is Morrow model [8]. Many researchers have modified the models with the characteristics of creep fatigue. Zhu [9] and Shi [10] used frequency and temperature as the variables to conduct a large number of contrast experiments, and found that the low cycle fatigue behavior of solder joints was strongly dependent on the temperature and frequency. Afterwards, frequency-modified Coffin-Manson and Morrow models are proposed respectively. The modified models have some limitations due to the fact that the correction parameters of these models were obtained by fitting experiment data. Thus, cumulative damage criterion is proposed to improve the accuracy and applicability of these models. By calculating the creep damage and fatigue damage respectively, and using linear damage summation to obtain the total damage of solder joints, it is possible to obtain better results than the frequency-modified methods. The key point of this modeling method is to consider the interaction of creep damage and fatigue damage [2]. Manson [11] proposed the strain range partitioning model that partition inelastic strain in a cyclic stress-strain hysteresis loop divided into three components. It separates a part of strain that represents the interaction of plastic and creep strain to characterize the creep-fatigue damage. In most cases, however, in order to simplify the model, the interaction of creep damage and fatigue damage is generally ignored.

The crack growth law can be also applied to predict creep fatigue life of solder joints. The crack growth process is divided into two stages: initiation and propagation. And the life of solder joints is the number of loading cycles which is required to achieve the final size. Darveaux [12] proposed crack initiation and propagation

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model to describe the failure of solder joints. The creep fatigue life is considered as an initiation life. The crack grow law provides a good physical explanation of damage [13]. Yao [14] used damage mechanics to study the failure process from the macro point of view to consider the influence of crack. The above references illustrate the damage modeling of creep-fatigue mechanism, which considers the interaction of creep and fatigue. The coupling relationship is rarely constructed by failure physics, but more dependent on empirical methods.

Moreover, considering the uncertainty of model parameters, current research for solder joints centers on damage modeling and life prediction rather than the reliability modeling of solder joints. Through the review of damage modeling, creep is essentially a time-dependent degradation process and low-cycle fatigue is time-independent shock process. And the creep degradation rate may be varying with the operation time, say, for warm standby systems [15] and Lithium-ion battery [16]. Rafiee [17] proposed a reliability models for devices subjected to dependent competing failure processes of degradation and random shocks. It contains a changing degradation rate due to particular random shock patterns. Feng [18] developed a reliability models for systems based on degradation and random shock modeling, which is then extended to a specific model for a linear degradation path as well as normally distributed load sizes and damage sizes. Zhang [19] studied the effect of epistemic uncertainty on the predicted reliability based on the multiple dependent competing failure processes. The problem of reliability modeling of solder joints can be solved based on the above method.

From the literatures review above, it can be seen that the coupling damage and reliability modeling of creep and fatigue are not taken into a full account. This study introduces coupling variables into the failure mechanism model combined with the specific failure process, and assumes that the creep fatigue is a competing failure process. A coupling damage and reliability model of creep and fatigue is developed in following paper. The paper consists of the following parts: in Section 2, pure fatigue and creep damage as well as the coupling relationship are analyzed. And based on model talked above, the coupling damage model is established in Section 3. Then the reliability model of competing failure processes of creep and fatigue is built in Section 4. Finally, in Section 1 and 2, a case study and conclusions are presented.

2. Fatigue and creep analysis

For fatigue-creep damage modeling of solder joints, the stress-strain analysis is the key of the modeling process. At present, studies have shown that the stress and strain in the solder joints exhibited periodic changes with the thermal cycling time [3]. The thermomechanical load caused by the coefficient of thermal expansion mismatch increases with increasing temperature, leading to a constant increase in the stress and strain of solder joints. In addition, the solder joints under thermomechanical load are subjected to elastic and plastic deformation. While elastic deformation is recoverable, the strain accumulation of solder joints still exists due to plastic strain. Creep plays a leading role when the solder joint is in a continuous high temperature. Stress relaxation occurs during the holding stage due to the elastic strain transformed to the creep strain in accordance with the decreasing of stress. The creep strain can be expressed as an increase of strain in a dwelling period. The creep curve is composed of three typical primary creep stages: decelerated, steady-state and accelerated creep stage. The decelerated creep stage is caused by elastic aftereffect. The steady-state creep stage is characterized by a creep rate almost unchanged. Due to that high temperature duration does not last long for the fatigue-creep cycle process, it can be considered that the solder joints only undergo the decelerated stage and steady-state stage. The creep rate can be assumed to have only a stable creep rate in the high temperature period in order to simplify the model. The stress and strain of solder joints begin to recover at a cooling phase. However, the strain is unable to return to the original state due to the existence of cumulative inelastic strain.

There is a cumulative phenomenon of stress and strain in the cyclic loading process. It can be seen that the interaction between creep and fatigue makes the material properties change. Therefore, we sketch the damage modeling of solder joints from two aspects: (1) consider the fatigue damage caused by the plastic strain during the heating and cooling phases and the creep damage by creep strain during the dwelling period; (2) consider the effect of different loading conditions on the degradation of solder joints. The damage models of creep and fatigue are established, and the coupling relationship between the mechanisms is considered from the viewpoint of material degradation. Finally, a new creep fatigue damage model is constructed. The overall framework of coupling damage modeling is illustrated in Fig. 1.

2.1. Fatigue analysis

Failure of electronic package in service commonly occurs due to low-cycle fatigue and creep at solder joint [5]. Fatigue failures can be attributed to thermo-mechanical stress in the solder joint, caused by differences in the coefficients of thermal expansion (CTE) [1]. The CTE mismatch results in the solder joints to withstand cyclic loading during temperature cycle. When the cumulative plastic strain accumulates to a certain extent, crack initiation and propagation occur in the concentration region of the solder joint. The Coffin-Manson fatigue model is widely used in fatigue analysis of solder joints, which is described as:

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f'\left(2N_f\right)^c \tag{1}$$

where $\Delta\varepsilon_p$ is the amplitude of local plastic strain, ε_f' is the fatigue ductility coefficient, N_f represents the fatigue life, and c is the fatigue ductility exponent. Assuming the fatigue damage follows the pattern of linear accumulation, the damage of one cycle is shown as:

$$d_f = \frac{1}{N_f} = 2\left(\frac{\Delta\varepsilon_p}{2\varepsilon_f'}\right)^{-\frac{1}{c}} \tag{2}$$

where d_f is one-cycle damage. The cumulative damage D_f of n cycles is:

$$D_f = \sum_{i=1}^{n}\frac{1}{N_{f(i)}} \tag{3}$$

2.2. Creep analysis

Creep damage is different from low-cycle fatigue damage. The latter is related to the number of load cycles while the creep damage is time-dependent. And the creep damage is mainly accumulated during the dwelling period [20]. The creep rupture is caused by nucleation of voids at intermetallic compounds and the subsequent growth through a continuous creep deformation involving a dislocation creep mechanism, such as lattice diffusion-controlled dislocation climb, coupled with a dispersion-strengthening mechanism [5]. The Monkman-Grant model is constructed to represent a link between rupture time and stable creep strain:

$$\dot{\varepsilon}_s t_c^{\beta} = C_{MG} \tag{4}$$

where $\dot{\varepsilon}_s$ is the stable creep strain rate, t_c is the creep rupture life, and the exponent β and constant C_{MG} are related to the material