TIME-DEPENDENT DEFORMATION BEHAVIOUR OF TIN-BASED BEARING ALLOY DURING TRANSFORMATION

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Abstract

Creep behavior of the Pb-61.9wt%Sn-2wt%Zn ternary alloy has been investigated. Constant tensile stress creep experiments were carried out under constant stresses ranging from 5.3 to 7.802 MPa and at the temperature range from 363 to 433 K . The creep strain rate increases and creep life time decreases as the applied stress level and temperature increase. Scanning electron microscopy analysis was performed on crept as well as uncrept parts of the specimens in order to examine the mechanisms of creep deformation. Grain boundary sliding is the possible creep mechanism within the given stress level and temperature.

Keywords: Creep; Pb-61.9wt%Sn-2wt%Zn ternary alloy; tensile stress; life time; Creep mechanism.

1. Introduction

Creep may be defined as the continuous deformation of a material with time when subjected to a constant stress or load. Its characteristics are known to depend on the applied stress, the temperature, and the microstructure of the sample [1]. Creep plays an important role in metal deformation, whenever the homologous temperature exceeds 0.5T (melting point) as for most solder alloys The amount and rate of straining during creep are established by the material itself under the imposed stress and temperature conditions [2]. It plays an important role in the mechanical behaviour of materials. Extensive deformation under constant stresses and without risk of fracture has been observed in a wide variety of alloy systems. Some experimental changes in the mechanical properties of materials were observed while undergoing a phase transformation [3].

A typical creep curve for metals can be divided into three stages. The first phase is the primary creep in which the creep rate decreases with time; the second phase is the steady-state creep in which the creep rate remains unchanged, showing a straight line; and the third phase is the accelerating creep in which the creep rate increases quickly over time until failure. For any creep curves, the second phase or the steady-state creep phase is the most important stage to analyze or predict the actual life time of material. In a creep curve, the slope of this stage gives the value of minimum creep rate which can be further used to determine some parameters in power law.

The traditional tin–lead solders have been widely employed as electrical interconnects in electronic industries. However, the toxic Pb can cause harmful influence on environment and health. On the other hand, the tin–lead solders would no longer satisfy the reliability requirement in high power electronic and optoelectronic components with the smaller size of solder joint and higher mechanical, thermal and electrical load in which the excellent creep resistance is essential[4].

Many Pb–Sn alloys are used in structural applications where creep resistance becomes an important property. One of the obvious ways to improve ductility is by adding alloying elements, and many studies have been performed, resulting in continuous improvement of Pb–Sn alloys. For this purpose, it is necessary to understand how the creep parameters change with alloying additions, repeated thermal cycles and applied stresses, consequently, the future application of these materials strongly depends on the success of improving their reliability with respect to the structural applications [5].

Creep behaviour of materials is generally affected by the applied stress, the deformation temperature, the microstructure of the examined material and also its grain size. Knowledge of the creep behaviour and the effect of second phase on creep deformation is important for understanding and predicting the creep behaviour of solder alloys and for better alloy design[6].

In this study, the tensile creep behavior of Pb-61.9wt%Sn-2wt%Zn solder alloy was investigated at different temperatures and stress levels. The study of creep behaviour for studied alloy samples under different stresses at high temperatures is aimed to identify the microstructure of the tested samples.

2.Experimental materials and procedures

2.1. Sample preparation

The ternary alloy Pb-61.9wt%Sn-2wt%Zn was prepared from high purity Pb, Sn and Zn of purity 99.99%. The appropriate weights of the elements for the ternary alloy were well mixed with $CaCl_2$ flux to prevent oxidation in a graphite mold. Casting in rod form was performed in a 15 x1 x 1cm graphite mold. The casting rod was annealed at 438K for 50 hours. The ingots were rolled into wires of diameter 1mm. Specimens with a gauge length of 50mm were prepared for tensile testing. In this study, the samples were annealed at 443K for 4 h and then slowly cooled to room temperature at cooling rate $T = 2 \times 10^{-2}$ Ks^{-1}. After this heat treatment, the samples were annealed at room temperature for one week before testing. This procedure permitted a small amount of grain growth and grain stabilization to occur [7].

2.2. Mechanical tests

The strain–time experiments were carried out using a conventional type tensile testing machine described elsewhere [8-11]. Isothermal strain–time experiments were performed under constant applied stresses ranging from 5.3 to 7.802 MPa at different deformation temperatures in the range (363–433 K). The elongation in the wire samples was measured by using a dial gauge sensitive to 10^{-5} m. The experimental error was found to be within ±0.5%. Environment chamber temperature controlled to ±1K could be monitored by using a thermo-computer in contact with the test sample.

3. Results and discussion

For a certain stress level, the continuous strain created during creep process depends mainly on: (i) grain size of the tested sample, (ii) deformation temperature, and (iii) interaction of dislocations and lattice defects with the solute atoms[12,13].

3.1. Features of creep curves

The creep curves of Pb-61.9wt%Sn-2wt%Zn alloy obtained at different deformation temperatures under different applied stresses for wire samples was obtained as shown in Fig. 1. The samples were investigated in the temperature range 363–433 K in steps of 10 K. As observed, raising deformation temperature affected the creep behavior in Fig. 1 from which the creep strain increased with increasing T while the applied stress is kept constant. The increase in the creep strain by increasing T (Fig. 1) for the alloy under investigation may be due to the decrease in density of the effective pinning centers with increasing T, allowing higher slip distances traveled by the moving dislocations. The trend in the creep curves at all the three levels of applied stresses suggests a rapid transition from a short primary creep regime, to a steady state and tertiary creep regime. This transition is easier to observe in the plot of strain rate versus time that is presented in Fig. 2a and b. It can be seen that each curve is characterized by all the three characteristic regions: (I) primary, (II) secondary or steady state, and (III) tertiary. Since the stress and temperature are constants, the variation in creep rates, $\dot{\varepsilon}$, suggests a basic change in the internal structure of the alloy during time.

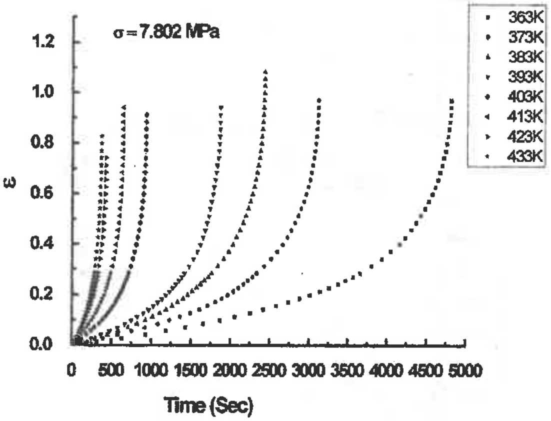

Fig. 1. Representative strain–time curves for Pb-61.9wt%Sn-2wt%Zn samples at different deformation temperatures.

The spcific features of the creep for Pb-61.9wt%Sn-2wt%Zn alloy is shown in Fig. 2a,and b. as creep rate–strain curves. Note that all curves showed a distinct minimum in the creep rate, ε˙, followed by a regime with an extended accelerating deformation rate.

At elevated temperatures , most pure metals and commercial alloys display normal creep curves., which are widely assumed to show clearly defined primary, secondary and tertiary stages. This traditional view seems to be fully consistent with the appearance of the curves presented in Fig. 2a,and b, which includes examples of the variations in creep strain ε with time for three regions of the Pb-61.9wt%Sn-2wt%Zn alloy , where the primary creep rate decreases with time due to strain hardening of the material , Steady-State creep where the strain increases linearly with time. From design point of view, this region is the most important one for parts designed for long service life because it comprises the longest creep duration. The main creep test result is the slope of this region which is known as the steady-state creep rate. During this stage of creep, there is a balance between strain hardening due to deformation and softening due to recovery processes similar to those occurring during the annealing of metals at elevated temperature, and the tertiary creep rate increases rapidly until failure or rupture. The time to failure is often called the time to rupture or rupture .

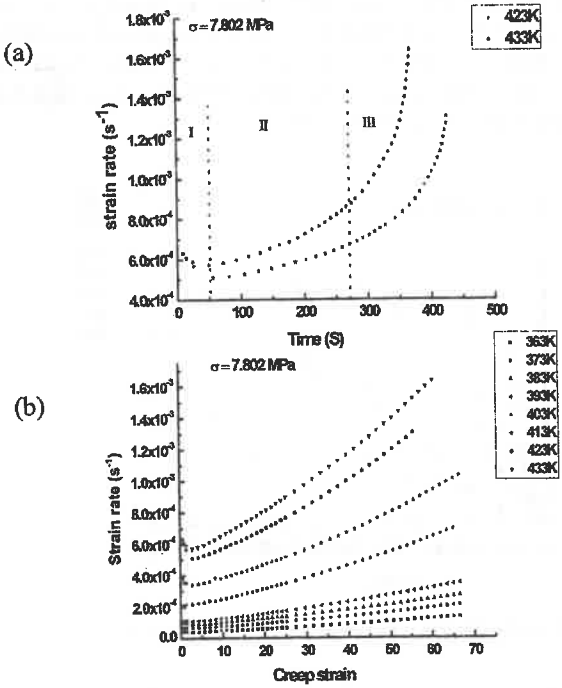

Fig. 2. (a) Creep rate–time curves depicting all the three stages of creep in the temperature 423K and 433K. (b) Creep rate–strain curves in the temperature range between 363 and 433 K for Pb–61.9 wt.% Sn-2 wt.% Zn alloy.

Fig. 3 illustrates the creep behaviour of the Pb-61.9wt%Sn-2wt%Zn alloy at 403K and 423K ,where strain is shown as a function of time for samples tested at various stress levels. In all cases, the alloy specimens displayed normal behaviour with respect to the applied stress and temperature, where at any constant temperature the rate of deformation increased with increasing stress and at any constant stress the rate of deformation increased with increasing temperature.

The creep strain increases with an increase in applied stress level and temperature. Then creep strain rate at any given time can be determined by differentiating creep strain versus time and the minimum rate was taken as the creep strain rate of steady-state stage. The total time from the beginning of primary stage to the end of tertiary stage is defined as the "creep lifetime".

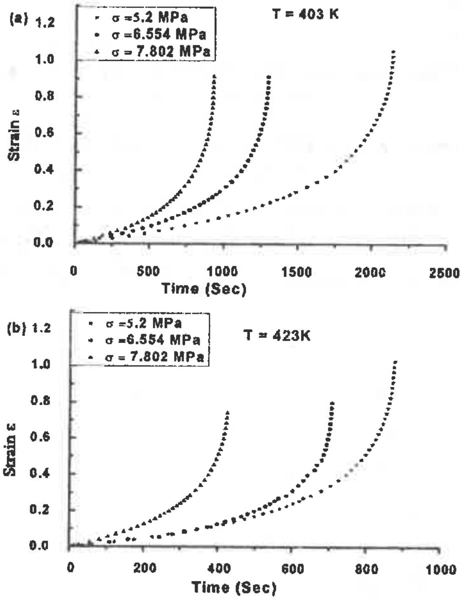

Fig. 3.Typical strain vs. time curves for the Pb-61.9wt%Sn-2wt%Zn alloy at (a)403K and (b)423K under different stresses.

Fig.4 exhibits the temperature dependence of the creep life time of studied alloy, under different stresses, at various temperatures between 363 and 433K. The creep life time was found to decrease with increasing temperature and/or decreasing the applied stress as shown in Fig. 4.As is well known [14], in high temperature engineering design the selection of a material needs to take into account its creep properties. If at a certain temperature this creep lifetime is beyond 1000 sec, the material is normally regarded as a suitable one for applications at that temperature from the standpoint of creep resistance. The diagram in Fig.4 is very useful in engineering practice. For example, a design engineer can use this diagram as are a reference in the selection of studied alloy for high temperature structural applications.

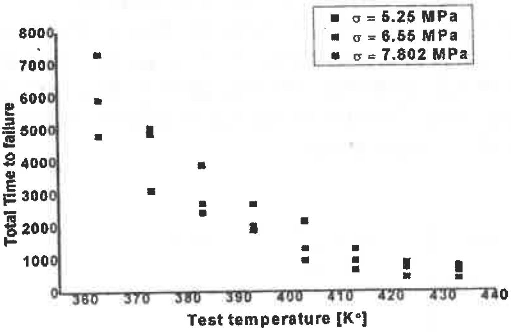

Fig. 4. The creep lifetime as a function of temperature under different stresses.

The variation in flow stress as a function of strain rate for Pb–61.9 wt.% Sn-2 wt.% Zn alloy was plotted in Fig. 5. The flow stress increased with strain rate in a typical sigmoidal curve, at the strain rate ranging from 4×10^{-4} to$1{\cdot}6\times 10^{-3}s^{-1}$.

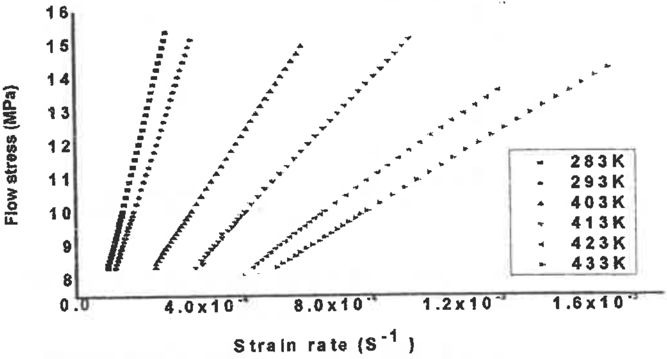

Fig. 5. The variation of flow stress as a function of strain rate in the temperature range between 383 and 433 K for Pb–61.9 wt.% Sn-2 wt.% Zn alloy.

3.2. Microstructure observation.

The microstructure of the specimens crept at various temperatures and applied stresses was observed using a scanning electron microscope (SEM) equipped with energy dispersive X-ray spectroscopy (EDX) analysis.

Fig. 6a-f shows the microstructure investigation for the studied alloy, the samples were crept at various temperatures in the range 373 - 423 K, at a fixed stress of 7.802 MPa. It is clear that the segregation of β-phase (Sn-rich phase) (light) takes place around the columnar grains of the dark phase (Pb-rich phase), thus the number of pinning dislocation points within the grain will decrease and hence the creep rate is increased. Also Fig. 6 shows the deformation microstructure changes with changing temperature. The main feature of all samples is that (a) the grains have an equiaxed shape, (b) some grains are displaced as a whole above or below the original surface, therefore, a lack of focus is observed, (c) the grains and phase boundaries become wavy and curved, (d) the grains are rotated and their boundaries are distorted[15,16].

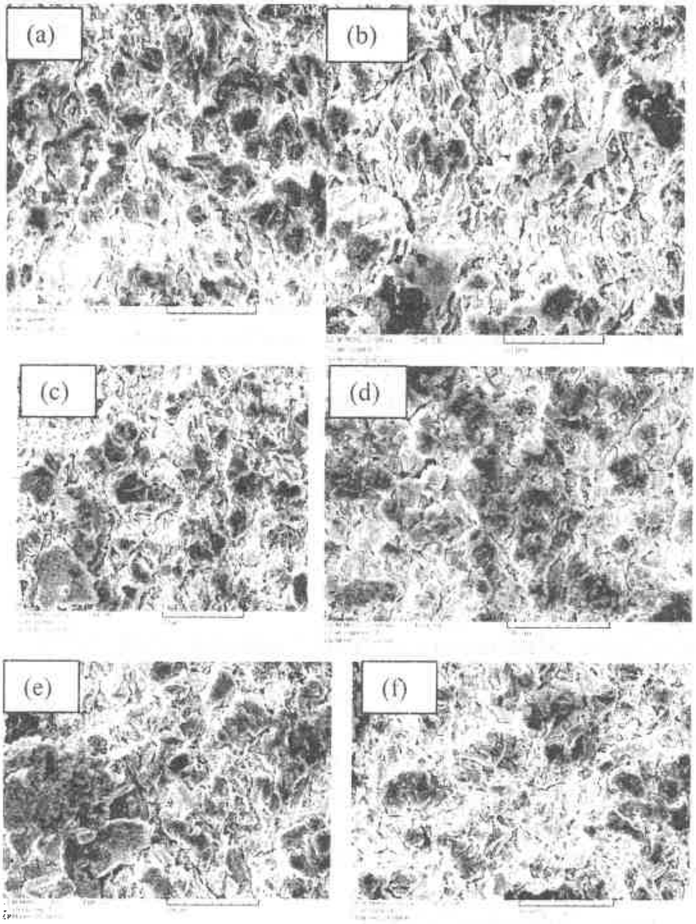

Fig. 6. SEM images of the specimens tested at 7.802MPa under different temperatures :(a) 373; (b) 383; (c)393; (d) 403;(e) 413 and (f) 423 K.

The mechanism by which a metal becomes rate-sensitive, depends on grain size. The important role of composition is its effect on grain growth. The greater the volume of second phase, the lower the rate of grain growth because of the relative immobility of interphase boundaries. Grain sizes were measured using a linear intercept technique. The initial grain sizes were 3.25 ± 0.2μm . The smaller grain size reduces the resistance to the transmission of slip across grain boundaries, which can decrease flow stress and increase the ductility of the alloy.

As for the effect of grain size on creep behavior at high temperatures, many researchers found that there is an optimum grain size for maximum creep resistance (lowest steady state creep rate), i.e., the creep rate goes through a minimum as the grain size is varied [17]. Whether this effect is due to grain boundary sliding or not needs to be examined. However, grain boundary sliding is believed to be the rate controlling mechanism of creep in fine grained materials at high temperatures.

4. Conclusions

The main conclusions to be drawn from this work may be summarized as follows:

(1)The Pb–61.9 wt.% Sn-2 wt.% Zn alloy exhibits the typical creep deformation characteristics. The creep strain increases and creep lifetime decreases with the improved applied stress level and temperature.

(2) The creep strain rate increases and creep lifetime decreases sharply with increasing applied stress level and temperature.

(3) The creep deformation of the Pb–61.9 wt.% Sn-2 wt.% Zn alloy is controlled by grain boundary sliding.

(4) The action of the alloying addition still needs more and more attention.

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سلوك التشوه المعتمد على الزمن للسبيكة التي أساسها القصدير خلال عملية التحول

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خلاصة البحث:

يتناول هذا البحث دراسة سلوك الزحف للسبيكة الثلاثية Pb-61.9wt%Sn-2wt%Zn . اعتمادا على الزمن ،حيث أجريت تجارب زحف إجهاد الشد الثابت عند إجهادات ثابتة تتراوح من 5,3 إلى 7,802 ميجا باسكال وعند مدى درجة حرارة من 363 إلى 433 كلفن. وخلصت الدراسة إلى أن معدل انفعال الزحف يزيد وزمن الزحف ينقص بزيادة الإجهاد المطبق ودرجة الحرارة. وأجري تحليل الماسح الإلكتروني المجهري على العينات لمعرفة آليات تشوه الزحف. وأوضحت النتائج أن انزلاق حدود الحبيبة هي آلية الزحف ضمن الإجهاد ودرجة الحرارة المعطاة.

الكلمات المفتاح: الزحف ،السبيكة الثلاثية Pb-61.9wt%Sn-2wt%Zn ;، ميكانيكية الزحف ، إجهاد الشد، ميكانيكية التشوه ، مدة الزحف .