Effect of Elevated Temperatures on SAC305 Solder Alloy Thermal Interface Material in a Microelectronic Assembly

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Abstract- In microelectronics assemblies, Thermal Interface Materials (TIMs) are vital to the reliability of the devices in operation. Some electronic devices operate in elevated temperature environments such as military and industrial applications. Hence, the need to evaluate the reliability of such devices at elevated temperatures. Tin-Silver-Copper lead-free solder TIMs have been used during the assembly process of some electronic devices operating under harsh temperature environments. In this study, the reliability of SAC305 lead-free solder TIM was considered at elevated temperatures ranging from 100 °C to 200 °C at 25 °C interval, and aged for about an hour. ANSYS finite element analysis software was employed for the design and evaluation of SAC305 lead-free solder model. The findings of the investigation demonstrated that the higher the harsh temperature environment, the lower the reliability of the SAC305 solder TIM. In addition, the highest residual fatigue life (36735 or 4.2 years) was recorded at 100 °C, while 200 °C recorded the lowest fatigue life (1014 or 0.12 years). The fatigue life is an indication of the lifespan of the TIM when in operation. This study will be beneficial to engineers assembling microelectronic products.

Keywords- elevated temperature; fatigue life; microelectronics; reliability; SAC305 solder

1 INTRODUCTION

In-silver-copper (Sn-Ag-Cu) or SAC solder alloys have been widely studied and are still studied (Aamir et al., 2020; Jiang, Moon and Wong, 2008). Lead-free solder joint reliability in electronics applications has been the focus of a lot of researchers (Huang, Wang, and Yub, 2020; Amalu and Eker, 2016; Lee, Nguyen and Selvaduray, 2000). However, some researchers have studied and are still studying the use of SAC solder alloys as thermal interface materials in electronics applications (Chiu and Kang, 2014; Jiang et al., 2018; Vijay, 2012).

In microelectronics applications, the effective dissipation of heat could be hindered by the reliability of the thermal interface materials used during the assembly process. According to Vijay (2012), lead-free solder materials have better conduction capabilities when compared to grease. It is evident that SAC solder alloys are gaining grounds in the electronic industry as thermal interface materials for several reasons. First, SAC solder alloys thermal interface materials have high thermal conductivity compared to other available thermal interface materials such as thermal grease. Second, SAC solder thermal interface materials could easily fill the interface or topology between the chip and heat sink interface because of their softness.

In addition, there are no pump outs when the device is operational because over time the SAC solder alloys becomes solidified, thereby bonding the interface between the chip and the heat sink. The malleability of the SAC solder alloy reduces the thermal resistance between the chip and heat sink interface, thereby increasing the heat dissipated from the device. Third, SAC solder alloys do not bake out over time when in operation compared to thermal greases that bake out over time, thereby increasing the thermal resistance. In addition, the dissipation of heat is reduced in the electronic device (Vijay, 2012).

The reliability of SAC solder alloys has always been an issue despite its ability to improve thermal conduction and the fact that it is readily available commercially (Satwara et al., 2017). Hence, the need to understand the reliability of SAC305 lead-free solder alloy thermal interface materials at elevated temperature ranges. Some military and industrial applications are expected to operate at elevated temperatures above 200 °C. Such applications include aircrafts, automotive, space exploration, deep oil/gas extraction, etc. (Buttay et al., 2011). In oil/gas exploration, electronic devices are expected to operate between 150 °C to 225 °C in deep oil wells (Buttay et al., 2011). In space exploration, electronic components could be exposed to temperatures as high as 480 °C. While automotive components could operate above 160 °C junction temperature. In addition, some aircraft electronic components could operate in ambient temperatures as high as 225 °C.

The study of the reliability behaviour of SAC lead-free solder alloy thermal interface material has become necessary due to the miniaturisation of electronic components. The implication of miniaturisation is that the need to add fans in electronic components are gradually being phased out. The absence of fans has increased the reliability challenges in electronic devices. The present study will give an insight towards how SAC lead-free solder alloy thermal interface materials will behave under harsh temperature environments. However, not enough work has been published on the reliability of SAC solder alloys as thermal interface materials, but researchers are advised to read the following references (Too et al., 2009; Montano et al., 2005; Subramanian, 2005) to have more insight on the works carried out by researchers in this field.

2 MATERIALS AND METHOD

2.1 MODEL DESCRIPTION

The designed microelectronic package comprises of a heat sink base (HSB), thermal interface material (TIM), and a flip chip. The components were mounted on a printed circuit board (PCB) using surface mount technology. The dimensions of the designed model are given as: 30 mm x 30 mm x 2 mm for the heat sink base (HSB), 10 mm x 10 mm x 0.035 mm for the TIM, and 10 mm x 10 mm x 0.5 mm x 0.035 mm for the heat sink base (HSB), 10 mm x 10 mm x 0.035 mm for the TIM, and 10 mm x 10 mm x 0.5 mm x 0.035 mm for the TIM.
mm for the chip. ANSYS finite element analysis software was employed for the design of the microelectronic assembly package (MAP). For simplicity of simulation, the PCB and heat sink fins were neglected in this study. It is assumed that this will not affect the final results since the author’s focus is on the TIM. A schematic of the designed model showing the HS-Base, chip, and TIM are presented in Figure 1. From Figure 1, the TIM is mounted between the chip and heat sink base as obtainable in electronic devices. The need of the TIM is to improve the thermal conduction between the heat sink and chip by filling any air gap between both surfaces in contact.

2.2 MATERIALS
The chip/heat sink assembly components are made up of materials such as silicon for the flip chip, Tin-Silver-Copper (SnAgCu) alloy solders for the TIM, and aluminium alloy for the HSB. The lead-free solder considered in this research work is SAC305 (Sn3.0Ag0.5Cu). The material properties of the SAC305 lead-free solder material are presented in Table 1. The linear elastic and isotropic material properties were used to simulate the chip and HSB, while temperature-dependent visco-plastic material properties were used in the simulation of the TIM. Over the years, the reliability of solder alloys has been analysed using Anand’s visco-plasticity constitutive model by researchers (Zhang, Liu and Ji, 2016; Ekpu et al., 2014; Ekpu et al., 2013; Yan and Li, 2009; Wang et al., 2001). The same Anand’s visco-plasticity constitutive model was employed in this research. This investigation is unique because the results of smaller solder joints have been extrapolated to investigate a larger solder die attach area. Table 2 presents the Anand visco-plasticity constitutive model parameters for SAC305 lead-free solders used in this study (Ekpu et al., 2014).

2.3 LOAD AND BOUNDARY CONDITIONS
Microelectronics devices are designed to operate in extreme conditions, such as in industrial and military applications. Hence, the need to analyse the components in such elevated temperatures. Alam, Shuhling and Lall (2017) stated that lead-free solders are exposed to very high temperatures in several harsh environment applications which includes well-boring, aerospace engines, and geothermal energy. The focus of this research is on SAC305 lead-free solders. The temperatures considered in this investigation are 100 °C, 125 °C, 150 °C, 175 °C, and 200 °C. These temperatures were sustained for one hour based on the input of the simulation parameters. The maximum aging temperature considered by Aamir et al. (2017) was 140 °C. In addition, this research assumed that the lead-free solder materials completed one cycle per hour based on the aged temperatures. This is in line with the requirements of the standards stated in JEDEC (2009).

Table 1. Material properties used in this investigation
(Yan and Li, 2009)

| Component | Young’s modulus, E (GPa) | Poisson ratio | Coefficient of thermal expansion (1/°C) |
|-----------|--------------------------|--------------|-----------------------------------------|
| Aluminium Heat Sink | 71 | 0.33 | 2.3E-05 |
| Silicon Chip | 130 | 0.22 | 2.46E-06 |
| SAC305 | 38.7 | 0.35 | 2.1E-05 |

Table 2. Anand constitutive material constants for SAC305 solder (Yan and Li, 2009)

| Description | SAC305 |
|-------------|--------|
| Initial value of deformation resistance, σ₀ | 45.9 | MPa |
| Activation energy, Q/R (K) | 7460 |
| Pre-exponential factor, A (1/s) | 5870 |
| Stress multiplier, ξ (dimensionless) | 2 |
| Strain rate sensitivity of stress, m (dimensionless) | 0.0945 |
| Hardening coefficient, h₀ (MPa) | 9350 |
| Coefficient of deformation resistance saturation value, s (MPa) | 58.3 |
| Strain rate sensitivity of saturation value, n (dimensionless) | 0.015 |
| Strain rate sensitivity of hardening coefficient, a (dimensionless) | 1.5 |

3 RESULTS AND DISCUSSIONS
3.1 MESH ANALYSIS
To achieve adequate and reasonable results, it is necessary that the designed models used in this investigation are meshed with a high degree of fineness in terms of meshes. The work done by Ekpu (2019) fully covered the requirements for the meshing model to achieve results that are practically related. Figure 2 presents the mesh of the developed model used in this study.

3.2 STRESS AND STRAIN ANALYSIS
Figure 3 presents the plot of stress with time for different aging temperatures. It was observed in Figure 3 that at a time of 720 seconds, the stress at 100 °C was 15.35 MPa while that of 200 °C was 19.16 MPa. However, at the end of the aging time of 3600 seconds, the stress at 100 °C was 20.57 MPa while that of 200 °C was 16.51 MPa. The trend at 720 seconds, which is the early stage of the aging process, showed that there was an increase in stress from low temperature to higher temperatures. However, the trend at the end of the aging time showed that the stress...
reduces from low temperature to higher temperatures as observed in Figure 3. In Figure 4, where the elastic strain is plotted against time, a similar trend found in Figure 3 was observed. The elastic strain reduces at the end of the aging time for temperature ranges of 100 °C to 200 °C.

Figure 5 presents the plot of stress versus elastic strain. The stress as observed in Figure 5, is directly proportional to the recorded elastic strain. This obeys the principle of Hooke’s law which could be described as the strain exerted by SAC305 lead-free solder TIM when a stress is applied within its elastic limit to the SAC305 solder. In addition, when the gradients were calculated for each of the points in Figure 5, it resulted in a Young’s modulus of 38.699 GPa approximately.

Figure 6 presents the resultant stress from the applied load to plastic strain. As expected, the effect of plastic strain on the SAC305 lead-free solder TIM was more at 200 °C and less at 100 °C. Figure 6 clearly shows that high temperature in a microelectronic assembly will lead to increased plastic strain in the system, which could lead to failure of the system. Similar type of stress versus strain curve was reported in the experimental work carried out by (Alam, Suhling and Lall, 2017; Aamir et al., 2017).
3.3 Fatigue Assessment

All Researchers (Syed, 2004; Pang, Xiong and Low, 2004; Yan and Li, 2009; Zhang, Liu and Ji, 2016) over the years have used different constitutive equations to predict the fatigue life of different lead-free solder joints under thermal loads. This investigation employed the Coffin-Manson plastic strain fatigue model to predict the fatigue life of the SAC305 lead-free solder thermal interface material currently being studied (Yan and Li, 2009; Zhang, Liu and Ji, 2016). This model is presented below:

\[ N_f = \frac{1}{2} \left( \frac{\Delta \varepsilon_p}{2 \varepsilon_f} \right)^2 \]  

(1)

\[ c = -0.442 - (6 \times 10^{-4})T_m + 1.74 \times 10^{-2} \ln(1 + f) \]  

(2)

\[ T_m = \frac{T_{\text{max}} + T_{\text{min}}}{2} \]  

(3)

Where \( N_f \) is the number of cycles to failure, \( \Delta \varepsilon_p \) is the plastic strain amplitude obtained from Figure 6 for different temperature ranges, \( \varepsilon_f \) is the fatigue ductility coefficient and is given by Yan and Li (2009) as 0.325, \( f \) is the fatigue ductility exponent, \( f \) is the thermal fatigue frequency given as 24 (cycles per day) based upon the aging time used in this study, and \( T_m \) is the thermal cycle mean temperature.

The numbers of cycles to failure with different temperature ranges are presented in Figure 7. In Figure 7, it is clearly seen that SAC305 has the highest number of cycles (36735) to failure at an aging temperature of 100 °C compared to others (the \( N_f \) at 200 °C is 1014). This implies that it will take approximately 4.2 years for SAC305 to fail at a temperature of 100 °C. While it will take approximately 0.12 years for SAC305 to fail at a temperature of 200 °C. However, it is observed from Figure 7 that as the temperature is increased at 25 °C intervals, the number of cycles to failure reduces accordingly with the aging time of 3600 seconds. Comparing the fatigue life of this study with experimental work on solder joints available in the literature (Zhang, Liu and Ji, 2016; Henshall et al., 2009; Yan and Li, 2009), it was discovered that similar low cycles to failure were recorded.

4 Conclusion

This investigation clearly shows that high temperature in microelectronics will definitely lead to reduction in the reliability of the product, which will lead to the electronic device failing early during operation. This was demonstrated by the large difference observed in the number of cycles to failure between the SAC305 lead-free thermal interface material at an aging temperature of 100 °C (\( N_f = 36735 \) or 4.2 years) and 200 °C (\( N_f = 1014 \) or 0.12 years) respectively. In general, being able to manage electronic devices within the allowable operating conditions specified by manufacturers will help in increasing the life span of such products.

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