CREEP FRACTURE BEHAVIOUR OF JOINTS SOLDERED BY A NANO-COMPOSITE SOLDER, LEAD-FREE AND CONVENTIONAL TIN-LEAD SOLDERS

X. P. Zhang [*1, 2], Y. W. Shi [3], Y. W. Mai [1], S. Shrestha[4] and L. Dorn[4]
[1] Centre for Advanced Materials Technology, School of Aerospace, Mechanical and Mechatronic Engineering, the University of Sydney, NSW 2006, Australia
[2] School of Mechanical Engineering, South China University of Technology, Guangzhou 510641, China
[3] School of Materials Science and Engineering, Beijing Polytechnic University, Beijing 100022, China
[4] Institute of Materials Surface Engineering and Technology, Technical University Berlin, D-10623, Germany

ABSTRACT

Creep resistance and thermal fatigue performance of soldered connections/joints are essential reliability concerns for microelectronic, optoelectronic and photonic packaging systems. In this study, creep fracture behaviour of lap shear joints soldered by a tin-lead based composite solder reinforced by nano-sized metallic particles and a lead-free Sn-Ag-Bi alloy solder was characterized at different homologous temperatures, with a comparison to a traditional Sn60Pb40 solder. The results show that at all temperatures tested the nano-composite solder has much better creep resistance than Sn60Pb40 solder, in terms of the creep rupture life. The lead-free Sn-Ag-Bi solder has superior creep performance to both Sn60Pb40 and nano-composite solders. The creep fractography analysis by SEM shows that a progressive shear deformation occurred as the main creep fracture mechanism. Sn60Pb solder joints deform dominantly by transgranular sliding, while Sn-Ag-Bi and nano-composite solder joints creep by intergranular mechanism through grain boundary sliding and voids growth. The mechanism of enhancing the creep resistance of nano-composite solder joints is that the nano-sized particulates with a uniform dispersion provide effective resistance by impeding grain boundary sliding and dislocation movement, besides the alloying effect of increasing elasticity modulus of the solder.

1 INTRODUCTION

The reliability and durability concerns are increasing significantly for soldered connections or joints commonly used in microelectronic, optoelectronic and photonic packaging systems. In microelectronic or optoelectronic packaging systems, solder connections/joints provide a crucial function as mechanical support, electrical and thermal interconnections. In service, soldered joints are under both electrical and mechanical interconnections, and thus subjected to a combined load of electrical, mechanical and thermal. It has been commonly agreed that creep and creep fracture resistance as well as thermal fatigue performance of soldered connections/joints are key reliability issues. In particular, in recent years the requirement on increased functionality and miniaturisation of modern electronic and optoelectronic components, where the operational temperatures and stresses increase the demands of mechanical property on soldered joints, has put forward a challenge on development of the solders with excellent anti-creep property. Especially, the creep resistance of solders and connections is critical for optoelectronics and photonics packaging where size

[*] Corresponding author. Email: xzhang@aeromech.usyd.edu.au *or* mexzhang@scut.edu.cn

stability and geometry alignment are highly demanded. Thus, characterization of creep fracture behaviour of solder joints is greatly significant for reliability evaluation and lifetime prediction of those systems. Moreover, lately there is an increasing global concern on use of the solders containing Pb which is regarded toxic to the environment and health, and this concern has brought regulatory and consumer pressure on the electronic, microelectronic and communication industry in many countries to reduce or completely eliminate the use of toxic Pb in most products. Therefore, there is another acute requirement for the solders to be lead-free, besides the requirement of above-mentioned properties [1-7].

In this study, creep fracture behaviour of lap shear joints soldered by a tin-lead based composite solder reinforced by nano-sized metallic particles was investigated at different homologous temperatures, with a comparison to the joints soldered by a lead-free Sn-Ag-Bi alloy solder and a traditional Sn60Pb40 solder; and the creep fracture mechanisms of different solder joints were analysed.

2 MATERIALS AND EXPERIMENTAL

Three solders were used in this work for comparative studies, that is, a nano-sized particulate reinforced tin-lead solder, a lead-free Sn-Ag-Bi alloy solder and a traditional Sn60Pb40 eutectic solder. Table 1 lists the nominal compositions of the solders. The nano-composite solder was fabricated by mixing nano-sized Ag or Cu powders (with a nominal size of 25~35 *nm*) with Sn60Pb40 powder (with an average size of 43 μm) [8]. The lead-free Sn-Ag-Bi solder was in continuous foil form manufactured by rapid quenching technique (with a thickness of 50 μm). The Sn60Pb40 solder was commercially available. The melting-point of the solders was measured by a modulated DSC (TA-Instruments) with a heating rate of 20 °C/min, as also shown in Table 1. The miniature copper dogbone-shaped lap shear joint specimens, with a gauge length of 15 *mm*, were used for creep testing. The single overlap soldered joint was in the middle of the specimen's gauge part which is 1.0 *mm* wide and 0.10 *mm* thick. The overlap length of joints is 1.0 *mm*. This specimen geometry is very close to the geometry of real solder connections in electronic packaging. The creep tests were carried out using a Dynamic Mechanical Analyzer (DMA 2980 model - TA Instruments) under a constant stress level of 18 MPa at different homologous temperatures (i.e., T/T_m, T_m is the melting-point of the solder in Kelvin) changing from 0.65 to 0.78.

Table 1: Solder alloy systems and their melting-points

Solders	Melting-point	Fabrication method
Nano-comp. solder: Sn60Pb40-Ag/Cu(V_f<3%)	183~200 °C	By mixing alloy powders
Lead-free solder: Sn-Ag-Bi (Ag+Bi<8%, wt)	210~228 °C	By rapid quenching
Eutectic Sn60Pb40	183~195 °C	Commercial available

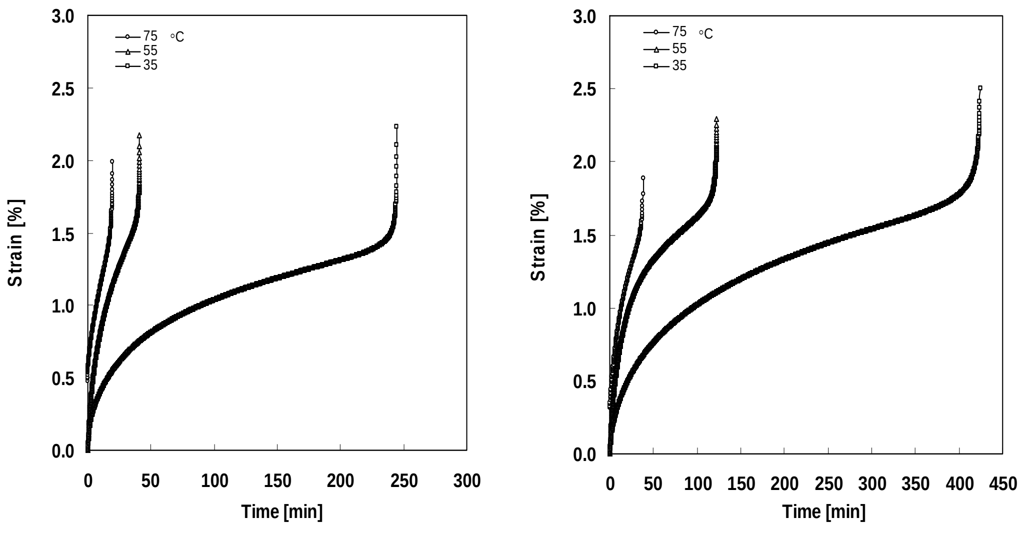
3 RESULTS AND DISCUSSION

3.1 Characteristics of creep fracture behaviour of soldered joints

The creep behaviour of soldered joints was characterized by loading the joint specimens and measuring evolution of strain against elapsed time under a given temperature and a constant stress. The typical creep curves of strain *versus* time for Sn60Pb40 and nano-composite solder joints under a tensile stress of 18 MPa at three temperatures (35, 55 and 75°C, corresponding to homologous temperatures of 0.68, 0.72 and 0.78) are shown in Fig.1. It is clear that both solders' joints show the typical creep deformation feature. The curve consists of three regimes, that is, primary creep, steady-state creep and tertiary creep. For the steady-state creep stage, the rate at which the strain occurs can be expressed by following:

$$\frac{d\varepsilon}{dt} = C\sigma^n \qquad (1)$$

where ε is the transient strain, σ the applied stress, C a proportionality constant, and n the stress-exponent. The time corresponding to the creep rupture in tertial creep state, is defined as creep life of the joints. It is clear that the creep life of all three solders' joints obviously decreases as the test temperature increases. Also it can be seen that the nano-composite solder joints have longer creep life than Sn60Pb40 solder joints at all temperatures tested. It should be indicated that at elevated temperatures (i.e., 55 and 75 °C) both solders' joints also show the typical creep deformation characteristics as that at relatively low temperature of 35 °C, if their creep curves are expressed in a small scale of time-axis.



(a) Sn60Pb40 solder joints (b) Nano-composite solder joints

Figure 1: The creep curves of solder joints at three different homologous temperatures

Figure 2 shows a comparison of creep curves for Sn60Pb40, lead-free Sn-Ag-Bi and nano-composite solder joints, under a tensile stress of 18 MPa at 75°C (i.e., $T/T_m=0.78$). It is clear that lead-free Sn-Ag-Bi solder has much better anti-creep performance compared to Sn60Pb40, and a superior creep resistance to nano-composite solder. It is worth indicating that at relatively low temperatures, Sn-Ag-Bi solder joints exhibit much better creep resistance than other two solders; for example, under the same stress level (18 MPa) at test temperatures of 35 and 55 °C, Sn-Ag-Bi solder joints did not fail after 100 hours (a longer test time than this has exceeded capacity of the equipment used, i.e., DMA).

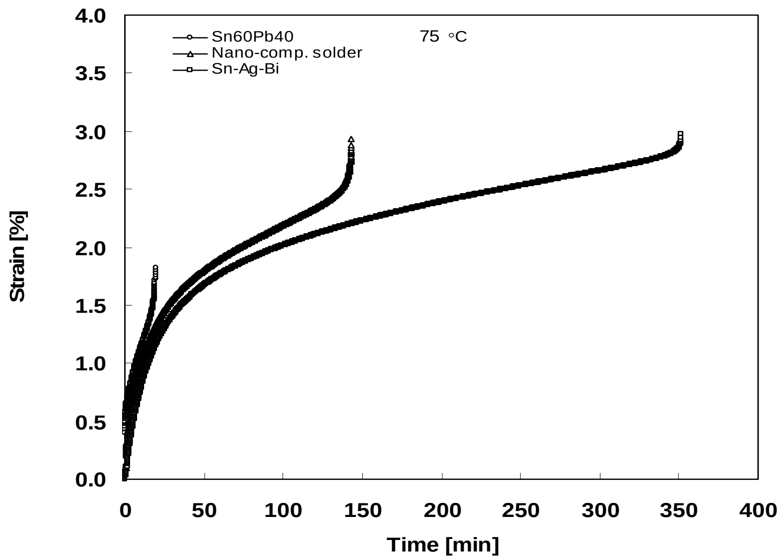
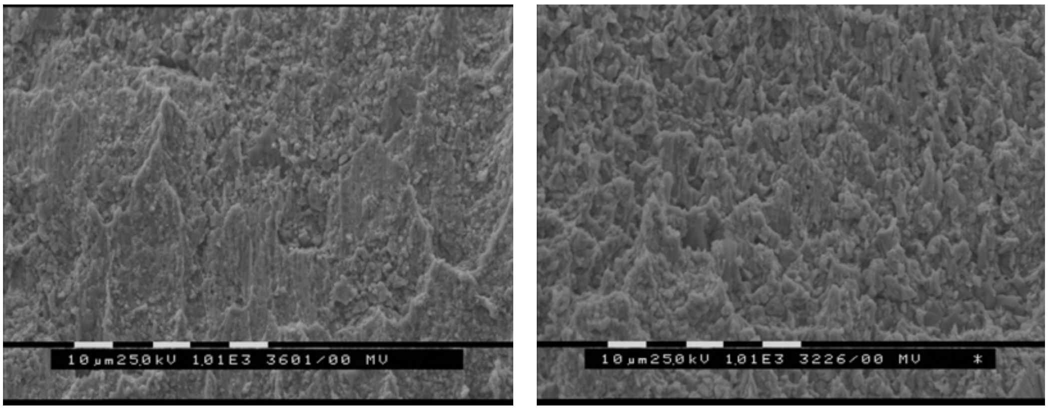


Figure 2: A comparison of the creep behaviour of three solder joints

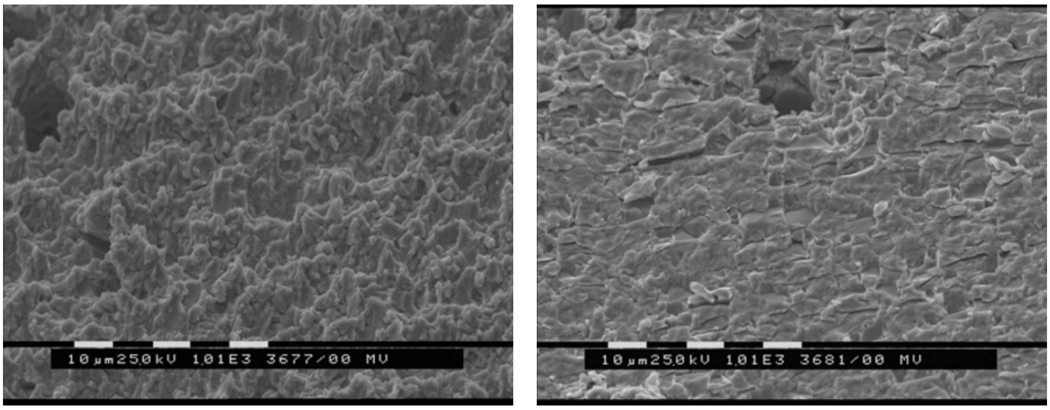
3.2 Creep fracture mechanism of Sn60Pb40, Sn-Ag-Bi and nano-composite solders

The observations of fractographies of the solder joints after creep fracture show that a progressive shear deformation occurred as the main creep failure mechanism, see Figs.3 and 4. In particular, Sn60Pb40 joints deform dominantly by transgranular sliding, see Fig.3 (b) where obvious sliding fracture feature exists; while Sn-Ag-Bi and nano-composite solder joints creep by intergranular mechanism through grain boundary sliding and boundary voids growth; especially grain boundary wedge cracks were found on Sn-Ag-Bi joint creep fractography, see Fig.4(b). Essentially, creep is a slow rate plastic deformation in materials, the plastic deformation occurs actually by sliding blocks of the crystal over another along the crystallographic slip planes. The slip is the result of the dislocation motion, which in turn is because of the lattice imperfection of the material.



(a) Sn60Pb40 solder joint (b) Nano-composite solder joint

Figure 3: Morphology of fractographies of two solder joints after creep fracture (75°C)



(a) at central position of the joint fractography (b) grain boundary wedge microcracks

Figure 4: Fractographies of the lead-free Sn-Ag-Bi solder joint after creep failure (at 75°C)

For metals or alloys, the creep deformation and failure occur mainly by three mechanisms: 1) intergranular creep mode, the most common mechanism of creep fracture in long-time creep failures; 2) transgranular creep fracture, generally occurred in short-time creep failures; and 3) Point rupture fracture due to dynamic recovery or recrystallization at high temperatures and low stress levels. As shown in Figs.3 and 4, Sn-Ag-Bi and nano-composite solder joints failed by intergranular creep fracture. The nano-composite solder has an enhanced creep resistance without sacrificing its ductility. The enhancement mechanism is that uniformly dispersed nano-sized particulates provide the effective resistance by impeding the grain boundary sliding and dislocation movement. Also, very importantly, the diffusion of Ag and Cu atoms to Sn-Pb matrix enhances the alloying effect besides a benefit in reducing surface tension of the solder [9], and thus increases the solder's elasticity modulus which has a significant influence on creep property. This is also true for lead-free Sn-Ag-Bi solder. Moreover, for polycrystals, grain size has an important influence on yield strength, fatigue and creep property of materials. These influences would rather be the effects of grain boundaries. The ratio of grain-boundary surface *S* to the volume *V* is related to the average diameter *D* [10], and expressed by:

$$\frac{S}{V} = \frac{2}{D} \qquad (2)$$

Clearly, a decrease in grain size results in an increase in specific grain boundary surface. This actually means an increased impediment to dislocation motion and grain boundary sliding. The nano-composite solder has a smaller grain size than Sn60Pb40 [8], this provides an additional benefit to creep property.

4 CONCLUSIONS

(1)The solder joints show the same typical creep behaviour as the bulk materials.

(2)Sn60Pb40 solder joints deform dominantly by transgranular sliding, Sn-Ag-Bi and nano-composite solder joints creep by intergranular mechanism through grain boundary sliding and grain boundary voids growth.

(3)The nano-composite solder has superior anti-creep performance to Sn60Pb40 solder. The reason of enhancing creep property of the solder is that uniformly dispersed nano-sized metal particulates provide effective impediment to the dislocation movement and grain boundary sliding, besides the alloying effect.

(4) Lead-free Sn-Ag-Bi solder has more superb creep resistance than both Sn60Pb40 solder and tin-lead based nano-composite solder.

REFERENCES

[1] Plumbridge, W. J. Solders in electronics, Journal of Materials Science, 31:2501, 1996.

[2] Hua, F. and Glazer, J. Lead-free solders for electronic assembly, Design and Reliability of Solder Interconnections. Mahidhara, R. K., and Frear, D. R. et al., Eds., the Minerals, Metals and Materials Society, Pennsylvania, USA, 65-73, 1997.

[3] Richards, B.P., Levoguer C.L., Hunt, C.P., Nimmo, K., Peters, S. & Cusack, P. Lead-free soldering:an analysis of current status of lead-free soldering, Rpt., Dept. Trade & Ind., 1: 1999.

[4] Bradley, E. and Hranisavljevic, J. Characterization of melting and wetting of Sn-Ag-X solders, IEEE Transactions on Electronic Packaging Manufacturing, 24: 255, 2001.

[5] Chen, Z.G., Shi, Y.W. and Xia, Z.D. Study on microstrucutre of a lead-free solder Sn-Ag-Cu-RE and its soldered joints, Journal of Electronic Materials, 31:1122, 2002.

[6] Tu, K. N., Gusak, A. M. and Li, M. Physics and materials challenges for lead-free solders, Journal of Applied Physics, 93:1335, 2003.

[7] Dorn, L., Herbert, F. and Shrestha, S. Pb-free solders under the laser beam, Proc. of System Integ. in Micro Electronics, Exhib. & Conf., Nuernberg, Germany, 27-29 July 2000, 349-357.

[8] Zhang, X. P., Shi, Y. W., Ye, L. and Mai, Y. W. A tin-based composite solder reinforced by nano- sized particulates and soldering ability, ACCM-4, Sydney, Australia, July 2004, A-688.

[9] Zhang, X. P., Wang, H. and Shi, Y.W. Influence of minute amount of elements Bi, Ag and In on surface tension and soldering process performance of tin-lead based solders, Journal of Materials Science: Materials in Electronics, 15:511, 2004.

[10] Dieter, G. E. Mechanical metallurgy. New York: McGraw-Hill, 3rd Ed., 1986.