Fracture behaviors and strength of Cu₆Sn₅ intermetallic compounds by indentation testing

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(Received 8 March 2011; accepted 20 May 2011; published online 5 July 2011)

In this study, the shear fracture behaviors of the Cu₆Sn₅ grains at the Sn-4Ag/Cu interface were studied by indentation test; the fracture mechanisms and shear strength were characterized through analyzing the indentation curves and fracture morphologies. Experimental results reveal that shear fractures of the Cu₆Sn₅ grains occur at the foundation or the center portion, depending on their size and shape, and there are bursts on the force-depth curves corresponding to the fracture. The shear fracture strength of the Cu₆Sn₅ grains fractured at their center portion is close to the shear strength of the Cu₆Sn₅ intermetallic compounds, and its average value is about 670 MPa. © 2011 American Institute of Physics. [doi:10.1063/1.3603032]

I. INTRODUCTION

Soldering is the most widely used connecting technology in electronic packaging because it not only provides the electronic connection, but also ensures the mechanical reliability of the solder joints. To form good solder joints, the presence of the intermetallic compounds (IMCs) between the solders and the substrate metals is desirable. However, the thick IMCs layer at the solder/substrate interface usually induces brittle fracture in the interfacial IMCs layer, which obviously degrades the reliability of the solder joints. Therefore, understanding of the fracture behaviors of the interfacial IMCs layer is of great importance on evaluating the reliability of the solder joints.

However, thus far, most studies on the mechanical properties of the IMCs only focus on their elastic modulus and hardness. Jiang et al. reported a micropillar compression test on mechanical properties of the IMCs, which is meaningful as it is the first report describing the strength and fracture mechanisms of the Cu₆Sn₅, while fracture of the Cu₆Sn₅ under compression loading is still a little bit different from that under the loading in the real service condition. Since the major mechanical loading subjected by the solder joints in service is the shear stress and, consequently, shear fracture is the common failure behavior of the interfacial IMCs (see Fig. 1(a)), the shear fracture behaviors and strength of the Cu₆Sn₅ grains are more meaningful to evaluate the reliability of the solder joints. Therefore, they were investigated in this study through a novel design of an experimental procedure using an indentation tester.

II. EXPERIMENTAL PROCEDURE

The solder used in this study is Sn-4Ag alloy, and the substrate is oxygen-free polycrystalline Cu. To prepare the test samples, a small block was firstly spark-cut from the Cu substrate and then its side surface for reflowing was ground and carefully polished. After air drying, a soldering paste was dispersed on the polished area and a piece of solder alloy was stuck on it. The prepared samples were put in an oven with a temperature of 260 °C, kept for 8 min after melting of the solder and then cooled down in air. The three-dimensional image of the interfacial Cu₆Sn₅ grains formed in this condition is shown in Fig. 1(b); it can be found that there are some protrudent Cu₆Sn₅ grains, which were chosen as the subjects investigated. After the reflowing process, a thin sheet was sliced from the sample and its side surface was ground and carefully polished (see Fig. 1(c)). To expose the Cu₆Sn₅ grains, the superficial Sn-4Ag solder around the joint interface was removed by corrosion, and the morphologies of the target Cu₆Sn₅ grains were observed by scanning electron microscope (SEM).

The DUH-211 Dynamic Ultramicroscopic Hardness tester was employed to conduct the indentation tests because it can record the dynamic load-depth relationships and the test using it is easy to carry out. The indenter is triangular pyramid and indentation location is the center portion of the target Cu₆Sn₅ grains, as illustrated in Fig. 1(c). The load was chosen as 20 mN and the loading speed was set as 1.90 mN/s. The force-depth relationships were recorded during the indentation process. After the indentation tests, the front views of the target Cu₆Sn₅ grains were firstly observed, then the cracked Cu₆Sn₅ fragments were flushed away by ultrasonic cleaning and the fracture surface of the target grains was also observed by SEM.

III. RESULTS AND DISCUSSION

A group of force-depth curves of the indentation tests are shown in Fig. 2; the depth in the figure is actually the shear displacement of the Cu₆Sn₅ grains. As in the figure, though the loads are 20 mN for all the tests, the displacements are quite different because the Cu₆Sn₅ grains have different size and shape. Nevertheless, there are similarities in all the curves. Within each curve, the depth increases approximately linear with increasing force during the initial deforming process. When the force increases to a certain
value, a depth burst occurs, which may correspond to the fracture in the Cu₆Sn₅ grain since it fractures in a cleavage mode. Besides, similar bursts have been observed when the Cu₆Sn₅ micropillars fracture under compression loadings by cleavage. After the burst, the depth again increases with increasing force and the slope is similar to the initial stage. For some curves, there are secondary bursts. As the bursts on different curves are quite different, the fracture morphologies of the correlating Cu₆Sn₅ grains were observed to reveal their differences.

Figures 3 and 4 show the morphologies of two representative Cu₆Sn₅ grains before and after the indentation tests for comparison. The morphologies of a Cu₆Sn₅ grain fractured at a low force are shown in Fig. 3. Figure 3(a) exhibits the target Cu₆Sn₅ grain before the indentation test, which is bamboo shoot-like in shape and the length is about 10 μm; the indentation location is indicated by the “X”. After the test, the target Cu₆Sn₅ grain only exhibited a little tilt compared with the initial state, while the surrounding little Cu₆Sn₅ grains were broken (see Fig. 3(b)). Figure 3(c) shows the front view after the ultrasonic cleaning. The target Cu₆Sn₅ was washed away, indicating that actually it has fractured at its foundation under the indentation test. The top views of the target Cu₆Sn₅ grain are presented in Figs. 3(d) and 3(e), respectively. Through comparing them, the fracture surface of the target Cu₆Sn₅ grain can be determined easily, as indicated by the circle.

Figure 4 shows the morphologies of a Cu₆Sn₅ grain fractured at a relatively higher force. The front view of the target grain before the test is shown in Fig. 4(a). As in the figure, the target grain is a little bit podgy compared with that in Fig. 3(a), and the indentation location is also indicated by the “X”. After the indentation test, it is interesting to find that there are some parallel cracks in the target Cu₆Sn₅ grain, but there is no breakage in the surrounding Cu₆Sn₅ grains (see Fig. 4(b)). According to the width and location of the cracks, the crack at the center portion of the grain is predicated to be formed initially, i.e., it is the primary fracture corresponding to the first depth burst in the curve, and the other cracks were formed in the further indentation process. Based on the predication, the primary fracture location is lined out in Fig. 4(a), and it is notable that the primary fracture occurs at the indentation location. After the ultrasonic cleaning, the cracked Cu₆Sn₅ fragments were washed away, as in Fig. 4(c), but the surrounding Cu₆Sn₅ grains still show no breakage. Figures 4(d) and 4(e) show the top views of the target grain before and after the test. Although the primary fracture surface is not the fracture surface in Fig. 4(e), it can be determined by comparing the front view and the top view of the target Cu₆Sn₅ grain based on a charting principle. After determining the fracture surfaces, their areas can be measured and the fracture strength of the Cu₆Sn₅ grains can be calculated.

Based on the foresaid discussions on the indentation curves and the fracture morphologies, the fracture processes of the two fracture modes are illustrated in Fig. 5. In all the figures, the contours of the Cu₆Sn₅ grains at the last stage are presented with the broken lines to clearly indicate the fracture process. Figures 5(a)–5(c) show the fracture processes of the Cu₆Sn₅ grain shown in Fig. 4. During the initial deforming stage, the Cu₆Sn₅ grain deforms elastically, as in Fig. 5(a). When the load increases to a critical value, the Cu₆Sn₅ grain fractures at its center portion (see Fig. 5(b)), inducing the first depth burst on the force-depth curve. As the fracture location is very close to the indentation location, the flexural torque on the fracture plane is little, and the fracture should be induced by the shear stress. In the latter process, the indenter is sustained by the residual part of the target Cu₆Sn₅ grain, as shown in Fig. 5(c); some parallel
secondary fractures are formed, while the surrounding Cu₆Sn₅ grains are not broken. The fracture processes of the Cu₆Sn₅ grain in Fig. 3 are illustrated in Figs. 5(d)–5(f). As in the figures, the Cu₆Sn₅ grain also only displays elastic deformation at the first stage, but fractures at its foundation when the load increases to a certain value. Because there is an arm of force between the fracture location and the indentation location, the Cu₆Sn₅ grain fractures like a cantilever, i.e., it is the flexural torque that causes the fracture, and the fracture occurs at the foundation, as the flexural torque there is the highest. The depth burst in this fracture mode is much higher than the first fracture mode, because the indenter should descend a larger distance until it can be sustained by the Cu₆Sn₅ grains around the target grain. As a result, the secondary fracture occurs in the surrounding Cu₆Sn₅ grains rather than in the residual part of the target Cu₆Sn₅ grain. It is predicated that the slender Cu₆Sn₅ grains are more likely to fracture at the foundation at a lower stress, while the podgy grains tend to fracture at the center portion at a higher stress. It has been widely accepted that the fracture behavior of the IMCs layer is affected by their thickness and morphologies;⁵,¹⁹ the present work provides a strong and direct support for that.

As discussed above, the primary fracture at the center portion is induced by the shear stress; therefore, the fracture strength in this condition can be considered similar to the shear strength of the Cu₆Sn₅ grains. After measuring the fracture surfaces of the Cu₆Sn₅ grains, the shear stresses

![Fig. 3](image1.png)

![Fig. 4](image2.png)
were calculated by dividing the force with the fracture area. Figure 6 shows the first stage of the strength-displacement (depth) curves of a few Cu$_6$Sn$_5$ grains fractured at their center portion; it can be found that the bursts occur at the stresses as high as about 670 MPa. Since the bursts correspond to the primary shear fractures in the Cu$_6$Sn$_5$ grains, the shear strength of Cu$_6$Sn$_5$ is easily estimated to be around 670 MPa. This is the first report on the shear fracture strength of the Cu$_6$Sn$_5$ intermetallic compounds. Jiang et al.\textsuperscript{15} have reported that the Cu$_6$Sn$_5$ micropillar fractures along certain crystallographic planes under compressive loadings; the fracture stress was around 1356 MPa, and the angle between the compressive direction and the fracture plane is about 60° in the images. Based on that, the shear fracture stress at the fracture plane is estimated to be about 587 MPa through dividing the shear component of the compressive stress by the area of the fracture plane, which is close to our results.

It is widely known that, with the decreasing trend in size of the solder joints, the solder joints now contain fewer Cu$_6$Sn$_5$ grains,\textsuperscript{1} which makes the fracture behaviors of the Cu$_6$Sn$_5$ grains more influential on the strength of the solder joints.\textsuperscript{20-22} Therefore, the results on the shear strength of the Cu$_6$Sn$_5$ grains will be very important for evaluating the reliability of the solder joints. In addition, as the indentation test in this study is easy to carry out, it is simultaneously expected that this experimental method can be popularized in investigating the fracture strengths of the IMCs.

IV. CONCLUSIONS

The shear fracture behaviors of the Cu$_6$Sn$_5$ grains were investigated using a dynamic micro hardness tester. The results reveal that there are bursts on the indentation curves corresponding to the cleavage fractures in the Cu$_6$Sn$_5$ grains. The Cu$_6$Sn$_5$ grains usually fracture at their foundation or the center portion, depending on their size and shape. The average shear fracture strength of the Cu$_6$Sn$_5$ grains is calculated to be around 670 MPa.

ACKNOWLEDGMENTS

The authors would like to acknowledge W. Gao and L. X. Zhang for sample preparation, indentation tests, and SEM observations. This work was financially supported by the National Basic Research Program of China under grant No. 2010CB631006 and the National Outstanding Young Scientist Foundation under grant No. 50625103.

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