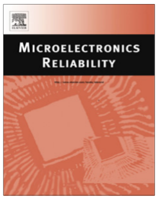
Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel



Low-cycle fatigue failure behavior and life evaluation of lead-free solder joint under high temperature

Yongxin Zhu *, Xiaoyan Li, Ruiting Gao, Chao Wang

School of Materials Science and Engineering, Beijing University of Technology, 100 Ping Le Yuan, Chaoyang District, Beijing 100024, PR China

ARTICLE INFO

Article history:
Received 4 April 2014
Received in revised form 22 August 2014
Accepted 22 August 2014
Available online xxxx

Keywords:
Solder joint
Fatigue failure
Life prediction
High temperature

ABSTRACT

In this study, low-cycle fatigue test was conducted for a lead-free solder joint at two test temperatures (348 K, 398 K) and three strain amplitudes (3%, 4%, and 8%). Fatigue failure behavior was analyzed and the fatigue life was evaluated using the Coffin–Manson relationship and Morrow energy-based model. The results show that the maximum load gradually drops with increasing the number of loading cycles. When the strain range or temperature is low, the maximum load drop curve can be divided into three stages. Then, it degrades into a linear stage with increasing the strain range or temperature. Both the softening of solder and the reduction of effective load-bearing area are responsible for the maximum load drop depending on the test condition. Fatigue crack initiates at the corner of the solder joint and propagates along the strain concentrated zone. Spacing distance between fatigue striations is enlarged with increasing the temperature in accordance with the degradation of fatigue resistance. In addition, both the Coffin–Manson model and Morrow energy-based model can be used to evaluate the fatigue life of solder joint under high temperature. The fatigue ductility exponent α in Coffin–Manson model and the fatigue ductility coefficient C in Morrow model are dependent on temperature, whereas other parameters in these two models keep stable under different temperature.

1. Introduction

Portability, minimization and high reliability are the current trend for electronic packaging industry. Because of the toxicity of lead, lead-free solder has been widely adopted considering the environmental legislation and market requirements [1,2]. Generally, solder joint in electronic devices is continually subjected to thermal cycling, and it is inevitable to cause cyclic strain due to coefficient of thermal expand (CTE) mismatch among different parts in the device. Consequently, fatigue failure may take place.

Many workers have studied the fatigue behavior of lead-free solders [3–9]. For example, Fakpan et al. [3] conducted the fatigue crack growth test of Sn3.0Ag0.5Cu solder, and indicated that the crack growth behavior of the solder was mainly depended on the testing frequency and temperature. At low frequency and high temperature, it was predominantly time-dependent, while cycle became determinant at high frequency and low temperature. Moreover, the failure mode was changed from transgranular fracture to transgranular–intergranular fracture for the Sn3.0Ag0.5Cu solder. Zhao et al. [4] found the same phenomenon in 96.5Sn3.5Ag lead free solder. Effects of strain ratio and tensile holding time on low-cycle fatigue of lead-free Sn3.5Ag0.5Cu solder were reported by Lin and Huang [5]. The result indicated that either strain ratio or tensile holding time increase would reduce the low-cycle fatigue life significantly. Kanchanomai et al. [9] elucidated that steps at the boundary of dendrite phases were the initiation sites of micro-cracks for Sn3.0Ag0.5Cu solder.

It should be mentioned that the solder joint failure behavior is quite different from the solder alloy due to the presence of interfacial boundaries and size effect of the joint [10]. The thickness of a solder joint is much smaller than that of a bulk solder used for fatigue test, so that the amount of plastic deformation can be vastly different. Considering this issue, lots of publications have been devoted to understand the low-cycle fatigue behavior of solder joint. Kanda et al. [11] studied the effect of holding time on low-cycle fatigue life of micro-solder joint and concluded that the low-cycle fatigue life of the Sn3.0Ag0.5Cu micro-solder joints was not strongly affected by temperature and holding time when the crack length is considered to define fatigue life. Influence of asymmetrical waveform on low-cycle fatigue life of micro-solder joints was also investigated by Kanda and Kariya [12] and the author found that grain boundary damage which has been reported in large-size specimens did not occur in Sn–Ag–Cu micro-size solder joints for which contain only a small number of crystal grain boundaries. Lee et al. [13] analyzed the fatigue life

---

* Corresponding author.

http://dx.doi.org/10.1016/j.microrel.2014.08.016

of Sn-based solder joints using the Coffin–Manson relation and Morrow's plastic-energy dissipation model under room temperature. The authors found that crack initiated at the solder wedge near the solder mask and subsequently propagated into the solder matrix, and both the life evaluation model gave consistent result. Tang et al. [14] found that fatigue life of Sn3.5Ag0.7Cu solder joint decreased with either increasing test temperature or reducing the test frequency, and proposed a modified Coffin–Manson model, which considered effect of temperature and frequency on the low-cycle fatigue life.

Although there have been some researches on the low-cycle fatigue failure behavior and life evaluation of lead free solder joint, the failure mechanism especially under high temperature is still unclear. Hence, in this study, fatigue failure behavior of lead-free solder joints under high temperature was investigated and fatigue life was also evaluated.

2. Experimental procedures

Sn3.0Ag0.5Cu solder was utilized in this study because it is considered as the most promising candidate for tin–lead solder [15]. The solder contained 96.5 wt.% Sn, 3.0 wt.% Ag, and 0.5 wt.% Cu. The solidus and liquidus were 490 K and 494 K, respectively. For low-cycle fatigue testing, a shear-lap solder joint sample was designed as shown in Fig. 1 in order to simulate the actual joint. Copper was selected as the substrate metal. The fabrication process of the solder joint was listed as follows: firstly, the Cu substrate, solder sheet, and the aluminum fixture was ultrasonic cleaned using anhydrous ethanol so as to remove the remained oil produced during the mechanical processing. Secondly, the copper substrate was dipped into 50 wt.% nitric acid for 20 s to remove the oxide layer and then rapidly placed in acetone to get rid of redundant nitric acid. Then the solder paste was dispersed on the end of the Cu substrate. At last, the solder sheet with dimension of 1 mm × 1 mm × 0.1 mm was applied between the two Cu sheets, and all of them were placed in the aluminum fixture. After that, the fixture was put into a reflow oven with a peak temperature of 533 K for 6 min, then took out the fixture and cooled in the air. The sample should be placed in air for two weeks in order to relieve the stress before fatigue test.

Fatigue test was conducted using a micro-force fatigue testing system with a heating furnace as schematically shown in Fig. 2. The temperature of sample rather than the heating chamber was determined by the thermocouple in order to get a more accurate temperature. All tests were conducted under displacement controlled mode using triangular waveform with the strain ratio $R = 0$. Moreover, the displacement rate was fixed as 4×10^{-2} mm/s. Three strain amplitudes (3%, 4%, and 8%), which were calculated from displacement amplitude divided by the gage length (1 mm), were selected. So, the strain rate is also 4×10^{-2}. For each stain range, two temperatures (348 K, 398 K) were selected to investigate the temperature effect. Every test condition was conducted for three times in order to get a more accurate result. All tests were terminated when the sample was completely fractured and the number of cycle was defined as the fatigue life.

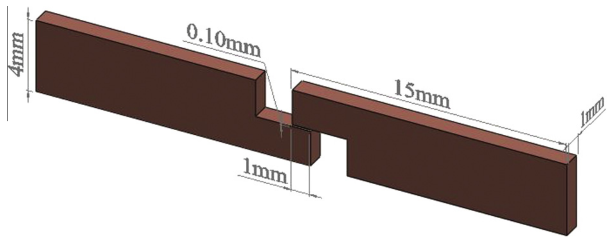


Fig. 1. Schematic diagram of shear-lap solder joint specimen.

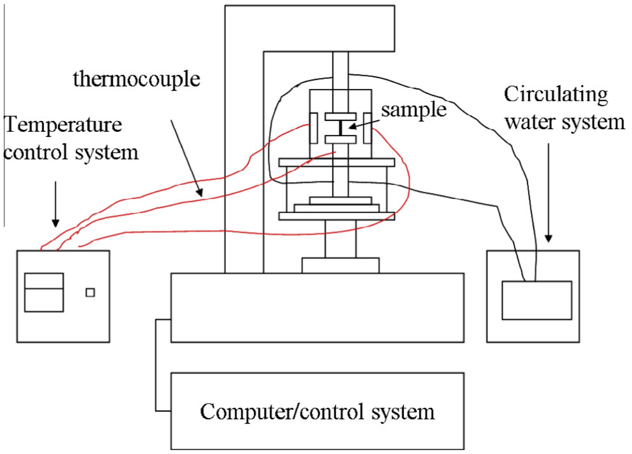


Fig. 2. Schematic diagram of micro-force fatigue testing system.

In order to observe the damage evolution, the side surface of some specimens was firstly grounded with 1000# and 2000# grit SiC abrasive paper and then carefully polished with 0.3 μm Al_2O_3 and 0.05 μm SiO_2 colloidal suspension. Scanning electron microscopy (SEM) and energy dispersive spectrometer (EDS) were used to reveal the failure mechanism.

3. Results and discussions

3.1. Maximum load drop during the fatigue test

Fig. 3 illustrates the maximum load drop curve with number of cycles. It is obvious that the maximum load drop curve can be

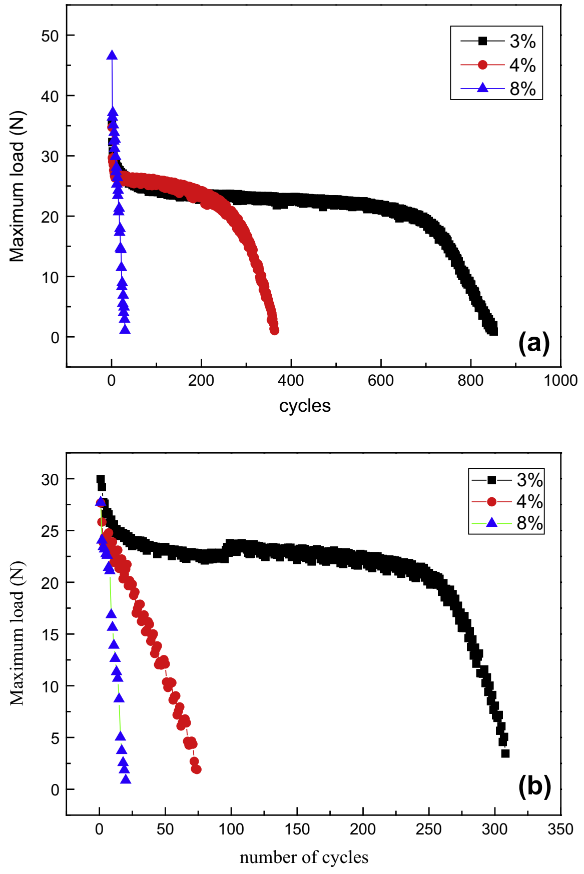


Fig. 3. Maximum load versus number of cycles under different temperature and strain range: (a) 348 K and (b) 398 K.