Evaluation of Absorbed Impact Energy of Sn–3.0Ag–0.5Cu (–xCo) Solder Joints with Co–P Plating a Using Ball Impact Test

Tomoya Daito*, Hiroshi Nishikawa**, Tadashi Takemoto**, and Takashi Matsunami***

*Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita City, Osaka 565-0871, Japan
**Joining and Welding Research Institute, Osaka University, 11-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan
***Okuno Chemical Industries Co., Ltd. 1-10-25, Hanaten-higashi, Tsurumi-ku, Osaka 538-0044, Japan

(Received June 30, 2010; accepted September 27, 2010)

Abstract
Sn–3.0mass%Ag–0.5mass%Cu (SAC) solder, which is widely used in Japan, has a relatively low impact reliability. This is because of the solder alloy hardness which induces a high stress concentration at the interface between the solder and the substrate. The impact reliability of the solder joint can be controlled by changing the composition of the under-bump metallurgy (UBM). This study aimed to determine the effect of electroless Co–P plating on the impact reliability of the solder joint using SAC, SAC–0.05Co and SAC–0.2Co solders. The intermetallic compound (IMC) layer formed at the interface between the three types of solder and the electroless Co–P plating was thinner than that of the SAC and electroless Ni–P plating. The hardness of the solders with electroless Co–P plating was lower than that with electroless Ni–P plating. The impact test results show that the solder joints with electroless Co–P plating are better at absorbing impact energy than SAC/Ni–P.

Keywords: Impact Test, Impact Reliability, Sn–3.0Ag–0.5Cu (–xCo), Co–P Plating, IMC Layer Thickness, Solder Hardness

1. Introduction
In response to health and safety concerns, lead-free soldering has become a popular technology in electronics packaging. Compared with lead-containing solders, the Sn–3.0Ag–0.5Cu (SAC, all mass% unless otherwise specified) solder widely used in Japan has a relatively low impact reliability owing to the solder alloy hardness, which induces a high stress concentration at the interface.[1–4] However, the solder joint is required to have high impact reliability for use in portable electronic products.

Because of their ease of implementation, ball impact tests have been widely adopted in assessing the reliability of the solder joints.[2, 5–8] Morita et al. proposed a miniature impact test to evaluate impact reliability by adopting the principle of the classic Charpy impact test.[9] This test has been used by various researchers to evaluate impact reliability.[2, 10–12]

It is reported that both the solder hardness and the intermetallic compound (IMC) layer at the interface affect the impact reliability of the solder joint.[1, 3, 9, 13–15] The formation of the interfacial IMC layer between the solder and the under-bump metallurgy (UBM) is essential in the manufacturing of reliable solder joints. However, the impact reliability of the solder joint decreases with increasing thickness of the interfacial IMC layer.[9] Solder hardness also has an effect on the impact reliability of the solder joint, as evidenced by the fact that low-Ag solder such as Sn–1Ag–0.5Cu has high impact reliability.[1, 3, 13–15]

The interfacial structure and bulk properties are strongly dependent on the UBM. The most common UBM is electroless Ni–P plated over copper pads. Electroless Ni–P plating acts as a diffusion barrier layer between the copper and the solder. However, due to nickel diffusion, phosphorus-rich layers form at the interface between the solder and electroless Ni–P plating after the multi-reflow and heat-treatment processes.[16, 17] Solder joint failure is related to the presence of these layers. The presence of these layers affects the mechanical reliability of the solder joints.[18] Magagnin et al. have proposed that electroless Co–P plating acts as diffusion barrier. They reported that
phosphorus-rich layers did not form at the interface between solder and electroless Co–P plating after soldering and heat treatment. This is attributed to the fact that electroless Co–P plating strongly limits interdiffusion and IMC layer formation as compared with electroless Ni–P plating.

In this study, in an attempt to improve the impact reliability of the solder joints, the influence of electroless Co–P plating on the interfacial structure, bulk properties, and impact reliability were investigated.

2. Experimental

Three lead-free solders, SAC, SAC–0.05Co, and SAC–0.2Co (3.9 mg each) were used in this study. Electroless Co–P(Au) plating and Ni–P(Au) plating finished Cu plate on FR–4 printed circuit boards (PCBs) (42.5 × 37.0 × 1.6 mm) were prepared as UBMs. The electroless Co–P plating and Ni–P plating were plated with gold to avoid oxidation of the cobalt and nickel surfaces. The electroless Co–P plating was 2 μm thick, the electroless Ni–P plating was 3 μm thick, and the immersion gold was in the range 0.03–0.05 μm. The phosphorus content was in the range 4–5mass% for the electroless Co–P plating and 7–8mass% for the electroless Ni–P plating. The solder mask diameters were 0.8 mm and solder with an activated flux (0.01 ml) was placed on the pad. The sample was heated in an infrared heating furnace under a nitrogen atmosphere to a reflow peak temperature of 516 K with the sample above 490 K for 122 s. The solder bump height above the UBM was about 860 μm.

The samples were then mounted in resin and polished for cross-sectional observation. The IMC layer thickness was measured using an optical microscope (OM) and a scanning electron microscope (SEM). A Vickers hardness measurement was performed for the central solder area of the cross section. A load of 0.098 N was applied to the specimen for 15 s during the measurement.

The miniature impact test was then carried out to evaluate impact reliability. Five impact tests were conducted to obtain an average value for each condition. The impact speed and the shear height were 1 m/s and 100 μm, respectively. Force-displacement curves were obtained from the impact test (Fig. 1). The area under the force-displacement curve until maximum force can be regarded as the solder’s ability to absorb impact energy. The solder bent length as measured after the impact test using the OM was also used to evaluate the solder’s ability to absorb impact energy. Figure 2 shows the method for the measurement of the solder bent length.

The maximum force obtained from the force-displacement curve, the solder bent length, and the area under the force-displacement curve until maximum force were used to assess the impact reliability of the solder joint.

3. Results and Discussion

A SEM observation was conducted to investigate the effect of the UBM on the interfacial microstructure between the solder and the UBM. The SEM images in Fig. 3 show the microstructures of the IMC layers formed by the reaction of the SAC, SAC–0.05Co and SAC–0.2Co solders with electroless Co–P plating and electroless Ni–P plating. The IMC layer that formed at the interface between the three types of solder and the electroless Co–P plating was thinner than that between the solders and the electroless Ni–P plating. The same tendency was observed in a previous study. Magagnin et al. reported that electroless Co–P plating strongly limits interdiffusion and IMC layer formation as compared with electroless Ni–P plating. In the electroless Co–P plating samples, the IMC layer at the interface between the solder and the electroless Co–P plating was very thin and smooth with no difference between the three different solder joints (SAC/
Co–P, SAC–0.05Co/Co–P and SAC–0.2Co/Co–P). On the other hand, there were differences between the three electroless Ni–P plating solder joints. The IMC layer that formed at the interface between the SAC solder and the electroless Ni–P plating was thin while that between the Co-containing solders and the electroless Ni–P plating was thick. The IMC layers between the Co-containing solders and the electroless Ni–P plating were much thicker than in the other four solder joints.

The miniature impact test was then carried out to evaluate impact reliability. The failure occurred at the interface between the solder and the UBM on the impact side. The relationship between the IMC layer thickness and maximum force is shown in Fig. 4. The maximum forces of the solder joints with electroless Co–P plating were almost the same value because their IMC layer thickness were very thin with no differences between the three different solders. On the other hand, the maximum forces of the solder joints with electroless Ni–P plating differed between the three electroless Ni–P plating solder joints because of the differences in the IMC layer thicknesses. The SAC/Ni–P solder joints with a thin IMC layer had a high maximum force as compared with the solder joints of SAC–0.05Co/Ni–P and SAC–0.2Co/Ni–P, which displayed a lower maximum force owing to the thick IMC layer. In the impact test, the maximum force is a key indicator of impact reliability. We focused on the SAC/Ni–P, SAC/Co–P, SAC–0.05Co/Co–P and SAC–0.2Co/Co–P solder joints because their solder joints had a high maximum force.

Figure 5 shows the relationship between the maximum force of the SAC/Ni–P, SAC/Co–P, SAC–0.05Co/Co–P and SAC–0.2Co/Co–P solder joints and the solder bent length. The solder joints with electroless Co–P plating had a larger bent length than that of the SAC/Ni–P. As the maximum force increased, the solder bent length appeared to increase for the solder joints with electroless Co–P plating. Although the SAC/Ni–P solder joint exhibited the highest maximum force, the solder bent length of SAC/Ni–P joint was shorter than all three of the joints with electroless Co–P plating.

Next, the influence of the solder hardness on the solder bent length was appraised. The solder hardness was measured by Vickers hardness testing as plotted in Fig. 6. The hardness of the solders with electroless Co–P plating was lower than that of the SAC solder with electroless Ni–P plating and decreased with increasing Co content. The sample of SAC solder with electroless Co–P plating and the samples of Co-containing solders with both electroless Co–P plating and electroless Ni–P plating exhibited an

![Fig. 4 Maximum force variation with increasing IMC thickness.](image)

![Fig. 5 Relationship between maximum force and solder bent length.](image)
extremely suppressed undercooling in solidification and significantly improved the microstructures of the solders by acting as nucleation sites for solidification. Figure 7 shows the microstructures of the solders with electroless Co–P plating and the SAC solder with electroless Ni–P plating. The microstructures of the solders with electroless Co–P plating were coarse, whereas that of the SAC solder with electroless Ni–P plating was fine. It is considered that the electroless Co–P plating samples have lower hardness than the SAC/Ni–P sample owing to their coarse microstructure. From the OM observation, there was no difference among the microstructures of the SAC, SAC–0.05Co, and SAC–0.2Co solders with electroless Co–P plating. However, it is estimated that the area fraction of Sn dendrites increases with increasing nucleation sites from adding Co. Hence, there would be differences among these microstructures, and it would have an effect on the hardness of the solders.

![Image](75x330 to 260x472)

**Fig. 6** Vickers hardness measurement results for the central solder area of the cross section.

![Image](68x86 to 267x267)

**Fig. 7** Microstructures of the samples: a) SAC/Co–P, b) SAC–0.05Co/Co–P, c) SAC–0.2Co/Co–P and d) SAC/Ni–P.

All three of the solder joints with electroless Co–P plating had a longer bent length than that of the SAC/Ni–P solder joint, as shown in Fig. 8. As the solder hardness increased, the bent length decreased, with the exception of the SAC–0.2Co/Co–P solder joint sample. The solder hardness of SAC/Ni–P joint was higher than that of all three of the solder joints with electroless Co–P plating. Therefore, the solder bend length of the SAC/Ni–P solder joint was the shortest despite exhibiting a higher maximum force than those of the three electroless Co–P plating joints.

The SAC–0.2Co/Co–P sample had a relatively short bent length despite its low hardness. Figure 9 shows the OM and SEM images of the microstructures of the SAC–0.2Co/Co–P sample. The 0.2Co addition induced the formation of coarse IMCs above the interfacial IMC layer, which was not observed for the SAC/Co–P, SAC–0.05Co/Co–P and SAC/Ni–P samples. EPMA analysis confirmed that the coarse IMCs formed near the interface were (Co,Cu)Sn3. The hardness of the area near the interface was 16.4 HV, whereas that of the central solder area was 13.6 HV. It is believed that this is why fracturing was more easily achieved. As a result, the SAC–0.2Co/Co–P sample had a shorter solder bent length and was not plotted on the
The ability of the solders to absorb impact energy as measured by the impact test is plotted in Fig. 10. Compared with the SAC/Ni–P solder joint, all three solder joints with electroless Co–P plating displayed greater ability to absorb impact energy. The relationship between the solder bent length and absorbed impact energy is shown in Fig. 11. As the solder bent length increased, the absorbed impact energy increased. The SAC–0.05Co/Co–P solder joint had the longest bent length and highest ability to absorb impact energy.

4. Conclusion

The influence of electroless Co–P plating on interfacial structure, bulk properties, and impact reliability were investigated and are summarized as follows:

(1) The IMC layer thicknesses at the interface of the three kinds of solders, namely, SAC, SAC–0.05Co and SAC–0.2Co and electroless Co–P plating were thinner than that between the SAC solder and electroless Ni–P plating.

(2) The SAC/Ni–P, SAC/Co–P, SAC–0.05Co/Co–P and SAC–0.2Co/Co–P solder joints with a thin IMC layer had a high maximum force as compared with the solder joints of SAC–0.05Co/Ni–P and SAC–0.2Co/Ni–P that displayed a lower maximum force owing to the thick IMC layer.

(3) The hardness of the central solder area of the cross section with electroless Co–P plating was lower than that with electroless Ni–P plating.

(4) All three kinds of solder joints with electroless Co–P plating had a longer bent length than that of the SAC/Ni–P solder joint because of lower solder hardness.

(5) The solder joints with electroless Co–P plating had a higher ability to absorb impact energy than the SAC/Ni–P solder joint because of their longer solder bent length.

(6) From the impact test results, it was found that the solder joint s with the thinner IMC layer and lower solder hardness possessed the higher impact reliability.

References


