In situ observations on shear and creep–fatigue fracture behaviors of SnBi/Cu solder joints

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Shear and creep–fatigue fracture behaviors of the SnBi/Cu solder joints were investigated in this study. The deformation and fracture morphologies were in situ observed by scanning electron microscope, and the fracture mechanisms were discussed based on the observation results. It is found that the SnBi solder in the solder joint shows good ductility under shear stress, there is serious deformation mismatch between the Sn and Bi phases in micro-scale but no macro-scale cracking occurs inside the solder, and the shear fracture occurs along the Cu/solder interface. Under creep–fatigue loadings, the strain of the solder joints increases rapidly during the initial few cycles, but the increase rate decreases due to strain hardening. After the strain hardening becomes saturated, the strain increases exponentially with increasing cycles and the damage inside the solder keeps developing, final fracture occurs inside the solder near the joint interface. As the plastic deformation of the SnBi solder concentrates at the grain boundary, it is predicated that grain-boundary sliding is the major creep deformation mechanism. The influencing factors on creep–fatigue resistance include the stress range, holding time and grain size of the solder. Based on the understandings, techniques to enhance the creep–fatigue resistance were proposed.

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1. Introduction

Lead-rich solders have been widely used in microelectronic assembly for many years. However, due to the toxicity of Pb, major industrialized countries have legislated to limit their application [1]. As a result, a series of lead-free alloys have been proposed. Among them, the SnBi alloy is one of the most promising candidates, especially in the low-temperature soldering field, because of its low melting point, high strength and superior creep resistance [2,3]. Since the solder joints in the Printed Circuit Board (PCB) should ensure the mechanical reliability of the solder joints under complex service conditions, one of the major concerns for the integrity of the solder interconnection is its mechanical property [4]. As the Bi-rich phase is the major phase in the SnBi eutectic structure and is much more rigid than the Sn-rich phase [5], the SnBi solder should display quite a different deformation behavior from most of the other Sn-base solders that contain only a little percentage of alloy elements. Therefore, the deformation and fracture mechanisms of the SnBi solder and solder joints are necessary to be investigated. However, most of the studies so far only focus on the microstructure of the SnBi solders [6,7]; few reports have investigated the microscopic deformation and fracture behaviors of the SnBi alloys under mechanical loadings.

In the PCB, the primary mechanical loadings carried out by the solder joints are the creep–fatigue stresses induced by thermal cycles [4]. As the chip, chip-carrier and PCB substrate in the electronic device are always different materials, their thermal expansion coefficients (TEC) are also quite different. As a result, when the device is heated or cooled from the equilibrium temperature, their expansion amounts are different and the solder joints between the components will suffer positive or negative shear strain [8]. Furthermore, cyclic loadings will occur when the electronic devices are turned on and off, and fatigue damage is also induced in the solder joints within each cycle. As the homologous temperature ($T/T_m$) of solder in electronic applications can easily exceed 0.75, creep deformation of the SnBi solder also plays an important role in the deformation and fracture of the solder joints. Therefore, the major mechanical failure of the solder joints during the service process should be induced by creep–fatigue damage, which is necessary to be further investigated.

For that reason, the shear and low-cycle creep–fatigue fracture behaviors of the SnBi/Cu solder joints are investigated in this study to reveal the deformation mechanisms of the SnBi solder under the stress similar to the real service condition. The Sn–58Bi (wt%) eutectic alloy is chosen as the solder, and Cu is selected as the substrate as it is the most widely used substrate material in PCB [9,10]. The low-cycle fatigue test with a holding time at the high stress is a common method to investigate the interaction between creep and fatigue [11], and the shear behaviors of the SnBi/Cu solder joints are investigated to find proper test condition for the creep–fatigue
tensile stage. The SnBi solder was prepared by melt-

2. Experimental procedure

The Cu substrate used in this study is cold-drawn oxygen-free-high conductivity (OFHC) Cu clava of 99.9% purity, and its yield strength is about 200 MPa. The SnBi solder was prepared by melting high purity (>99.99%) tin and bismuth at 800 °C for 30 min in vacuum. To prepare the solder joint samples, the Cu clava was first spark cut into small blocks with a step, and then the surfaces for soldering were ground and electrolytically polished. After air drying, a soldering paste was dispersed on the polished area to ensure sufficient wetting reaction. The steps of the two Cu blocks were butt to butt, a Sn–58Bi alloy sheet was sandwiched between them and graphite plates were clamped on the sides of the Cu blocks to avoid the outflow of the molten solder. Then the prepared samples were put in an oven with a temperature of 260 °C, kept for 8 min after the melting of the solder and then cooled down in air. After that, the soldered samples were sliced into specimens by spark cutting; the side surfaces were firstly ground with 2000# SiC abrasive paper and then carefully polished for the interfacial microstructural observations. The dimensions of the final treated samples for shear and fatigue tests are presented in Fig. 1.

Both the shear and creep–fatigue tests were carried out by LEO super 35 scanning electron microscope (SEM) equipped with a Gatan MTEST2000ES Tensile Stage, image of the tensile stage and clamping of the sample are also shown in Fig. 1. As the Cu substrates only show very little elastic deformation and the deformation of the solder joints concentrates inside the solder, the shear strain rate was calculated by dividing the cross-beam speed with the length of the solder/Cu joint interface, which can express the deformation of the solder more precisely. The shear tests were performed under a cross-beam speed of 0.05 mm min$^{-1}$ to get a shear strain rate of about $8 \times 10^{-4}$ s$^{-1}$. To observe the deformation morphologies and show the stress relaxation behaviors of the solder joints, the shear tests were stopped at some certain stresses. According to the shear strength, the stress ranges of the creep–fatigue tests were set as 2–20 MPa and 2–22 MPa. Besides, the holding time was set as 120 s as the stress relaxation occurs very fast. Because the working temperature of the electronic device is usually higher than the room temperature, the creep–fatigue tests were set as tension–tension mode. Both the macroscale and microscale deformation morphologies were in situ observed by SEM. The full view of the solder joints deformed for different cycles were firstly observed to show the general fracture process. As the plastic deformation of the solder joints concentrates in the solder and fracture of the solder joints usually occurs at the joint interface, microscopic deformation morphologies at these regions were tracked to reveal the deformation and crack initiation processes.

3. Results and discussion

3.1. Shear fracture behaviors of SnBi/Cu solder joints

Fig. 2 exhibits the shear stress–strain and stress–time relationships of the Sn–58Bi/Cu solder joints. The shear strains of the solder joints were calculated by firstly subtracting the displacement of Cu from the total displacement, and then divided the result with the length of the solder/Cu joint interface. It can be found from Fig. 2(a) that the yield strength of the solder joint is about 24 MPa at the current strain rate, and the fracture strength is about 32 MPa. However, obvious stress relaxation has occurred even when the test was stopped at 20 MPa. Generally, the stress relaxation behavior is related with the applied stress and holding time. As shown in Fig. 2(b), the relaxation rate is higher at higher stress, and both the stress and the relaxation rate decrease with increasing holding time. It has been reported that the stress relaxation behaviors of the Sn3.5Ag and Sn9Zn solder alloys are similar to the aforementioned behavior when the tensile tests were stopped at a constant stress [11], which suggests some validity for characterizing the dependence of tensile strength on time as an indicator of creep behavior. According to the shear strength and stress relaxation rates at different stresses, the stress ranges of the creep–fatigue tests were chosen as 2–20 MPa and 2–22 MPa to get proper lifetimes, and the holding time was chosen as 120 s since the stress relaxation occurs very fast. In that stress ranges, the Cu substrate only shows a very little elastic deformation, while the deformation and stress relaxation of the solder are obvious.

The macroscopic shear deformation and fracture behaviors of the Sn–58Bi/Cu solder joints are shown in Fig. 3, and the corresponding strains are tagged in each figure to indicate the deformation process. Fig. 3(a) shows the morphology of the solder joint before the shear test, in which the surface of the SnBi solder is very flat. The strain in Fig. 3(b) is 0.112, and the solder joint has displayed a slight plastic deformation inside the solder, but not very obvious. In Fig. 3(c), the strain is 0.211 and the plastic deformation becomes obvious in macro-scale. With increasing strain, the plastic deformation inside the solder becomes more and more serious. At the strain of 0.273, a micro-scale slide crack has appeared at the corner of the solder joints, as shown in Fig. 3(d), and obvious roughness at the surface of the solder can be observed. Fig. 3(e) shows...
the deformation morphologies at the strain of 0.421, in which more cracks can be observed along the joint interface. Moreover, some microcracks inside the SnBi solder were also observed. In Fig. 3(f), the slide crack at the interface has evolved into a macroscopic crack and the solder joint fractures along the joints interface shortly after that. During the shear fracture process, the strain concentrates inside the solder as the yield strength of the Cu substrate is very high, but there is no macroscopic cracking inside the solder even when its strain was up to 0.6, indicating that the SnBi solder has superior ductility in macro-scale. However, as the strength and hardness of the two phases are quite different, serious deformation mismatch may easily occur between the two phases.

The microscopic deformation and fracture behaviors of the SnBi/Cu solder joints are shown in Fig. 4. Fig. 4(a)–(c) shows the deformation behaviors of the SnBi solder during the shear process. In Fig. 4(a) the strain is 0.116, but serious plastic deformation has occurred inside the solder. The deformation mismatch between the Sn and Bi phases induces many steps at the surface, and some irregular microcracks were observed at the phase boundary. It can be predicated that these microcracks will decrease the resistance of the solder to plastic deformation. Fig. 4(b) gives the deformation morphology of the solder at the strain of 0.231, which shows little difference from Fig. 4(a), only a bit more serious. The deformation morphology at the strain of 0.421 is shown in Fig. 4(c). Compared with that in Fig. 4(a), the plastic deformation is much more serious, some solder even crack into little grains. However, there is still no long cracking inside the solder. Because the microcracks inside the solder are irregular and have different orientations, they can hardly develop into long cracks. In fact, fracture of the solder joint often initiates at the Cu/solder joint interface. The deformation morphologies at the joint interface are shown in Fig. 4(d)–(f). In Fig. 4(d), the plastic deformation of the solder is not very serious, but a step appeared along the solder/Cu interface, because the transverse shrinkages of the solder and Cu are different. In Fig. 4(e), the plastic deformation of the solder becomes obvious and the step has evolved into microcracks. With increasing strain, the microcracks become wider and connect to form larger cracks (see Fig. 4(f)), inducing a final fracture along the joint interface. According to the observations above, it is concluded that there is deformation mismatch between the two phases of SnBi solder, but the mismatch will not result in macro-scale cracking. It is the deformation mismatch between the Cu substrate and solder that induces the final fracture of the solder joints along the joint interface.

3.2. Creep–fatigue fracture behaviors of SnBi/Cu solder joints

The strain–cycle relationships of the solder joints during the creep–fatigue processes are shown in Fig. 5, and the two figures show the relationships in two different coordinates (see Fig. 5(a) and (c)). During the initial few cycles of the creep–fatigue test, the
Fig. 4. (a)–(c) Deformation morphologies of SnBi solder during the shear process; (d)–(f) deformation morphologies at the SnBi/Cu joint interface.

strain increases rapidly but the increment per cycle decreases, as in Fig. 5(a), which should result from the cyclic strain hardening of the solder during the fatigue process \([16,17]\). After a few cycles, the average strain increment per cycle decreases to a minimum value and then increases gradually with increasing cycles. As the strain is mainly contributed by plastic deformation of the solder, it is predicated that the capacity of the solder to resist the plastic deformation decreases with increasing cycles in that process. In micro-scale, it is the deformation mismatch inside the solder that brings in the damage and decrease the resistance of solder to plastic deformation. The stress–time curve of a few cycles in the stress range of 2–22 MPa is shown in Fig. 5(b), it is found that there is obvious stress relaxation during the holding period at 22 MPa, and the relaxation rate becomes very low after holding for 120 s. Based on that, it is can be found that the stress ranges and holding time have significant influence on the creep–fatigue behaviors. Since the

Fig. 5. Strain–cycle relationship of the creep–fatigue tests in (a) linear and (c) exponential coordinate systems, and (b) strain–time curves of a few cycles.
strain–cycle curves are similar to the exponential lines, two exponential lines were drawn to fit the strain–cycle curves, and one can find that the fitted lines match well with the strain–cycle curves. Therefore, the strain is exhibited by exponential coordinate system in Fig. 5(c). As in the figure, the strain–cycle shows a linear relationship during the intermediate stage. For the lattermost few cycles, the increasing rate of strain becomes very high and deviates a little from the straight line, which should be due to the serious damage inside the solder joints and cracking at the joint interface prior to the final fracture. According to the above results, the process can be divided into three stages, i.e. strain hardening stage, exponential deforming stage and final fracture stage, respectively. For the samples tested at different stress ranges, the fracture processes are similar, only the lifetime is different. As the strain and cycle follows an exponential relationship, the exponential deforming stage can be described by an exponential function including the strain and cycles:

\[ \varepsilon = A \exp\left(\frac{N}{B}\right) + C \]  

where \( \varepsilon \) is the shear strain, \( N \) is the life cycle and \( C \) is a constant.

In the stress range of 2–20 MPa, \( A \) is 0.0123, \( B \) is 39.2 and \( C \) is \( 7.95 \times 10^{-3} \), while \( A \) is 0.0329, \( B \) is 18.3 and \( C \) is \( 1.16 \times 10^{-2} \) in the stress range of 2–22 MPa. As the constant \( C \) is very little, the major difference is in \( A \) and \( B \), which should be dominated by the stress range and holding time. Therefore, these two factors are the major extrinsic influencing factors on fatigue lives. As in Fig. 5, a little increase in the upper holding stress (20–22 MPa) can lead to a sharp decrease in the lifetime. If the upper holding stress increases a little more, the solder joints will fracture in very few cycles. In contrary, the lifetime will increase sharply when the stress decreases a little. For the solder joints in the electronic device, the thermal stress is induced by variation of the service temperature, and the upper holding stress is dominated by the maximum service temperature. Therefore, the creep–fatigue damage of the solder joints can be alleviated obviously by a slight modification of the service temperature.

The macroscopic deformation and fracture morphologies of the solder joint tested in the stress range of 2–20 MPa are shown in Fig. 6; and the strain and cycles are also tagged in the images. The 9 images are corresponding to the three stages of the creep–fatigue processes. In the first stage, there is no visible plastic deformation inside the solder in macro-scale, as shown in Fig. 6(a), although the strain hardening of the solder is obvious. Fig. 6(b)–(g) shows the deformation morphologies of the second stage. In Fig. 6(b)–(d), the plastic deformation of the solder can be observed, but not very serious, and the increasing rate of strain is very low. In the latter process, the plastic deformation of the solder is much more serious and has become damaged rather than hardening (see Fig. 6(e)–(g)). The serious damage of the solder will decrease its resistance to plastic deformation, leading to a higher increasing rate of strain. Besides, a deformation band appears at the corner of the solder joint in this stage and evolves into the primary cracking with increasing cycles. Prior to the final fracture, the cracking at the joint interface is serious and induces a sharp increase in strain, as in Fig. 6(h) and (i), and final fracture occurs inside the solder near the joint interface.

It has been exhibited in Fig. 6 that the creep–fatigue fracture also occurs near the joint interface, which is similar to the shear fracture in macro-scale. However, the crack initiation mechanisms are a little bit different in micro-scale. Fig. 7 shows the interfacial deformation and the evolution process of the primary creep–fatigue cracks, and the corresponding strain of each figure is tagged at the corner. In Fig. 7(a) and (b), the strain is very little, but a slight deformation band has appeared at the corner of the sample. As the strain concentration at the corner is serious, the deformation band develops faster than that at the interior of the solder. As in Fig. 7(c)–(e), the deformation band becomes longer and more serious with increasing strain. In Fig. 7(f), the deformation band has evolved into a cracking near the joint interface, and the damage rate of the solder joint accelerates in the later cycles and final fracture

![Fig. 6. Macroscopic creep–fatigue deformation and fracture morphologies of SnBi/Cu solder joints.](image-url)
occurs along the crack. Therefore it is the deformation bands near the joint interface and parallel to the shear direction that evolve into the primary creep–fatigue cracks. In contrast, the primary cracking of the shear fracture is evolved from the deformation mismatch between the solder and Cu substrate. Moreover, the deformation mechanisms of the SnBi solder during the creep–fatigue processes are also a little bit different from the shear deformation process, which will be discussed in the next section.

3.3. Deformation behaviors of SnBi solder during creep–fatigue process

As the strain of the solder joints is contributed by plastic deformation of the solder, the deformation mechanisms are necessary to be revealed in detail. The deformation morphologies of the Sn–58Bi solder at a certain region of the SnBi/Cu solder joint during the creep–fatigue process are shown in Fig. 8, and the strains are tagged in the images. Before the tests, the surface of the SnBi solder is very flat. After deformed for a few cycles, some roughness and streaks appear on the surface of the solder, as in Fig. 8(a) and (b). With increasing cycles, the plastic deformation becomes more and more serious, and the roughness and deformation bands become obvious, as exhibited in Fig. 8(c) and (d). Besides, it can be found that the streaks are actually deformation bands. It has been observed that the grain size of the air-cooled SnBi solder is about 100–200 μm[18], which is similar to the size of the particles encircled by the streaks. Through a careful examination on morphologies of the deformation bands, it is predicated that the deformation bands appear along the grain boundaries of the solder. In Fig. 8(e) and (f), it is interesting to find that the deformation of the solder is not uniform. Around the deformation band, the plastic deformation is serious, while the deformation is little in the other regions. Moreover, if comparing the angle of the boundary indicated by the arrow, one can find a slight rotation of solder grain. To better understand the deformation mechanisms, the deformation morphologies around the solder grain are observed at higher magnification and shown in Fig. 9. The backscattering images were taken to reveal the deformation distribution, because only the microcracks in the serious plastic deformed areas can be identified as dark stripe in the backscattering images. In Fig. 9(a), a thin irregular circle of dark stripe is observed. Compared with the secondary electron images with similar strain (see Fig. 9(b)), it can be found that the dark cycle is a reflection of the serious plastic deformed area around the grain. In Fig. 9(c), the strain is higher and the non-uniform of deformation distribution at different areas becomes more obvious. Besides, there is also a little deformation mismatch between the two phases inside the solder grain. However, that mismatch is far less serious and cannot be identified in the backscattering image. Fig. 9(d) shows the backscattering electronic image of deformation at the strain of 0.403, in which the circle around the grain becomes
In the observations in Figs. 8 and 9, it is predicated that the plastic deformation inside the grain is still little. Fig. 9(e) shows the configuration of the SnBi solder, which fits well with the phenomena shown in Figs. 8 and 9. As the creep deformation is mainly contributed by grain-boundary sliding, it is predicated that the size of the solder can affect the creep–fatigue resistance of the SnBi/Cu solder joints.

4. Conclusions

The deformation and fracture behaviors of the SnBi/Cu solder joints under shear and creep–fatigue loadings were investigated by in situ observation in this study. Based on the experimental results and discussions above, the following conclusions can be drawn:

1. The SnBi solder in the SnBi/Cu solder joint exhibits good ductility under shear loadings. Although there is serious deformation mismatch between the two phases of the solder in micro-scale, no macro-scale cracking can occur inside the solder. It is the deformation mismatch between the Cu substrate and solder that induces a step at the solder/IMC interface, which evolves into cracks with increasing strain and induces the shear fracture along the joint interface.

2. The creep–fatigue fracture process can be divided into strain hardening stage, exponential deforming stage and final fracture stage, and fracture occurs inside the solder near the joint interface. Since the ratios of the first and last stages are very low, the second stage and further the creep–fatigue process can be described by exponential function. The stress range and holding time have significant influence on the creep–fatigue lifetimes.

3. The major creep deformation mechanism of the SnBi solder is grain-boundary sliding. The plastic deformation concentrates at the grain boundary, while the deformation inside the solder grain is little. The creep resistance of the solder joints can be improved through heat treattments that can increase the grain size of the solder.

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