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Du, Leiming; Zhao, Xiujuan; Poelma, Rene; Van Driel, Willem; Zhang, Guoqi

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# High-temperature creep properties of a novel solder material and its thermal fatigue properties under potting material

1st Leiming Du
*Department of Microelectronics*
*Delft University of Technology*
Delft, The Netherlands
L.Du@tudelft.nl

2nd Xiujuan Zhao
*Research*
*Signify*
Eindhoven, The Netherlands
susan.zhao@signify.com

3rd Rene Poelma
*Research*
*Nexperia*
Nijmegen, The Netherlands
rene.poelma@nexperia.com

4th Willem Van Driel
*Research*
*Signify*
Eindhoven, The Netherlands
willem.van.driel@signify.com
*Department of Microelectronics*
*Delft University of Technology*
Delft, The Netherlands
w.v.driel-1@tudeflt.com

5th Guoqi Zhang
*Department of Microelectronics*
*Delft University of Technology*
Delft, The Netherlands
g.q.zhang@tudelft.nl

***Abstract*—SnBiAgCu solder alloy is an attractive soldering material for temperature-sensitive electronic devices due to its excellent creep properties. This study firstly reports the creep properties of SnBiAgCu solder alloy under different temperatures. Results show that the addition of Bi resulted in better creep resistance compared with that of commercial SAC305 (Sn-3.0Ag-0.5Cu). Secondly, dynamic mechanical analyses were performed to get the storage modulus and glass transition temperature of potting compounds. Finally, a finite element modeling based analysis were used to figure out the different failure mechanism due to the presence of potting materials. The accurate simulation data offers an optimization reference for the selection of solder and potting materials.**

***Index Terms*—solder, potting material, creep, thermal fatigue**

## I. INTRODUCTION

In the past few years, the lead-free solder alloy (e.g., SnAg, SnAgCu) has been widely used in electronic packaging, which has been a mainstream replacement of leaded solder alloys (PbSn) for environmental protection. To meet the increased demand for a longer lifetime of electronic components during their applications, the creep properties of the solder joint under high temperatures is one critical issues to address. Many previous studies have been proposed to enhance the creep behaviors by adding fillers into base solder alloys [1, 2]. For example, the addition of Cu to SnAg was reported moderately enhance the creep resistance at both room temperature and elevated temperature [1]. The SnAg with Ni fillers presents higher creep resistance at room temperature compared with SnAgCu alloys, but has insignificant effect under high temperature. Moreover, Shen et al [2] studied effect of nano-metallic fillers (Cu, Ni) on the creep properties of SnBi solder alloys. They found an optimum filler concentration for creep resistance enhancement is identified at which there is a balance between the effects of particle pinning and microstructure refinement.

Potting materials are used to protect the electronic components from harsh condition, such as extreme temperatures, mechanical vibration and humidity [3]. However, it was found that there was a earlier decapsulation in solder joint with the potting materials. The mechanism of such failure is contributed to the shrink or expansion stresses exist in the solder due to the thermal expansion of the potting compounds. In this study, the creep properties of a novel solder alloy (SnBiAgCu) are reported and compared with SnAgCu solder alloy. Secondly, the visco-elasticity properties of the potting material are characterized by dynamic mechanical analysis (DMA) tests. Finally, a set of thermo-mechanical simulations based on the finite element method (FEM) is performed. The effect of potting material on the energy density distribution and stress distribution of solder joints is obtained.

## II. EXPERIMENTAL SECTION

### A. Mechanical tests

Firstly, the solder alloys were subjected to uniaxial tensile tests at a strain rate of $0.001\mathrm{s}^{-1}$ across different temperatures (25°C, 75°C, 125°C) to determine their stress-strain curves. Each temperature level was tested using three specimens. Secondly, four creep stress levels were selected based on the ultimate tensile strength (UTS) measured, namely 0.25UTS, 0.35UTS, 0.45UTS, and 0.55UTS, respectively. Subsequently,

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creep tests were conducted at three different temperatures (25°C, 75°C, 125°C). Thirdly, DMA tests are carried out across a temperature range from -50°C to 30°C, with a test frequency set at 3 Hz.

### *B. Finite element simulation*

A FEM simulation is used to compute the thermal-mechanical reactions of solder interconnects while undergoing thermal cycling. The study focuses on a package (SOD323) with gull-wing leads and a diode frequently utilized in LED drivers. As illustrated in Fig. 1, Ansys Workbench is employed to develop a three-dimensional (3D) finite element model representing one-quarter of the diode. A substructure technique is employed to enhance the FEM calculation efficiency without sacrificing accuracy. Notably, the displacement is set as 0 in directions perpendicular to the symmetric planes, and the vertex located at the intersection of the symmetric planes, as shown in Fig. 1, is kept fixed.

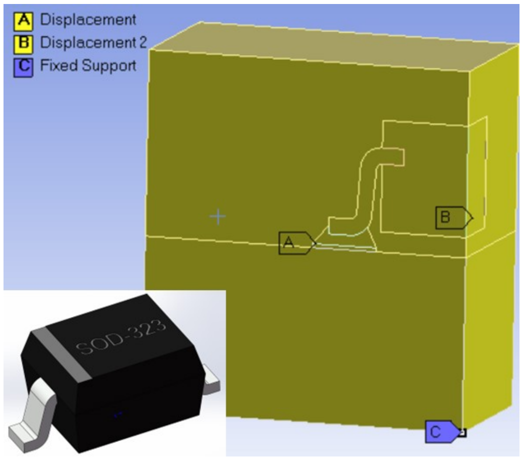

Fig. 1. Schematic of a quarter of SOD323 model used in FEM and boundary condition.

## III. RESULTS AND DISCUSSION

### *A. Creep properties of SnBiAgCu*

Fig. 2 illustrates the stress-strain curves at three distinct temperatures (25°C, 75°C, 125°C). The ultimate tensile strength (UTS) values show a considerable reduction as the temperature rises. Specifically, when the temperature increases from 25°C to 75°C, the UTS declines from 47.2 MPa to 37.2 MPa. Furthermore, the UTS keeps decreasing, reaching 25.5 MPa at 125°C. This aligns with the notion that elevated temperatures tend to weaken solder materials. The elongation ranges from 2.5% to 8%, and it appears that the elongation is not sensitive to temperature alterations from 25°C to 75°C, disregarding the discreteness. However, at higher temperatures such as 125°C, the uniformity of elongation is significantly affected.

Fig. 3 shows the typical creep behavior of SnBiAgCu solder alloys. The curves appear to be conventional at 25°C, displaying a distinct primary creep (stage I) with distinct secondary creep (stage II) immediately after loading. While the curves at 75°C and 125°C presents negligible primary creep (stage I). The minimum creep rate was taken as the steady-state stage creep strain rate, as shown in Fig. 4. The variations in creep rate suggest a fundamental change in the internal stress of the alloy sample over time. Fig. 5 shows that the creep resistance of SnBiAgCu is higher than that of SAC305 solder alloy due to the refinement structure. The refinement grain of SnBiAgCu solder alloys is caused by the Bi addition, which will impede the dislocation movement more efficiently, and thus it will help to decrease the creep rate [4].

Potting materials belongs to the category of viscoelastic materials that exhibit significant dependence on temperature in their stress-strain behavior. Specifically, as the temperature increases, the elasticity of the potting material decreases while its viscosity increases. Consequently, the strain response becomes delayed at higher temperatures due to the increased viscidity of the material. Fig. 6 shows the curves of storage modules (*E'*), loss modulus (*E"*) and tan delta. From tan delta curve, it is clear that glass transition temperature ($T_g$) of this potting material is -10°C. As the electronic components have operation temperatures over 100°C or under -20°C, the thermal expansion coefficient (CTE) mismatch between different materials will cause tremendous stress. In order to study the effect of potting materials on the thermal fatigue properties of solder materials, finite element modeling is performed in the following.

### *B. Finite element modeling*

The package under consideration in this study is the SOD323, which contains a diode and features gull-wing leads. This package is extensively utilized in LED drivers. Given that the solder interconnects are expected to undergo creep deformation under thermal cyclic conditions, the Garofalo-Arrhenius creep model [5] is employed to simulate their creep behavior. The temperature range is -40 to 120°C. And the initial temperature is set as 120°C. As the inelastic strain energy density per cycle is stable after 3 cycles, 4 cycles were performed in FEM simulation in this study.

The strain energy distribution at the end of $4^th$ cycle within the solder interconnect is illustrated in Fig. 7. Fig. 7a shows the strain energy of the component without potting materials. Fig. 7b shows the strain energy of the component with potting materials. It indicates that the highest amount of energy is concentrated in the solder interconnect without potting materials. As the mechanical properties of solder presents high temperature sensitivity. The creep deformation accounts for the main failure mechanism under thermal cyclic condition. While when the solder joints are surrounded by the potting material, the strain energy distribution presents significant difference. The higher strain energy density concentrates at the interface of potting materials and solder joints. This is caused by the CTE mismatch among potting material, solder joint and Cu lead frame.

Fig. 8 shows the stress distribution of solder joint. It is clear that potting materials will cause higher stress inside the solder joints. The shrink under the low temperature and the

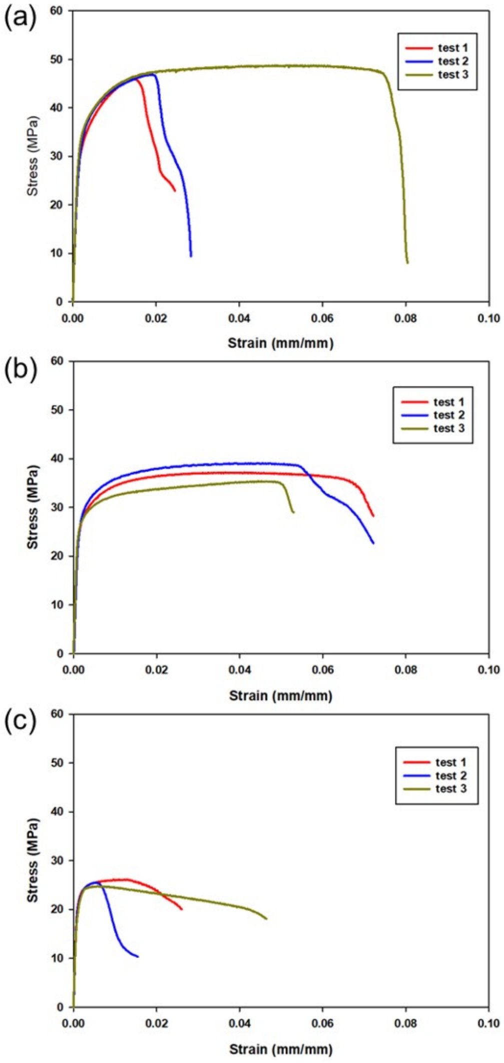

Fig. 2. Tensile curves of SnBiAgCu: (a) 25°C; (b) 75°C; (c) 125°C.

expansion under the high temperature of the potting materials will induce tensile or compression stress on the solder joints, which produce more plastic deformation. Moreover, the potting material will be very hard when the temperature is lower than its $T_g$. As the $T_g$ of potting material used in this study is -10°C, which is higher than the minimum temperature during the thermal cyclic process, low temperature is anticipated to be more harmful than high temperature. To decrease the CTE mismatch, a potting materials with lower $T_g$ is very important for the low temperature application of electronic components.

## IV. CONCLUSION

The study compared the high-temperature tensile and creep properties of a novel solder material, SnBiAgCu, with commercial SAC305. It was found that the addition of Bi improved the tensile strength and creep resistance of the new solder alloy by limiting dislocation movement. The tensile strength

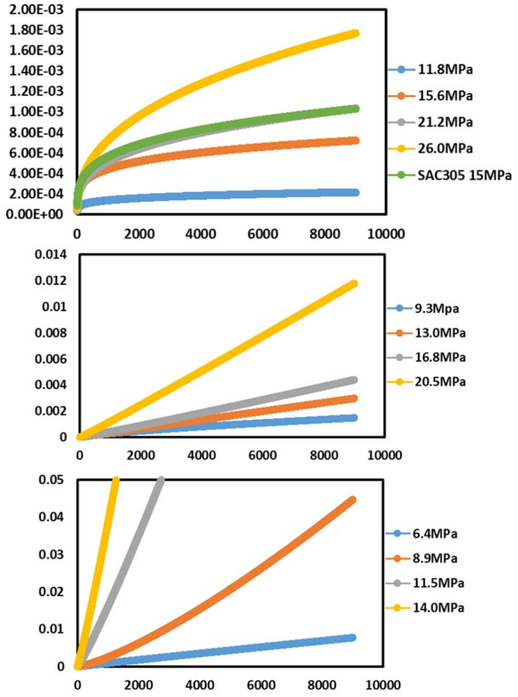

Fig. 3. Creep curves of SnBiAgCu: (a) 25°C; (b) 75°C; (c) 125°C.

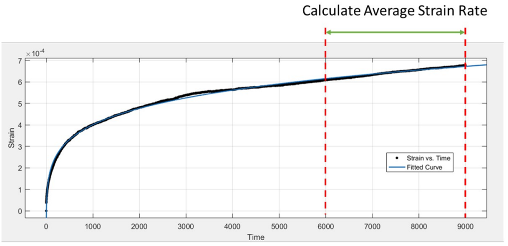

Fig. 4. Method of calculating creep rate from creep curves

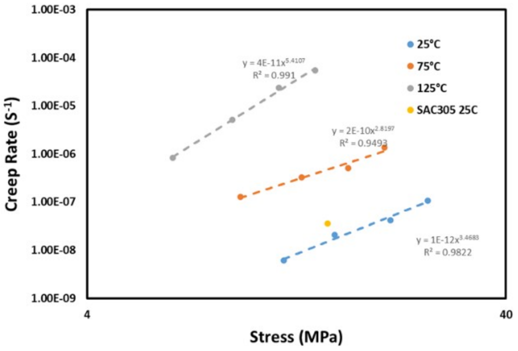

Fig. 5. Creep rate of SnBiAgCu at 25°C, 75°C, 125°C and SAC305 at 25°C.

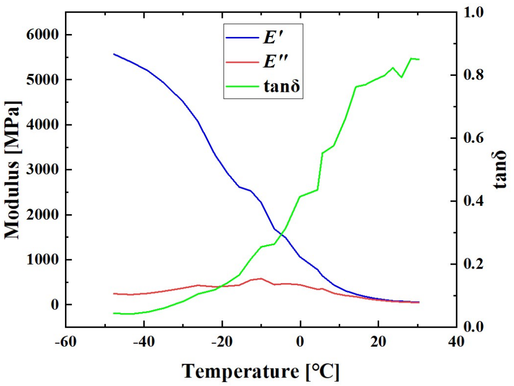

Fig. 6. DMA curves of potting materials

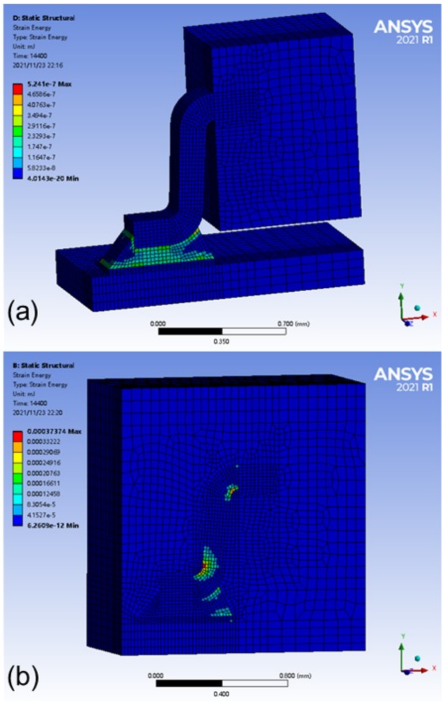

Fig. 7. Strain energy density distribution (a) without potting; (b) with potting.

of SnBiAgCu is 47.2 Mpa at room temperature (25°C), 37.2 MPa at 75°C, and 25.5MPa at 125°C, which are significant higher than those of SAC305 solder alloy. Meanwhile, the creep rate of SnBiAgCu is lower than that of SAC305. Thus, SnBiAgCu presents better mechanical properties than SAC305 solder alloy.

The thermal fatigue analysis revealed that the use of potting materials caused significant plastic deformation in the solder joint, leading to early failure during application. At low temperatures, significantly below the transition glass temperature of the potting material, severe plastic deformation occurred within the solder. To prevent this, it is recommended to select potting materials with lower $T_g$ for use in low-temperature environments.

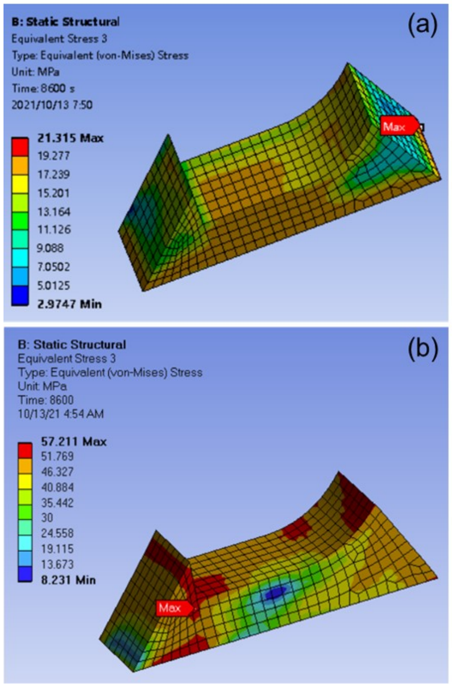

Fig. 8. Stress density distribution (a) without potting; (b) with potting.

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