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Tensile properties and wettability of SAC0307 and SAC105 low Ag lead-free solder alloys

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Abstract In this article, the tensile properties of low Ag lead-free solder alloys, SAC0307 and SAC105, are examined under various strain rates and temperatures. The wettability of these solders on Cu pad is also characterized by using different fluxes. The SAC305 and Sn37Pb solder alloys are also studied for comparison. Our results show that the properties of all solder alloys are dependent on the strain rate and temperature. The ultimate tensile strength increases monotonously with the increment of strain rate. Both SAC0307 and SAC105 alloys possess lower strength and higher elongation ratio than SAC305 and Sn37Pb alloys. For all the fluxes used in this study, the SAC0307 and SAC105 alloys show the similar wettability to SAC305, whereas worse than that of Sn37Pb alloy. Increasing the activity of the flux does not improve the wettability of the SAC solder alloys on Cu pad effectively.

Introduction

The extensive research has been performed during the transition from conventional Sn–Pb eutectic solders to lead-free solder alloys. Among the numerous lead-free solder alloys, the Sn–Ag–Cu (SAC) ternary alloys have been regarded as one of the most promising candidates for the replacement of Sn–Pb eutectic solder due to their superior properties [1–4]. All the commercial Sn-based solders, both the Pb-bearing and Pb-free solders, can form a reliable electrical and mechanical interconnection on the substrates.

Following with the increase of the IC package density and subsequent distortion and stress thereof in the solder joints, the solder alloy is crucial to endure the severe deformation. Unfortunately, the increase strength of Sn-based solder alloys often compromises the ductility and impact reliability. In particular, some commercial SAC lead-free solders with high Ag content exhibit poor reliability under the high strain rate loading conditions [5, 6]. Recently, it has been found that the low Ag SAC alloys, such as the Sn-0.3Ag-0.7Cu (SAC0307) and Sn-1.0Ag-0.5Cu (SAC105), exhibit both higher bulk compliance and higher plastic energy dissipation than SAC405 or SAC305 [4–6]. At the JEITA lead-free Activities Report Meeting in 2007, Senju Metal Industry Co. Ltd. (SMIC) reported two kinds of lead-free solders, say, SAC0307 and SAC105, for the second-generation lead-free solder. A study conducted in Shanghai Huaqing welding and soldering materials technological company showed that the SAC0307 solder alloy has a similar soldering ability as SAC305 when a certain flux was applied. Furthermore, it has been reported that the SAC0307 soldered joint showed a better anti-impact reliability under high speed impact tests, as the cohesive fracture mode in solder matrix was dominant in most of the solder joints [6, 7]. Apparently, the SAC0307 and SAC105 alloys are more economic due to the lower content of Ag. Therefore, SAC0307 and SAC105 will be ones of best second generation lead-free solder alloys to replace SAC305, SAC387, or SAC405.

Most of the previous studies, however, were mainly focused on the interfacial characterization and failure mode

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[8–11]. Although the strain rate and temperature effects on mechanical properties have been done on SAC solders with high initial Ag (e.g., >3.0 wt%) [12, 13], very few studies are on the SAC0307 and SAC105 solder alloys. This article is devoted to investigate some primary properties of SAC0307 and SAC105 solder alloys, such as tensile strength and elongation ratio, under different strain rates and temperatures. The wettability of these solder alloys on Cu substrate is also examined by using various soldering fluxes.

Experimental procedure

Three types of solder alloys, namely, SAC0307, SAC105, and SAC305, are used in this study. The alloys were melted at 350 °C under nitrogen atmosphere for 1 h in a ceramic crucible and then cast into a rectangle mold. The cooling rate is about ~0.8 °C/s, which is close to the realistic reflow soldering process. The dog-bone type specimens were fabricated with the gauge length of 20.0 mm and rectangular cross section of 1.0×3.0 mm^2.

The experiments were conducted by using Instron5848 micromechanical tester in which a temperature-controlled chamber is assembled. The temperature variation inside the chamber is less than ± 1 °C. To explore the effects of the strain rate and temperature on the properties of the solders, the tensile tests were performed at the strain rate from 10^{-4} to 1.0 s^{-1}, and the chamber temperatures were kept at 25, 80, and 125 °C, respectively.

To prepare the specimens for the wettability test, the solder alloys were cut into disk-shape (200.0 ± 2.0 mg) with the thickness of 2.2 mm and diameter of 4.0 mm. The specimens were then soldered on Cu substrate at 260 °C for SAC-based lead-free solders and 220 °C for Sn37Pb solder. Three types of commercial rosin-base fluxes (3.0 mL) were used during the soldering. The first one is R type flux which is pure electrical rosin without any activators or halogen. The second one is RMA type flux which is mildly activated rosin and the chloride content is about 0.1%. The third one is RA type flux which is activated rosin and the chloride content is about 1.2%. After soldering, the spread area was measured as the precursor to assess the solder wettability on Cu pad. The nitrogen protection effect on the solder wettability was also examined.

Results and discussion

Effect of strain rate on tensile properties

It has been found that the mechanical properties of Sn-based lead-free solder alloys are varying with the strain rates [13–16]. This rate-dependent property is crucial for the assessment of solder joint reliability. In this study, the ultimate tensile strength (UTS) of SAC0307, SAC105, SAC305, and Sn37Pb bulk solders were measured at different strain rates, say, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, and 1.0 s^{-1}. The results in Fig. 1 indicate that for all the solder alloys the tensile strength increases monotonously with the increment of strain rate. In fact, due to the strain rate change from 10^{-4} to 1.0 s^{-1}, the amplitude of UTS is changed by 60, 84, and 105% for SAC0307, SAC105, and SAC305, respectively. The Sn37Pb solder alloy is more sensitive to the strain rate, that is, its UTS increases by 159% when the strain rate is changed from 10^{-4} to 1.0 s^{-1}.

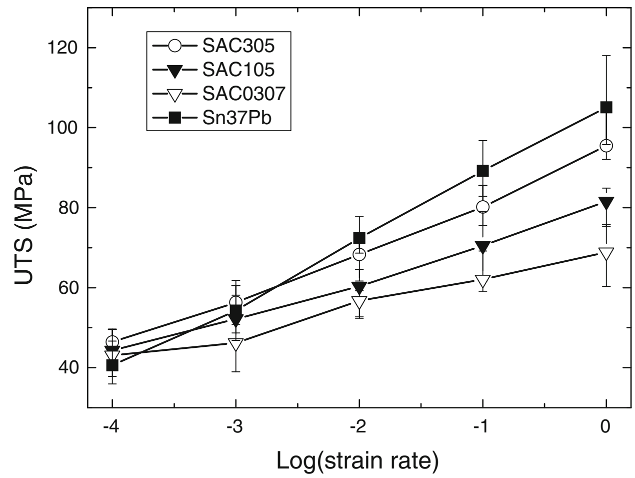

Fig. 1 Strain rate effect on the UTS at room temperature (25 °C)

The strain rate sensitivity index m is adopted to evaluate the rate-dependent behavior of the solder alloys, which is given by:

$$\sigma = C \cdot \dot{\varepsilon}^m \tag{1}$$

where, σ is the stress, C is a constant, and $\dot{\varepsilon}$ is the strain rate. Thus, the m values can be calculated based on the lnσ versus $\dot{\varepsilon}$ relation. The m values are determined as 0.078, 0.067, and 0.054 for SAC305, SAC105, and SAC0307 solders, respectively. For SAC105 and SAC0307 alloys, there is no available published data for comparison. The m value of SAC305 is in a good agreement with the existing results, that is, 0.080 [2, 16]. Apparently, among all three lead-free SAC alloys, the SAC0307 solder exhibits the lowest strain rate sensitivity, that is, SAC305 > SAC105 > SAC0307. The lower strain rate sensitivity values indicate a lower stress strengthening effect for the SAC0307 and SAC105 solders, which leads to a lower stress concentration at high strain rate regime. Additionally, a lower ultimate tensile strength (UTS) usually corresponds to the lower yield strength. Compared with SAC305, it is evident that the SAC0307 and SAC105 solders can be more effective to release the interface energy between solder and substrate. Thus, the SAC0307

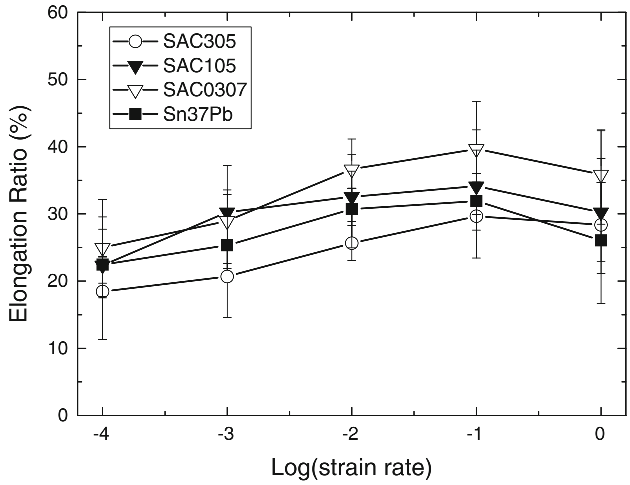

Fig. 2 Strain rate effect on the elongation ratio at room temperature (25 °C)

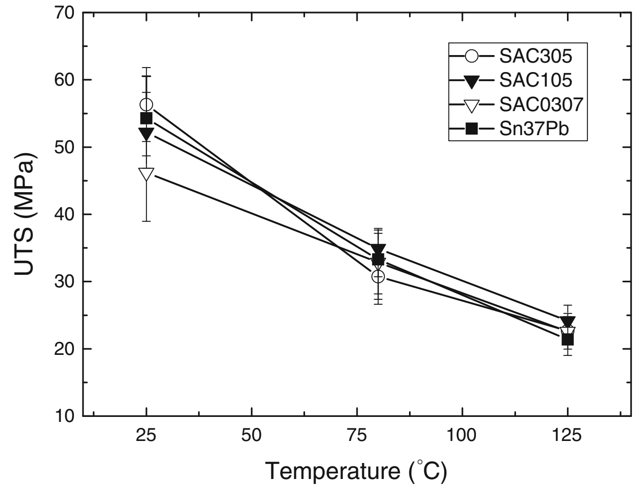

Fig. 3 The UTS evolution as a function of temperature at a constant strain rate, 10^{-3} s^{-1}

and SAC105 solder joints are anticipated to show better shock/drop reliability owing to their lower UTS and *m* values. This is consistent with the previous study on SAC105 solder [4].

Figure 2 shows the effect of strain rate on the elongation ratio of the solder alloys. It can be seen that the elongation ratio gradually increases with the strain rate between 10^{-4} and 10^{-1} s^{-1}, and then declines at the higher strain rate 1.0 s^{-1}. For the lead-free solders, the elongation ratio decreases with the increment of the Ag content, that is, the SAC0307 solder shows the highest elongation within the strain rate regime herein. The Sn37Pb eutectic solder shows a moderate elongation ratio. The elongation ratio is regarded as an indicator of the material ductility, that is, the solder alloy with higher elongation possesses a better ductility and higher deformation tolerance.

Effect of temperature on tensile properties

To evaluate the temperature effect on the solder properties, the monotonic tensile tests were performed at 25, 80, and 125 °C, respectively. It has been found that the high strain rate will result in a significant increase of the yield strength [17]. Therefore, in order to eliminate the effect of strain rate on the testing results, a relatively small strain rate, say, 10^{-3} s^{-1} was used in this study. As illustrated in Fig. 3, the UTS values of all solder alloys show temperature dependence. That is, the UTS decrease with the elevated temperature. At 25 °C, the SAC0307 strength is the lowest while the SAC305 is the highest in lead-free solder alloys, indicating that the Ag addition can strengthen the Sn-based solders effectively. At a higher temperature 125 °C, the tensile strength of lead-free solders is comparable to the Sn37Pb solder.

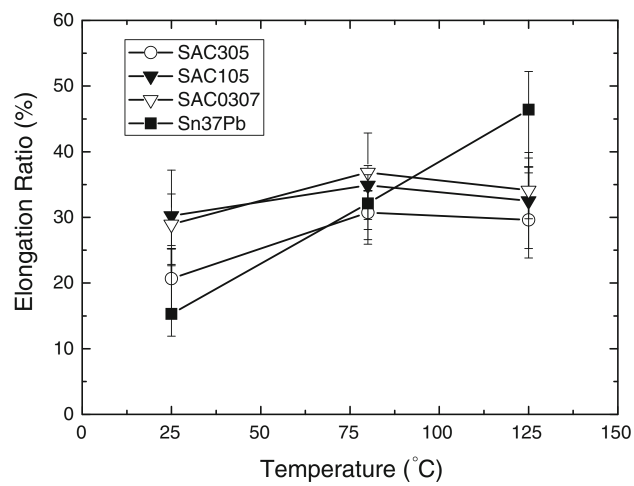

Fig. 4 The elongation ratio evolution as a function of temperature at a constant strain rate, 10^{-3} s^{-1}

The evolution of elongation ratio against the temperature was also studied, as illustrated in Fig. 4. For Sn37Pb solder, the elongation ratio increases monotonously from 25 to 125 °C. The lead-free solders behave somewhat differently from Sn37Pb. At the low temperature regime (25–80 °C), the elongation ratio of SAC lead-free solders increases with the temperature. However, this value tends to decrease at higher temperature (125 °C). Furthermore, in the entire temperature regime (25–125 °C), it is interesting that the SAC0307 and SAC105 solders show a higher elongation ratio than SAC305.

Solder wettability on Cu substrate

Three types of soldering fluxes, namely R, RMA, and RA, were applied to estimate the solder wettability on Cu

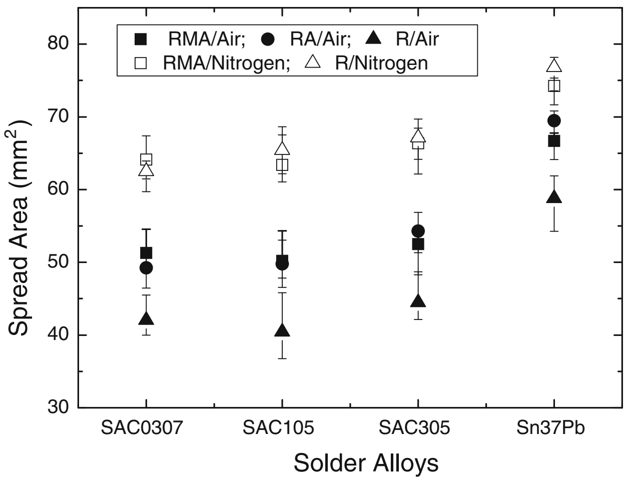

Fig. 5 The measured spread area of solders on Cu substrate by using three types of fluxes

substrate. The spread area after soldering was measured as the precursor of the solder wettability on Cu and the results are presented in Fig. 5. For all the fluxes used in this study, the Sn37Pb solder has a larger spread area on Cu pad than the SAC lead-free solders, regardless of nitrogen atmosphere. This is evident that Sn37Pb has a better wettability on Cu pad than SAC lead-free solders. The three SAC lead-free solders exhibit the similar wettability on Cu pad, which indicates that the Ag content in SAC solders does not impact the wettability on Cu significantly. In addition, the RMA and RA fluxes are more functional on the wettability than the R flux. Clearly, the soldering wettability is significantly improved by using the nitrogen protection. And this improvement is more profound for the SAC lead-free solders.

Discussion

Three phases are coexisted in the bulk SAC lead-free solder alloys during solidification, that is, beta-Sn, and two intermetallic compound (IMC) phases, i.e., Ag_3Sn and Cu_6Sn_5. In fact, all three lead-free solders (SAC0307, SAC105, and SAC305) in this study are hypoeutectic alloys, in which the beta-Sn is the primary phase and grows as interbranched dendrites. A ternary eutectic network is formed by the residual Sn, Ag_3Sn, and Cu_6Sn_5 particles. It has been found that the initial Ag and Cu contents in SAC lead-free solders will influence the fraction of primary beta-Sn phase dramatically. For instance, the fraction of beta-Sn in SAC105 is determined as 35%, while it is only 11% in SAC305 alloy [4]. The ternary eutectic structure is highly strengthened by brittle Ag_3Sn and Cu_6Sn_5 IMC particles. Considering the better ductility of beta-Sn, the SAC solder alloy with low initial Ag content is expected to show lower tensile strength and higher elongation ratio, which in turn improves the bulk compliance and plastic energy dissipation ability of the solder joints. It is anticipated that the SAC0307 and SAC105 solder joints exhibit better drop reliability than SAC305 solder joint.

These results show that the UTS of all the solders monotonously decrease with the increment of temperature. This may be attributed to the thermal softening of the materials. Such phenomenon is readily linked to the atomic energy of the materials. Following with the increase of temperature, the ions adsorb the thermal energy and reach a new equilibrium state with wider vibration amplitude, which in turn softens the materials [18]. At the low temperature regime (25–80 °C), the elongation ratio of all the solders increase following with the temperature is also due to the thermal softening effect. However, at a higher testing temperature (125 °C), the coarsening of Ag_3Sn and Cu_6Sn_5 IMC particles in SAC lead-free solders tends to be profound, which is anticipated to deteriorates the elongation ratio of these alloys significantly. Figure 6 shows the remarkable IMC particles coarsening behavior at 125 °C. No visible difference of Ag_3Sn coarsening is found in all three lead-free solders, although more larger-size Cu_6Sn_5 particles are formed in SAC0307 solder due to its higher initial Cu concentration. On the contrary, the Sn37Pb solder alloy does not contain any IMC particles, thus its elongation ratio continues to increase at higher temperature (125 °C). In the meantime, the coarsening deteriorates the strengthening effect of the IMC particle, and thus the beta-Sn structure is dominant in UTS at higher temperature. That is why all three lead-free solders show the comparable UTS to that of Sn–Pb solder at 125 °C.

It has been demonstrated that the Pb presence will lower the surface tension of liquid Sn-based solders. Thus, the Sn37Pb shows the best wettability on Cu pad, compared with the lead-free SAC solders. Figure 7 depicts the interfacial reactive products formed between the solders and Cu pad. Compared with Sn–Pb/Cu reactive couple, a much severe interface reaction is detected at the lead-free SAC/Cu interfaces according to the thickness of IMC layer. All the lead-free solder joints show the scallop-like IMC layer. However, it can be reasoned that the stronger reaction at the SAC/Cu interface does not improve the reactive wetting, compared with Sn37Pb/Cu reactive couple. It has been reported that minor addition can change the interfacial reaction significantly [19]. In order to improve the wettability, the minor addition should be capable to lower the surface tension, rather than enhancing the interfacial reaction. Our results also show that the SAC solder wettability is not dependent on the initial Ag content. Thus, it can be deduced that the Ag addition does not change the surface tension remarkably. Another promising finding is that the wettability of SAC0307 and SAC105 on Cu pad is

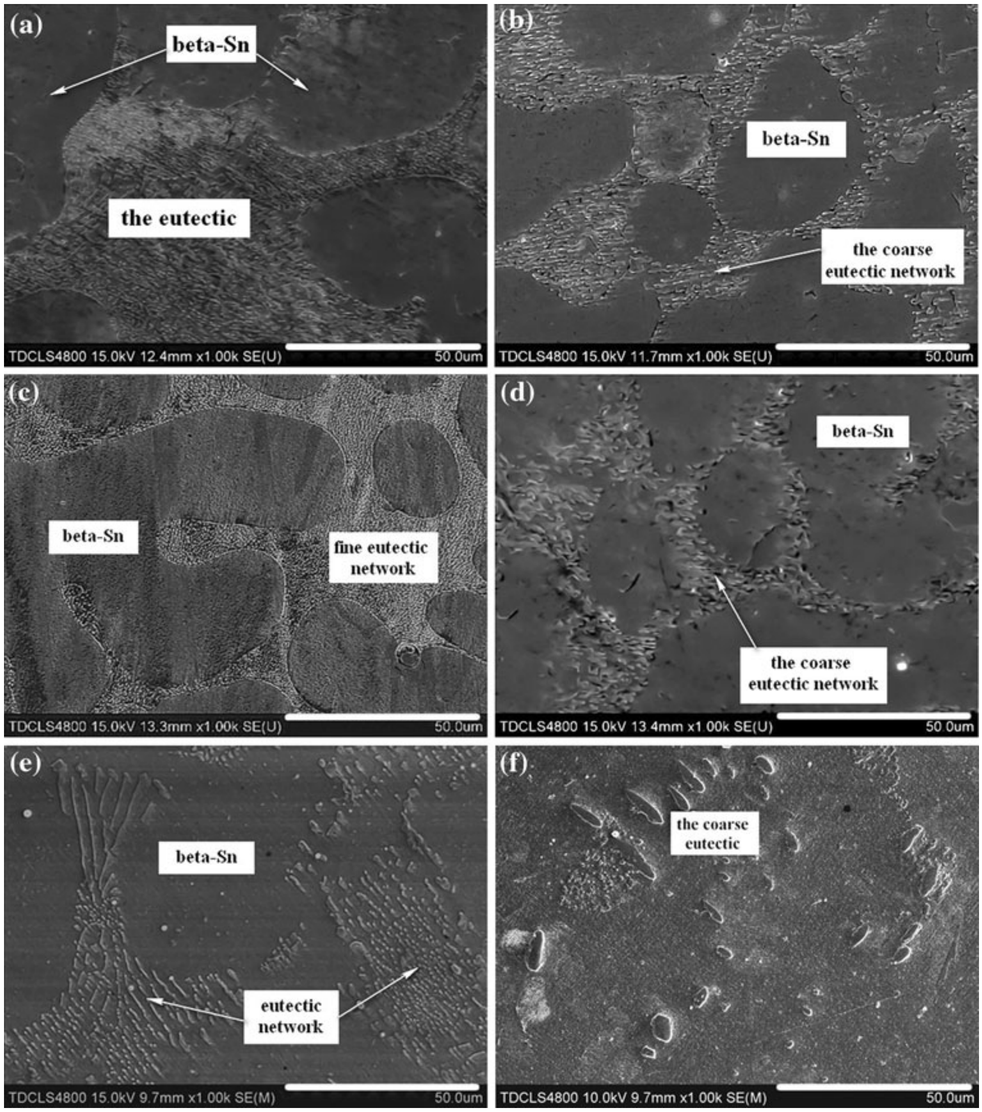

Fig. 6 The effect of temperature on the microstructure of the SAC-based solder alloys: **a** SAC305, as cast; **b** SAC305, aging at 125 °C for 8 h; **c** SAC105, as cast; **d** SAC105, aging at 125 °C for 8 h; **e** SAC0307, as cast; and **f** SAC0307, aging at 125 °C for 8 h

comparable to commercial SAC305 solder. Moreover, under nitrogen atmosphere, the wettability difference between SAC lead-free solders and Sn37Pb is significantly reduced. Accordingly, the SAC0307 and SAC105 are all possible for the commercialized use in electronic assembly and packaging.

Conclusions

The tensile properties of low Ag content lead-free solder alloys, SAC0307 and SAC105, were examined at different strain rates and temperatures. The wettability of these solder alloys on Cu pad were also tested by using different fluxes. The following conclusions can be drawn:

(1) At the strain rate regime (10^{-4}–1.0 s^{-1}), higher strain rate leads to a larger UTS for all the solder alloys. Basically, the SAC0307 and SAC105 alloys show a lower tensile strength whereas a higher elongation ratio than SAC305 and Sn37Pb.

(2) The tensile properties of all the solder alloys are temperature dependent. The tensile strength of all the solder alloys decreased monotonously with the elevated temperature. Within the temperature regime in this study (25–125 °C), the SAC0307 and SAC105 alloys show a lower tensile strength whereas a higher ductility than SAC305.

(3) The lead-free solders bearing low Ag content, SAC0307 and SAC105, exhibit the comparable wettability on Cu to SAC305. Although the wettability of

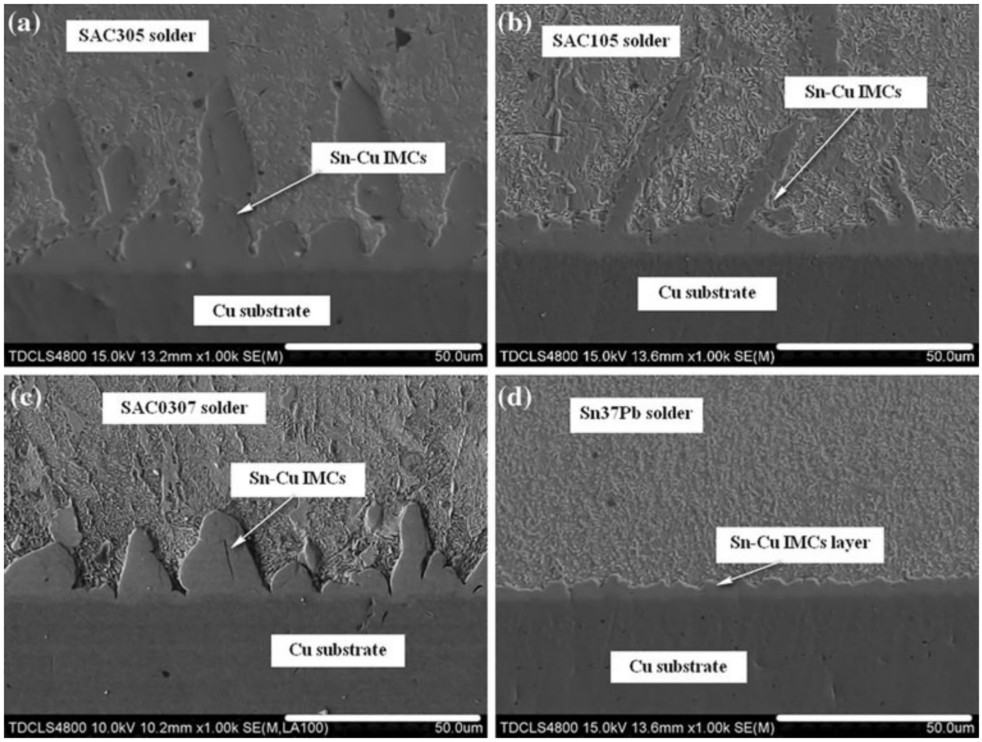

Fig. 7 The interfacial IMCs formed between the solder and Cu substrate: **a** SAC305/Cu, **b** SAC105/Cu, **c** SAC0307/Cu, and **d** SnPb/Cu

SAC0307 and SAC105 is still worse than conventional Sn37Pb solder, this difference is significantly reduced by introducing the nitrogen protection during soldering process.

(4) Overall, the testing results, such as tensile properties and wettability, indicate that the SAC0307 and SAC105 are the promising alternate candidates for SAC305 as the second generation lead-free solders.

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