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The study of mechanical properties of Sn–Ag–Cu lead-free solders with different Ag contents and Ni doping under different strain rates and temperatures

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ABSTRACT

In this paper, the tensile tests were conducted at 25 °C to investigate the effect of Ag content and Ni doping on the microstructures and mechanical properties of Sn–3.0Ag–0.5Cu, Sn–2.0Ag–0.5Cu, Sn–1.0Ag–0.5Cu, Sn–1.0Ag–0.5Cu–0.05Ni and Sn–1.0Ag–0.5Cu–0.02Ni solders. The effect of strain rate on mechanical properties was investigated for each solder using stain rates of 10^{-5} s^{-1}, 10^{-4} s^{-1}, 10^{-3} s^{-1}, 10^{-2} s^{-1} and 10^{-1} s^{-1}. In addition, the effect of temperature on mechanical properties was investigated for Sn–1.0Ag–0.5Cu–0.02Ni solder by conducting tests at −35 °C, 25 °C, 75 °C and 125 °C. Test results show that the elastic modulus, yield stress and ultimate tensile strength increase with increasing strain rate and Ag content, but they decrease with increasing temperature. The elastic modulus, yield stress and ultimate tensile strength are lower and the elongation is larger for Sn–1.0Ag–0.5Cu–0.05Ni solder compared with Sn–1.0Ag–0.5Cu–0.02Ni solder. The strain rate and Ag content dependent mechanical property models have been developed for Sn–Ag–Cu solders for the first time. In addition, the temperature and rate-dependent mechanical property models have also been developed for Sn–1.0Ag–0.5Cu–0.02Ni solder. The microstructures of solders were also analyzed. The Ag content affects Ag_3Sn intermetallic compound dispersion and Sn dendrite size. The microstructures of solder have fine Sn dendrites and more dispersed IMC particles for the high Ag content solder, which makes the solder exhibit high strength and yield stress.

1. Introduction

With the increasing requirement for lead-free solders, it is useful to understand how different 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 [1–30]. Results showed that the Ag content affects thermal fatigue life and drop lifetime for the soldered assembly with Sn–*x*Ag–Cu lead-free solder joint. The thermal fatigue life increases with increasing Ag content in Sn–*x*Ag–Cu lead-free solders due to the Ag content affecting solder fatigue resistance and mechanical properties [2]. However, the drop performance of electronic assembly with Sn–*x*Ag–Cu lead-free solder joint is worsened with increasing Ag content in Sn–*x*Ag–Cu solder [3]. Hence, the different effect trends of Ag content on thermal fatigue life and drop performance were obtained. In order to improve drop performance without reducing the thermal fatigue life of the electronic assembly with Sn–Ag–Cu lead-free solders, some metal additives, such as Ni, Zn, Fe, Co and rare-earth (RE) elements, have been introduced into Sn–Ag–Cu solders to refine the microstructures and reduce the intermetallic compound growth [4–10,13–22]. Among the additives, Ni is one dominant and widely used doping material in Sn–Ag–Cu solders due to its excellent performance in improving solder microstructure, reducing IMC growth and increasing the drop lifetime of electronic assembly [4–10]. Liu et al. [8] reported that the Ni addition has a positive effect on the growth of $(CuNi)_6Sn_5$ layer but negative effect on the growth of Cu_3Sn layer around the interface between Sn–3.8Ag–0.7Cu–*x*Ni solder and Cu substrate during isothermal aging condition and that the IMC grains are refined with the Ni addition increasing. The Cu_3Sn growth is usually linked to the formation of Kirkendall voids, which in turn increases the potential of interfacial brittle fracture [11]. As a result, drop test performance is improved for Sn–Ag–Cu solder joints with a small amount of Ni addition due to thickness reduction of the refined Cu_3Sn layer [12]. The study by Wang et al. [9,10] showed that the minimum effective Ni addition to Sn–2.5Ag–0.8Cu solder is in a range of 0.01–0.03 wt.%. This is effective in suppressing the Cu_3Sn growth and does not cause

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an excessive Cu_6Sn_5 growth during the reflow stage and aging condition. Recently, some researchers found that the addition of RE elements in Sn–Ag–Cu solders can refine the microstructure and improve the tensile strength and wettability [14–22]. Wang et al. [17] reported that the solderability and mechanical properties of Sn–3.8Ag–0.7Cu solder can be improved by adding light RE Ce in a range of 0.03–0.05 wt.% because the Ce makes the Cu_6Sn_5 and Ag_3Sn precipitates become smaller and uniformly distributed. The creep rupture time of Sn–3.8Ag–0.7Cu solder can be improved by adding 0.05 wt.% Ce as creep damages are reduced and microcrack propagation site is changed due to refinement of IMC particles [18]. Shi et al. [19] reported that adding small amount of heavy RE Er can also improve the wettability, mechanical strength and creep rupture life of Sn–3.8Ag–0.7Cu solder alloy due to the refining of IMC particles and the proper Er content in solder should be in a range of 0.05–0.25 wt.%. Noh et al. [20] investigated the effect of adding Ce to low Ag content solder (Sn–1.0Ag) on microstructure, wettability and mechanical properties using three Ce contents of 0.1 wt.%, 0.2 wt.%, and 0.3 wt.%. The results showed that the microstructures of Sn–1.0Ag–*x*Ce solder become finer and the tensile strength of solder increases with increasing Ce, but the wettability increases in the order: Sn–1.0Ag–0.3Ce, Sn–1.0Ag–0.5Ce and Sn–1.0Ag–0.1Ce [20]. The RE elements are known to be easily oxidized and the excessive RE addition would deteriorate the microstructure and wettability. The rapid growth of tin whiskers has been observed on the surface of Sn–3.0Ag–0.5Cu–0.5Ce solder joints of ball grid array (BGA) packages due to the coarse $CeSn_3$ intermetallic cluster effect [21]. The rapid tin whisker growth can be prevented by adding 0.2 wt.% Zn into Sn–3.0Ag–0.5Cu–0.5Ce solder and the tensile strength of Sn–3.0Ag–0.5Cu–0.5Ce–0.2Zn solder improved significantly compared with that of Sn–3.0Ag–0.5Cu–0.5Ce solder [22]. However, the long-term reliability, such as thermal cycling and the electromigration effect due to high current density, are not clear for lead-free solders with RE addition compared with Ni doped solders, which needs to be investigated. So far, most of the studies focused on the effects of Ag content and metal additions on the solder microstructures [7–10,13–25]. Even though some researchers [2,26,27] investigated the effect of Ag content on fracture behavior and fatigue properties of Sn–Ag–Cu solder, there is a lack of a systematic investigation in the effect of Ag content and metal additions on the mechanical properties of Sn–Ag–Cu solders, e.g., elastic modulus and yield stress. Such mechanical property data are essential for finite element modeling and simulation to help in the design-for-reliability of electronic assembly. Therefore, the main objective of this paper is to develop the Ag content dependent, strain rate-dependent and temperature dependent mechanical property models for Sn–Ag–Cu solders.

In this paper, the effect of Ag content on the mechanical properties of Sn–*x*Ag–0.5Cu solders and the effect of Ni addition on the mechanical properties of Sn–1.0Ag–0.5Cu solder were investigated through the tensile tests for bulk solder specimens. Based on Pang's investigation, the mechanical properties of lead-free solder were similar for both bulk solder and solder joint [28]. So the mechanical properties from bulk solder test can be used in finite element modeling and simulation for the stress–strain behavior evaluation of microscale solder joint. It is known that solder mechanical properties vary significantly with temperature and strain rate [28–30]. In this paper, three different Ag contents including 1 wt.%, 2 wt.% and 3 wt.% Ag in Sn–*x*Ag–0.5Cu solders, and two Ni additives including 0.02 wt.% and 0.05 wt.% Ni in Sn–1.0Ag–0.5Cu solder were investigated. The mechanical properties such as elastic modulus, ultimate tensile strength (UTS), yield stress and elongation, were compared for different solders. The effect of strain rate on the mechanical properties of Sn–Ag–Cu solders was also investigated in a range from 10^{-5} s^{-1} to 10^{-1} s^{-1}, which covered the solder strain rate encountered in thermal cycling, mechanical cyclic bending and vibration loads. The microstructures of different solders were also analyzed based on scanning electron microscope (SEM) images. In addition, different testing temperature conditions including −35 °C, 25 °C, 75 °C and 125 °C were used for Sn–1.0Ag–0.5Cu–0.02Ni solder to investigate the effect of temperature on the mechanical properties of solder.

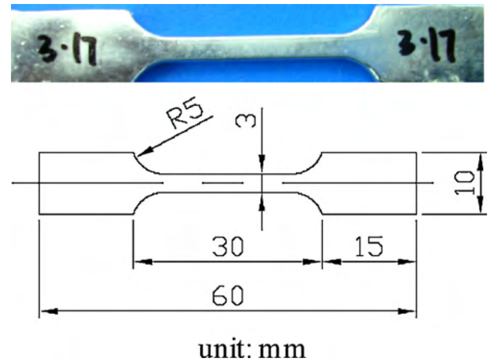

Fig. 1. Geometry of solder specimen.

2. Experimental procedures

The Sn–Ag–Cu bulk solder specimens with flat dog-bone shape were used in this work. Fig. 1 shows the solder bar specimen and its dimensions. The thickness of solder bar is 3 mm. The solder alloys were melted and maintained 100 °C above their respective melting point for 20 min. The bulk solder specimens were cast inside the designed aluminum mold, which was preheated to 120 °C above the melting points of the solder alloys. Then, the specimens were naturally air-cooled at ambient temperature (25 °C). Before the testing, the specimen was annealed at 100 °C for 2 h to reduce the residual stress induced in the sample preparation. Then, the solder bar was fixed onto a testing grip at two ends of specimen using a universal tester as shown in Fig. 2. An extensometer was secured onto the specimen surface to measure the strain of solder. In this work, a length of 10 mm was used as a gauge length. Tensile force added on the specimen was measured by a load cell for stress calculation. The stress–strain curve can be obtained from the measurement data by extensometer and load cell. The strain rate can be controlled by adjusting loading speed. For testing conditions at high and low temperatures, a thermal chamber was used to enclose the tested specimen to provide the designed temperature condition.

This paper focuses on the effect of Ag content, Ni doping, strain rate and temperature on the mechanical material properties of lead-free solders. Five different solders were prepared with the following nominal composition: Sn–3.0Ag–0.5Cu (SAC305), Sn–2.0Ag–0.5Cu (SAC205), Sn–1.0Ag–0.5Cu (SAC105), Sn–1.0Ag–0.5Cu–0.05Ni (SAC105Ni0.05) and Sn–1.0Ag–0.5Cu–0.02Ni (SAC105Ni0.02). Table 1 lists the detailed chemical compositions of five solder alloys. Five samples were tested under the same testing condition for each solder 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, SAC205, SAC105, SAC105Ni0.05 and SAC105Ni0.02 solders under different strain rates of 10^{-5} s^{-1}, 10^{-4} s^{-1}, 10^{-3} s^{-1}, 10^{-2} s^{-1}, and 10^{-1} s^{-1}, respectively to investigate the effect of Ag content, Ni additive and strain rate on the mechanical properties of solder, such as elastic modulus, yield stress, ultimate tensile strength (UTS) and elongation. In this paper, the elastic modulus, also called Young's modulus, of solder was obtained from the elastic part of the tensile stress–strain curve. The yield stress of solder was considered as the stress value at which 0.2% plastic strain occurs. The UTS of solder was considered as the maximum stress in the stress–strain curve. In addition, the effect of temperature on the mechanical properties of SAC105Ni0.02 solder was investigated by conducting tests at at −35 °C, 25 °C, 75 °C and 125 °C, so as to develop the temperature dependent mechanical properties for SAC105Ni0.02 solder.

The microstructures of solders were analyzed based on the scanning electron microscope (SEM) images. The SEM samples were prepared by dicing, resin molding, grinding and polishing processes. The effects of Ag content on IMC distribution and Sn dendrite were examined to understand the effect of Ag content on the mechanical properties of solders.

3. Results and discussion

3.1. Effect of strain rate on solder mechanical properties

Fig. 3 shows the typical ductile failure mode of Sn–3.0Ag–0.5Cu solder. Necking and surface coarsening phenomena were observed