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Fatigue and dwell-fatigue behavior of nano-silver sintered lap-shear joint at elevated temperature

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ABSTRACT

Load-controlled fatigue and dwell-fatigue tests were conducted at elevated temperature to describe the high temperature mechanics behavior of nano-silver sintered lap-shear joints. The results showed that the shear strength of nano-silver sintered lap-shear joints was strongly temperature dependent, and almost halved at the temperature of 325 °C. The Basquin model was used to assess the fatigue life of the joints at elevated temperature and the constants in the model were figured out, which yielded good prediction for experimental data. In dwell-fatigue tests, at the temperature of 325 °C, creep was found the dominant factor that resulted in failure acceleration and cyclic life reduction. With the temperature decreasing to 225 °C, the creep played a less important role to the total deformation.

1. Introduction

First level packaging involves the interconnect technology, which interconnects the chip to a carrier and provides mechanical continuity, physical protection, electrical connection, as well as thermal cooling for the integrated circuit [1–3]. The performance of interconnect technology is crucial to the integrity of integrated circuit, which in turn is vital to the overall functioning of the assembly [4,5]. The existing traditional interconnect technologies consist of wire bonding, solder reflowing and conductive adhesive curing. In recent years, the ever-smaller feature size of integrated circuit imposes increasingly stringent requirements on weight reduction, size miniaturization as well as high thermal dissipation capability of integrated circuit [6–10]. The appearance of high power density systems like wide-band gap semiconductors makes the operating temperature higher, which is beyond the capability of traditional die-attaching materials and interconnect technologies. The present situation of electronic packaging is promoting the introduction of a superior die-attach technology for high-power electronic packaging to the market place.

In the 1970s, the viewpoint of diffusion welding silver film was firstly introduced by O'brien et al. [11], and thus a new die-attaching technology named low-temperature sintering technology was remarkably promoted. Under the mechanical pressure of about 40 MPa, micro-sized silver powder could be sintered at temperature below 300 °C [12]. From then on, silver was used widely in microelectronic packaging as a promising interconnection material between substrates and chips because of its superior electrical/thermal conductivity, high melting temperature (T_m = 960 °C), and good reliability. However, for brittle silicon chips and ceramic substrates, the aided pressure might be destructive even slightest irregularities [13,14]. To raise the sintering driving force of this interconnection material, Bai and Lu introduced a paste which was mainly formed by nano-sized silver powders, and gained the close attention of both scientists and power electronics engineers [15].

Before the nano-silver sintering technology coming into practical application, both the sintering process and the mechanical properties of nano-silver paste have been studied. In recent years, a low-temperature sintering profile with sintering temperature of 285 °C, heating rate of 10 °C/min, and holding time of 60 min was introduced by Wang et al. [16]. Yu et al. studied the tensile behavior of low-temperature sintered nano-silver films and proved that accumulation of plastic strain took place in silver-bonding layer during thermal cycling, which might lead to the final failure of the chip-attachment [1]. Wang et al. stated that the fatigue failure of sintered silver paste was dominated by ratcheting response, especially for elevated temperature [7]. These studies only revealed the properties of sintered silver film, which in turn imposed a limitation on consideration of the thermally induced strain. However, the service environment of the electronic equipment was very complex with frequently mechanical vibration and temperature change. Both cyclic loads and stress concentration were induced by the thermal expansion coefficient mismatch between substrates and chips in actual application [17–20]. As a result, Li et al. [21–23] constructed a lap-shear structure to study the mechanical properties of sintered nano-silver as a joint. Based on this lap-shear structure, fatigue and dwell-fatigue tests were conducted in this article in order to understand the cyclic failure

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mechanism of nano-silver sintered lap shear joint at elevated temperature. The relationship between creep damage and fatigue damage in the low-cycle regime was studied.

2. Sample preparation and experiment procedure

The nano-silver sintered lap shear joints were employed as specimens in this study. The pastes with nano-silver particles smaller than 50 nm were provided by NBE Tech, LLC [24]. Widely used Cu with purity of about 99.9% was chosen as substrates [25]. After sintered according to a recommended heating profile for chip attachment as shown in Fig. 1 [21–23], the specimens of 2 mm × 1 mm and thickness of 50 μm were obtained as exhibited in Fig. 2. All the tests were conducted on Micro Uniaxial Fatigue Testing System (MUT-1020) provided by CARE Measure & Control Co., Ltd. as given in Fig. 3.

In order to obtain the shear stress–strain relation of sintered lap shear joints as the base for cyclic tests, a series of shear tests were conducted at four different ambient temperatures of 25 °C, 125 °C, 225 °C and 325 °C. The loading conditions of fatigue and dwell-fatigue tests are listed in Table 1. All the shear and cyclic tests were conducted under stress-controlled mode. Three samples were conducted for every loading condition.

In the present study, the shear strain was determined by dividing the joint displacement over the lapped joint thickness. In order to remove the effects of substrate and machine compliance, the joint displacement, which was used to transform into shear strain, was revised by elastic theory calculating and non-contact measurement, respectively.

3. Results and discussions

3.1. Shear behavior

As shown in Fig. 4, the effect of temperature on strain of nano-silver joints can be concluded. At room temperature of 25 °C, the failure strain is less than 1.5%, which contains a small part of plastic strain and thus a brittle failure. With the temperature increasing, the shear modulus decreases and the plastic flow of the joint is more obvious [21]. The average shear strength under four ambient temperatures is given in Fig. 5. With the gradually increasing of temperature, the shear strength decreases. At room temperature of 25 °C, the shear strength is as high as nearly 28 MPa, which almost halved at the temperature of 325 °C (13.3 MPa).

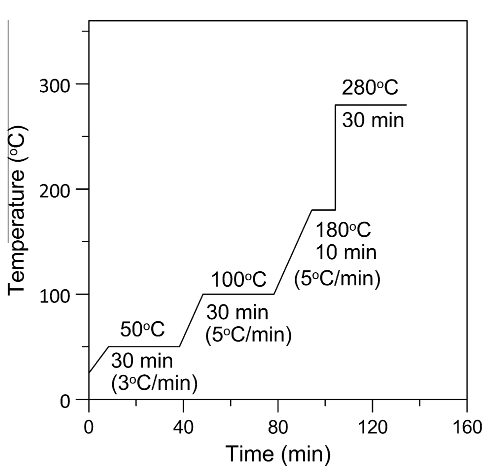

Fig. 1. Sintering profile of nano-silver paste.

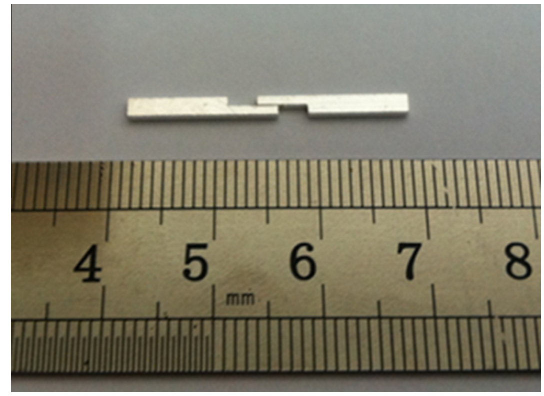

Fig. 2. Prepared sintered nano-silver lap-shear structure.

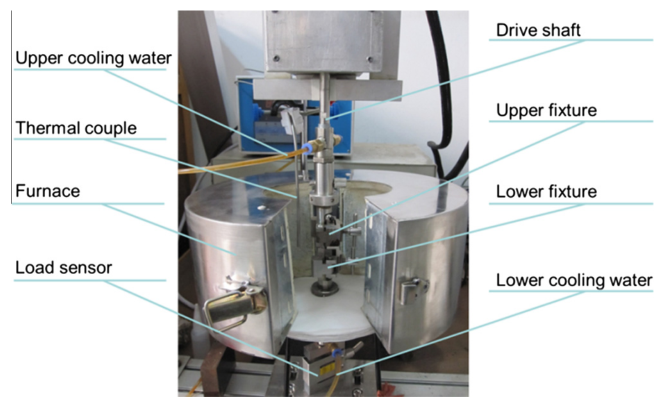

Fig. 3. The testing apparatus.

3.2. Fatigue tests of fully reversed at elevated temperature

3.2.1. Fatigue behavior

Fig. 6 shows shear stress–strain hysteresis loops under different loading amplitudes at 325 °C. From Fig. 6 it can be found that the shear strain amplitude increases with the increasing of loading amplitude under fully reversed loading situation. The increase of hysteresis loops with loading amplitudes demonstrates the larger energy dissipating per unit volume during a cycle, which results in shorter cyclic life [26,27].

The plot of shear strain range versus number of cycles as shown in Fig. 7 illustrates that the initial shear strain range increases as the increase of the loading amplitude. The evolution of shear strain range can be divided into three stages. The first stage takes the longest duration of the fatigue life at constant shear strain amplitude. When the fatigue test steps into the second stage, the shear strain slowly increases, which can be considered as the crack propagation. In the third stage, the fatigue damage accumulation accelerates and results in ultimate failure.

The strain–stress hysteresis loops of the nano-silver joint at load amplitude of 6 MPa and 8 MPa are taken as examples in Fig. 8. The enclosed area of the hysteresis loops represents the cyclic plastic energy consumed in each cycle. At the given loading amplitudes, the enclosed area gradually increases with the number of cycles. The hysteresis loop experiences a rapid increase before the nano-silver joint coming to the final failure.

The temperature effect on hysteresis loops under 7 MPa and 7 MPa loading amplitude is shown in Fig. 9. It can be found that at higher temperature of 325 °C, the loops are wider and thus more plastic strain is accumulated in one cycle. As a result, the fatigue life at the temperature of 325 °C is shorter than that at the temperature