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INVESTIGATING THE MICROSTRUCTURAL AND MECHANICAL PROPERTIES OF PURE LEAD-FREE SOLDERING MATERIALS (SAC305 & SAC405)

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Abstract

The Sn–Ag–Cu (SAC) solders with low Ag or Cu content have been identified as promising candidates to replace the traditional Sn–Pb solder. In this study, an extensive discussion was presented on two major area of mechanical properties and microstructural investigation of SAC305 and SAC405. In this chapter, we study the composition, mechanical properties of SAC solder alloys and microstructure were examined by optical microscope and SEM and mechanical properties such as tensile tests, hardness test and density test of the lead solder alloys were explored. SAC305 and SAC405 alloys with different Ag content and constant Cu content under investigation and compare the value of SAC305 and SAC405. From this investigation, it was reported that tensile strength is increased, with an increase of Ag content and hardness and density were also increases in the same manner.

Keywords: Lead-free solder, Sn–Ag–Cu alloys, Microstructure, Mechanical properties

INTRODUCTION

Soldering is the most important joining process in the electronics industry. To the environmental concerns and health hazards associated with Pb-Sn solders, several studies have been focused on lead-free solder alternatives [1]**.** It is important to ensure that the thermal, mechanical and physical properties of lead-free solders are superior to those of Sn-Pb solders. Since the portable electronic products increased to high speed, light weight, continual miniaturization and multi-functionality of integrated circuits, the transition to Pb-free solders occurred to compact with the increase in portable electronic products. So in the reliability condition, both the thermal cycling loading and drop performance are important for portable electronic products. The most important for electronic industry appears to be the Sn-Ag-Cu (SAC) alloys eutectic or near eutectic alloy system. These alloys can offer an excellent combination of better thermal, mechanical and wettability compared to Pb-Sn solders. Moreover, the SAC solders alloys have a good quality joint with different substrates, i.e chip scale package as well as ball grid array (BGA) interconnect. The main reason for weak mechanical properties of solder joint is the large formation of Ag_3Sn and Cu_6Sn_5 IMC, so these problems need to be resolved. For that reason, the industries mostly use the low-Ag SAC solder alloys such as SAC105, SAC205 and, SAC305, which have low cost and better performance than eutectic or near-eutectic SAC alloys in drop impact reliability [1, 7].

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With the requirement of lead-free solders, it is necessary to understand that how different lead-free solders affect the reliability of microelectronic assembly when subjected to different loading conditions such as thermal cycling, bending, vibration and drop impact. The Sn–Ag–Cu solder is one commonly used lead-free solder in surface mount technology (SMT) assembly for microelectronics. Many studies were conducted on Sn–Ag–Cu lead-free solders. Results showed that the Ag content affects the mechanical properties and microstructures with Sn–xAg–Cu lead-free solder joint [2, 7].

Pb-free solders are good alternatives to traditional Sn-Pb solders alloys and their existence are great efforts in course. The traditional Sn–Pb solder alloy is the dominant solder material in the industry because of their very low melting temperature.

In the context of the environmental and human precaution, Sn-Pb has not been widely promoted. Since 2006 the environmental protection agencies (RoHS and WEEE) have banned the lead-containing portable electronic products because lead and lead-containing products are toxic substances and it would be very harmful to the well-being of humans and the environment. So the researchers are trying to find the other alternatives without Pb and lead-free solders are good alternatives because lead-free solders are non-toxic [3, 8].

Sn–Ag alloys have three different Ag_3Sn morphologies during solidification. Various researchers have been shown IMCs i.e. Spheroids, needles and platelets type intermetallic (Ag_3Sn) particles. Regarding the mechanical strength, the Ag_3Sn IMC is brittle in nature when compared with the Sn-rich matrix. Under stressed loading conditions, serious problems can be carried by the brittle nature of the Ag_3Sn intermetallic. It has been described that Sn–Ag solder having a coarse dendritic microstructure with fiber-platelets like Ag_3Sn particles has lower corrosion resistance when compared with that of the same alloy having a microstructure characterized by finely and homogeneously distributed spheroids like fiber Ag_3Sn IMC particles. The aim of this paper is to develop a comparative analysis of the mechanical properties of different lead-free solder alloys with those of the traditional Sn–Pb alloy. Experimental results characterizing the microstructural and mechanical properties of SAC305 and SAC 405 alloys. These two SAC solder alloys have been selected due to two main reasons: (i) to determine the effect of silver content on the microstructure and mechanical behavior and (ii) these alloys have been subjected a contradiction in the research [8].

For higher density packages, flip-chip interconnects are increasingly used in daily life. Eutectic Sn-Pb alloy is one of the most popular solders used in flip chip today. Lead-free solder balls are environmentally friendly technology at this time for the electronics industry. Many researchers have been proposed for lead-free solders for material characteristics in manufacturing, reliability, and performance, such as melting temperature, solderability, cost, and long-term reliability. As SAC solders (3 to 4 wt% of Ag) having lower melting points and good solderability with good reliability, these solders are the primary lead-free solder compositions for flip-chip solders [4, 9].

In the electronics industry, the solder joint reliability is a great concern under thermal and mechanical loading. For the reliability assessment, reliability testing and computational modeling are common methods. Compare to actual reliability tests, the modeling is more efficient than actual, which are time-consuming, expensive, and require a more manpower for failure analysis and measurement.

The material properties of the solder joint are needed for modeling. Therefore, for a reliable numerical model, it is very important to characterize material properties accurately. Various researchers have been reported on the characterization of mechanical properties of lead-free solders and lead solders. Tensile and compressive tests are the

conventional techniques used for characterization. Compare to the bulk solder bars, the material properties of the small solder joints are different which used in electronics assembly because they have different microstructures and different intermetallic compound layers. It is necessary to perform characterization on actual solder joints for the effects of microstructures and intermetallic compound distribution. For the characterization of mechanical properties of actual solder joints, the conventional techniques, nanoindentation can be used. But these techniques provide only the properties of the individual phases in the solder joints and does not provide a value for the Poisson's ratio [5, 10].

In recent years, the portable electronics products are highly demanded because of the shrinking in size of electronic components and solder joint dimensions. Furthermore, by the government legislation, the electronics industry has been adopted to lead-free solders due to environmental and health concerns issues from the use of Pb-based solders. In the recent time, several lead-free solders have been developed such as Sn-Bi, Sn-Ag, Sn-Cu, and Sn-Ag-Cu alloys. Sn-Ag-Cu (SAC) is nontoxic solder alloy and it has good mechanical properties and wettability. It the most widely used lead-free solders this time. However, according to the literature, Sn-Pb solders are less brittle in nature than SAC solder alloys with high Ag content because, in SAC solder, the intermetallic compounds (IMC) Ag_3Sn IMC formed at the SAC solder/Ag interface and Cu_6Sn_5 and Cu_3Sn are formed at the SAC solder/ Cu interface. In addition, the high Ag content SAC solder increases the cost of the products compared to the low Ag content SAC solder alloy. Thus, it is mandatory to choose the low-Ag-content SAC alloys. Reducing the Ag content can improve the reliability of SAC solder joints in dynamic environments. It has been proved that to further enhance the properties of SAC solder alloys, alloying elements such as Sic, Bi, Ni and, Ce have been added in lead-free solder alloys [3, 6, 11].

EXPERIMENTAL PROCEDURES

Before the start, the experiment, composition of lead-free solder had to check by the inductively coupled plasma mass spectrometry (ICP-MS). Table1 shown the composition of SAC305 and SAC405 which provided by the HENKEL and also checked by inductively coupled plasma mass spectrometry (ICP-MS).

Tab.1. Composition of SAC305 and SAC405 provided by HENKEL (wt %).

Alloy name by Henkel	Sn	Ag Henkel	Ag ICP	Cu	Cu Henkel	Cu ICP
SAC305	96.5	2.9524	3.03	0.5	0.5955	0.76
SAC405	95.5	3.9918	3.81	0.5	0.5992	0.52

Five specimens had to be cast of SAC 305 and SAC 405 and furnace temperature was 400°C. These specimens had to be cast at room temperature and holding time was 45 minutes in the furnace. The solder alloys were melted in the furnace and maintained 100°C above their respective melting point for 45 minutes. The solder specimens were cast inside the designed mold. Then, the specimens were naturally air-cooled at room temperature. The specimen was annealed at 100°C for 2 h to reduce the residual stress, induced in the sample preparation before the testing. Then, the solder bars were fixed onto a testing grip at two ends of a specimen using a universal testing machine.

Tensile tests were conducted on bulk solder cylindrical dog bone SAC305 and SAC405 solder specimens. Figure 1 shown, the dog-bone-shaped bulk solder specimens for the uniaxial tensile test were prepared by machining from casted lead-free solder bar

SAC305 and SAC405. The specimens had a total length of 60 mm and a gage length of 30 mm. The diameter of the gage length was 5mm.

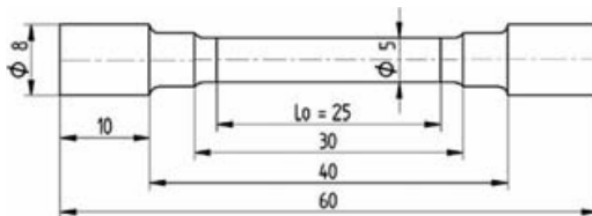


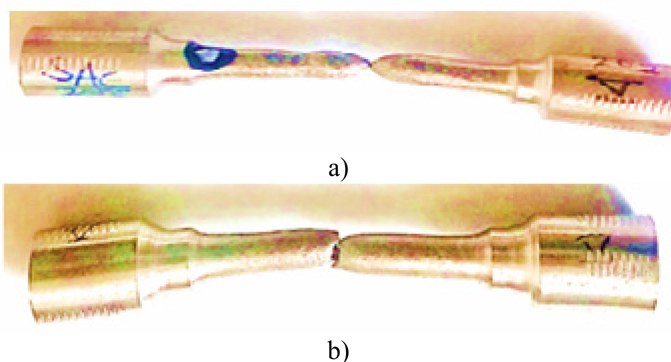
Fig.1. Dog-bone-shaped tensile test specimen.

This paper focuses on the effect of Ag content and the mechanical material properties of lead-free solders. Five samples were tested under the same testing condition for each specimen to obtain the reliable and repeatable results. Then, the mechanical properties were obtained by averaging testing data. The tensile tests were conducted at room temperature (25°C) for SAC305 and SAC405. The microstructures of solders (SAC305 and SAC405) were investigated based on the microscope and scanning electron microscope (SEM) images. The SEM samples were prepared by dicing, resin molding, grinding and polishing processes. The effects of Ag content on IMCs (Ag_3Sn and Cu_6Sn_5) distribution and Sn dendrite were examined to understand the effect of Ag content on the mechanical properties of solders.

RESULTS AND DISCUSSION

Effect of strain on solder mechanical properties

Figure 2 shows the ductile failure mode of SAC305 and SAC405 solder alloys. Necking and surface coarsening analysis were analyzed for the tested solder before complete failure.



a)

b)

Fig.2. Typical ductile failure of (a) SAC305 and (b) SAC405 solder.

The tensile stress–strain curves of Sn–3.0Ag–0.5Cu and Sn–4.0Ag–0.5Cu solder alloys are shown in figure 2(a) and figure 2(b). The strain affects the mechanical properties

significantly. The solder has been effected on the ductility with large elongation and plastic deformation before fracture. UTS and elongation increase with increasing tensile strain.

Effect of Ag content on solder mechanical properties and microstructures

Figure 3 shows the stress–strain curves for SAC305 and SAC405 solders under the same loading conditions. The Figure shows also that the tensile strength of solder increases with increasing the Ag content but ductility reduces when the Ag content increases in Sn–Ag–Cu solder. Therefore, high Ag content solder joint has lower drop lifetime in the electronic assembly when subjected to drop impact, which is the testing results given by Amagai et al. [12]. The low Ag content solders are mainly used in the portable electronic assembly for handheld electronic products to improve the drop performance of solder joint [12, 13].

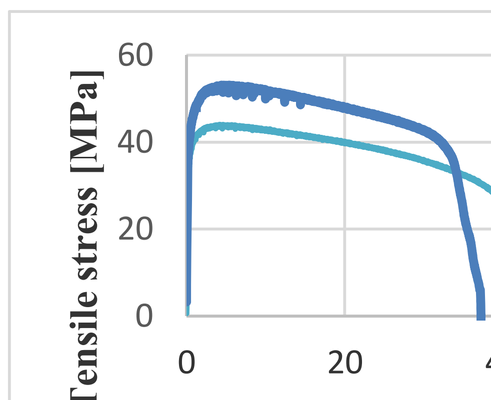


Fig.3. Effect of Ag content on the stress–strain curves of SAC305 and SAC405 solders.

Microstructural characterization of solder

The microstructure of the SAC305 (Sn-3.0Ag-0.5Cu) and SAC405 (Sn-4.0Ag-0.5Cu) solders having a Sn matrix phase where Ag_3Sn needles-like and Cu_6Sn_5 in the bulk form are uniformly distributed in an Sn rich phase. In order to investigate the effect of Ag content on the solder mechanical properties and microstructures by the scanning electron microscopy and microscope were used to study the microstructures of lead-free solders. Figure 4 and 5 shows the SEM images and microscopic images of microstructure for different Sn–Ag–Cu solders. It can be seen that the Ag content affects the Ag_3Sn and Cu_6Sn_5 intermetallic compound (IMC) precipitate. In Sn–Ag–Cu solder amount of Ag_3Sn and Cu_6Sn_5 IMCs increases when the Ag content increases and distributed in a Sn-rich matrix. Therefore, finer Sn dendrites have been seen in the microstructure of solder which has the higher Ag content and more IMC precipitates in solder with higher Ag content such as SAC405.

The typical example of low and high-magnification SEM microstructure of SAC305 and SAC405, alloy of IMC phases are shown in Fig.5. The show the microstructures of SAC305 and SAC405 consists of β-Sn dendrites and mixture of Ag3Sn and Cu_6Sn_5 IMCs distributed within Sn-rich matrix. Similar microstructures were reported in other SAC studies [11]. In Figure 4 and 5, the needle-like particles are identified as Ag_3Sn IMCs, whereas an irregular polygon of IMC particles are Cu_6Sn_5. These large IMCs (Ag3Sn and Cu_6Sn_5) particles are present in near eutectic lead-free solders, and could lead

to failure due to the high interfacial energy between the solid solder and IMCs particles [15].

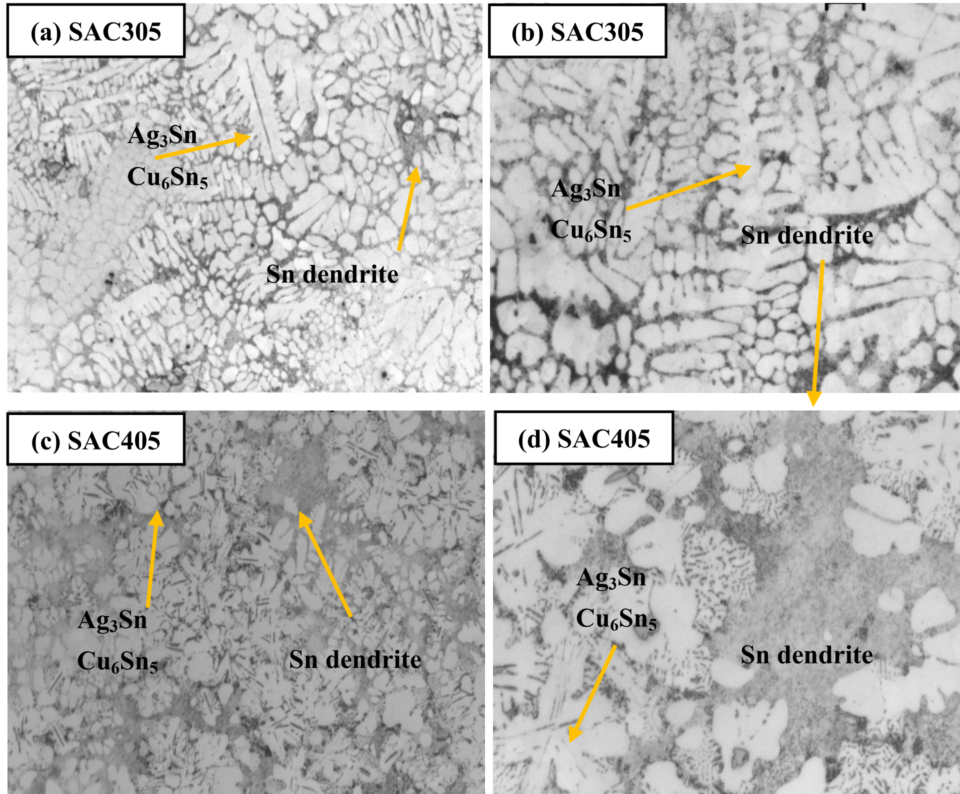
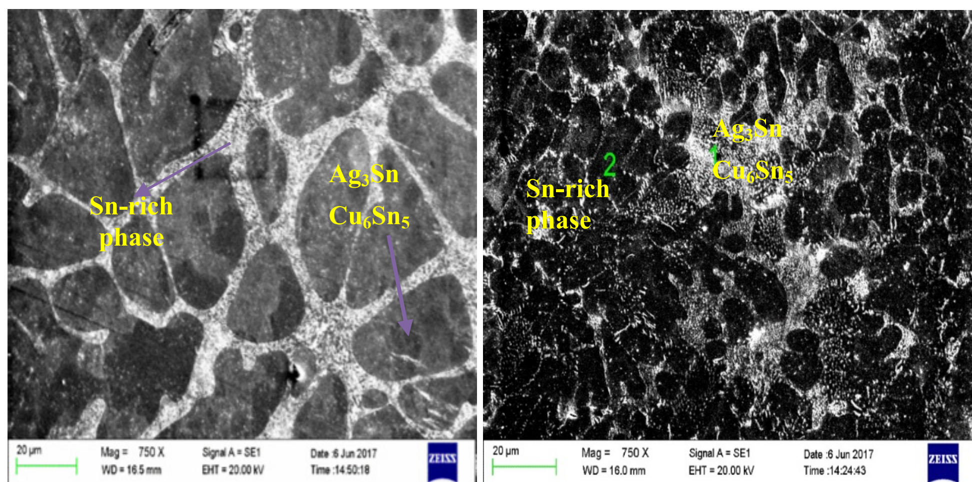


Fig.4. Low and high magnification microstructures of SAC305 (a, b) and SAC405 (c,d).

Melting behavior

Alloys having low silver content have two distinct melting phases. One is Sn-Ag eutectic and second is high-temperature phase corresponding to Sn-Cu eutectic. The melting temperature of the SAC305 and SAC405 solders were determined by DSC analysis. The Sn-Ag3.0-Cu0.5 and The Sn-Ag4.0-Cu0.5 solder were found to have a melting interval of 215-220°C and 217-219°C.



a) b)

Fig.5. SEM images of the microstructure of Sn–Ag–Cu solders: (a) SAC305 and (b) SAC405.

General tensile and hardness test

The tensile properties of SAC305 and SAC405 solder alloys are mainly controlled by their microstructures, which depend on the amount of Ag content, shape and size of IMC particles and their distribution in alloy matrix. Figure 6, Figure 7 and Table 2 compare the tensile properties and hardness properties of plain SAC207 solder.

Tab.2. Tensile and hardness properties of the solders SAC305 and SAC405.

Alloy	Hardness (HV)	Tensile strength (MPa)
SAC305	13.47	40.95
SAC405	13.98	43.70

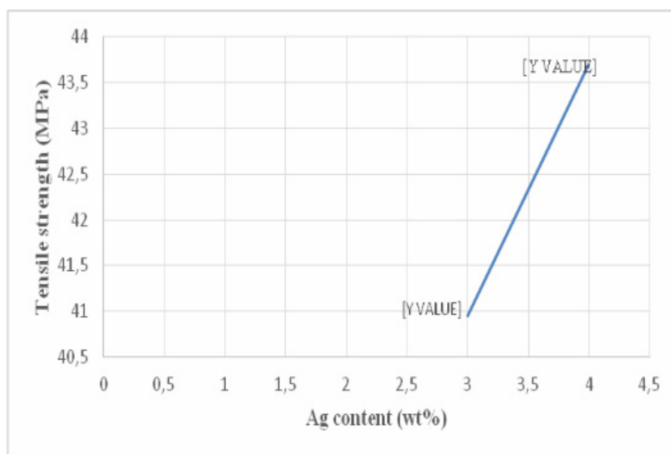


Fig.6. Comparative tensile curves for SAC305 and SAC405 solder alloys.

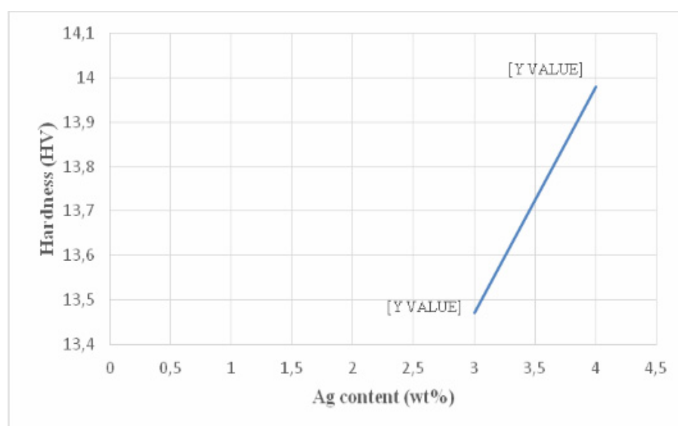


Fig.7. Comparative hardness curves for SAC305 and SAC405 solder alloys Figure caption.

Figure 6 and Figure7 shown that the tensile strength of SAC405 is higher than SAC305 and hardness of SAC405 is higher than SAC305. Ag content is a basic reason for these mechanical properties.

CONCLUSION

Silver content is very important for the soldering process and solder joint reliability. Based on the present investigations described in this work, several conclusions may found regarding a comparative evaluation of microstructural and mechanical deformation behavior of SAC305 and SAC405 solders. In this study, an extensive discussion has been presented on two major area of mechanical properties and microstructural investigation of SAC305 and SAC405. From this present experimental investigation, the following main conclusions can be drawn:

1. Microstructures were examined by optical microscope and SEM images. Needle-like Ag_3Sn and Cu_6Sn_5 intermetallic compound (IMC) precipitate were found and saw in Sn–Ag–Cu solder amount of Ag_3Sn and Cu_6Sn_5 IMCs increases when the Ag content increases and distributed in a Sn-rich matrix. Therefore, finer Sn dendrites were seen in the microstructure of solder which has the higher Ag content and more IMC precipitates in solder with higher Ag content such as SAC405.
2. Melting interval of the SAC305 and SAC405 solders were determined by DSC analysis. The Sn-Ag3.0-Cu0.5 and The Sn-Ag4.0-Cu0.5 solder were found to have a melting interval of 215-220°C and 217-219°C.
3. The tensile strength of SAC305 is 40.95 MPa and SAC405 is 43.70 MPa which is higher than SAC305 and hardness of SAC305 is 13.47 HV and SAC305 is 13.98 HV which is higher than SAC305.

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