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Shear punch creep behavior of cast lead-free solders

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ABSTRACT

Creep behavior of the tin-based lead-free Sn–2Bi, Sn–5Sb, and Sn–9Zn, binary alloys was studied by the newly-developed shear punch creep testing (SPCT) technique in the temperature range 298–375 K. Assuming a power law relationship between the creep rate and shear stress, stress exponents of 8.4–11.4, 8.5–11.5, and 6.4–9.3 and average activation energies of 63.4, 61.4 and 40.2 kJ mol^{-1} were obtained for Sn–2Bi, Sn–5Sb, and Sn–9Zn, respectively. These creep parameters are in good agreement with those determined by tensile, impression, and indentation creep testing of the same materials reported in the literature. Among all tested materials, as indicated by their minimum creep rates, the solution hardened Sn–2Bi showed the highest creep resistance followed by Sn–5Sb with weak solution and particle hardening effects, and Sn–9Zn that benefits merely from particle hardening. Different creep behaviors of the materials were discussed in terms of their microstructural features.

1. Introduction

Lead-containing solder alloys have extensively been used in the microelectronic packaging industry. This is mainly due to the unique combination of low melting point, wettability, strength, creep and corrosion resistance, and low cost they can offer. The use of these materials, however, has been restricted in recent years due to serious environmental and toxicological concerns [1]. Therefore, a great deal of attention has recently been paid to the development of alternative lead-free solders [2,3]. Accordingly, many lead-free Sn-based alloy systems with different alloying elements such as Ag, Bi, Cu, In, Ni, Sb, and Zn have been developed and their microstructures, mechanical properties and wettability have been reported.

Among the developed lead-free solders, the near eutectic Sn–9Zn solder alloy possesses the lowest melting temperature of about 198 °C, which is very close to the 186 °C of the eutectic Sn–Pb alloy [4]. Moreover, Sn–9Zn benefits from low cost as well as good mechanical properties [2,5] and acceptable creep resistance [6]. Another suitable alternative to lead-containing solders used in electronic packaging is the near-peritectic composition, Sn–5Sb, with a relatively high melting point of 245 °C. It has been reported that while antimony atoms in solution have only a minor effect on the creep resistance [7], alloys with higher concentrations of antimony contain a uniform distribution of SnSb precipitates which provide a significant strengthening effect that reduces the creep rate of the material [8]. Bismuth has also been used as the alloying element in the binary Sn–Bi systems to provide suitable substitutes for Sn–Pb solder alloys [9,10]. The Sn–2Bi alloy with a melting point of about 229 °C can be considered as a potential material for lead-free soldering applications. This material has proved to have very good creep properties due to the solid solution hardening effects of Bi in the Sn matrix [11,12]. Due to the relatively low melting points (186–245 °C) of the above-mentioned solder alloys, even room temperature corresponds to high homologous temperatures in the range 0.58–0.65, at which creep is the most important deformation mechanism. It has been reported that in such cases the material resistance to cyclic creep deformation, which results from thermal mismatch between electronics packages and substrates and/or power on/off cycles, is of great concern [9].

Localized creep testing methods such as impression and indentation techniques have long been used in the assessment of creep behavior of solder alloys [13,14]. These methods can be particularly advantageous when the material is only available as small test pieces or there are difficulties with the machining of samples made of very soft materials such as solder alloys. Shear punch testing with a flat-ended cylindrical punch, which is based on blanking operation, is another miniature testing technique often used for evaluating mechanical properties of materials [15]. Since this technique can be performed under a constant load, the creep behavior can be studied by considering the time dependence of the punch displacement in the recently developed shear punch creep test (SPCT). This test that has been recently applied to the thin rolled Sn–5Sb [16] and Mg alloy sheets [17] has proved to

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produce creep data that are in good agreement with those obtained in tensile creep tests. In both cases, the homogeneous wrought microstructure of the materials guaranteed a reproducible set of data, which was well correlated to the creep characteristics of the materials obtained in tensile creep tests. However, the cast materials with a possibility of microstructural inhomogeneities are usually deemed to be unsuitable for localized evaluation of their mechanical properties. On the other hand, although the bulk creep properties of the solder materials are of prime concern, it is quite desirable to test small pieces of the alloys which are of similar size to the real solder volumes used in microelectronic joints. This would exclude the possibility of size effects, which could adversely affect the creep results.

It is thus the aim of this paper to compare the shear punch creep behavior of three as-cast Sn–2Bi, Sn–5Sb, and Sn–9Zn alloys, having different strengthening mechanisms of pure solid solution hardening, particle and solid solution hardening, and pure particle hardening, respectively. It is also intended to check the correspondence of the creep results with those obtained by other approaches.

2. Experimental procedure

2.1. Materials and processing

The materials used were Sn–2 wt% Bi, Sn–5 wt% Sb, Sn–9 wt% Zn binary alloys. They were prepared from high purity (99.98%) tin, bismuth, antimony, and zinc, melted at 100 K above their melting temperature in an electrical furnace under an inert argon atmosphere, and cast into 16 mm diameter bars. In order to ensure that the slabs had similar initial microstructures, the slabs were homogenized at 0.85 of their melting point (T_m, K) for 10 h. Optical microscopy was used to examine the microstructural evolution of the materials. These specimens were polished with 0.25 μm diamond paste, followed by polishing on a microcloth without any abrasive. Etching was carried out using a 2% nitric acid and 98% alcohol solution at room temperature. X-ray diffraction analysis was carried out on selected samples using Philips X'pert to identify the constitutive phases in each alloy. In these tests, polished samples were exposed to Cu-K_α radiation ($k=1.54056$ Å) in the 2θ range of 20–100° with an accelerating voltage of 40 kV and a scanning speed of 2° min^{-1}.

2.2. Shear punch creep tests

The homogenized cast bars were cut into 1 mm thick slices using an electrodischarge wire cut machine. These slices were then ground to a thickness of about 0.7 mm for the shear punch creep tests. In the SPCT, a schematic view of which is shown in Fig. 1, the sheet sample was securely clamped between two die halves and was subjected to a constant-stress creep, imposed by a flat-ended cylindrical punch. Tests were carried out under constant punch stresses in the range 10–26 MPa and in the temperature range of 298–375 K, using a screw driven MTS material testing system equipped with a three-zone split furnace. A shear punch fixture with a 3.175 mm diameter flat cylindrical punch and 3.225 mm diameter receiving hole was used. After locating the specimen in the fixture, the assembly of the specimen and fixture were accommodated by the split furnace. The assembly was then heated to the test temperature and held for 20 min to establish thermal equilibrium in the testing arrangement before the load was applied. After application of the load, the punch displacement (h) was recorded automatically as a function of time. The required load to perform the test at the initial stress of τ was calculated using the following equation:

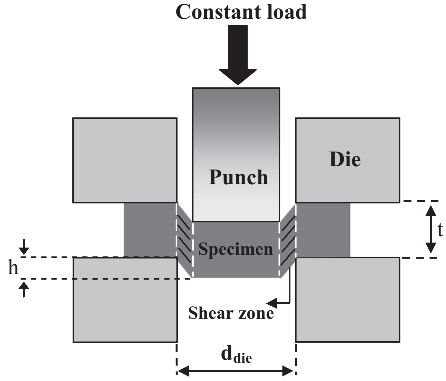

Fig. 1. Schematic representation of shear punch creep die assembly [16].

$$P=\tau\pi dt \tag{1}$$

where P is the punch load, t is the specimen thickness, and d is the average of the punch and die hole diameters.

3. Results and discussion

SPCT curves were obtained by plotting normalized punch displacement ($\delta=h/t$, where h is the displacement) against time. These curves, obtained at $T=310$ K are shown in Fig. 2. As can be seen, similar to conventional tensile creep, the third stage of creep, where creep rate sharply increases with time, can be clearly observed in the SPCT curves. The sudden increase in creep rate at the beginning of stage three of creep process, which is regarded as an indication of the termination of the second stage of creep, can be used in determining the minimum creep rates. Variation of creep rates during the SPCT tests at $T=310$ K are shown in Fig. 3. The presence of minimum creep rates and the three stages of creep are evident in these figures. The existence of the tertiary creep stage in SPCT offers some advantages over other localized testing methods of indentation and impression. These test methods are compressive in nature, in which necking and fracture of the specimen do not occur and thus it is not possible to record a third stage of the curve, which normally occurs in a conventional tensile creep test. This means that creep life of the tested materials cannot be assessed by these approaches. In contrast, SPCT is capable of determining creep life of the materials, due to its nature that includes failure and fracture.

Tensile minimum creep rate ($\dot{\varepsilon}_{min}$) of a metallic material can be correlated to the applied stress (σ) by the well known power-law equation. Assuming an analogy between tensile and shear minimum creep rates ($\dot{\delta}_{min}$) from one side and tensile and shear stresses (τ) from other side, the shear minimum creep rate can be expressed by the well-known Dorn Equation [18], modified for shear deformation as [16]

$$\dot{\delta}_{min}=A\left(\frac{GbD_o}{KT}\right)\left(\frac{\tau}{G}\right)^n\exp\left(\frac{-Q}{RT}\right) \tag{2}$$

where A is the material parameter, G is the shear modulus, b is the Burgers vector, D_o is the frequency factor, K is the Boltzmann's constant, T is the temperature, τ is the applied stress, n is the stress exponent, Q is the creep activation energy, and R is the universal gas constant. Due to the constancy of b, D_o and K, it is possible to obtain the stress exponent, n, at any given temperature from plots of $\ln(\dot{\delta}_{min}T/G)$ versus $\ln(\tau/G)$. Similarly, the creep activation energy Q can be obtained at constant (τ/G) levels from plots of $\ln(\dot{\delta}_{min}T/G)$ versus $1/T$. The elastic modulus of tin is described by E (MPa)= 76,087–109T (K) [19]. The shear modulus (G) of the material can