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Micro-mechanical and fracture characteristics of Cu_6Sn_5 and Cu_3Sn intermetallic compounds under micro-cantilever bending

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Abstract

This study focuses on the fracture characteristics of Cu_6Sn_5 and Cu_3Sn micro beams under micro-cantilever bending tests. These micro beams were fabricated by focused ion beam (FIB) from the Sn-rich solder joints aged at 175 °C for 1132.5 h, and then tested using a nanoindenter with a flat tip. Experimental results show that both Cu_6Sn_5 and Cu_3Sn micro beams underwent elastic deformation before their failure. From fractographic analysis, both cleavage fracture and intergranular fracture can be identified from the tested Cu_6Sn_5 micro beams, while only intergranular fracture was found in Cu_3Sn micro beams. Furthermore, based on the experimental results, finite element analysis was carried out to evaluate the tensile fracture strength and strain of Cu_6Sn_5 and Cu_3Sn micro beams. For Cu_6Sn , the tensile fracture strength was estimated to be 1.13 ± 0.04 Pa and the average tensile strain was 0.01. The tensile fracture strength and strain of Cu_3Sn were evaluated to be 2.15 ± 0.19 GPa and 0.016, respectively.

Keywords: Intermetallics; Fracture; Focused ion beam machining; Finite-element modelling; Mechanical testing

1 Introduction

Due to environmental and health concerns, various lead-free solder alloys have been proposed to replace lead containing solders. Currently, Sn-based solder alloys with additions such as Cu, Ag are widely employed in electronic package industry [1-3]. Comparing to Sn

Pb solder alloys, Sn-rich solder alloys have higher melting temperatures and higher Sn contents. Thus, it can react rapidly with a common metallic substrate (Cu), forming thick Cu

Sn intermetallic compounds (IMCs) at the interfaces during reflowing and service, which arouses some reliability issues [4-7].

Although an initial formation of IMCs can establish a good metallurgical bond between solder and substrate after soldering process, excessive growth of IMCs formed during ageing would deteriorate the interfacial integrity, due to their brittle nature and mismatch of physical properties (e.g. elastic modulus and coefficient of thermal expansion) with solders and substrates [4,8-10]. With an increasing trend towards miniaturization of microelectronic products, volume ratio of the IMCs in solder joints tends to be higher, which affects their mechanical integrity significantly [11,12]. Especially for three-dimension (3D) integration, solder joints consisting of IMCs fully act as entire interconnections through transient liquid phase bonding or eutectic bonding processes [13-15]. Hence, it is crucial to obtain a comprehensive understanding on mechanical properties of Cu

Sn IMCs formed in Sn

Cu solder joints.

Presently, significant efforts have been made to characterise mechanical properties of Cu

Sn IMCs in solder joints (i.e. Cu_6Sn_5 and Cu_3Sn) with various techniques. For instance, numerical analysis provides an approach to estimate the elastic moduli of Cu_6Sn_5 , Cu_3Sn and Ag_3Sn [16-18]. Moreover, bulk intermetallics were prepared through casting and annealing processes to enable mechanical tests at a macro-scale [19,20], but residual porosity and oxides may emerge from these processes, degrading applicability of the results. Besides, the microstructure of bulk IMC samples are considerably different from interfacial IMCs layers in solder joint. Some preliminary studies [19-22] reported that the Young's modulus of Cu_6Sn_5 shows a large degree of variability. Therefore, it has been considered that an *in-situ* micro-scale test, e.g. nanoindentation, would be appropriate to obtain Young's modulus and hardness of these IMCs in solder joints at micro-scale [4,23-25]. Furthermore, some works were reported on the fracture characteristics of individual IMCs in solder joints through micro-scale tests. For example, the compression and shear fracture characteristics of individual Cu_6Sn_5 pillars formed at the Sn-rich solder/Cu interface were investigated [26-28]. However, the tensile fracture behaviours of individual Cu_6Sn_5 and Cu_3Sn IMCs at the interfaces of Sn-based solder joints remain unclear, which demand further investigations.

In this paper, micro beams of Cu_6Sn_5 or Cu_3Sn for cantilever bending tests were fabricated by FIB milling at Sn99Cu1 solder/Cu interfaces ageing at 175 °C for 1132.5 h. Electron back-scattered diffraction (EBSD) was utilised to reveal the interfacial microstructure as well as the sizes of Cu_6Sn_5 and Cu_3Sn grains at the interfaces, subject to the location and dimension of Cu

Sn IMC beams fabricated with FIB. The tensile fracture behaviours of Cu_6Sn_5 and Cu_3Sn micro beams were studied through the results of micro-cantilever bending tests, followed by a finite element analysis to estimate the tensile strength of Cu_6Sn_5 and Cu_3Sn micro beams. After the bending test, fracture morphologies and composition of Cu_6Sn_5 and Cu_3Sn samples were examined by scanning electron microscope (SEM) and energy dispersive X-ray (EDX) to understand the fracture mechanisms of Cu

Sn IMCs.

2 Experimental and modelling procedures

2.1 Samples preparation

In this work, polycrystalline Cu sheets (purity: 99.9%, 5 mm thickness) and Sn99Cu1 solder alloys were used as substrates and solder materials, respectively. Firstly, a trench of subsidence, with dimensions of 15 mm × 15 mm × 2.5 mm (shown in Fig. 1(a)), was milled at a corner of the Cu sheet. Proper amount of Sn99Cu1 solder was placed within the trench and then reflowed at 270 °C for approximately 2 min. Next, the as-reflowed samples were stored in a vacuum oven, ageing at 175 °C for 1132.5 h to facilitate a further growth of interfacial Cu

Sn IMC layers. Then, the samples were ground and polished carefully to a 0.05 µm finish with colloidal silica to reveal the interfacial microstructure and the Cu

Sn IMCs formed at the Sn99Cu1/Cu interfaces, which were subsequently cross-sectional milled and characterised through SEM, EDX and EBSD incorporated in a FIB equipment (FEI, Nova 600 Nanolab Dual Beam). Cross-section milling was performed with Ga ion of 30 kv using 500 pA aperture, preparing the surfaces with low milling damage for a generation of EBSD patterns.

Fig. 1 Schematics of Cu

Sn IMC micro beams preparation: (a) Sn99Cu1 solder joints before FIB milling; Preparation of (b) Cu_6Sn_5 and (c) Cu_3Sn micro beams at the Sn99Cu1/Cu interfaces.

Micro beams of Cu_6Sn_5 and Cu_3Sn for cantilever bending tests were then individually fabricated by FIB milling at selected locations of the Sn99Cu1/Cu interfaces, as illustrated in Fig. 1(b) and (c). The dimensions of Cu_6Sn_5 and Cu_3Sn micro beams were $3 \times 3 \times 10 \text{ }\mu\text{m}$ and $1.5 \times 1.5 \times 10 \text{ }\mu\text{m}$, respectively, due to the restraint of available thicknesses of the IMC layers at the interfaces. To ensure a consistent composition of Cu_6Sn_5 or Cu_3Sn micro beams, the FIB milling must be operated along the horizontal (or in parallel to) directions of the corresponding IMC layers at the interfaces, as seen in Fig. 1(b) and (c). A low beam current of 500 pA (voltage: 30 kV) was employed in final polishing to minimize an effect of Ga implantation and re-deposition of milled materials on the sample surfaces [29].

2.2 Micro-cantilever bending tests

Micro cantilever bending tests were conducted on Cu_6Sn_5 and Cu_3Sn beams to acquire load-displacement curves using a nanoindentation system (Micro Materials, Nano Test 600, Wrexham, UK). A flat cylindrical indenter with a diameter of 5 μm was used to minimize localized stresses at the indenter/beam contacting regions (as shown in Fig. 1(a) and (b)). The central points of these contacting regions were approximately 7.5 μm away from the bottom of the IMC micro beams. The indentation system was carefully calibrated to achieve the location accuracy within 1 μm before the test; three beams for each type of IMCs were tested under the same conditions to ensure the reliability and accuracy of the experimental results. The parameters and settings for the cantilever bending tests were listed in Table 1. The loading rate of Cu_6Sn_5 and Cu_3Sn micro beams was set as 0.10 mN/s and 0.02 mN/s, respectively, since the cross-sectional area of Cu_6Sn_5 beam is approximately 4 times as large as that of Cu_3Sn beam. Therefore, deformations of both Cu_6Sn_5 and Cu_3Sn micro beams are under similar straining conditions, i.e. strain rate, for direct comparison. After the bending tests, fracture surfaces of Cu_6Sn_5 and Cu_3Sn micro beams were further examined by SEM and EDX.

Table 1 Parameters and settings for cantilever bending tests on Cu_6Sn_5 and Cu_3Sn micro beams.

Parameters	Cu_6Sn_5	Cu_3Sn
Pre-defined maximum depth	3 μm	1 μm
Initial load	0.05 mN	0.05 mN
Loading rate	0.10 mN/s	0.02 mN/s
Unloading rate	0.10 mN/s	0.02 mN/s
Dwelling time at maximum load	0 s	0 s

2.3 Modelling

To understand a stress distribution within the Cu

Sn IMC beams during the nanoindentation tests, finite element analysis was carried out with Abaqus software (version 6.12). Geometries of FE-models were based on the prepared IMC micro beams of Cu_6Sn_5 and Cu_3Sn before mechanical tests, as illustrated in Fig. 2. To improve efficiency and accuracy of the numerical analysis, the models were meshed with two different sizes of quadratic elements (C3D20): a fine mesh in the regions around the bottom of the micro beam and a coarse mesh for the rest area (as shown in Fig. 2). Mechanical properties of the indenter[25, 27, 30-34], the Cu

Sn IMCs and the support of the micro beams are given in Table 2. A force measured from the experimental test was applied on top of the indenter in the model to simulate a cantilever bending process. The support of beams (the regions highlighted in Fig. 2) were fixed during the simulation. Moreover, the simulation was based on four assumptions: 1) Cu_6Sn_5 and Cu_3Sn are both isotropic materials; 2) The flat end of the indenter is parallel to the top surface of the micro beam at the beginning of bending tests; 3) the diamond indenter and the IMC beams were both subject to elastic deformation in the tests according to reported researches [26-28]; 4) The deformation in the area beyond the finite element models is negligible.

Fig. 2 The finite element models with meshes of (a) Cu_6Sn_5 and (b) Cu_3Sn samples during micro-cantilever bending.

Table 2 Mechanical properties of materials in the finite element analysis.

Materials	Young's Modulus	Poisson's ratio
Cu_6Sn_5	115.5 GPa [27]	0.31 [3130]
Cu_3Sn	134.2 GPa [3231]	0.299 [25]
Diamond indenter	1141 GPa [3332]	0.07 [3332]
Cu	129.8 GPa [3433]	0.339 [3534]

3 Results and discussions

3.1 Observation of IMCs, Cu_6Sn_5 and Cu_3Sn micro beams

To acquire a comprehensive understanding of the initial microstructure, an EBSD analysis of the Sn99Cu1/Cu interfaces before milling IMC micro beams was carried out and its image is shown in Fig. 3. From this image, a platinum layer in the top right corner was deposited for protection of the adjacent materials during the FIB milling process (the milling direction was from right to left in this figure). The boundaries of the Sn99Cu1 solder, Cu_6Sn_5 layer, Cu_3Sn layer and Cu substrate within the Sn-rich solder joints are marked by the white lines. It can be observed that the sizes of Cu_6Sn_5 grains range from 2 to 15 μm , while the sizes of Cu_3Sn grains are smaller than 1 μm after ageing up to 1132.5 h.

Fig. 3 An EBSD image of the interfacial microstructure at the Sn99Cu1/Cu interfaces.

According to Fig. 3, the minimum thickness of the Cu_3Sn layer at the interfaces is less than 4.5 μm . Cu_3Sn micro beams were prepared from this thin Cu_3Sn layer between Cu substrate and Cu_6Sn_5 layer. Moreover, in view of the fact that the boundaries of each phases were not parallel, the width of Cu_3Sn micro beams were therefore set as 1.5 μm , much smaller than the width (3 μm) of Cu_6Sn_5 micro beams.

FEG-SEM images of typical Cu_6Sn_5 and Cu_3Sn micro beams are shown in Fig. 4(a) and (b), respectively. It is important to remove the materials near the micro beams, so as to leave sufficient space allowing the subsequent indentation without any blockages prior to the fracture of IMC beams. The dimensions of Cu_6Sn_5 and Cu_3Sn micro beams were $3 \times 3 \times 10 \mu m$ and $1.5 \times 1.5 \times 10 \mu m$, respectively, as shown in Fig. 4(a) and (c). To confirm the constitution of the fabricated beams, their chemical composition was examined by EDX across these IMC beams as indicated in Fig. 4(a) and (c). The EDX results were illustrated in Fig. 4(b) and (d), confirming these two types of IMC beams consist of only Cu_6Sn_5 or Cu_3Sn phase, respectively.

Fig. 4 SEM micrograph of a Cu_6Sn_5 micro beam (a) and its EDX spectrum (b); SEM micrograph of a Cu_3Sn micro beam (c) and its EDX spectrum (d).

3.2 Fracture mechanisms of Cu_6Sn_5 and Cu_3Sn IMCs

The fracture surfaces of Cu_6Sn_5 beams after the micro-cantilever bending tests are presented in Fig. 5. The micro beams fractured at their bottom as the results of failure likely due to the highest tensile stress induced in these beams under the bending load [26,35,36]. In observation on the fracture surfaces among Cu_6Sn_5 micro beams, two typical fracture surfaces, which indicate different fracture modes due to the bending test, were found and shown in Fig. 5(a) and (c).

Fig. 5 Fracture surfaces and their schematic locations of the tested Cu_6Sn_5 micro beams: (a) SEM morphology of cleavage fracture surface; (b) schematic location of Cu_6Sn_5 beams in Cu_6Sn_5 layer; (c) SEM morphology of intergranular fracture surface; (d) schematic location of Cu_6Sn_5 beams in Cu_6Sn_5 layer.

In Fig. 5(a), as marked with dash lines, the initial area at the bottoms of Cu_6Sn_5 micro beams before the bending were in rectangular shape. However, the actual fracture cross section (solid lines) was extended with a significant increase in the area after the micro-mechanical tests. This was attributed to the involvement and fracture of adjacent materials in connection to the beam bottom along certain crystalline planes where further extended stresses induced. Notably, the ellipse region highlighted in Fig. 5(a) was resulted from the damage by the rear of the indenter after the fracture. Generally, the fracture surface of this Cu_6Sn_5 micro beam is relatively smooth as there was only a single Cu_6Sn_5 grain involved in the fracture section, which indicates a cleavage fracture mode, as reported elsewhere [26,27,37].

However, another typical fracture surface of Cu_6Sn_5 micro beam was also observed, as presented in Fig. 5(c), where the beam fractured and directly aligned at the bottom of the beam without any further extension. By examining the details within the fractured zone as defined by the solid lines in Fig. 5(c), it is apparent to see there are multiple grains involved in the fracture at that specific cross section where the boundaries of Cu_6Sn_5 grains are marked by the dash lines in Fig. 5(c). As the result, a typical intergranular fracture has occurred, which should be considered as another fracture mode of Cu_6Sn_5 micro beams under the micro-mechanical tests.

Therefore, different fracture modes of Cu_6Sn_5 micro beams should be considered subject to the crystallite structure of the beam near or close to the bottom lines of the beam, for instance, the number of Cu_6Sn_5 grains involved at the point of fracture. This has been clearly observed from the EBSD image presented in Fig. 3, where the variation of the grain sizes ranging from approximately $15\text{ }\mu\text{m}$ – $2\text{ }\mu\text{m}$ can have considerable effects on the fracture mechanism of Cu_6Sn_5 micro beams at the solder/Cu interfaces. Accordingly, subject to the selected locations of the IMC beams for FIB milling, there was a single Cu_6Sn_5 grain involved at the bottom of a Cu_6Sn_5 micro beam when the crack was initiated, thus a cleavage fracture occurred. However, as it is clearly seen a mixture of multiple Cu_6Sn_5 grains was involved in the fracture at the bottom of another beams, which has led to a typical intergranular fracture. Based on the EBSD results, the schematics given in Fig. 5(b) and (d) indicate the locations within the Cu_6Sn_5 IMCs layers at the solder/Cu interface where Cu_6Sn_5 micro beams was likely selected and tested, which have resulted in the cleavage and intergranular fracture shown in Fig. 5(a) and 5(c), respectively.

In comparison to Cu_6Sn_5 micro beams, only one fracture mode was found in Cu_3Sn micro beams. Fig. 6(a) shows the typical fracture surface of Cu_3Sn micro beam after bending tests. Accordingly, as highlighted with the broken lines, the original cross-sectional area at the bottom of the beam fractured under the bending load, which has resulted in the fracture surface of Cu_3Sn beam as highlighted by solid lines in Fig. 6(a). As it has been clearly observed in the EBSD images in Fig. 3, this Cu_3Sn layer at the solder/copper interface consists numerous refined grains presenting a polycrystalline structure, thereby there are always multiple grains to partake the fracture near the bottom of the beam (Fig. 6(b)), which can be as small as sub-micron sizes (approximately $0.4\text{ }\mu\text{m}$) due to the ageing. The grain size of Cu_3Sn seen in this study are within the similar range as reported in a previous study [38]. The bottom of the beams was the stress concentration site where the maximum stress locates. Once a crack initiates at this location, it will preferentially propagate along the grain boundaries where the adhesion strength is weaker. Hence, the grain boundaries of Cu_3Sn can facilitate the crack propagation notably once the cracks initiated, leading to intergranular fracture in a Cu_3Sn micro beam. And this fracture mode have has also been observed by the other researchers [39].

Fig. 6 The intergranular fracture surface of Cu_3Sn micro beams due to the cantilever bending: a) SEM image on the fracture surface, b) schematic illustration of the beam location in the Cu_3Sn IMC layer at the interface.

3.3 Tensile fracture strength of Cu_6Sn_5 and Cu_3Sn micro beams

Fig. 7(a) and (b) show the selected initial region where the increase of the load with the displacement was recorded till the fracture of the micro beams for both Cu_6Sn_5 and Cu_3Sn IMCs, respectively. The complete profiles of load-displacement data of Cu_6Sn_5 and Cu_3Sn micro beams were also plotted as embedded in the Fig. 7(a) and (b) to provide an overview of the bending tests. According to these embedded curves, the entire bending test can be divided into three stages, including the initial loading stage (stage 1), middle stage (stage 2) and unloading stage (stage 3). In the second stage, the indenter was subject to a swift motion due to the fracture of the beam till it reached the maximum depth, from which point the unloading commenced. The swift motion of the indenter may lead to the damage accidentally as shown in Fig. 5(a) in this stage. It is found that the fractures had taken place within the initial loading stage (stage 1). Therefore, the initial loading region is of particular interests, primarily possessing the mechanical response of IMC micro beams, and enlarged as shown in Fig. 7(a) and (b) to further elaborate the mechanical properties of these Cu

Sn IMCs. This presents the elastic deformation of both Cu

Sn IMC micro beams as indicated by the linear relationship of load-displacement curves prior to the fracture.

Fig. 7 The load-displacement curves from the micro-cantilever bending tests on (a) Cu_6Sn_5 micro beams and (b) Cu_3Sn micro beams.

As reported in a previous study [40], if materials exhibit elastic-plastic behaviour under cantilever bending, the load-displacement curves must deviate from the linear relationship until reaching the yield strength of the materials. In this work, both Cu_6Sn_5 and Cu_3Sn micro beams only showed elastic (linear) behaviour before failures. From the data in Fig. 7(a) and (b), the fracture force of Cu_6Sn_5 and Cu_3Sn micro beams can thereby be estimated, which are in the range of 2.11 mN-2.27 mN and 0.6 mN - 0.64 mN for Cu_6Sn_5 and Cu_3Sn micro beams with the corresponding deflection of 0.45 μ m-0.47 μ m and 0.54 μ m - 0.63 μ m, respectively.

According to the loading nature and the geometry of the micro beams, the fracture of the IMC micro beams could be possibly resulted from the combination of both tensile and shear stress induced within the bottom of the micro beams due to the cantilever bending. It is therefore not possible to simply conduct a calculation based on the mechanics of bending to obtain the fracture strength of the IMC micro beams since the fracture mechanisms of Cu_6Sn_5 and Cu_3Sn micro beams were unclear. In order to determine the fracture strength of the IMC micro beams, finite element simulations of Cu_6Sn_5 and Cu_3Sn micro beams under the bending were carried out, which can also assist to further elaborate the ~~fracture mechanism~~fracture modes (The "fracture mechanism" was replaced with "fracture mode" followed the reviewer's suggestion.) by visualising the stress distribution across the IMC micro beams under the bending.

With the parameters and boundary conditions presented in Section 2.3, the simulations were performed to the initial stage of the bending up to the point of fracture, and validated based on the load-displacement curves obtained through experimental bending tests. The results of load-displacement curves generated by the modelling are plotted with the experimentally derived curves for Cu_6Sn_5 and Cu_3Sn micro beams in Fig. 8(a) and (b), respectively. The simulation results provided a very close approximation and an excellent consistency to the experimental results for both Cu_6Sn_5 and Cu_3Sn micro beams. This can provide an approach to determine the fracture strength of Cu_6Sn_5 and Cu_3Sn micro beams by extracting the tensile or shear stresses that were induced at Cu_6Sn_5 and Cu_3Sn samples based on the modelling results as this was found difficult to derive purely through the experimental data.

Fig. 8 The load-deflection curves obtained from experiment and modelling of (a) Cu_6Sn_5 , and (b) Cu_3Sn micro beams under the same conditions of cantilever bending.

The results of tensile stress distribution derived from the simulation of Cu_6Sn_5 and Cu_3Sn micro beams are illustrated in Fig. 9(a) and (b), respectively. The tensile stresses of cross-sections at the bottom of beams are also given in the embedded images in Fig. 9(a) and (b) for more details of the tensile stress distribution. Apparently, beside slight concentrations of stresses at the locations in contact with the indenter (region 1 in Fig. 9(a) and (b)), in both case, a significant stress concentrations is located near the bottoms of the beams (region 2 in Fig. 9(a) and (b)). This is because of the maximum bending stresses in this region as the result of cantilever bending. Therefore, it is not surprising that the fracture occurred near the bottom of the beams when the stresses reached the fracture strength with the increase of the bending force applied by indenter. However, it is still difficult to determine the fracture

strength as it has to be correlated to the local stresses (tensile and shear stress) of concentration and the potential failure modes.

Fig. 9 The distribution of tensile stress under the applied load prior to the fracture: (a) a Cu_6Sn_5 micro beam. (b) a Cu_3Sn micro beam.

To clarify the effect of shear stress, the shear stress distribution in Cu_6Sn_5 and Cu_3Sn micro beams was also obtained and presented in Fig. 10(a) and (b), respectively. Furthermore, the cross-sectional views at the bottoms of beams are also provided to reveal the details of the distribution of shear stress as embedded inside the Fig. 10(a) and (b). It indicates the potential locations of fracture when the shear stress causes the failure. From Fig. 10(a) and (b), the highest shear stress is located at the point of contact on the beam with indenter (region 1 in Fig. 10(a) and (b)) other than the bottom of IMC micro beams (region 2 in Fig. 10(a) and (b)). Clearly, the maximum shear stress at the point contacting with indenter did not reach the shear strength, thereby, no failures can be observed at these contacting points. This was confirmed by the experimental results that have been presented in Figs. 5 and 6, which displays the final failure of Cu_6Sn_5 and Cu_3Sn micro beams near the bottom of beams other than the contact point with indenter. This suggests that the fracture of these micro beams were primarily attributed to the maximum tensile stresses that had been resulted near the bottoms of the micro beams, i.e. region 2 shown in Fig. 9(a) and (b). Therefore, the fracture mechanisms of Cu_6Sn_5 and Cu_3Sn cantilever beams were both determined by the limit of maximum tensile stress that the micro beams can sustain near the bottom of the beams, leading to the tensile fracture, which is in accordance with the work previously reported [26].

Fig. 10 The distribution of shear stress under the applied load prior to the fracture: (a) a Cu_6Sn_5 micro beam. (b) a Cu_3Sn micro beam.

Based on the above failure mechanisms, the tensile fracture strength was estimated as the mean value of simulations conducted using three sets of experimental data, which is approximately 1.13 ± 0.04 GPa for Cu_6Sn_5 micro beams. Similarly, the tensile fracture strength of Cu_3Sn micro beams can also be acquired in the range of 2.15 ± 0.19 GPa. This value almost doubled the value of tensile fracture strength of Cu_6Sn_5 micro beams. From the EBSD images presented in Fig. 3, it is obvious that the Cu_3Sn IMC layer consists of more refined polycrystalline microstructure involving significant amount of grain boundaries, which is one of the reasons that has made this type of IMCs much stronger. Based on Hooke's law with the obtained tensile strength estimated above and Young's modulus of the Cu

Sn IMCs listed in Table 2, the tensile strains of Cu_6Sn_5 and Cu_3Sn at the point of fracture in this study can be deduced as 0.01 and 0.016, respectively.

4 Conclusions

Both experimental and modelling techniques were employed to investigate the fracture behaviours of Cu_6Sn_5 and Cu_3Sn cantilever beams at a micro-scale under bending tests. The Cu_6Sn_5 and Cu_3Sn micro-cantilever beams were prepared by FIB along the interfaces of the Sn99Cu1/Cu solder interconnects after ageing for 1132.5 h at 175 °C. The correlation between the microstructure of the interfacial IMC layers and the fracture characteristics was revealed based on the examinations of the fracture surfaces as the results of beam bending through SEM and EBSD analysis; as such the fracture mechanisms for both Cu_6Sn_5 and Cu_3Sn micro beams can be proposed and tensile strength of Cu_6Sn_5 and Cu_3Sn micro beams were subsequently determined with the assistance of numerical simulations.

1. During the micro-cantilever bending tests using the nanoindentation tester, both Cu_6Sn_5 and Cu_3Sn micro beams deformed elastically with the increase of applied loads, leading to the final fracture of these micro beams near their bottom.
2. SEM examinations has indicated that both cleavage and intergranular fracture can occur at the bottom of Cu_6Sn_5 micro beams subject to the number of Cu_6Sn_5 grains involved at the bottom of Cu_6Sn_5 micro beams due to the non-uniform polycrystalline structure at the interface of solder joints. However, the much finer and uniform crystalline structure of Cu_3Sn grains has resulted in only intergranular fracture as observed from the fracture surface of the Cu_3Sn micro beams.

3. Given the loading conditions under the cantilever bending tests, through numerical simulation it was revealed that the fracture **mechanisms/modes** of IMC beams were primarily attributed to the maximum tensile stress that had exceeded the tensile strength of the micro beams surrounding the bottom of the beams. This has been confirmed by the experimental results. The maximum shear stress, which was found to be located at the contact point between indenter and micro beams, were relatively lower, thus unable to cause any fractures as it also has been observed experimentally.
4. Based on the modelling results, it is possible to determine the tensile fracture strength and strain of the Cu_6Sn_5 and Cu_3Sn micro beams under the bending tests; they are 1.13 ± 0.04 GPa (strength) and 0.01 (strain), 2.15 ± 0.19 GPa (strength) and 0.016 (strain), respectively.

Uncited reference

[30]..

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Graphical abstract

Highlights

- Cu_6Sn_5 and Cu_3Sn micro-beams were prepared by FIB for cantilever bending test using a nanoindentation system.
- The correlation between IMCs crystalline structures and the fracture characteristics of Cu_6Sn_5 and Cu_3Sn was ~~also~~ proposed.
- ~~Finite element analysis was carried out to clarify the fracture mechanism of Cu_6Sn_5 and Cu_3Sn micro-beams by elaborating the stress distribution across the beams under the cantilever bending.~~ Finite element analysis was conducted to clarify the fracture modes of Cu_6Sn_5 and Cu_3Sn under micro-cantilever bending.
- ~~The fracture strength of Cu_6Sn_5 and Cu_3Sn were estimated based on the numerical simulation and micro-cantilever bending experiments.~~ The fracture strength of Cu_6Sn_5 and Cu_3Sn were estimated based on simulation and micro-mechanical test.

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