The Influence of Strain Rate and Temperature on the Deformation Behaviour of 63Sn/37Pb and 60Sn/40Pb Solder Alloys

Woei-Shyan Lee, Lien-Wen Chen and Lu-Ting Yeh

Department of Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan, R. O. China

The influence of strain rate and temperature on plastic deformation behaviour of 63Sn/37Pb and 60Sn/40Pb solder alloys is investigated by means of a computer controlled servo-hydraulic machine over a temperature range of -40 to 80°C at constant strain rates of 10^{-3} , 10^{-2} and 10^{-1} s^{-1} . The fracture characteristics of deformed specimens are analyzed using scanning electron microscopy and correlated with macroscopic behaviour. The results indicate that the flow stress of both alloys is largely dependent on strain rate and temperature. The 63Sn/37Pb alloy, however, is stronger than 60Sn/40Pb over the range of 25 to 300°C . The change in flow behaviour is related to differential strain rates and temperature sensitivities. Over the strain rate and temperature range studied, 60Sn/40Pb exhibits higher strain rate and temperature sensitivities than 63Sn/37Pb. 60Sn/40Pb rupture resistance is found superior to 63Sn/37Pb in light of fracture observations revealing an absence of damage as well as an absence of flow instability. 63Sn/37Pb fracture is catastrophic at a strain rate of 10^{-3} s^{-1} and is characterized by shear. With decreasing test temperature, more edge cracks appear due to enhanced brittleness. The use of a deformation constitutive equation in combination with the parameter values obtained through these tests allows for an accurate description of the deformation behaviour of both tin-lead alloys over the range of conditions used in this study.

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1. Introduction

Tin-lead alloys are used extensively in integrated circuit (IC) packages and semiconductor devices as solder joint materials because of their high electrical conductivity, low melting point, good corrosion resistance and excellent chemical stability.¹⁻³⁾ For surface mount packaging, the solder joints are the only electrical and mechanical connections between the surface mounted component and the printed circuit board. During the soldering operation and subsequent joint life, stress induced either thermally or mechanically in these joints can be high, especially when the circuit board component assemblies are encapsulated. As a result of imposed stress, the solder joint experiences elastic, plastic and viscoplastic deformations.⁴⁻⁶⁾ Eventually these deformations cause the accumulation of microcracking and damage in the solder joint. When the damage energy exceeds the material's crack initiation energy, the initiation of cracks becomes inevitable. Designing solder joints with improved mechanical performance and fracture resistance requires better understanding of the deformation behaviour of bulk solder materials over a wide range of strain rates and temperatures.

Since tin-lead alloys are strain rate and temperature sensitive materials, their stress-strain and fracture behaviours are significantly affected by these two deformation factors and can be described in terms of different mechanisms.⁷⁻⁹⁾ Some studies have been performed on tin-lead solder with different compositions under a wide range of conditions.¹⁰⁻¹⁸⁾ For instance, the deformation of Pb-Sn eutectic alloys has been studied by Grivas *et al.*,¹¹⁾ with results showing that both conventional and superplastic deformation behaviours occur simultaneously via independent mechanisms. The thermal fatigue fracture studies of Pao *et al.*¹³⁾ for PbSn solder joints indicated that the predominant failure mode was the initiation of a crack near the Al_2O_3 /solder interface and subsequent propagation into the joint, resulting in a mixed transgranular and

intergranular fracture. Vaynman *et al.*¹⁵⁾ reported effects of strain range, temperature, frequency and hold time on isothermal fatigue of low-tin lead based solder and showed that high lead solder exhibited cyclic hardening and stress saturation during total strain controlled tests. A creep rupture model based on both micromechanics and fracture mechanics has been developed by Wong *et al.*¹⁶⁾ to predict the two-phase eutectic solder creep-resistance process. Unfortunately, most of these researchers have concentrated on mechanical properties such as tensile or shear strength, creep rupture resistance, or fatigue resistance under very low strain rate levels (10^{-8} to 10^{-3} s^{-1}). No significant information is available as to the mechanisms of compressive deformation behaviour of bulk solder materials at relatively high strain rates ($>10^{-3} \text{ s}^{-1}$). Therefore, the goal of the present work is to investigate the effects of strain rate and temperature on the compressive deformation behaviour of 63/37 and 60/40 tin-lead alloys at strain rates of 10^{-3} , 10^{-2} and 10^{-1} s^{-1} over a temperature range from -40 to 80°C . A strain, strain rate and temperature dependent equation is used to model the observed deformation behaviour. The relative behaviour of both 63/37 and 60/40 tin-lead solder materials is also compared in order to determine, quantitatively, the best solder alloy for a given application.

2. Experimental Procedure

Two types of solder alloys, 63Sn/37Pb and 60Sn/40Pb, were used in this study. The tested material was prepared by melting appropriate proportions of tin and lead, both of 99.99 pct purity, in air and air-casting into a copper mould of dimensions 10 mm $\times$ 38 mm $\times$ 95 mm. These ingots were homogenized at 433 K for 72 h in a silicon oil bath. The final composition of the alloy was checked by chemical analysis. Cylindrical specimens of 8 mm in diameter and 8 mm in height were then machined by traveling-wire EDM from the ingot billet. During machining, the edges of the specimen

were chamfered to avoid fold-over in the initial stages of compression. A commercial molybdenum disulfide (Molykote) was used as lubricant.

Compression tests were carried out at temperatures ranging from -40 to 80°C at constant strain rates of 10^{-3} , 10^{-2} and 10^{-1} s^{-1} by means of a computer controlled servo-hydraulic machine (DARTEC, Stourbridge, West Mid-lands, UK). This machine was equipped with an exponential decay of the actuator speed so that constant true strain rates in the range 10^{-3} to 10^1 s^{-1} could be imposed on the specimen. All the specimens were deformed continuously to a true strain of 0.7. For temperature testing, the low temperature was obtained by controlling the flow of liquid nitrogen into an insulated environmental chamber surrounding the specimen. The high temperature was obtained by enclosing the specimen in a clam shell radiant-heating furnace with automatic temperature control. Specimen temperature was monitored with one Chromel-Alumel thermocouple attached directly to the specimen. Temperature was controlled to within $\pm 1^\circ\text{C}$. The load-stroke curves obtained from the compression tests were converted into true-stress—true-plastic strain curves by subtracting the elastic portion of the strain and using the standard equation for true stress and true strain calculations.

Following mechanical testing, fracture feature observation was conducted. Sections of the fracture surface were treated with standard metallographic procedures for microscopic examinations. Observation of the fracture features was carried out with a Jeol JXA-840 scanning electron microscope operating at an acceleration potential of 2.5 kV.

3. Experimental Results and Discussion

The true stress-strain curves of 63/37 and 60/40 tin-lead alloys deformed at -40 , 25 and 80°C under strain rates of 10^{-3} , 10^{-2} and 10^{-1} s^{-1} are shown in Figs. 1(a) and (b), respectively. Both alloys exhibit highly deformability, with flow stress, strain hardening rate and the shape of the flow curve being sensitively dependent on strain rate and temperature. For a given temperature, the flow stress increases with the strain rate, but it decreases with an increase of temperature under a specific strain rate. If we compare the difference in flow stress resulting from both strain rate and temperature, it is clear that flow stress is more strongly influenced by temperature. In terms of strain hardening effects, it is found that increasing strain rate and temperature results in a decreasing rate of strain hardening. A distinct strain hardening behaviour appears at our low temperature of -40°C , while a steady-state plastic flow is observed at our high temperature of 80°C . Although the curve shapes and flow characteristics of both 63Sn/37Pb and 60Sn/40Pb alloys are similar, for a given strain rate and temperature, the flow resistance of the 63Sn/37Pb alloy is always greater than that of the 60Sn/40Pb alloy.

Based on the results shown in Fig. 1, the strain rate sensitivity, defined in incremental form as $\beta = d\sigma/d\ln\dot{\epsilon} = (\sigma_2 - \sigma_1)/\ln(\dot{\epsilon}_2/\dot{\epsilon}_1)$, of the flow stress as a function of temperature for both 63/37 and 60/40 tin-lead alloy at a true strain of 0.4 are given in Fig. 2. At all temperatures investigated, the strain rate sensitivity decreased continuously with temperature for both alloys. The low value of strain rate sen-

Fig. 1 Flow stress-strain curves of (a) 63Sn/37Pb and (b) 60Sn/40Pb alloys deformed at different strain rates and temperatures.

Fig. 2 Variations of strain rate sensitivity as a function of temperature for deformation at a true strain of 0.4 under different strain rate ranges.

Fig. 3 Variations of temperature sensitivity as a function of strain rate under different temperature ranges.

sitivity obtained at 80°C suggests that thermal softening effects dominate the deformation process, thereby reducing the strain hardening rate. Comparison of strain rate sensitivity also shows that 60Sn/40Pb strain rate sensitivity is higher than 63Sn/37Pb for a given temperature. Since test temperatures have a strong effect on flow stress, this dependence may be represented quantitatively as a temperature sensitivity $n_a = \ln(\sigma_2/\sigma_1) / \ln(T_2/T_1)$, where the flow stresses σ_2 and σ_1 are obtained in tests conducted at the constant temperatures T_2 and T_1 respectively, under the same strain rate value, and $T_1 = 25^\circ\text{C}$. The plot of Fig. 3 shows the variation of average temperature sensitivity with strain rate for both alloys under two different temperature ranges. For both specimens, the temperature sensitivity decreases with increasing strain rate for each temperature range, but the 60Sn/40Pb alloy shows a sharper decrease compared with the 63Sn/37Pb alloy. In addition, for a given strain rate, the temperature sensitivity obtained at the high temperature range is greater than that of the low temperature range, especially for 60Sn/40Pb. In fact, temperature sensitivity is one of signs indicating thermal softening of the material for deformation processes; the more the temperature sensitivity increases, the more the flow resistance decreases.

Fracture features of both alloys are examined by scanning electron microscopy. In the case of 60Sn/40Pb, under all the deformation conditions, no fractures appear in the specimen. In contrast, 63Sn/37Pb deformed at a strain rate of 10^{-3} s^{-1} under all three tested temperatures shows catastrophic shear failure along a plane inclined at an angle of about 45° with respect to the compression axis as a result of true deformation instability (Fig. 4). If we focus on the equatorial plane of the cylindrical surface, more edge cracking is observed as the temperature decreases. Examination of the fracture surface shows that at the high temperature of 300°C , Fig. 5(a), transgranular fracture occurs along the planes of maximum shear stress without large secondary cracks. The presence of fractured soft-appearing isolated knobbls on the transgranular fracture regions demonstrate that visco-plastic behaviour exists in the instability shear regions during the high temperature deformation process. As the test temperature decreases to 25 and -40°C , a distinctly different fracture morphology is observed. At 25°C , Fig. 5(b), localized plastic flow is evident at the fracture region. The flow striation lines are closely

Fig. 4 SEM micrographs of 63Sn/37Pb after fracture at 10^{-3} s^{-1} and at (a) 80°C , (b) 25°C , (c) -40°C .

spaced and well aligned with the shear direction, which confirms the existence of unstable flow due to flow localization. Significant amounts of internal cracks are also present on the surface. Similar fracture morphology is observed in the specimens deformed at -40°C , Fig. 5(c), but the flow striation areas are relatively shallow and flat, indicating a greater brittleness in the low temperature specimens.

Finally, in order to describe the flow response of both tin-lead alloys in terms of a constitutive relationship form that can be used in computer code to model and predict solder behaviour, the data in the plots of Fig. 1 are used to determine the material constant of the constitutive equation,¹⁹⁾

$$\dot{\epsilon} = AF(\sigma) \exp(-Q/RT) \quad (1)$$

where $F(\sigma)$ is a function of the applied stress and has following possible forms:

Fig. 5 Fracture surface features of 63Sn/37Pb observed at 10^{-3} s^{-1} and at (a) 80°C, (b) 25°C and (c) -40°C.

$$F(\sigma) = \begin{cases} \sigma^n & \text{if } \alpha\sigma < 0.8 \\ \exp(\alpha\sigma) & \text{if } \alpha\sigma > 1.2 \\ [\sinh(\alpha\sigma)]^n & \text{for all values of } \sigma \end{cases}$$

The form of $F(\sigma) = [\sinh(\alpha\sigma)]^n$ is chosen for the present work, whereupon eq. (1) may be rewritten as follows:

$$[\sinh(\alpha\sigma)]^n = A\dot{\epsilon} \exp(-Q/RT) \quad (2)$$

where α , n and A are the experimental constants, Q is the activation energy, R the gas constant and T is the absolute temperature (K). Table 1 lists the experimentally determined material constants for both 63Sn/37Pb and 60Sn/40Pb alloys. By using these specific material constants in eq. (2), the flow stress-strain values can be calculated for strain rates between 10^{-3} and 10^{-1} s^{-1} and temperatures between -40 and 80°C

Fig. 6 Comparison between predicted and measured true stress-true strain curves for 63Sn/37Pb deformed at (a) 10^{-3} s^{-1} and (b) 10^{-1} s^{-1} .

Table 1 Materials constants for 63Sn/37Pb and 60Sn/40Pb alloys.

Alloy	α	n	Q (kJ/mol)	$\text{Ln}A$
63Sn/37Pb	1.4×10^{-3}	9.66	57.09	$-53.122 + 3.161\epsilon$ $-2.84\epsilon^2 + 0.808 \ln T$
60Sn/40Pb	1.1×10^{-3}	11.48	53.17	$-56.324 + 2.367\epsilon$ $-3.064\epsilon^2 + 1.80 \ln T$

at true strains of $0.02 \sim 0.7$. Figures 6 and 7 show an example of the comparison between calculated and experimental curves for 63Sn/37Pb and 60Sn/40Pb deformed at different temperature under strain rates of 10^{-1} and 10^{-3} s^{-1} , respectively. The agreement between measured and predicted curves is reasonable. In the worst case, the average error in the flow stress estimate is 4.23% and the standard derivation

Fig. 7 Comparison between predicted and measured true stress-true strain curves for 60Sn/40Pb deformed at (a) 10^{-3} s^{-1} and (b) 10^{-1} s^{-1} .

is 2.7%.

4. Conclusions

The deformation characteristics of both 63Sn/37Pb and 60Sn/40Pb alloys by compression have been determined over practical strain rate and temperature ranges. The results show

that both strain rate and temperature affect strongly the stress-strain response of the tested alloys. Flow stress increases with increasing strain rate or with decreasing testing temperature. However, the 63Sn/37Pb alloy is found to be stronger than 60Sn/40Pb alloy over the range of 25 to 300°C . The observed flow behaviour of the two alloys can be described successfully by a proposed constitutive equation. The calculated flow curves are in close agreement with the measured data. Fracture observations reveal that the rupture resistance of 60Sn/40Pb is better than that of 63Sn/37Pb in view of the absence of damage as well as flow instability. The fracture of 63Sn/37Pb is catastrophic at a strain rate of 10^{-3} s^{-1} and occurs at an angle of 45° with respect to the compression axis. Finally, it is noted that fracture surface features vary drastically with testing temperature.

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