Effect of Multiple Reflow Cycles on Intermetallic Compound Creation

Václav Wirth, Karel Rendl, and František Steiner

Department of Technologies and Measurement, Faculty of Electrical Engineering,
University of West Bohemia, Pilsen, Czech Republic
vwirth@ket.zcu.cz

***Abstract**: This paper deals with the effect of the solder profile and multiple reflow cycles on intermetallic compound (IMC) creation. Soldered joints between PCB and 1206 size chip resistors were made from SAC 305 or SnBi solder alloy. Samples were reflowed one to six times with one of the two different soldering profiles for each soldering alloys. The thickness and composition of IMC layers were measured and observed with a scanning electron microscope. The growing of IMC layers thickness was observed. The results are presented depending on greater value of heating factor and number of reflow cycles. The shear forces for the components were measured and the fracture interfaces were inspected.*

1. Introduction

Soldering is the most common technology used for conductive connection of components in the electronic packaging. Eutectic Sn-Pb alloy was often use for soldering. Due to the Legislative Regulation, lead-free solder alloys are currently used. Several solder alloy systems have been preferred as alternatives for Sn-Pb solder. Binary systems Sn-Ag, Sn-Cu, Sn-Bi or Sn-Zn are commonly used. Next elements are often added to improve characteristics (e.g. melting point, wettability, and microstructure). Their use has some differences from the use of classical lead solder. Especially, there is the need to increase the temperature of reflow for soldering alloys. Solder alloys with high content of bismuth are the exception. These alloys have lower melting points than the lead solder alloys. Reflow profile affects the formation of a solder joint and its structure. On the interface of jointed surface and solder, a layer of intermetallic compound (IMC) is formed. This layer significantly affects characteristic of a solder joint. On the one hand, it ensures higher mechanical strength of a joint and IMCs are much more fragile than a solder thereby reduce the lifetime of a solder joint on the other hand. The increasing complexity and miniaturization of components and PCBs makes it impossible to produce product with solder joints which go through a single reflow. Solder joints further evolve during the next reflows. The thickness of the IMC layers should increase and it can affect reliability of the solder joints [1]. The article is devoted to the effect of multiple reflow cycles on IMC creation and mechanical properties of a soldered joint.

2. Intermetallic Compounds

Intermetallic compound is composed of definite proportions of two or more elemental metals. Due to their mechanical and physical properties, intermetallic compounds are specific. IMC layers significantly affect mechanical and electrical properties of the solder joints [2]–[4]. A large number of studies have been informed about the microstructure and creation interfacial IMC during soldering and ensuing solid-state aging process. In case of using tin-rich solder and copper as the base material of the conductive layer of PCB, it will create Cu_6Sn_5 intermetallic compound. Thermal aging effect creates the second Cu_3Sn IMC and significantly decreases the mechanical properties of solder alloys [5].

It is possible to influence the IMC creation by proper solder profile selection. Specifically, the time above the melting point during soldering and reflow temperature is concerned. Heating factor parameter ($Q\eta$) is defined as integral of temperature T(t) above the melting point of solder alloy [6], see Formula 1. Where, T_m expresses the melting temperature of used solder alloy. Graphically demonstrated meaning of the formula, the area above the melting temperature of SAC305 solder alloy is shown in Figure 1. This factor includes both soldering profile influences. There are already a number of studies concerning the IMC formation and growth with thermal aging, but a limited number of studies were focused on the effect of multiple reflow cycles and lead-free solders.

$$Q_\eta = \int_{t_1}^{t_2} [T(t) - T_m] \; dt \qquad (1)$$

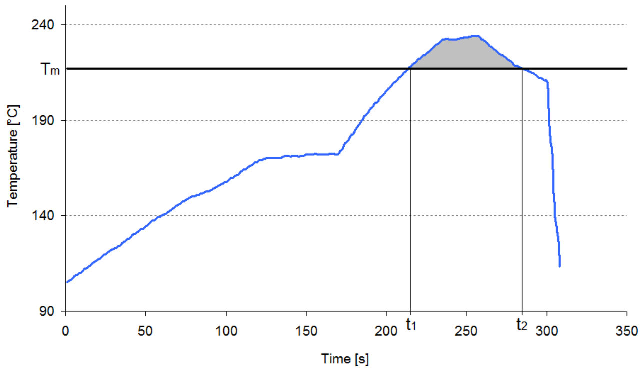

Fig. 1. Soldering profile with designated Q_η

3. EXPERIMENTAL PROCEDURES

The weight percent composition of solders used in this experiment were 58% Bi-42% Sn (SnBi) and 96% Sn-3% Ag-0.5% Cu (SAC305). The melting point of SnBi solder is 139 °C. The second alloy SAC305 has the melting point 218 °C. Solders were used in the form of solder paste with particle size of 25–45 µm and flux content 10% (SnBi) and 11.5% (SAC305). The pastes were put on soldering pads with a stencil printing.

PCBs without surface finish were used to make test samples. The PCBs just with clean copper surface were used. The size of each PCB was 50 mm x 25 mm. On one side, there were made soldering pads for ten SMD chip packages, see Figure 2. Chip resistors of 1206 size were placed to solder paste on each PCB.

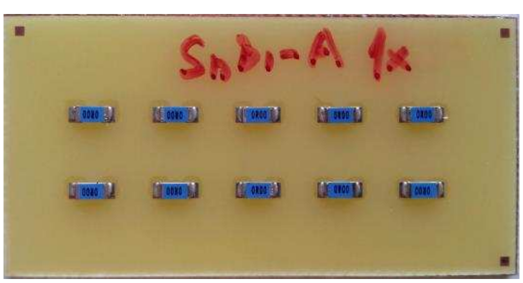

Fig. 2. PCB with ten 1206 chip components

Table 1. Reflow oven setup

Profile	Preheat zone 1 [°C]	Preheat zone 2 [°C]	Reflow zone [°C]	Belt speed [cm/min]
SAC-A	150	220	270	35
SAC-B	150	220	270	29
SnBi-A	110	120	185	53
SnBi-B	110	120	185	44

The two reflow profiles were chosen for each solder alloys. Soldering profiles are described by values of heating factor. "A" profiles have value of Qη about 250 s°C and Qη value of "B" profiles is 500 s°C. A small convection oven with three heating zones was used for samples reflow. Different values of heating factor were reached by conveyor belt speed change. The setup of reflow oven is shown in Table 1. Temperature during each reflow cycle was measured and recorded every second. From measured waveform, Qη value was calculated according to Formula 1. The profiles are shown in Figure 3. The PCBs were reflowed one, two, four or six times with one profile. Two PCBs were made for each number of cycles, each solder alloys and both profiles (32 pieces of PCB and 320 pieces of component in total). The PCBs were marked labels. The label is composed of solder alloy tag (SnBi or SAC), soldering profile letter (A or B) and number of reflow cycles (1x, 2x, 4x or 6x).

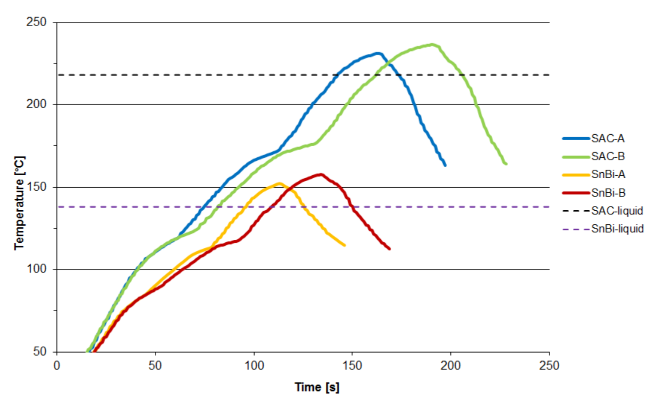

Fig. 3. Soldering profiles and melting points of solder alloys

After that metallographic cross-sections were created from the samples. Four components of each group were used for it. The rest of components (16 pieces) were used for shear test. Confocal Laser Scanning Microscope was used for solder/copper interface scanning. Also, IMC thickness was measured by this microscope. The layer was measured on 10 spots for each image and average values were consequently calculated. The element identification of IMC layers was observed with Phenom ProX scanning electron microscope (SEM).

Principal of mechanical strength measurement is shown in Figure 4. LabTest 3.030 was used. Settings of the device was as follows: feedrate of tear tool – 20 mm/min, return of jaws – 200 mm/min, criterion of test end when reaching 70 % of maximal force (F_{max}). For each kind of tested sample there were measured 16 values of maximal force during testing. These values were consequently statisticly processed.

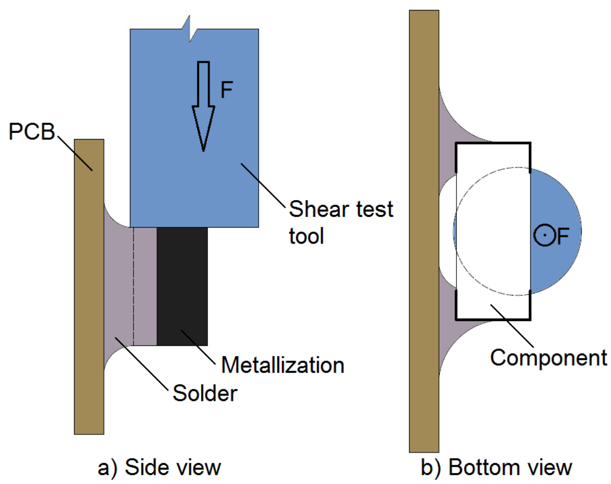

Fig. 4. Principle of shear test

4. RESULTS AND DISCUSSION

The microstructure of the solder joints were observed with the number of reflow cycles. Compositions of microstructures were observed with SEM for both solder alloys. Figure 5 shows SEM picture of SnBi-A 6x sample and Table 2 contains elements analysis. Cu_6Sn_5 IMC is formed on interface solder/Cu.

Table 2. SnBi-A 6x sample elements analysis

Atomic Concentration	Cu [%]	Sn [%]	Bi [%]
Spot 1	100	-	-
Spot 2	49.3	50.7	-
Spot 3	-	-	100
Spot 4	-	92.9	7.1

The interface between Cu and SAC solder consists of very thin Cu_3Sn layer and Cu_6Sn_5 layer. The microstructure of SAC-A 6x solder joint is shown in Figure 6. Table 3 describes concentrations of elements in Figure 6. Cu_6Sn_5 and Ag_3Sn IMCs are formed in solder mass [7]. The fifth spot concentration does not correspond with Ag_3Sn. The size of this IMC is small for electron beam of SEM and surroundings include tin.

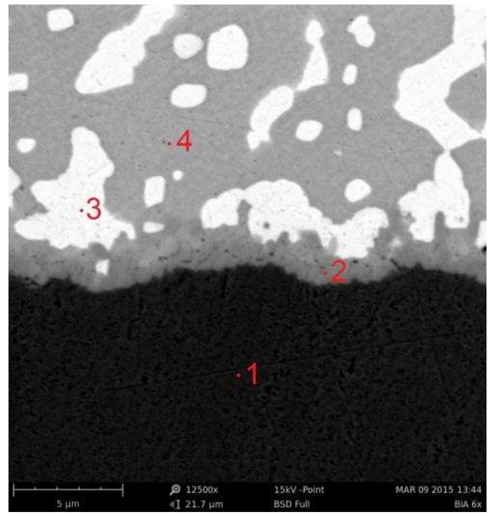

Fig. 5. SEM picture of SnBi-A 6x

Table 3. SAC-A 6x sample elements analysis

Atomic Concentration	Cu [%]	Sn [%]	Ag [%]
Spot 1	100	-	-
Spot 2	69.2	30.8	-
Spot 3	51.8	48.2	-
Spot 4	49.6	50.4	-
Spot 5	-	72.2	27.8
Spot 6	-	100	-

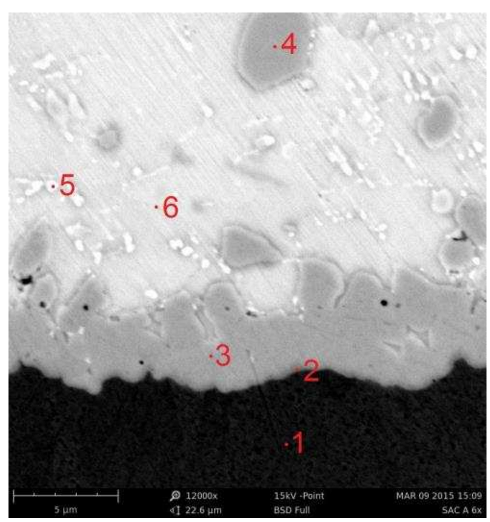

Fig. 6. SEM picture of SAC-A 6x

The composition of the IMC layer was not changed, but the thickness increased with rising value of heating factor and number of reflow cycles. The measured IMC is Cu_6Sn_5; for Cu_3Sn it has not recorded measurable thickness. This layer would be probably created during joint aging. The influence of reflow cycles on the IMC thickness is observed in Figures 9. The growth of IMC layer is approximated with linear function. The IMC layer grows faster with "A" soldering profiles. Difference between "A" profile and "B" is negligible for SnBi solder alloy. IMC layer of SAC solder alloy is thicker than layer of SnBi solder.

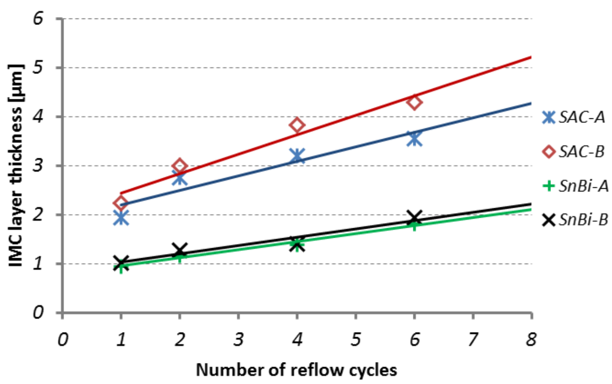

Fig. 9. Variation of IMC layer thickness during multiple reflows

The thickness of IMC layer is shown as a function of heating factor in Figure 10. The value of heating factor is calculated as multiple of Qη number. "A" profiles have Qη value 250 s°C and Qη value of "B" profiles is 500 s°C. IMC layers are thicker with profiles A than profiles B at the same Qη value.

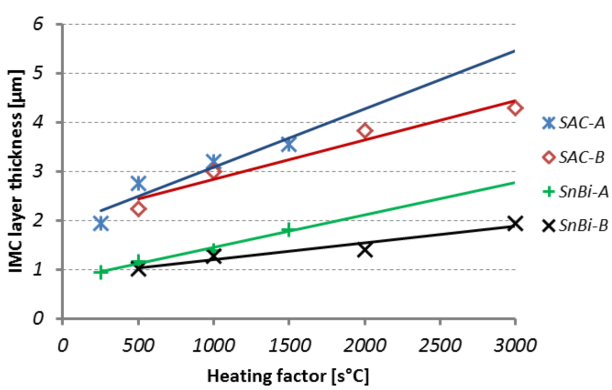

Fig. 10. Thickness of IMC layers as a function of heating factor value

The maximal force required to tear-off a component from the PCB was recorded during the mechanical shear strength test. The reached values were statistically analysed and the results can be seen in Figures 11 and 12. Red dots indicate the average values.

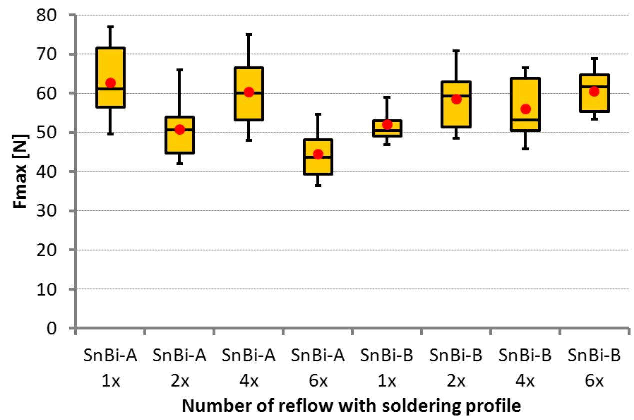

Fig. 11. Boxplot of maximal shear force with SnBi solder alloy

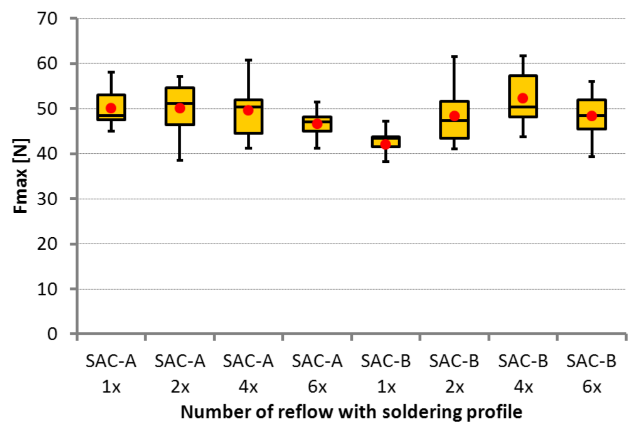

Fig. 12. Boxplot of maximal shear force with SAC solder alloy

The shear force did not vary greatly with the number of reflow cycles. This means that the growth of IMC layer did not affect the maximal force. The shear test tool broke the terminal off the component and it limits maximal force required to tear-off a component. SnBi samples had greater mechanical strength than SAC thanks to smaller heat stress of components during SnBi reflow soldering. The metallization of new component and the rest of terminal after the mechanical shear strength test are shown in Figure 13. Whole bottom side of terminal or major part remain on the solder. It is shown in Figure 14.

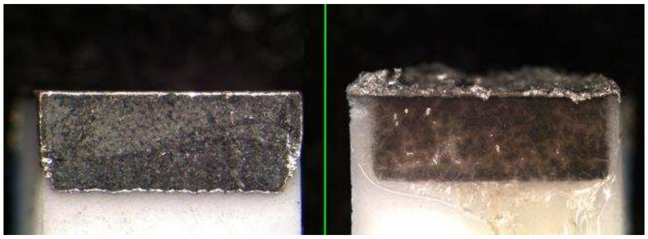

Fig. 13. The metallization of component underside, new component (left), component after test (right)

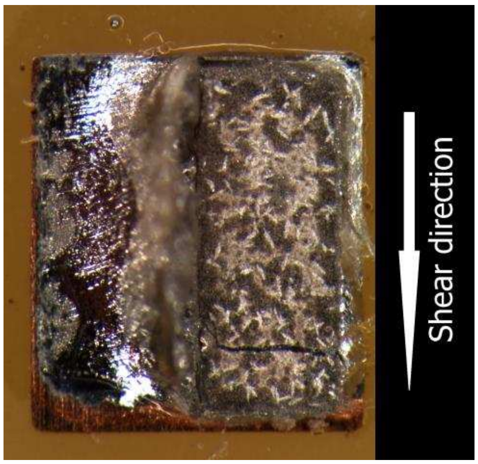

Fig. 14. The fracture SAC-A 1x solder joint

5. CONCLUSION

The paper presents the effect of multiple reflow cycles on IMC creation and mechanical properties of soldered joints. This paper has clearly shown that the increasing number of reflow cycles cause the growth of IMC layer. The interface solder/Cu pad was observed. SnBi IMC layer grows more slowly than SAC IMC layer. The soldering profile with greater heating factor creates thicker IMC layer. The maximal shear force for tear-off component did not vary greatly with the number of reflow cycles. The shear strength of both solder joints (SnBi and SAC) is higher than that of the tested components terminal. In our future research we intend to concentrate on an effect of heating factor on creation IMC layers and their growth.

6. ACKNOWLEDGEMENT

This research has been supported by the European Regional Development Fund and the Ministry of Education, Youth and Sports of the Czech Republic under the Regional Innovation Centre for Electrical Engineering (RICE), project No. CZ.1.05/2.1.00/ 03.0094 and the Student Grant Agency of the University of West Bohemia, grant No. SGS-2015-020 "Technology and Material Systems in Electrical Engineering“.

REFERENCES

[1] B. I. Noh, J. M. Koo, J. W. Kim, D. G. Kim, J. D. Nam, J. Joo, and S. B. Jung, “Effects of number of reflows on the mechanical and electrical properties of BGA package,” *Intermetallics*, vol. 14, pp. 1375–1378, 2006.

[2] F. X. Che and J. H. L. Pang, “Characterization of IMC layer and its effect on thermomechanical fatigue life of Sn-3.8Ag-0.7Cu solder joints,” *J. Alloys Compd.*, vol. 541, pp. 6–13, 2012.

[3] D.-G. Kim, J.-W. Kim, S.-S. Ha, B.-I. Noh, J.-M. Koo, D.-W. Park, M.-W. Ko, and S.-B. Jung, “Effect of reflow numbers on the interfacial reaction and shear strength of flip chip solder joints,” *J. Alloys Compd.*, vol. 458, no. 1–2, pp. 253–260, Jun. 2008.

[4] K. Dušek and M. Tučan, “Influence of mechanical stress and temperature aging on a change of electrical connection resistance,” *2008 31st Int. Spring Semin. Electron. Technol. Reliab. Life-time Predict. ISSE 2008*, pp. 41–44, 2008.

[5] H. Ma, J. C. Suhling, Y. Zhang, P. Lall, and M. J. Bozack, “The influence of elevated temperature aging on reliability of lead free solder joints,” *Proc. - Electron. Components Technol. Conf.*, pp. 653–663, 2007.

[6] B. Tao, Y. Wu, H. Ding, and Y. L. Xiong, “A quantitative method of reliability estimation for surface mount solder joints based on heating factor Q η,” *Microelectron. Reliab.*, vol. 46, pp. 864–872, 2006.

[7] X. Liu, M. Huang, Y. Zhao, C. M. L. Wu, and L. Wang, “The adsorption of Ag3Sn nano-particles on Cu-Sn intermetallic compounds of Sn-3Ag-0.5Cu/Cu during soldering,” *J. Alloys Compd.*, vol. 492, pp. 433–438, 2010.