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Effect of Yttrium on the Fracture Strength of the Sn-1.0Ag-0.5Cu Solder Joints

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This is a preliminary investigation on the mechanical properties of Pb-free Sn-1.0Ag-0.5Cu solder joints containing 0.02 wt.% to 0.1 wt.% Y under a range of thermal aging and reflow conditions. Despite the significantly thicker intermetallic compound (IMC) formed at the solder joint, the 0.1 wt.% Y-doped joint exhibited a higher fracture strength than its baseline Sn-1.0Ag-0.5Cu counterpart under most aging and reflow conditions. This may be associated with the formation of Y-Cu IMCs formed at the interface between the solder and the Cu substrate, because the Y-Cu IMCs have recently been referred to as relatively 'ductile' IMCs.

Key words: Aging, intermetallics, fracture, impact behavior, solder

INTRODUCTION

Owing to concerns about the environment and health hazards resulting from the use of Pb in conventional SnPb solders, a significant effort has been devoted to developing Pb-free Sn-Ag-Cu solders.[1] The widespread use of Pb-free solders in the microelectronic packaging industry has, however, been stymied by the formation of relatively thick, brittle Cu-Sn intermetallic compounds (IMCs) at the solder joint;[2] the high melting point of the Sn-Ag-Cu alloy system has also been problematic. More importantly, compared to their Pb-containing counterparts, these solders have a significantly lower drop resistance, which poses a serious problem for a variety of promising mobile applications.[3,4] This resistance can be improved by increasing the elastic strain energy of the joint during high-speed tensile loading. In other words, the drop resistance can be increased by either reducing the Young's modulus of the solder material or increasing the high-speed fracture strength at the solder joint.[4] Furthermore, the wettability, creep strength, and tensile strength of Pb-free solders can be improved by doping the solder joints with small amounts of a rare-earth (RE) element.[5] In the present study, we evaluate a potential drop-resistant Pb-free solder solution by adding small amounts (0.02 wt.% to 0.1 wt.%) of Y to the Sn-1.0Ag-0.5Cu solder. We examine the formation of Y-Cu IMCs at the Sn-1.0Ag-0.5Cu solder joint and its effect on the high-speed ball-pull strength of the solder joint. This study constitutes the first-ever report on the formation of a Y-Cu IMC at the Pb-free solder joint.[6]

EXPERIMENTAL PROCEDURE

Four types of commercially available 400-μm-diameter Ball-Grid Array (BGA; MK Electron, Korea) solder balls were examined. These balls had compositions of Sn-1.0Ag-0.5Cu-xY (x = 0, 0.02 wt.%, 0.05 wt.%, and 0.1 wt.%, hereafter referred to as SAC105, SAC105+0.02Y, SAC105+0.05Y, and SAC105+0.1Y, respectively). Cu-organic solderability preservative (Cu-OSP) was used for the solder surface finish. The solder balls were attached to the substrates in a seven-zone reflow oven (1706 EXL, Heller, USA) under a N_2 atmosphere. All samples were reflowed 1, 5, or 10 times. A preheat temperature of 150 ± 2°C and a peak temperature of ~245°C were used during soldering. In addition, selected samples were isothermally aged at 150°C for 0 h to 500 h after reflow. The high-speed ball-pull tests were performed at a speed of 400 mm/s using a Dage 4000HS

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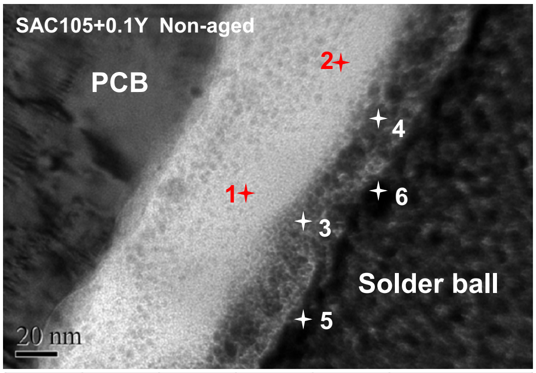

No.	Cu	Y	Ag	Sn	Total(at.%)
1	63.35	36.65	0.00	0.00	100.00
2	34.94	65.06	0.00	0.00	100.00
3	94.90	5.03	0.00	0.00	100.00
4	97.73	0.00	0.37	1.90	100.00
5	95.37	0.00	0.26	4.38	100.00
6	94.64	0.00	5.36	0.00	100.00

Fig. 1. TEM image and EDS analysis showing the elemental distribution and composition of Y-Cu intermetallic compounds at the solder joint interface between the PCB and the Sn-1.0Ag-0.5Cu solder ball doped with 0.1 wt.% Y.

tester (Dage Inc., Buckinghamshire, UK). The resulting fracture surfaces and cross-sections of the solder joints were examined using a scanning electron microscope (SEM; JSM5410, JEOL, Japan), a transmission electron microscope (TEM; JEOL, Japan), and an electron probe micro analyzer (EPMA; Shimadzu, Japan).

RESULTS AND DISCUSSION

Although EPMA analysis provided no clear indication of such a small amount of Y in the SAC105 solder balls, TEM energy-dispersive spectroscopy (EDS) results revealed that Y and Cu formed IMCs; these IMCs were formed at the solder joint interface between the Cu pad and the solder ball. Figure 1 shows a TEM image and the corresponding EDS analysis that reveals a narrow distribution of Y at the interface between the ball and the pad. These results confirmed that Y-Cu IMCs formed only at the interface; i.e., there was no Y detected inside the ball.

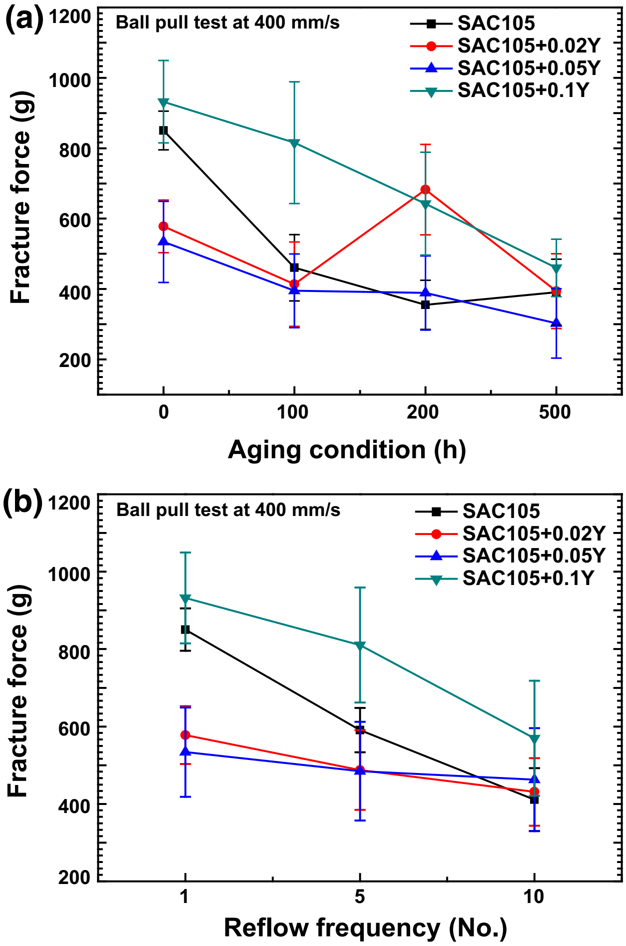

Fig. 2. Dependence of the ball-pull fracture force of the solder joints on the (a) aging time at 150°C and (b) reflow frequency.

Figure 2 compares the mean fracture forces occurring during the high-speed ball-pull testing at 400 mm/s of the SAC105+Y and baseline SAC105 solder joints. These tests were performed at 150°C for aging times of up to 500 h and reflow frequencies ranging from 1 to 10 times. Although the addition of 0.02Y or 0.05Y seemed to have no clear effect on the strength of the solder joint, 0.1Y resulted in improved high-speed ball-pull strength under both aging and reflow conditions. More specifically, the ball-pull strength (932 g) of the non-aged SAC105+0.1Y solder joint was approximately 10% higher than that of the non-aged baseline SAC105 (850 g), as shown in Fig. 2a. Indeed, the dependence of the mechanical properties of SAC solder materials on the variation in the composition of a rare-earth element has been reported in the literature. For example, Chen et al. reported that the addition of Ce could be beneficial for the creep resistance of SAC705 only within a certain range of Ce composition.[7] In addition, both the yield strength and ductility of the NiAl alloy depend on the addition content of a rare-earth element such as Y, Ce, Nd, and Dy, and showed the highest values at the composition near 0.05%.[8]

Previous studies showed that the fracture force decreases, in general, with increasing aging time or reflow frequency.[9,10] Despite this tendency, however, the 200-h-aged SAC105+0.1Y joint still exhibited an 81% higher strength (Fig. 2a) than that of the baseline SAC105 (355 g). On the other hand, the unusually high ball-pull strength of the 200-h-aged SAC105+0.02Y cannot be clearly understood at the present moment. We assume that the composition of Y is too small to result in any apparent influence in the fracture strength of both the SAC105+0.02Y and

SAC105+0.05Y samples. In fact, the fracture strength values for the two samples are very similar to each other within the error range after 0 h, 100 h, and 500 h aging times, except for the 200 h aging time. Similar unusual fracture strength values in the fracture force of a solder joint are often observed, and have been reported elsewhere without any claim of a relevant mechanism.[11–13] Further study may be needed to collect more data values and generate a statistically meaningful conclusion in the fracture strength of SAC105 with smaller Y contents. On the other hand, the strength of the 0.1Y-doped joint (~13% to 59%) decreased gradually after reflows of up to 10 times. However, this reduced strength (570 g) was still significantly higher (Fig. 2b) than that (411 g) of its baseline counterpart with the same pre-conditioning. This is important, because reflow of up to 4 times may be required in a package assembly process, and the number of reflows can affect the mechanical and electrical properties of the joints.[14] The SAC105+0.1Y solder joint had the highest strength and was, therefore, analyzed in further detail.

In order to determine the basis of the increased strength of the 0.1Y-doped joint, we first compared the IMC thickness of the SAC105 with and without 0.1Y. This comparison was made because, in general, the fracture force decreases while the IMC thickness increases with increasing aging time.[3,15] Therefore, we examined the effect of the IMC thickness on the strength of the 0.1Y-doped SAC105. Figure 3 shows the dependence of the IMC thickness of the SAC105+0.1Y joint on aging time (0 h to 500 h) at 150°C, and the corresponding SEM images. Despite its substantially higher high-speed ball-pull strength after 500 h of aging, the IMC thickness of the SAC105+0.1Y joint is almost twice as thick as that of its baseline SAC105 counterpart. For example, the former and latter have approximate thicknesses of 5.8 ± 0.9 μm and 3.2 ± 0.4 μm, respectively, after being aged for 200 h. The interfacial diffusion mechanism in the IMC layers during aging is not completely understood and a further systematic study should be performed to determine the mechanistic reasoning behind it. However, addition of an element, despite being small, often increases the interfacial IMC thickness of a solder joint. For example, the IMC thickness in Sn-3.8Ag-0.7C solder with addition of 0.5 wt.% Ni was reported to increase during aging.[16] This is probably due to the formation and growth of an additional IMC that is associated with the newly added element; in our case, the thicker IMC thickness may be attributed to the formation and growth of the additional Y-Cu IMC that was formed and grew during aging. Although some previous studies suggest that the IMC thickness, which increases with the aging time, has a considerable effect on the mechanical properties of a solder joint,[9,10] the composition of the solder joint appears to have a greater effect than does the thickness variation of the solder joint.

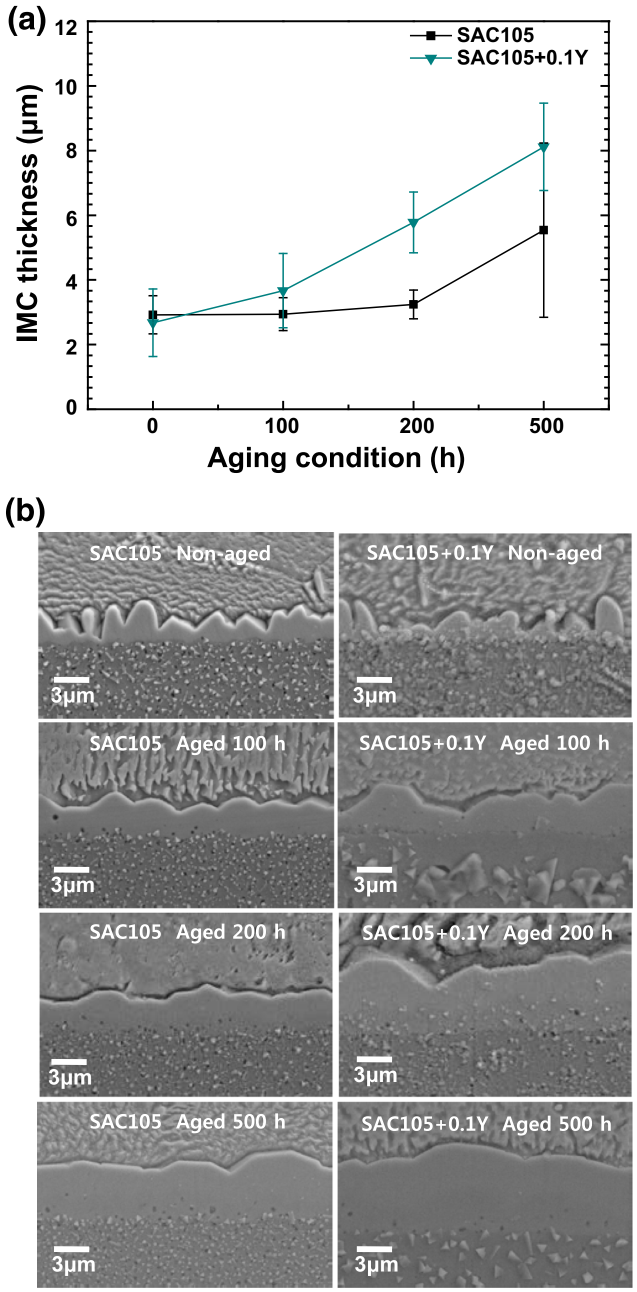

Fig. 3. (a) Dependence of the IMC thickness of the SAC105+0.1Y solder joints on aging time at 150°C and (b) the corresponding SEM images.

The brittle IMCs, such as Cu_6Sn_5 and Cu_3Sn, are known to form at the SAC solder joint with the Cu-OSP surface finish;[16] these IMCs have a high hardness of 3.4 GPa to 3.7 GPa and low fracture toughness of 1.4 MPa m$^{1/2}$ to 1.7 MPa m$^{1/2}$.[10] In this study, the effect of 0.1Y on the fracture strength of the solder joint during the high-speed ball-pull test is not yet clearly understood; a previous study suggests that the stress-induced partial transformation to the B27 structure near dislocation pile-ups strengthens the material but weakens the plastic flow,[17] which might have contributed to the improvement in the fracture strength of the SAC105+0.1Y solder joint. It is of particular interest to note that relatively ductile Y-Cu IMCs are also likely to be formed at the 0.1Y-doped SAC105 solder joint (Fig. 1); the Y-Cu IMCs are known to show significantly higher fracture toughness of up to ~12 MPa $m^{1/2}$ and lower hardness of down to 2.4 GPa.[18,19] This study constitutes the first-ever investigation of the positive effect of Y on the Pb-free SAC solder joint IMCs and requires further analysis for a thorough understanding of the mechanism associated with the effect of Y on the fracture strength and ductility of the SAC105 solder joint.

CONCLUSIONS

Sn-1.0Ag-0.5Cu solder joints doped with 0 wt.% to 0.1 wt.% Y were subjected to high-speed ball-pull testing. The 0.1 wt.% Y-doped joint exhibited higher fracture strength than its baseline SAC105 counterpart under both thermal aging and reflow conditions. In addition, the IMC thickness of the former was ~180% larger than that of the latter. Based on our preliminary analysis, the higher fracture strength of the 0.1 wt.% Y-doped solder joint was attributed to the ductile nature of the Y-Cu IMCs rather than the thickness of the IMC measured at the joint.

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