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Intermetallic growth study on SnAgCu/Cu solder joint interface during thermal aging

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Abstract The intermetallic compound (IMC) growth behavior at SnAgCu/Cu solder joint interface under different thermal aging conditions was investigated, in order to develop a framework for correlating IMC layer growth behavior between isothermal and thermomechanical cycling (TMC) effects. Based upon an analysis of displacements for actual flip-chip solder joint during temperature cycling, a special bimetallic loading frame with single joint-shear sample as well as TMC tests were designed and used to research the interfacial IMC growth behavior in SnAgCu/Cu solder joint, with a focus on the influence of stress–strain cycling on the growth kinetics. An equivalent model for IMC growth was derived to describe the interfacial Cu-Sn IMC growth behavior subjected to TMC aging as well as isothermal aging based on the proposed "equivalent aging time" and "effective aging time". Isothermal aging, thermal cycling (TC) and TMC tests were conducted for parameter determination of the IMC growth model as well as the growth kinetic analysis. The SnAgCu/Cu solder joints were isothermally aged at 125, 150 and 175 °C, while the TC and TMC tests were performed within the temperature range from −40 to 125 °C. The statistical results of IMC layer thickness showed that the IMC growth for TMC was accelerated compared to that of isothermal aging based on the same "effective aging time". The IMC growth model proposed here is fit for predicting the IMC layer thickness for SnAgCu/Cu solder joint after any isothermal aging time or thermomechanical cycles. In addition, the results of microstructure evolution observation of SnAgCu/Cu solder joint subjected to TMC revealed that the interfacial zone was the weak link of the solder joint, and the interfacial IMC growth had important influence on the thermomechanical fatigue fracture of the solder joint.

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1 Introduction

In most electronic assembles, solder joints provide both electronic and mechanical support to the components. Because reliability losses in many electronic systems are identified with failure of solder joints rather than device malfunctions, more and more concerns are focused on the solder joint reliability [1]. One of the most important reliability issues is the microstructure evolution of the solder joint during service, in which the formation and growth of intermetallic compound (IMC) between the solder and substrate has been considered to be an essential one [2]. In the past decades, research works were made to explore the formation mechanisms and growth kinetics of the interfacial IMC with the focus on the morphological features and growth rate under different thermal aging conditions. Various results were reported by different researchers on this topic [3–6]. Nevertheless, the mechanism of the interfacial IMC growth was not well understood and need to be further investigated.

Throughout their service lives, solder joints in electronic packages experience both thermal and mechanical loading, which would have effect on the atoms diffusion and IMC growth behavior [7, 8]. It has been reported that the IMC growth in solder joints during thermomechanical cycling (TMC) is a result of both static and strain-enhanced aging [9, 10]. However, the effect of the stress–strain cycling on the IMC growth was hardly presented, and the quantitative description for IMC growth under TMC aging has become an important problem to be solved.

Accordingly, in this paper, the morphology and growth behavior of interfacial IMC in Sn3.0Ag0.5Cu/Cu solder joints under different thermal aging conditions is studied. The IMC growth behavior subjected to isothermal aging and TMC is compared, with a focus on the influence of stress–strain cycling on the growth kinetics. Based on this, we attempt to develop a methodology for predicting the IMC layer growth behavior for long-term thermal aging. In addition, the effect of the IMC growth on the thermomechanical fatigue fracture of the solder joint is also discussed.

2 Experimental procedures

2.1 Specimen preparation

Rectangular Cu bars (3 mm × 3 mm × 12 mm) were used as the substrates in the present study. A Sn3.0Ag0.5Cu Pb-free solder sheet (3 mm × 3 mm × 0.5 mm) was placed between two aligned Cu bars in an Al mould and then the mould with the specimens was heated in a reflow oven to form sandwich-like solder joint specimens. The soldering process itself was carried out applying a near-industrial reflow temperature profile for lead-free soldering in a commercial reflow oven, and the temperature profile employed is shown in Fig. 1.

2.2 Thermomechanical loading device and strain measurement

Based upon an analysis of displacements for actual flip-chip solder joints subjected to temperature cycling, a special bimetallic loading frame with single joint sample was designed, as shown in Fig. 2. The assembly consisted of a marble frame and two metal bars which were made of Invar alloy and aluminum respectively. The solder joint sample was mounted between Al and Invar grips, which were attached to the marble frame. The loading frame, with the difference in the coefficient of thermal expansion (CTE) between Al and Invar is about 20×10^{-6} K^{-1}, was used to impart temperature-dependent shear displacements to the solder joint sample as ambient temperature changed. Thereby, the solder joint was subjected to TMC loading during temperature cycling test. Shear strains of the solder joint during TMC were obtained by strain gauge measurement. Eight high-temperature strain gauges were glued on the centre of the Invar and aluminum bars to measure the mechanical strains in the test, and the shear strains of the solder joint were deduced from the data of four special Wheatstone bridges measurement monitored simultaneously. The difference in the thermal properties between the strain gauge and the loading bars was determined and compensated from measurements of strain gauge output with temperature on free standing bars. The change of temperature was also monitored and recorded synchronously using thermocouple which was placed on the loading frame, and the typical temperature cycling profile is shown in Fig. 3.

2.3 Thermal aging tests

Isothermal aging, thermal cycling (TC) and TMC tests were conducted for interfacial IMC growth investigation. During isothermal aging, the specimens were aged at 125, 150 and 175 °C for different time to evaluate the influence of aging temperature and aging time on the IMC growth kinetics. During TC and TMC, the samples were subjected to a cycling temperature reliability test in a two-zone furnace chamber, which follows the JESD22-A104-C standard temperature range of −40 to 125 °C, with a cycle time of 40 min and the dwell time of 15 min at each temperature extreme, as shown in Fig. 3. What deserves to be mentioned is, to differentiate between the TMC and pure TC, a series of TC tests were carried out using the single joint sample (see Fig. 2) without the loading frame, i.e. the specimen experienced the temperature cycling over the

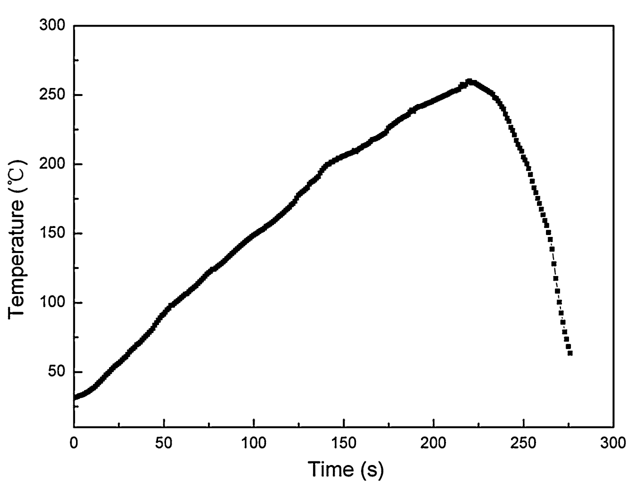

Fig. 1 Reflow temperature profile

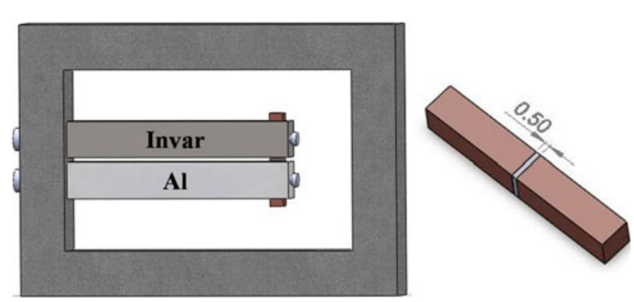

Fig. 2 Bimetallic loading frame and solder joint sample for TMC test

same temperature cycling profile as that during TMC but without any externally applied stress. Test specimens were extracted out from the furnace chamber several hundred cycles to investigate the morphological and interfacial behavior of the solder joint. The IMC growth behaviors under above three different thermal aging conditions were compared.

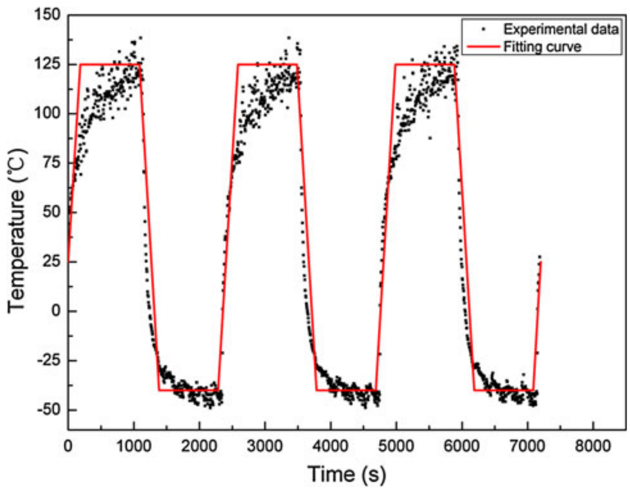

Fig. 3 Temperature cycling profile

2.4 Microstructure observation and IMC thickness measurement

Scanning electron microscopy (SEM) was used to observe the microstructural evolution of the solder joints. X-ray energy dispersion spectrometry (EDS) combined with X-ray diffraction (XRD) analysis was performed to determine the phase composition of the solder joint interfacial region. For XRD experiments, after solder joint samples were broken and the fracture surfaces were ground, these ground surfaces (3 mm × 3 mm) were used for plan view XRD measurements of interfacial region.

To observe clearly the morphology of IMC at the interface, the sample was etched slightly by 94 % C_2H_5OH + 4 % HNO_3 + 2 % HCL solution. The mean thickness of the total IMC layer was digitally measured by pixel method using Photoshop and Image J software.

3 Results and discussion

3.1 Interfacial IMC morphology and growth behavior

Figure 4 shows the microstructure evolution of the interfacial zone in Sn3.0Ag0.5Cu/Cu solder joint aged at

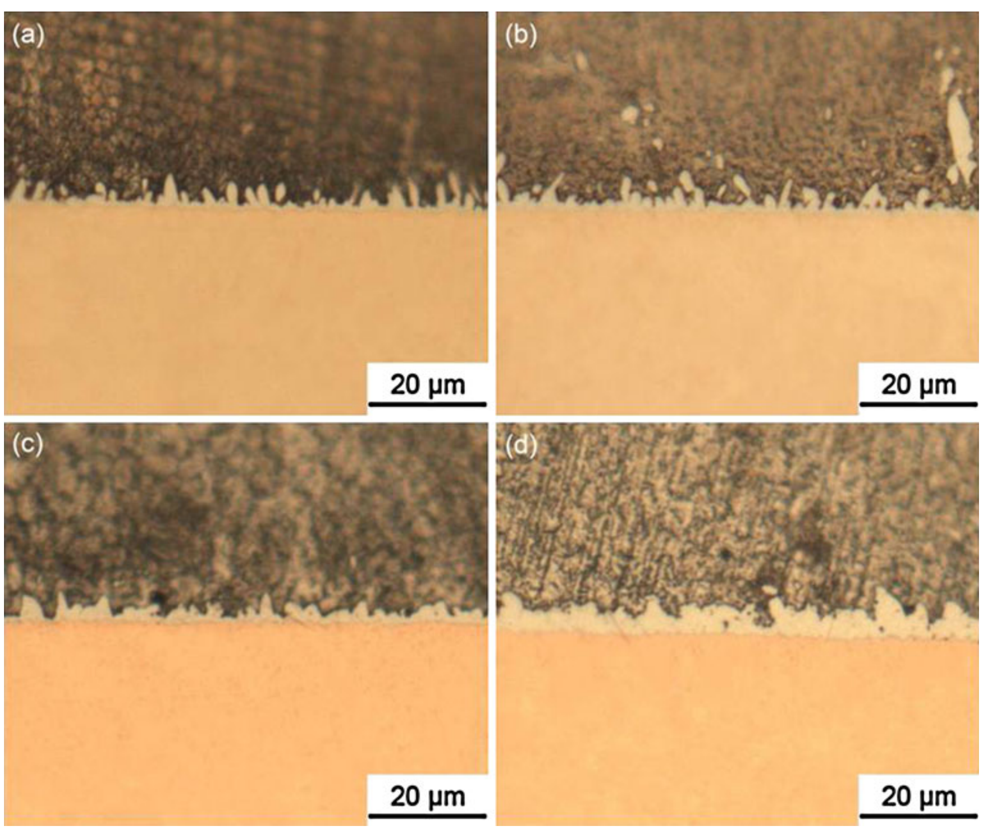

Fig. 4 Cross-sectional micrographs of interfacial zone in Sn3.0Ag0.5Cu/Cu solder joint aged at 125 °C for different aging time. **a** 0 h, **b** 36 h, **c** 120 h, and **d** 360 h

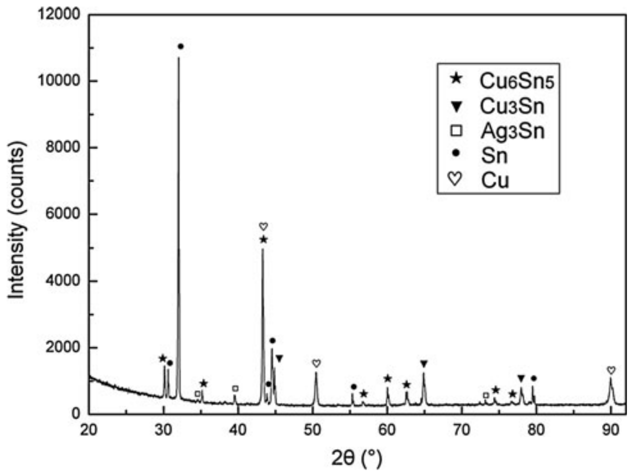

Fig. 5 XRD pattern for interfacial region of a solder joint aged at 125 °C for 360 h

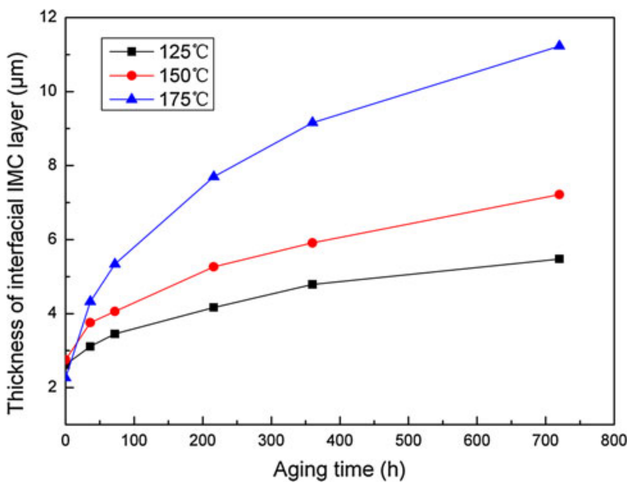

Fig. 6 IMC layer thickness versus isothermal aging time

125 °C for different aging time. The light-gray scallop-like intermetallic regions on the optical micrographs are the IMCs. The phase and element composition of the IMCs was verified by SEM–EDS and XRD analysis. It was found that only Cu_6Sn_5 was formed in the as-soldered samples, and the intermetallic layer was very rough and irregular. During isothermal aging, an increase in the thickness of the IMC layer and a coarsening of the grains were noted. It was noted that, apart from a thickening of the IMC layer, the boundary between the solder and the IMC layer was flattened during isothermal aging. The Cu_3Sn was found in the later stage of isothermal aging, the layer of which, however, was more uniform in its thickness and more planar (see Fig. 9b).

The XRD analysis results showed that there was similar phase composition in interfacial regions of solder joints under different thermal aging conditions. Figure 5 shows the typical XRD pattern for solder joint interfacial region

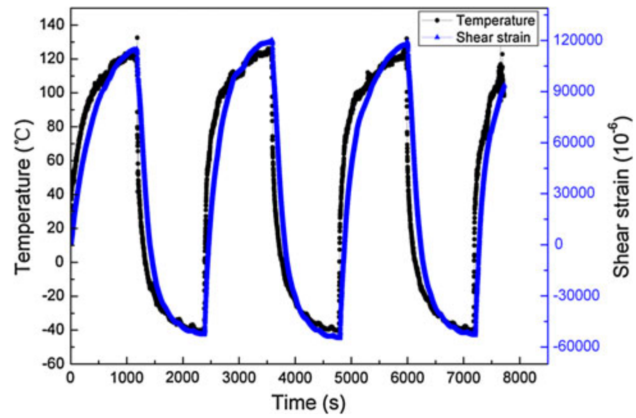

Fig. 7 Shear strains of the first three cycles for the solder joint sample under TMC

of the plan view. The major phase of IMCs turned out to be Cu_6Sn_5 by matching the search with the data from the International Centre for Diffraction Data. Peaks of Cu_3Sn can also be seen, but the intensity is much lower compared to Cu_6Sn_5.

Figure 6 shows the changes in the average thickness of the total IMC layer with isothermal aging time. It is obvious that the thickness of IMC increased with increasing thermal aging time. And higher IMC growth rate was expected for higher aging temperature.

TMC in solder joints has been usually regarded as a thermally induced mechanical process, which would have effect on the atoms diffusion and IMC growth behavior. It has been reported that the IMC growth in solder joints during TMC is a result of both static and strain-enhanced aging. However, the effect of strain-enhanced aging on the IMC layer growth has been hardly presented. To examine this point more closely, the shear strains of the solder joint under TMC was measured, and Fig. 7 shows the shear strains of the first three cycles for the solder joint sample. The accumulative strain per cycle of the solder joint was determined as $\Delta\gamma = 0.353$, which was calculated from the strain data of the third cycle. Meanwhile, the thickness of the interfacial IMC layer in the solder joint for different cycles was measured.

Figure 8 shows cross-sectional morphology of the interfacial zone in Sn3.0Ag0.5Cu/Cu solder joint subjected to TMC aging for 0, 144, 288, 480 cycles. The interfacial Cu-Sn intermetallic layers are located as the light-gray scallop-like regions.

Interfacial IMC growth behaviors under three different thermal aging conditions (isothermal aging, TC and TMC) were compared. Figure 9 shows SEM micrographs of a same magnification for the solder/Cu interface after the three thermal aging conditions, for which the total elapsed time of b, c and d was all 320 h. It is noted from Fig. 9 that

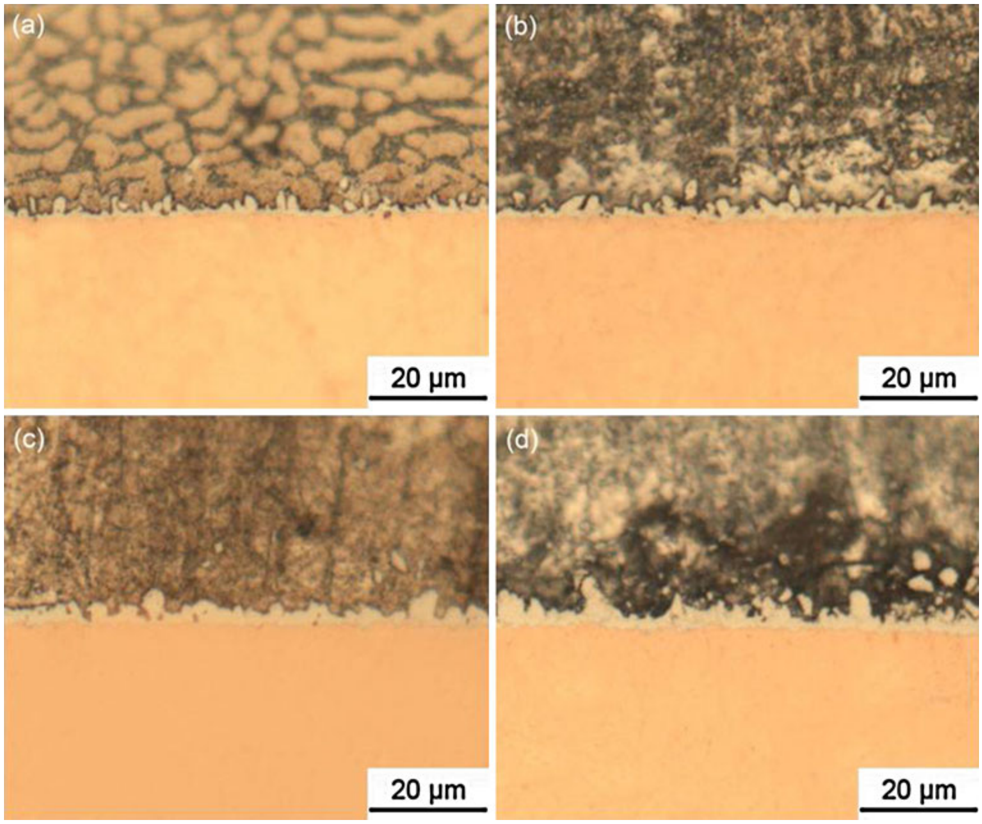

Fig. 8 Cross-sectional micrographs of interfacial zone in Sn3.0Ag0.5Cu/Cu solder joint after different thermomechanical cycles. **a** As soldered, **b** 144 cycles, **c** 288 cycles, **d** 480 cycles

there was spalling behavior of IMC in Sn3.0Ag0.5Cu/Cu solder joints subjected to TC and TMC aging, however, which was not found for isothermal aging condition. The spalling phenomenon was caused by (1) interface structure change and (2) cyclic shear stress- strain induced during temperature cycling [11].

Furthermore, it is interesting to note that there were quite a lot voids in the IMC layer of the solder joint after hundreds of thermomechancial cycles (see Fig. 9c), which is named as Kirkendal voids. Earlier studies reported the formation of kirkendall voids in the Cu-Cu_3Sn interface and Cu-Sn IMC layer when the SnAgCu/Cu solder joint was subject to isothermal aging [12]. In the Cu-SnAgCu solder reaction couple, the diffusing Cu atoms arrive at Cu_3Sn-Cu_6Sn_5 and Cu_6Sn_5-solder interfaces and result in the growth of both IMC layers towards the solder. Because of the unbalanced Cu-Sn interdiffusion through interface, atomic-level vacancies left by the migrating Cu atoms on the bare Cu side are not filled by Sn atoms. These vacancies coalesce into the so-called Kirkendall voids. For as reflowed specimen shown in Fig. 9a, no voids could be seen in the interfacial zone. While after 480 thermomechanical cycles of aging, it can be seen that quite a lot voids formed in the IMC layer. This voiding process seems to be much faster than that of the solder joint subjected to isothermal aging or TC aging.

Figure 10 shows the thickness increments of the total IMC layer corresponding to the conditions of b, c, and d in Fig. 9 respectively. And the comparison result of the IMC thickness in solder joints subjected to isothermal aging exposure at 125 °C and TMC with temperature range of −40 to 125 °C is shown in Fig. 11, the standard of the comparison was based on the same "effective aging time" t_{eff}. Time t_{eff} for isothermal aging is the total aging time, while for TMC or TC aging t_{eff} roughly equals to the total accumulated dwell time at upper soak temperature.

It can be seen from Figs. 10 and 11 that the growth of Cu-Sn IMC under TMC aging was accelerated compared to that of isothermal or TC aging based on the same t_{eff}. This can be contributed to the combined effects of thermal treatment and stress–strain cycling during TMC. The combined effects would lead to crystal lattice distortion and atomic diffusion acceleration, thereby promoting the IMC growth [8, 13]. This is consistent with the phenomenon observed in Fig. 9, since the IMC growth under TMC was accelerated, the corresponding voiding process could be accelerated, too.

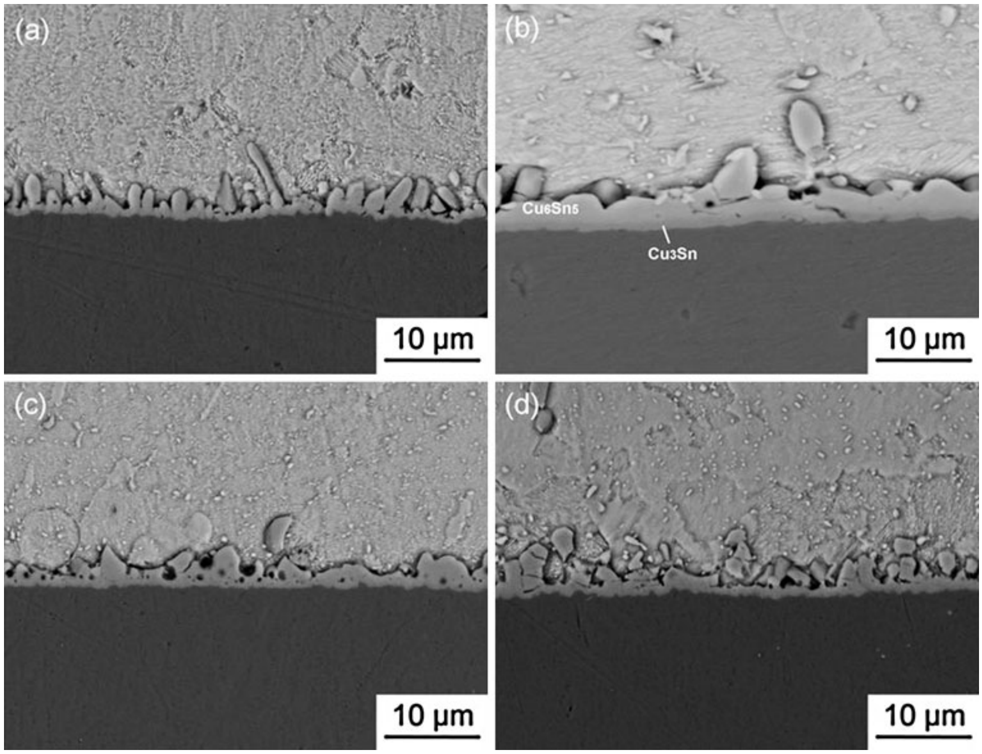

Fig. 9 Cross-sectional micrographs of interfacial zone in Sn3.0Ag0.5Cu/Cu solder joint. **a** As soldered, **b** isothermal aging at 125 °C for 320 h, **c** TMC aging for 320 h (480 cycles), **d** TC aging for 320 h (480 cycles)

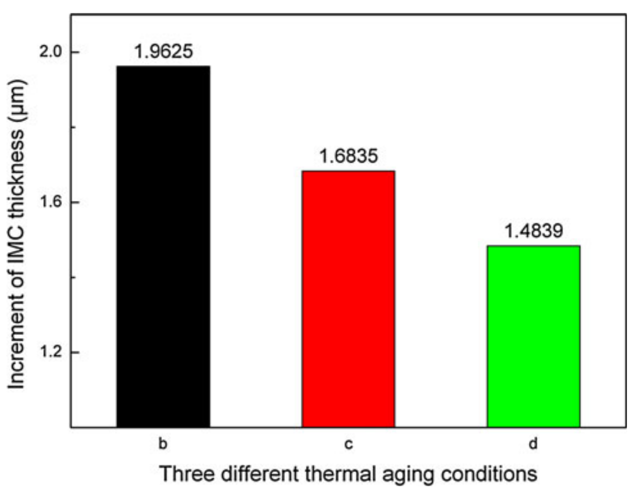

Fig. 10 IMC thickness increments corresponding to the conditions of *b*, *c*, and *d* in Fig. 9 respectively

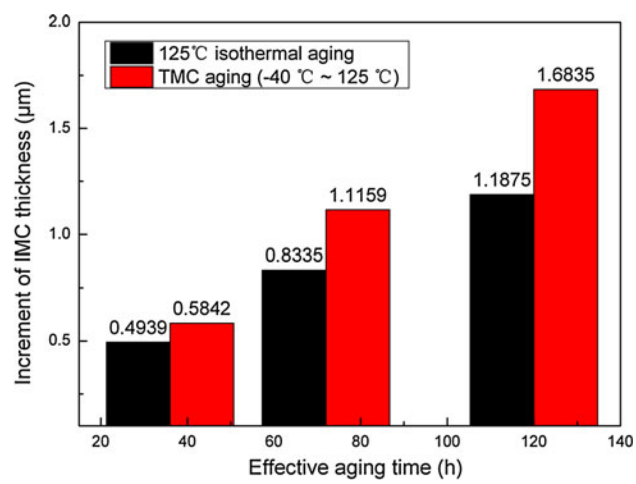

Fig. 11 Comparison of the IMC layer thickness in solder joints subjected to isothermal aging and TMC aging based on the same t_{eff}

3.2 IMC growth kinetic and modeling

3.2.1 IMC growth under isothermal aging

Generally, the IMC growth during the service condition (here after understood as solid state reaction) is controlled by diffusion mechanism, and power law equation as shown in Eq. (1) has been widely used to describe the IMC growth behavior.

$$x = x_0 + At^n \quad (1)$$

where x is the IMC layer thickness at time t, x_0 is the IMC layer thickness under the as-soldered condition, A is growth constant, and n is the time exponent. The temperature dependence of the growth constant A is given by the Arrhenius type equation as.

$$A = A_0 \exp\left(\frac{-Q}{RT}\right) \quad (2)$$

where A_0 is pre-exponential factor, Q is the apparent activation energy, R is the universal gas constant (8.314 J mol^{-1} K^{-1}), T is the absolute temperature. Substituting Eq. (2) into Eq. (1), IMC thickness can be expressed as a function of two variables, time and temperature, such that.

$$x - x_0 = A_0 t^n \exp\left(\frac{-Q}{RT}\right) \tag{3}$$

For isothermal aging condition, the growth kinetics of the IMC layers were assessed by linear regression analysis of the thickness data (as shown in Fig. 6) applied to Eq. (3), which was rewritten as.

$$\ln(x - x_0) = \ln A_0 + n \ln t - \frac{Q}{RT} \tag{4}$$

Figure 12 shows the log plot of the growth kinetics of the interfacial IMC layers during isothermal aging (MKS units). The values of the time exponent n were 0.59 ± 0.030, 0.51 ± 0.018 and 0.49 ± 0.020 for 125, 150 and 175 °C isothermal aging conditions respectively, which indicated that the diffusion process dominated the growth of the IMC layers. In this study, the value of the time exponent n was determined as 0.5 for later kinetic analysis.

Submitting $n = 0.5$ into Eq. (3), then linear regression analysis for $(x - x_0)$ against $t^{0.5}$, and $\ln A$ against $1/T$ were used to determine A_0 and Q, as shown in Figs. 13 and 14 (MKS units).

Based on the data analysis above, the apparent activation energy Q was determined as 33.1 kJ mol^{-1} and the pre-exponential factor A_0 was 3.83×10^{-5} ms$^{-1/2}$. Then the IMC thickness was expressed as (MKS units).

$$x - x_0 = 3.83 \times 10^{-5} \sqrt{t} \cdot \exp\left(\frac{-33.1 \times 10^3}{RT}\right) \tag{5}$$

The parameters of IMC growth kinetic obtained from isothermal aging are useful in formulating an IMC growth model for TMC aging condition, and which is deduced in section II.

3.2.2 IMC growth under TMC aging

It is noteworthy that Eq. (5) can be conveniently applied to the description of IMC growth behavior under isothermal aging, for which aging temperature is constant over aging time. However, the IMC growth kinetic analysis for TMC or TC aging is not as simple as that for isothermal aging because the diffusivity of elements through the IMC layer is temperature and time dependent during TMC.

Vianco et al. [3] studied the isothermal and TC aging behavior of Sn37Pb/Au-Pt-Pd thick film couples. They proposed an empirical relationship to find out the "equivalent aging time", which is defined as one-half of the TC time, at "equivalent isothermal aging temperature" corresponding to the temperature range of TC. Pang et al.'s

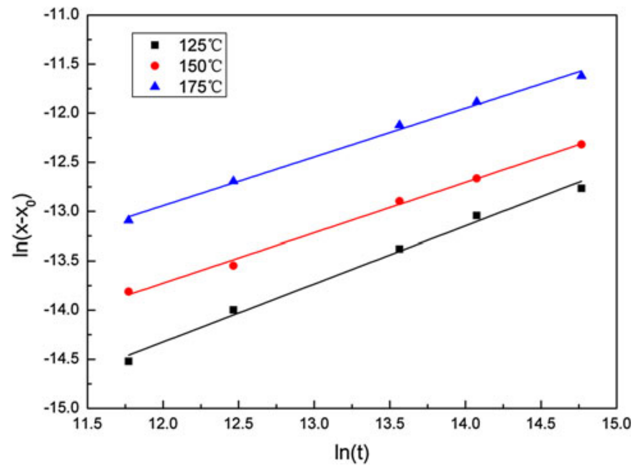

Fig. 12 Log plot of the growth kinetics of IMC layers at Sn3.0Ag0.5Cu/Cu solder joint interfaces during isothermal aging

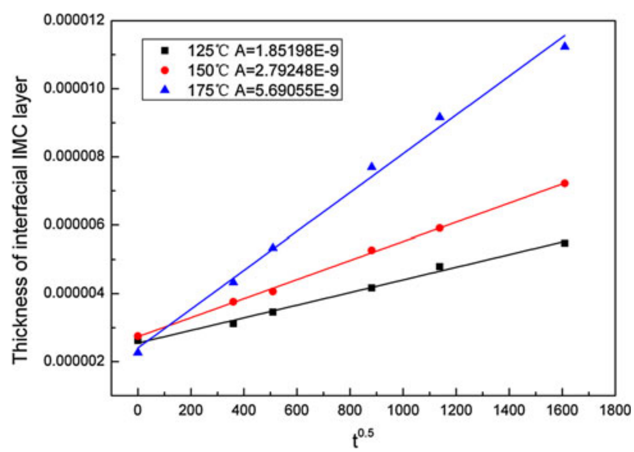

Fig. 13 IMC thickness versus square root of aging time

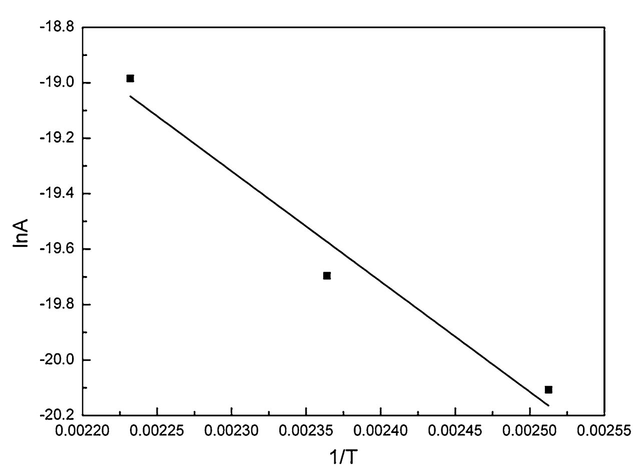

Fig. 14 Arrhenius plot for the growth of IMC during isothermal aging

Table 1 Summary of IMC growth kinetic constants for SnAgCu/Cu solder joint

Constant	Value
n	0.5
A_0	3.83×10^{-5} ms$^{-1/2}$
Q	33.1×10^3 J mol^{-1}
φ	1
N	3.133×10^3 s

research result show that the growth rate of IMC at lower temperatures (<70 °C) is much slower than that at higher temperatures (>125 °C), and at temperature below 50 °C, an immeasurably slow growth rate of IMC was expected [14]. Xu [4] compared the IMC growth rate when solder joints were subjected to isothermal aging and TC, and proposed a simplified model for IMC growth behavior under TC aging, such that.

$$x - x_0 = A_0 t_{eff}^n \exp\left(\frac{-Q}{RT}\right) \quad (6)$$

where t_{eff} is "effective aging time", which equals to the total accumulated dwell time at upper soak temperature, n, Q and A_0 can be determined via isothermal aging tests, see section I.

Vianco's and Xu's researches have given some insight about the interfacial IMC growth kinetic into TMC effects. However, the effect of stress–strain cycling on the IMC growth under TMC was not presented. Dutta et al. [13, 15] proposed an equation of coarsening kinetic for IMC particles in the solder substrate under isothermal aging and TMC, which would offer reference for the growth kinetic analysis of interfacial IMC. It is identified that, compared to that of isothermal aging condition, the stress/strain generated in the solder joint during TMC will result in strain enhanced aging, which would promote the interfacial IMC growth.

Based upon above analysis, in order to correlate IMC growth behavior between isothermal and TMC effects, the interfacial IMC growth kinetic under TMC aging may be derived as follows.

$$x - x_0 = A_0 t^n \exp\left(-\frac{Q}{RT}\right) \quad (7a)$$

$$= A_0 t_{eq}^n \exp\left(-\frac{Q}{RT_{top}}\right) \quad (7b)$$

$$= A_0 \left(t_{eff} + \Delta t\right)^n \exp\left(-\frac{Q}{RT_{top}}\right) \quad (7c)$$

$$= A_0 \left(t_{top} m + 2N\varphi\dot{\gamma} t_{ramp} m\right)^n \exp\left(-\frac{Q}{RT_{top}}\right) \quad (7d)$$

$$(7)$$

The values of the parameters n, A_0 and Q were determined from isothermal aging tests. In Eq. (7), t_{eq} is defined as "equivalent aging time", which is proposed for correlating IMC growth behavior between isothermal and TMC effects; t_{eff} is "effective aging time", the definition of which is the same as that of Eq. (6); t_{top} is the dwell time at upper soak temperature during one cycle; m is number of elapsed cycles; T_{top} is the upper soak temperature of the TMC; t_{ramp} is the up or down ramp time during one cycle; and Δt represent the strain enhanced aging effect on IMC growth during TMC.

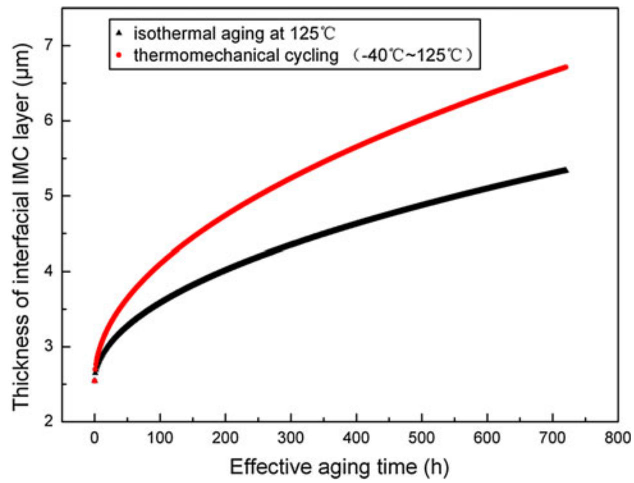

Fig. 15 IMC thickness versus "effective aging time" predicted by Eq. (7)

It is well known that phase coarsening may be greatly accelerated when deformation is superimposed on temperature because of enhanced diffusion caused by the increased vacancy concentration induced by plasticity [16]. The term Δt in Eq. (7c), therefore, needs to be replaced by an appropriate stress/strain history-dependent function, such that $\Delta t = 2N\varphi\dot{\gamma}t_{\mathrm{ramp}}m$ [13], in which $\dot{\gamma}$ is the shear strain rate imposed on the joint during TMC; φ is the ratio of plastic strain to total strain imposed during the ramp; the term $2\varphi\dot{\gamma}t_{\mathrm{ramp}}$, represents the accumulative inelastic strain during one cycle (the value can be calculated from Fig. 6 as that $2\varphi\dot{\gamma}t_{\mathrm{ramp}} = 0.353$; N is a kinetic constant representing strain-enhanced aging that scales the vacancy concentration to $\dot{\gamma}$, the value of which can be estimated from a series of IMC thickness data subjected to TMC for different cycles, since t_{top}, t_{ramp}, n, T_{top} and $\dot{\gamma}$ are known for a given TMC condition, and $\varphi \approx 1$.

Note that for $\dot{\gamma} = 0$, $(x - x_0)$ represents the IMC growth caused by static aging only, whereas when $\dot{\gamma} \neq 0$, IMC growth includes contributions caused by both static and strain-enhanced aging. Table 1 lists the values of the parameters in Eq. (7) calculated by analyzing the IMC growth data under isothermal and TMC aging conditions.

Figure 15 shows the IMC thickness changes for isothermal and TMC aging conditions, predicted by Eq. (7), with "effective aging time". It can be seen that the growth

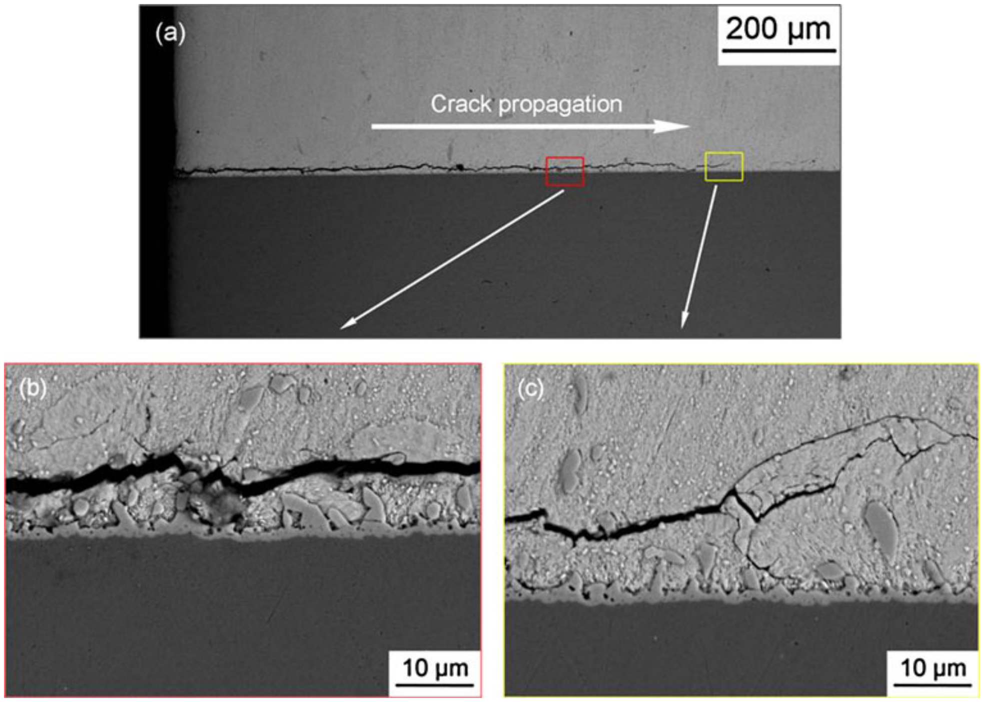

Fig. 16 Crack profile of the solder joint sample under TMC

of interfacial IMC under TMC was accelerated compared to that under isothermal aging based on the same "effective aging time", the trend of which reflected was the same with that of the experimental results indicated (see Fig. 11). As a result, with the determined n, Q, A_0 and N from isothermal aging and TMC, the thickness of interfacial IMC layer in SnAgCu/Cu solder joint after any isothermal aging time or thermomechanical cycles could be predicted by Eq. (7).

3.3 TMC failure of the solder joint

TMC affected solder joint fracture in two divergent ways. First, it caused a thicker, albeit less topographically rough, IMC layer. The thicker layer promoted brittle fracture, degrading the joint property [5]. On the other hand, aging softened the solder [17], allowing the crack to propagate through the solder more easily. As shown in Fig. 16, examination of the crack profiles under TMC revealed that, the majority of the crack path in the solder joint was close to the interface. As there was cyclic shear loading imposed on the solder joint sample which was induced by the CTE mismatch between the bimetallic bars during temperature cycling, presence of constraints in the solder/IMC layer tends to accumulate damage in this region. Moreover, a thicker IMC layer caused by TMC would result in greater constraint effect in the solder/IMC bonding zone, thus accelerating the interfacial zone failure of the solder joint [18].

Since the catastrophic crack that affects the reliability of solder joint occurs in solder region close to the solder/IMC interface, important features in this region is presented specially in Fig. 16b, c. Although IMC layer is considered to be mechanically brittle compared to the other entities present in the solder joint, thermomechanical fatigue induced catastrophic crack formation was not observed to occur within this layer. However, the catastrophic crack formed about one-grain diameter away from the solder/IMC interface. The location of this catastrophic crack can be attributed to the stress concentration resulting from the constraints of the IMC layer and the preferred orientation of Sn grains adjacent to the solder/IMC layer interface [19]. The latter can result in significant stresses from CTE mismatches at the grain boundaries present at about one-grain diameter away from the solder/IMC interface; while the former would intensify stress concentration, thus accelerating crack propagation. Because of the constraints and internal stress build-up, the catastrophic crack develops ultimately here. On the other hand, in regions away from this interface, internal stresses that develop, irrespective of their magnitude, are dissipated away by grain boundary sliding and decohesion.

4 Conclusions

In this study, the intermetallic compound (IMC) growth behavior at SnAgCu/Cu solder joint interface under different thermal aging conditions was investigated, with the aims focused on the exploration of the influences of thermal and stress/strain on the growth kinetics of IMC as well as the solder joint failure behavior. The following conclusions can be drawn from the current study:

The IMC growth rate increased with isothermal aging temperature, and growth of interfacial IMC in solder joint subjected to TMC was a result of both static and strain-enhanced aging. IMC growth for TMC was accelerated compared to that of isothermal aging based on the same "effective aging time".

A methodology for predicting the interfacial IMC growth behavior for long-term thermal aging was developed. The IMC growth model proposed here is fit for predicting the thickness of interfacial IMC layer in SnAgCu/Cu solder joint after any isothermal aging time or thermomechanical cycles.

The interfacial zone was the weak link of the SnAgCu/Cu solder joint, and the interfacial IMC growth had important influence on the thermomechanical fatigue fracture of the SnAgCu/Cu solder joint.

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