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TECHNICAL PAPER

Assessment of the Performance of Sn–3.5Ag/Cu Solder Joint Under Multiple Reflows, Thermal Cycling and Corrosive Environment

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Abstract The solder joint performance of Sn–3.5Ag/Cu combination was studied under multiple reflows, thermal cycling and exposure to the corrosive environment. Factorial experiment was carried out to assess the effect of individual parameters and the interaction of parameters on the shear strength of the solder joint. The results showed that the combination of thermal cycling and immersion in corrosive media resulted in the maximum decrease in the shear strength followed by the combination of multiple reflows and corrosive media. The shear strength reduced with the increase in immersion duration in corrosion medium. Factorial experiment was analyzed using analyis of variance (ANOVA). The results indicated that the individual parameters had a significant effect, whereas the effect of interaction of these parameters was less significant on the performance of the solder joint. Fracture surface indicated mixed mode of failure and the occurrence of fracture predominantly in the bulk solder.

Keywords Multiple reflows · Thermal cycling · Corrosive medium · Shear strength

1 Introduction

The reliability of the solder joint is crucial in the electronics industry. It is practically assessed by its ability to sustain the service environment. The service environment includes multiple reflows, temperature extremes, mechanical shocks, frequent power on/off cycles, corrosive environment, etc. [1, 2]. Research work so far has been carried out by considering the effect of any one of the environmental factors on the reliability of the solder joint. In a practical scenario, solder joints are often subjected to a combination of two or more factors which degrade the properties of the joint faster than expected. In the present study, the joint shear strength of Sn–3.5Ag lead-free solder alloy was assessed under the conditions of multiple reflows, thermal cycling and the corrosion medium.

2 Materials and Methods

Spherical balls of Sn–3.5Ag lead-free solder (Alfa Aesar, USA) weighing approximately 0.08 g were used in the present study. Mirror-polished bare copper substrates (Cu) of dimension, ϕ12.5 mm × 8 mm were used. The average surface roughness (R_a) of the substrates was maintained at 0.018 μm throughout the study. The optimum reflow time, i.e., the time corresponding to the end of gravity regime (T_{gz}) [3], for Sn–3.5Ag solder reflowed on Cu substrate was measured using the dynamic contact angle analyzer (FTA 200). Sn–3.5Ag/Cu solder joints were prepared at the reflow temperature of 260 °C for the reflow time of T_{gz}. A set of solder joint samples were subsequently reflowed for ten reflow cycles using reflow oven (Infrared IC Heater, T962) by following the thermal reflow profile shown in Fig. 1. Another set of solder joint samples were subjected to thermal cycling for ten cycles using the thermal cycling profile shown in Fig. 2. The heating and cooling cycles in thermal cycling experiments were performed using a muffle furnace and liquid nitrogen, respectively. The solder joints were thereafter immersed in 0.1 N HCl solution and

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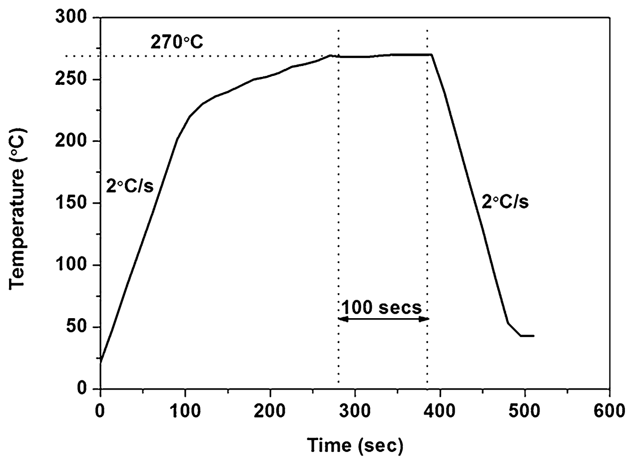

Fig. 1 Thermal profile of multiple-reflow process

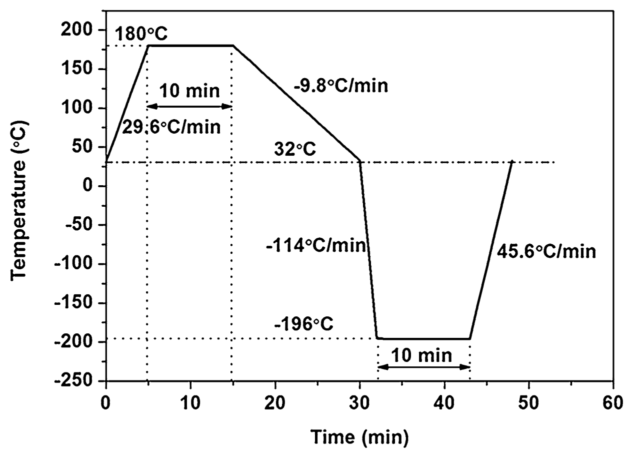

Fig. 2 Thermal profile of thermal cycling process

seawater for 12, 24 and 240 h, respectively. The growth of the interfacial intermetallic compounds (IMC) was examined under a scanning electron microscope (SEM, JEOL JSM 6380LA). The shear test was performed on reflowed solder ball samples using Nordson DAGE 4000Plus bond tester. The shear tool height of 0.5 µm from the substrate surface and shear speed of 200 µm/s were used in the experiment. Fracture surfaces were analyzed using SEM.

3 Results and Discussion

3.1 Measurement of T_{gz} for Sn–3.5Ag Solder

The spreading of Sn–3.5Ag solder on the Cu substrate is depicted as the decrease in contact angle of the molten solder with respect to the reflow time as shown in Fig. 3. T_{gz} for Sn–3.5Ag solder alloy was measured to be 60 s. Solder joints reflowed for this reflow time resulted in the formation of a very thin interfacial intermetallic compounds IMC and showed maximum bond strength [3].

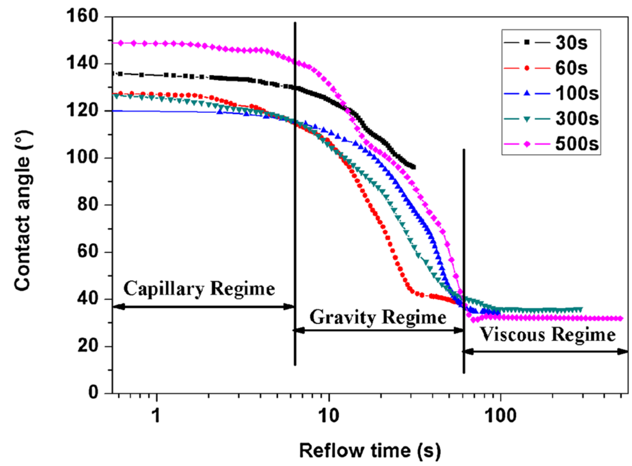

Fig. 3 Plot showing relaxation behavior and various regimes involved during spreading of Sn–3.5Ag solder on bare Cu substrate at 260 °C for various reflow times

3.2 Interfacial Microstructure

Figure 4 shows the interfacial microstructure of as-reflowed, thermal-cycled and multiple-reflowed Sn–3.5Ag/Cu solder joints. The as-reflowed solder joint yielded a very thin layer of Cu_6Sn_5 IMC with the average thickness of 1.37 µm at the interface having the scallop morphology. The IMC thickness of solder joint subjected to ten thermal cycles was found to be about 1.46 µm, and the morphology remained unchanged. No significant increase in IMC thickness was observed since thermal cycling was performed only for ten cycles with a short dwell period at 180 °C. However, the Ag_3Sn IMC was refined from coarse globular form to superfine spheroidal shape in the bulk solder with thermal cycling. Multiple reflows resulted in a thick and uniform Cu_6Sn_5 IMC layer formation with the average thickness of 1.57 µm. The coarsening of Ag_3Sn IMC in the bulk matrix was observed with multiple reflows. The interfacial IMC region of the solder joints immersed in corrosive media remained unchanged irrespective of the immersion duration used in this study, indicating that the corrosion had occurred only on the surface of the bulk solder.

3.3 Bond Shear Strength

Ball shear test was used to assess the shear strength of the solder joints after subjecting them to multiple reflows, thermal cycling and corrosive media. The joint strength under different environments is represented in Fig. 5a–c. The percentage reduction in the shear strength was calculated with respect to the shear strength of the as-reflowed solder joint. The reduction in shear strength due to multiple reflows could be attributed to the growth of interfacial Cu_6Sn_5 IMC layer and coarsening of Ag_3Sn IMC in the

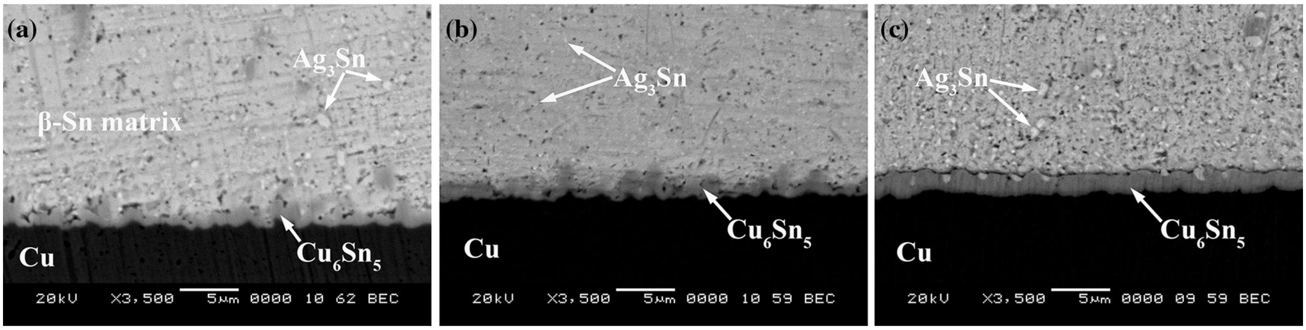

Fig. 4 Interfacial microstructure of Sn–3.5Ag/Cu solder joint reflowed for 60 s at 260 °C, **a** as-reflowed, **b** after ten thermal cycles and **c** after ten reflow cycles

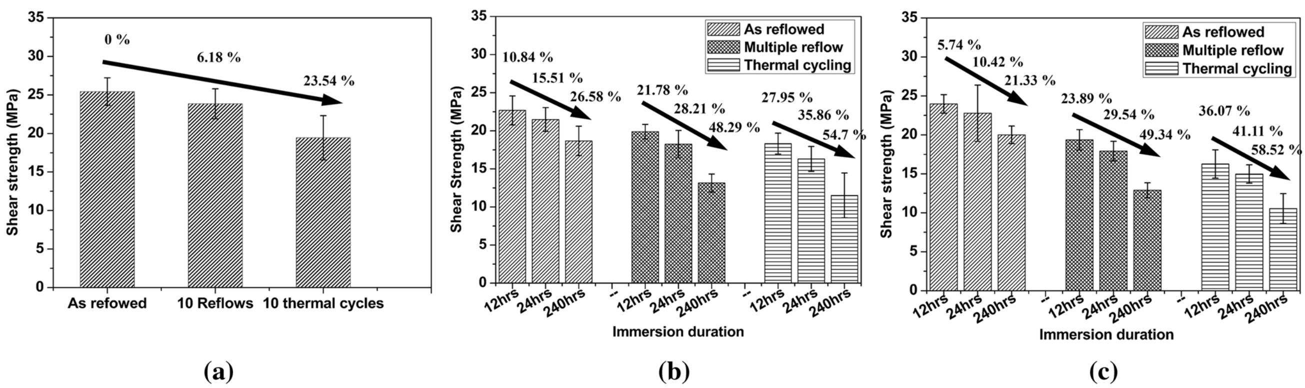

Fig. 5 Comparison of shear strength of solder joint subjected to **a** multiple reflows and thermal cycling, **b** immersed in 0.1 N HCl for various durations and **c** immersed in seawater for various durations

bulk solder which increased the brittleness of the joint. The maximum decrease in shear strength was observed for the thermal-cycled solder joints. The decrease in shear strength could be attributed to the thermal stresses that evolved due to the difference in the coefficient of thermal expansion (CTE) of the bulk solder, IMC layer and substrate leading to evolution of thermal strain in the joint [4]. During thermal cycling, the Ag_3Sn IMC was spheroidized into finer spheroids which enhanced the ductility of the solder bulk [5]. Corrosive medium dissolved the Sn-rich phase from the bulk solder and formed corrosive products. Dispersed Ag_3Sn IMC in the Sn matrix got washed away easily, leaving corroded pits on the surface of solder bulk [6]. These corroded pits served as weak spots for initiation of cracks during the shear test. As the immersion duration in corrosion medium increased, these corroded pits were found to grow into the bulk solder which further reduced the shear strength.

3.4 Factorial Experiment

The analysis of the various parameters affecting the shear strength of the solder joint was performed using a factorial experiment to assess the effect of individual parameters as well as interaction of the parameters. The shear strength was taken as the dependent variable. The independent variables included thermal treatment (A) with three levels, viz. as-reflowed, ten reflows and ten thermal cycles; corrosion medium (B) with three levels, viz. no medium, 0.1 N HCl and seawater; and immersion duration (C) with four levels, viz. 0,12, 24 and 240 h. The results of factorial analysis are shown in Table 1. The results showed that the individual parameters, viz. A, B, C, and the interaction parameter BC had significant effect on the reduction of the shear strength since these parameters were significant at the significance level of 1%. The interaction parameter AB was significant at a significance level of 5%, indicating its effect at a lower level. The interaction of all three parameters ABC was significant at 10%, indicating a very mild effect on the shear strength.

3.5 Fracture Surface Analysis

The SEM micrographs of the fractured surface of the solder joint are shown in Fig. 6. The fracture surface exhibited a mixed mode of failure. The fracture propagated from the bulk solder to the brittle Cu_6Sn_5 IMC at the interface. Shear marks on the fractured surface indicated the occurrence of

Table 1 Analysis of variance (ANOVA) table

Source of variation	Sum of squares	Degree of freedom	Mean square	F ratio (F_o)	F distribution value	Remark
Thermal treatment (*A*)	192.99	2	96.5	23.8	$F_{0.01,2,36} = 5.26$	Significant at $\alpha = 1\%$
Corrosion medium (*B*)	914.77	2	457.38	112.80	$F_{0.01,2,36} = 5.26$	Significant at $\alpha = 1\%$
Immersion duration (*C*)	371.22	3	123.74	30.51	$F_{0.01,3,36} = 4.39$	Significant at $\alpha = 1\%$
AB	51.21	4	12.80	3.16	$F_{0.05,4,36} = 2.64$	Significant at $\alpha = 5\%$
AC	26.81	6	4.47	1.10	$F_{0.1,6,36} = 1.95$	Insignificant
BC	5018.982	6	836.5	206.3	$F_{0.01,6,36} = 3.362$	Significant at $\alpha = 1\%$
ABC	90.04	12	7.50	1.85	$F_{0.1,12,36} = 1.73$	Significant at $\alpha = 10\%$
Error	145.98	36	4.05	1		
Total	6812.01					

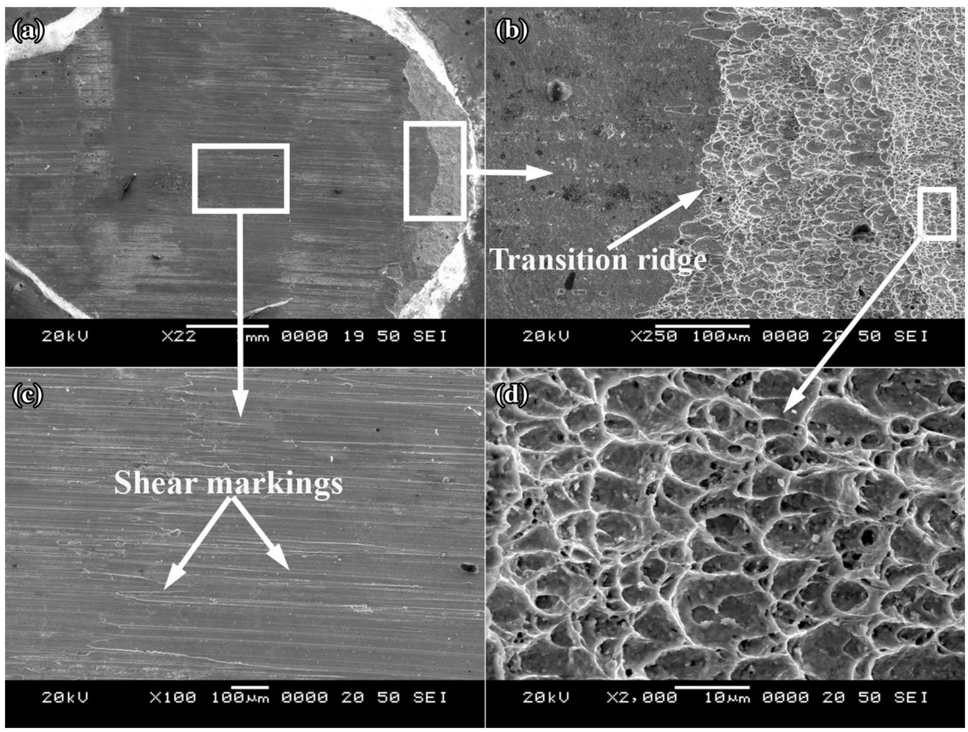

Fig. 6 **a** Fractured surface of the Sn–3.5Ag/Cu solder joint, **b** enlarged part showing transition ridge, **c** ductile fractured area showing shear markings and **d** enlarged view of brittle fractured area

pure ductile failure predominantly in the bulk solder. During the shear test, higher stresses were concentrated at the end of the reflowed solder drop. This was due to the increasing back stress evolved by work hardening of the solder alloy during the shear test. Therefore, the deformation could be clearly seen at one of the edges of fractured surfaces where the shear tool had stopped after the test. The deformed region at the right end of the fracture surface indicated the occurrence of brittle fracture through the interface. The fracture through the bulk solder and the interface was separated by a transition ridge. The solder joints subjected to multiple reflows, thermal cycling and corrosive environment showed similar type of mixed mode of failure with predominantly ductile failure in the bulk.

4 Conclusion

Based on the study of assessment of the performance of Sn–3.5Ag/Cu solder joint under multiple reflows, thermal cycling and corrosive environment, the following conclusions were drawn:

- The optimum reflow time (T_{gz}) for the Sn–3.5Ag solder reflowed on the copper substrate was found to be 60 s.
- The combination of thermal cycling and immersion in corrosion medium showed maximum reduction in the shear strength of the solder joint followed by multiple-reflowed and as-reflowed solder joint with immersion in corrosion medium.

- The solder joints immersed in seawater showed a greater reduction in shear strength compared to that with 0.1 N HCl solution.
- The analysis of variance (ANOVA) indicated significant effect of thermal treatment, corrosion medium and immersion duration in corrosion medium on the shear strength of the solder joint at 1% significance level. However, the interaction of the three parameters was significant only at 10% level of significance.
- Fracture analysis indicated that the fracture propagated from the bulk solder to the brittle Cu_6Sn_5 IMC at the interface exhibiting a mixed mode of failure.

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