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Investigating the thermomechanical properties and intermetallic layer formation of Bi micro-alloyed low-Ag content solders

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ABSTRACT

In our research, we performed comparative analyses concerning various lead-free SAC (Sn96.5Ag3Cu0.5, Sn95.5Ag4Cu0.5) and two types of micro-alloyed SAC (SnAgCu + Bi + Sb) solder alloys. The mechanical properties of these solder alloys were characterised by measuring the shear strength of 0603 (1.5×0.75 mm) size chip resistors' joints. We designed a testboard, which contains fifty pieces of 0603 size resistors for mechanical characterisation and for measuring the thickness of intermetallic layers. During the experiment, twenty-eight pieces of testboards were soldered with vapour phase soldering (seven with each solder alloy) and sixteen of them were subjected to Thermal-Shock (TS) life-time tests with temperature range of +140 to −40 °C up to 2000 cycles. The intermetallic layer (IML) formation was investigated with Scanning Electron Microscopy (SEM) and Scanning Transmission Electron Microscopy (STEM) methods; and the growth of the layer was analysed by measuring the IML thickness on cross-sectional samples after given TS cycles. It is shown that the thickness of the intermetallic layer in as-reflowed samples (samples without aging) depends on the silver content of the given alloy. Besides, the layer growth rate during Thermal Shock tests is affected by the number of intermetallic layer grain-boundaries along a unit of length.

1. Introduction

In recent years, several investigations have been carried out concerning micro-alloyed solders. The main aim of these studies was to find lead-free solder alloys with lower cost, but with the same quality properties as the commercially available SAC alloys (SnAgCu – Tin–Silver–Copper) by reducing silver content. Although silver improves the mechanical properties of a lead-free solder joint, the main concern with those alloys is that when improper cooling rate is applied during reflow soldering, large Ag_3Sn intermetallic compounds (IMC) may form [1–6]. Generally, three types of Ag_3Sn compounds morphology can be found: particle-like, needle-like, and also plate-like. The sequential evolution or modification of Ag_3Sn compounds during a decreasing cooling rate is usually particle-like → needle-like → plate-like [3].

These plate-like Ag_3Sn IMCs are very brittle and during the cool down phase of the reflow, they can initiate cracks in the solder joints and can result in the so-called shrinkage defect [7]. Additionally, they can promote the crack propagation along their boundary during the life-time of electronic circuits, thus reducing their reliability [8]. If the silver content in the solder is lower, there will be less Ag_3Sn IMC inside; the large Ag_3Sn plates may be effectively minimized by using SnAgCu alloys with hypoeutectic silver compositions of approximately 2.7 wt% or below [8,9] Therefore, besides the cost reduction, the decrease of silver content can have a positive effect on the mechanical properties of solder joints as well. The application of such reduced silver solder compositions in SnAgCu alloys, however, will require careful evaluation with respect to their thermomechanical fatigue properties [10]. The dynamic mechanical properties of low-silver content SAC alloys can be improved by adding micro-alloys into them [11]. Perevezentsev et al. observed that micro-alloying with Germanium increases the strength of SAC alloys by 18% [12], while Pandher et al. found that micro-alloying with Bismuth increases the number of drops that a solder joint can withstand in drop shock tests [13].

Besides the pure mechanical properties of an alloy, the mechanical strength of a solder joint also depends on its shape, which is greatly affected by the wettability of that alloy. Several research have been carried out to find such micro-alloys and even nanoparticles which are able to improve the wetting properties (reducing the wetting angle) of lead-free alloys. Nadia et al. reported that adding copper nanoparticles can reduce the wetting angle of

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SnAg3.5 solders. They found that adding 0.7 wt% nanoCu into the solder reduces the wetting angle from 27° to 20° [14]. However, adding more nanoCu (2.8 wt%) into the solder can increase its Vickers Hardness up to 21.3 HV. This can have a negative impact on the drop shock strength of solders because higher stress will arise in the solder for the same displacement. That is why low solder hardness (a soft solder) improves the drop test performance [15].

Although there are many papers in the field of micro-alloyed solders, further development of micro-alloyed SAC solders requires to re-analyse their thermomechanical properties in details. Therefore we performed investigations regarding the IML formation of different micro-alloyed solder joints and we also compared them to the traditional SAC305 (Sn96.5Ag3Cu0.5) and to the SAC405 (Sn95.5Ag4Cu0.5) alloys. Additionally, we analysed the thermomechanical properties of these solder joints by investigating their mechanical behaviour during TS tests.

2. Experimental

In our experiment, four kinds of solder alloys were compared in aspect of shear strength of solder joints. The exact alloy composition is listed in Table 1. We soldered 28 testboards with these alloys, each containing 50 pieces of 0603 (1.5 × 0.75 mm) size chip resistors.

The solder pastes were deposited onto the testboards by stencil printing (DEK248), using a 100 μm thick, laser cut stainless steel stencil. Afterwards, the resistors were placed by an Essemtec Quadra Laser semi-automatic pick and place machine. At last, the soldering was performed by vapour phase soldering (Asscon Quicky 450) to ensure as similar heating conditions for all samples as possible. The vapour phase soldering actually uses a liquid with high boiling point (above the liquidus point of the solder alloy) which is heated up and saturated vapour is generated. Then the assembly is immersed into the vapour; the vapour condensates onto the surface of the assembly, and the released latent heat provides the energy to melt the solder alloy [16,17]. The advantage of this soldering method is that the heat transport stops automatically when the temperature of the assembly reaches the temperature of the saturated vapour, thus providing uniform temperature distribution along the surface of the assembly [18,19]. During the soldering, the heating factor was set to be 1000 K s. The heating factor (1) is the integral of the temperature $T(t)$ above the melting point of the alloy [20].

$$Q_\eta = \int_{t_1}^{t_2} (T(t) - T_l)dt, \quad (1)$$

where Q_η is the heating factor (K s), $T(t)$ is the measured temperature (K), (t_2–t_1) is the time above liquidus (s), and T_l is the melting point of the alloy. The temperature profile of the vapour phase soldering was measured at two locations on the testboard; at the centre (Sensor 2) and at near to the edge of the board (Sensor 1). The profile is illustrated in Fig. 1. The cooling rates at the two locations were within the range of recommendations for lead-free solders: 1.94 and 2.22 K/s at the centre and at the edge respectively.

After the soldering, 16 samples were subjected to Thermal Shock tests with temperature range of +140 to −40 °C for up to 2000 cycles (Fig. 2) to obtain information about the thermomechanical properties of the different solder alloys. The temperature range has been set according to industrial standards for automotive electronics.

The mechanical properties of the joints were examined by shear strength measurements (DAGE2400 tester: speed – 200 μm/s, height – 5 μm), which were carried out on samples after 24 h of the soldering (as-reflowed state) and on other samples after the aging. The difference between the measured values was tested by Student's two-sample t statistical hypothesis test. Beside the shear strength measurements, cross-sectional analyses were performed as well on all samples to inspect the intermetallic layer growth in the case of the different solder alloys. The thickness of the Cu_6Sn_5 intermetallic layer was measured in SEM–BSE (Scanning Electron Microscopy–Backscattered Electron Detector, FEI Inspect S50) images. The Cu_3Sn intermetallic layer was measured with STEM (Scanning Transmission Electron Microscopy) on as-reflowed samples and with SEM on aged samples. The samples were etched with focused ion beam (FIB; JEOL JEM-9320FIB, 30 kV) and the developed intermetallic were observed by FIB scanning ion microscopy (FIB–IM) with a 60° tilt angle (with a Ga ion source and acc. voltage of 30 kV). The TEM samples were created on the intermetallic layer of the SAC405 and mSAC2 alloy types. The TEM samples were etched with FIB, and the microstructures and compositions were observed by transmission electron microscopy (TEM; JEOL 2100-F, 200 kV) equipped with energy-dispersive X-ray spectroscopy (EDX).

Table 1
Alloy composition of solders under investigation (wt%).

Solder alloy	Sn	Ag	Cu	Bi	Sb
SAC405	95.5	4	0.5	–	–
SAC305	96.5	3	0.5	–	–
mSAC1	98.4	0.8	0.7	0.1	–
mSAC2	98.9	0.3	0.7	0.1	0.01

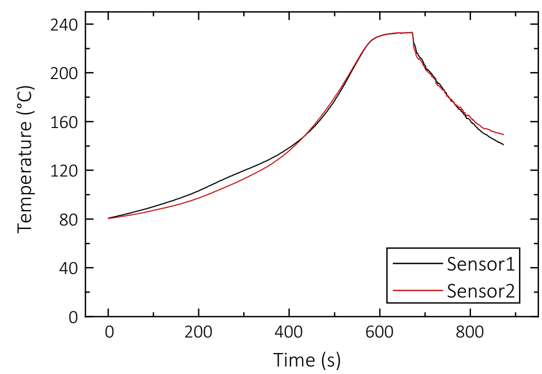

Fig. 1. Temperature profile of the vapour phase soldering.

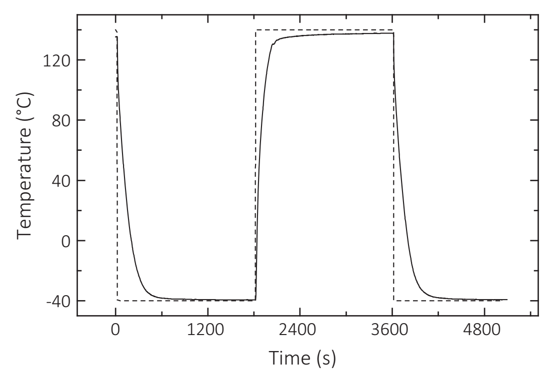

Fig. 2. Temperature profile of Thermal Shock test (+140 to −40 °C, soak time: 1800 s).

3. Results

After inspecting the solder joints, shear strength measurements were performed to characterise the mechanical properties of the alloys. The difference between the mean of the measured values was tested by Student's t-test at a confidence level of 95%. The initial shear strength of the joints before applying to life-time tests is illustrated in Fig. 3 and the result of the corresponding hypothesis tests is collected in Table 2.

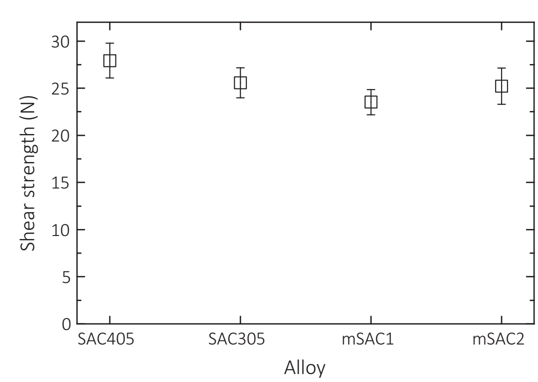

Fig. 3. Shear strength of as-reflowed samples.