Creep Behavior of Annealed Lead-free Solder for High-power Electronic Device

Xu LONG1,* , Wen-bin TANG1, Zheng-hu ZHU2, Yan-pei WU3, Lian-feng REN3 and Yao YAO1

1School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, Xi’an 710072, People’s Republic of China
2No. 8511 Research Institute, China Aerospace Science and Industry Corporation, Nanjing 210007, People’s Republic of China
3Space Research Institute of Electronics and Information Technology, Aerospace Science and Technology Corporation, Xi’an 710100, People’s Republic of China

*Corresponding author

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Abstract. The present paper investigated the annealing effect on creep behaviour of lead-free Sn-3.0Ag-0.5Cu (w.t., SAC305) solder material. According to the previous finding by nanoindentation and uniaxial tensile experiments, the optimal annealing condition of SAC305 solder was believed as 210°C for 12h to minimize the residual stress and stabilize the mechanical property of annealed solder. In order to simulate the high-temperature environment of high-power devices, the annealing temperature at 210°C is adopted with varying duration from 12 hours to 48 hours as the creep deformation usually results from long-term working conditions. The creep deformations in the time history for different cases are compared and discussed. Steady-state creep rate is also calculated to quantitatively reflect the annealing effect on creep resistance. In general, a longer duration of annealing at 210°C will increase the specimen’s time to failure and decrease the steady-state creep rate. Besides, failure modes of annealed specimens are examined by scanning electron microscopy images. It is found that with increasing the annealing duration, the specimen intends to fracture in a more ductile way with a greater ultimate tensile strain.

Introduction

In the modern electronic packaging structures, the mechanical reliability of solder joints has a significant impact on the stability of the device. As the size of the electronic devices becomes smaller and smaller, and the performance of the electronic devices continues to increase, the reliability of the solder joint structure has been challenged [1]. So this question has received more and more attention recently. And the creep behavior of the SAC305 solder joint has been investigated by some people [2-4].

For electronic components used in extreme conditions, such as artificial satellites, they usually need to endure higher temperatures [5]. Especially, chip solder joints are often subjected to a high temperature due to the large current density in high-power electronic devices [6]. Regarding high service temperature, the solder joints of such electronic devices experience a thermal process which is essentially similar to annealing treatment [7]. But the effect of annealing on mechanical performance of lead-free solder joint is still unclear. Therefore, in order to evaluate the reliability of solder joints under extreme conditions, it is important to investigate the effect of annealing on the creep performance of solder joints.

Specimen Preparation and Experimental Procedure

The specimens used in this experiment were made of SAC305 solder balls and copper rods with a diameter of 1.0 mm. In order to improve the strength of the joint, the diameter of the solder ball is
There are four steps in the preparation of the specimens. Firstly, high-purity copper rods with a diameter of 1.0 mm were cut into pieces with a length of 45.0 mm. Then the ends of the copper rods were polished with abrasive paper and ultrasonically cleaned. Secondly, the solder wire was cut into pieces with a length of 12 mm and placed on a quartz plate at the temperature of 265°C until each solder wire melt into a solder ball with a diameter slightly greater than 1.0 mm. Thirdly, the prepared copper rods and solder balls were placed on a grooved quartz plate with a careful alignment with their central lines. Subsequently, after flux was pasted onto their contact surfaces, the quartz plate was moved into reflow machine with the peak temperature of the profile set at 265°C and the dwell time of 2 min. Lastly, after reflow soldering, the redundant solder was carefully removed from the joint and the surface of the joint was ground and cleaned for the following test. As shown in Figure 1, the average length of the solder joint is 3.15 mm, and the length of the entire specimen is about 93.0 mm.

According to the previous finding by nanoindentation and uniaxial tensile experiments, the optimal annealing condition of SAC305 solder was believed as 210°C for 12h to minimize the residual stress and stabilize the mechanical property of annealed solder. In this work, the annealing of the specimen was carried out in a high temperature test chamber with the temperature set at 210°C. The annealing duration were determined to be 12 hours, 24 hours and 48 hours. Three specimens were repeated for each annealing duration. After annealing process, specimens were aged for 96 hours at room temperature in order to stabilize their microstructure.

The creep tests were conducted by a micro-force tensile machine, with a force control accuracy of 0.001 N and a displacement accuracy of 0.001 mm. The tests were conducted at room temperature, so no thermal effect was applied on the prepared specimen after the annealing treatment. By applying the tensile force of 20N, the applied tensile stress was set as 25.5 MPa in the solder specimens. A computer was used to control the loading rate and collect strain-time data as well.

![Figure 1. Prepared Cu/SAC305/Cu solder joint](image1)

![Figure 2. Stress-strain curve of SAC305 solder after annealing.](image2)
Experimental Results

From the unified stress-strain responses at the strain rate of $5 \times 10^{-4}$ s$^{-1}$ as shown in Figure 2 based on tensile experiemental results [6], annealing has a significant impact on the SAC305 tensile properties. After the annealing process, the yielding-hardening transition stage of the solder material is gradually improved. This means that the annealing may alliviate the micro-scale defect and release the residual stress due to mechanical machining.

The creep strain-time curves of Cu/SAC305/Cu joints after 210°C annealing are shown in Figure 3. For a more reliable result, there were 3 specimens for each annealing condition. Due to the presence of micro defects in specimens, the results of the creep test will be lower than the theoretical value in the ideal material. So the specimen which lasted for the most time to failure (denoted by red ball-symbols fitted with a dashed curve in Figure 3) was selected to represent the creep behaviour of the individual condition.

![Figure 3. Time to fracture of solder specimens after different annealing durations.](image)

![Figure 4. Creep-time curves of Cu/SAC305/Cu joints after annealing.](image)

| Annealing duration | 12 hours | 24 hours | 48 hours |
|--------------------|----------|----------|----------|
| Steady-state creep rate | $4.697 \times 10^{-6}$ s$^{-1}$ | $0.799 \times 10^{-6}$ s$^{-1}$ | $0.597 \times 10^{-6}$ s$^{-1}$ |

The creep deformation-time curves of Cu/SAC305/Cu joints after 210°C annealing are shown in Figure 4. After numerical calculations based on best-fit regression, the steady-state creep rates of the specimens after annealing for 12 hours, 24 hours and 48 hours were listed in Table 1. It is obvious that
due to the increase in annealing time, the steady-state creep rate of the specimen decreases and the ability of the specimen to resist creep is significantly improved. Similarly, the steady-state creep rate of the specimens with different cooling rates has been investigated by the authors [8] and it was found that the SAC305 solder with the lowest cooling rate owns that smallest steady-state creep rate. Therefore, both slower cooling condition and longer annealing duration achieve a smaller steady-state creep rate. It is speculated that their effects due to sufficient thermal process attribute to the same mechanism by reducing residual stress and alleviate micro scale defects such as voids. On the other hand, it can also be seen from Figure 4 that after 48 hours of annealing, the creep resistance of the solder joint has been greatly improved so that no fracture occurred at the end of the test after a sufficient duration.

After the creep test, microscopic observations of the solder joints were carried out by scanning electron microscopy. As shown in Figure 5, the elongation of the specimen annealed for 24 hours is greater than the specimen annealed for 12 hours. As the specimen annealed for 48 hours is so ductile, no fracturing or obvious necking occurred at the end of measurement. So it is safely concluded that with the increasing annealing duration, the SAC305 solder intends to fracture in a more ductile way with a greater ultimate tensile strain. This ductile failure mode will benefit the creep resistance as discussed in Figure 4 and Table 1.

![Figure 5. Fracture behaviour of solder joints after different annealing durations.](image)

Summary

This paper investigates the annealing effect on creep behaviour of SAC305 solder material to simulate the high-temperature environment of high-power devices. With the annealing temperature at 210°C and varying durations from 12 hours to 48 hours, the creep deformation is experimentally measured under a constant tensile force of 20N. It is found the creep resistance of solder material is higher if a greater annealing duration is applied. That is, the steady-state creep rates are $4.697 \times 10^{-6}$ s$^{-1}$, $0.799 \times 10^{-6}$ s$^{-1}$, and $0.597 \times 10^{-6}$ s$^{-1}$ for the solder specimens after annealing durations for 12 hours, 24 hours and 48 hours, respectively. In addition, the failure modes of annealed specimens are also assessed by scanning electron microscopy. The conclusion is that the specimen after a greater annealing duration intends to fracture in a more ductile way with a greater ultimate tensile strain. This is also consistent with steady-state creep measurement based on the creep deformation-time responses.

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