



## Effect of Deformation on the Mechanical Properties of Sn-5wt%Sb Alloy

Sadiq H. Khoreem<sup>1</sup>, Abdo M. Meftah<sup>2\*</sup> and T. T. Alnahari<sup>3</sup>

<sup>1</sup>Department of Physics (Material Science Research Lab), Faculty of Science, Sana'a University, Yemen.

<sup>2</sup>Department of Physics (Nanoscience Research Lab.), Faculty of Applied Science, Thamar University, Yemen.

<sup>3</sup>Department of Chemistry, Faculty of Applied Science, Thamar University, Yemen.

### Authors' contributions

This work was carried out in collaboration among all authors. Author SHK designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors AMM and TTA managed the analyses of the study. Author AMM managed the literature searches. All authors read and approved the final manuscript.

### Article Information

DOI: 10.9734/AJR2P/2019/v2i430108

#### Editor(s):

- (1) Dr. Khalil Kassmi, Professor, Department of Physics, Faculty of Science, Mohamed Premier University, Morocco.  
(2) Dr. Jelena Purenovic, Assistant Professor, Department of Physics and Materials, Faculty of Technical Sciences, Kragujevac University, Cacak, Serbia.

#### Reviewers:

- (1) Takuo Sakon, Ryukoku University, Japan.  
(2) Subramaniam Jahanadan, Labuan Matriculation College, Malaysia.  
Complete Peer review History: <http://www.sdiarticle4.com/review-history/42127>

Original Research Article

Received 18 March 2019  
Accepted 22 May 2019  
Published 07 November 2019

### ABSTRACT

Sn-5wt%Sb is one of the materials considered for replacing Pb-bearing alloys in electronic packaging. The mechanical response of Sn-5wt% Sb solder alloy has been tested under different strain rates and three deformation temperatures. The behavior of true strain-time of Sn-5wt% Sb solder alloy has been investigated over strain rates of and deformation temperatures of 313, 333, and 353 K. Three-load creep tests were carried out at each temperature for of the wire samples to alloys. The deformation behavior and grain growth mechanism were investigated by strain-time curve analysis and microstructure observations. The results obtained show that the general characteristics of strain-time curve and microstructure of Sn-5wt% Sb alloy sensitively depend on the deformation temperature and strain rate. New free grains have been nucleated in microstructures in the process of dynamic recrystallization. These grains grow during deformation, forming coarser structure and elongation. The dynamic recrystallization and grain growth increase

\*Corresponding author: E-mail: meftah2090@gmail.com, meftah2090@tu.edu.ye;

with increasing deformation temperature and decreasing strain rate. From the steady state creep rate the stress exponent is described in terms of the heat treatment temperatures. The stress exponent (n) were determined to clarify the deformation mechanism. Based on the n values, it is suggested that the rate controlling creep-deformation mechanism is dislocation climb. This study revealed that the solder alloy Sn-5wt%Sb have potential to give a good combination of higher creep resistance and rupture time.

*Keywords: Solder alloys; deformation curves; strain rate; stress exponent.*

## 1. INTRODUCTION

Lead-tin alloys are the dominant solders are used extensively in the electronic industry for electrical and mechanical interconnects. This is because of its superior mechanical properties, low cost, low melting-point, good plasticity, excellent corrosion resistance, and good electrical conductivity [1,2]. But, due to the toxicity of lead present in these solders, environmental and legislation trend to reduce or eliminate the use of lead from a wide variety of uses. So, many studies tend to intensify the work to form a new lead-free solder alloy with improved properties [3,4]. There is a set of the binary alloys chosen as candidates for lead-free solder: Sn-Bi, Sn-Ag, Sn-Zn, Sn-Cu and Sn-Sb, in which Sn is the principal component. Alloys of tin with antimony have received amount of attention because of their high specific gravity, low price, good hardware connection, quick solidification, and high melting temperature (518 K), is the chosen alloy for soldering the spheres used in Ball Grid Array (GBA) and Flip Ball Grid Array (FBGA). that improves its mechanical properties [5,6]. Using this solder alloy inside a component will allow the component to be soldered into its next higher assembly, without the problem of the solder joints inside the component reflowing and creating defects. Also, its high melting-point makes it ideal for soldering leads to silicon diodes, and platinum- or rhodium-iron temperature sensors for operation up to 500 K. The dimensional stability of a solder joints is predicted on the basis of its mechanical properties [7,8]. Investigation of the mechanical properties of Sn-Sb alloys is very important for the use of Sn-Sb solders. Recently, this alloy system was subjected to many studies [9,10], included the effect of rapid solidification as well as the effect of bismuth addition on structure and properties of this alloy system. It is highly desirable to have a solder that has a high melting point, high creep resistance, mechanical strength, ductility, and so on. This solder alloy is often subjected to cycle loading conditions imposed by thermal stresses. Mechanical

responses play an important role at this homologous temperature. The temperature dependence of the stress-strain behavior of the alloy needs to be considered. The occurrence of creep deformation in Sn-5wt%Sb alloy, and its explanation, have not yet been reported. Determinations of these properties are necessary for structural analysis and evaluation of thermal fatigue life of the solder joint. In this paper, the creep deformation behavior of Sn-5wt%Sb is investigated experimentally at different deformation temperatures (DT) and strain rates (SRs). The objective of the present study is to identify the cause and nature of the work-softening of Sn-5wt%Sb solder alloy by determining the effects of SR and DT on the strain -time curve and microstructure of the Sn-5wt.%Sb

## 2. EXPERIMENTAL WORK

Sn-5wt%Sb lead free solder alloy was examined. The compositions were prepared from high purity (99.99%) component materials. All components were melted under vacuum. Casting was done in a graphite mold and the ingot (rod of 1 mm diameter) was swaged to form wire samples of 1 mm diameter and 80 mm in length. Each alloy samples were annealed for 4 hr at temperature of 393K, and then leave in furnace to cold slowly into temperature of 298K. Tensile creep tests were carried out with a computerize tensile testing machine. Creep tests were carried out at temperatures (313- 333-353 k) under different applied stresses ranging from 2.49,6.24 and 9.98MPa using an horizontal testing machine connected to a personal computer via a force sensor and science workshop interface.

## 3. RESULTS AND DISCUSSION

The samples were independently deformed during creep at 383, 413, and 433 K using different stresses of 2.49, 6.24 and 9.98 MPa. We easily transformed the recorded data from the force-displacement tests to true strain-time and strain rate-time curves for the samples. The

creep strain rate (shown in Fig. 2. at any given time is then determined by differentiating creep strain history with respect to time. Typical true strain–time curves obtained are shown in Fig. 1 over the DT and DS ranges examined. At a given DT, this figure shows the effect of SR variations during deformation of the specimens. It should be noted that the tensile strength decreases with the decreasing SR. This is a result of the long time needed for the process of thermal activation and the cycling lifetime increasing with increasing tensile strength of the solder [11]. The improved creep resistance and strength in these alloys have been attributed to the solid-solution hardening effects of Sb [12] and formation of SnSb intermetallic particles [13,14]. In the Sn–Sb alloy system, the near-peritectic Sn–5%Sb alloy, with a melting point of 245°C, has been considered as a potential material having the advantages of good creep resistance [15,14–16] and superior mechanical properties [17]. Since only one sample was used at each stress level and the stress was increased every time the sample reached steady-state deformation, as expected, the creep deformation is small at low stress level and increases dramatically with increasing the tensile stress and with increasing the temperature. Apparently, the similar accelerating effects on creep deformation from the stress, temperature are observed. This suggests that the enlargement of stress and temperature all can reduce the life of electronic devices. In addition, it can be seen that, all the creep strain–time curves obtained in this study display tow classic stages: Namely the primary and secondary creep, which are similar to the

results of conventional creep tests. Nevertheless, the secondary creep, i.e. steady-state creep is mainly concerned about during the following analysis. These results suggest that there always exists a steady state creep deformation under the simulated conditions. The steady-state creep rates were evaluated at each stress level, and the variation of the steady-state creep rate with the applied stress at various temperatures is shown in Figs. 2 each test was continued until the minimum true strain rate was identified. Fig. 2 shows that, as expected, the secondary creep rate increases and the rupture life decreases with increasing stress at each temperature.

Fig. 2 shows the effect of DT and DSR on the strain rate levels at a stress of 2.49 to 9.98 MPa. The tensile strength decreases with increasing DT. This is because thermal activation occurs faster at higher temperatures. This results in the resistance to deformation increasing with decreasing DT and increasing SR. Generally, at low temperatures, the strain increases rapidly on loading, and work-hardening takes place, followed by an intermediate steady-state. In this case, grain-boundary sliding (GBS) with concomitant grain growth may be the dominant mechanism. In the high temperature stage, the flow strain increases rapidly on loading and reaches a peak strain, followed by a gradual decrease. Work-softening is a common phenomenon of many alloys on deformation at high temperatures and SRs. The flow-softening of the curve indicates that occurs [18]. In Figs. 1 and 2, the strain-softening stage is more obvious for higher DTs or lower SRs.

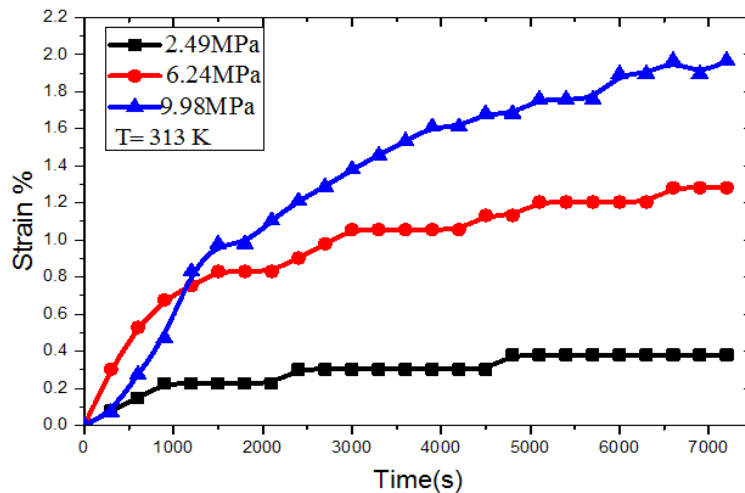


Fig. 1.a. Creep curves at constant temperature T=313K, for Sn-5wt%Sb, & different stress 2.49MPa, 6.24MPa, 9.98MPa

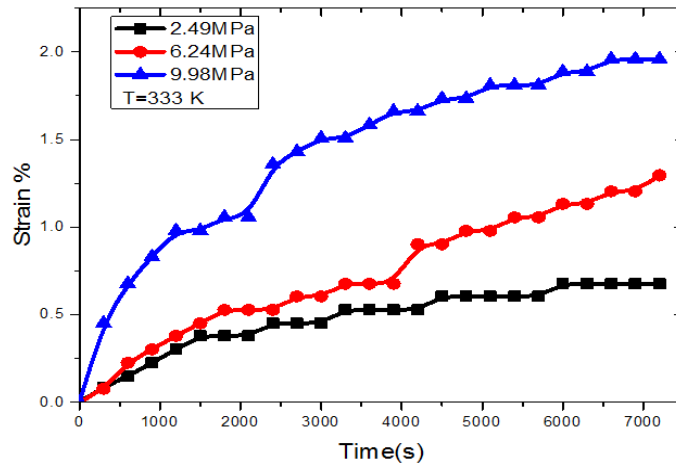


Fig. 1.b. Creep curves at constant temperature  $T=333\text{K}$ , for Sn-5wt%Sb, & different stress 2.49MPa, 6.24MPa, 9.98MPa

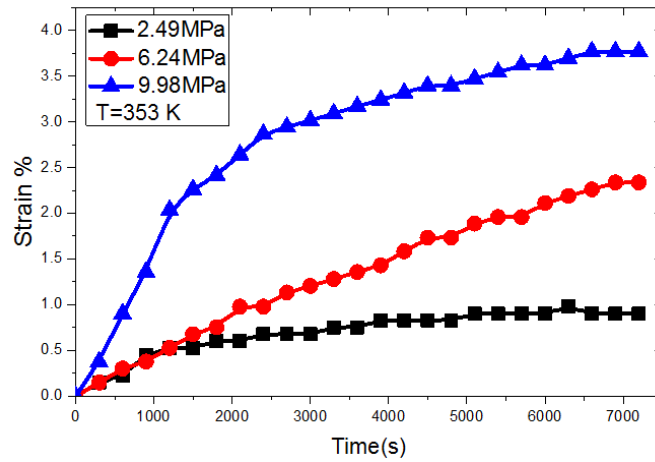


Fig. 1.c. Creep curves at constant temperature  $T=353\text{K}$ , for Sn-5wt%Sb, & different stress 2.49MPa, 6.24MPa, 9.98MPa

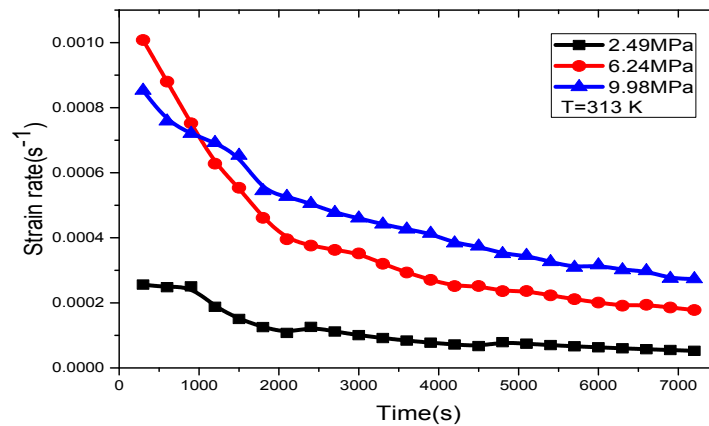


Fig. 2.a. Creep rate – time (0-7200s) curves at constant temperature  $T=313\text{K}$ , for Sn-5wt%Sb, & different stress 2.49MPa, 6.24MPa, 9.98MPa

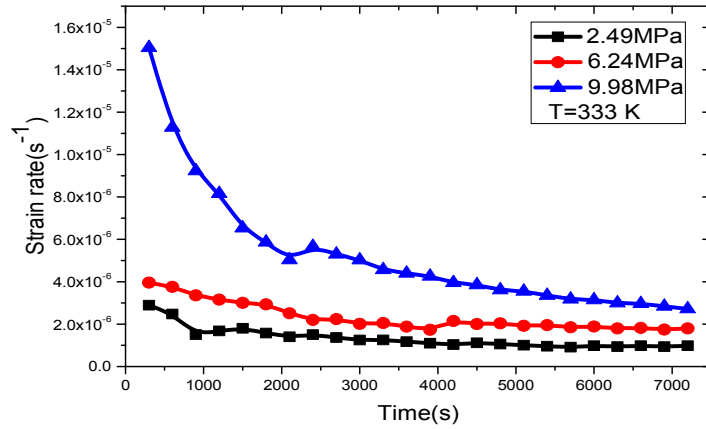


Fig. 2.b. Creep rate – time (0-7200s) curves at constant temperature T=333K, for Sn-5wt%Sb, & different stress 2.49MPa, 6.24MPa, 9.98MPa

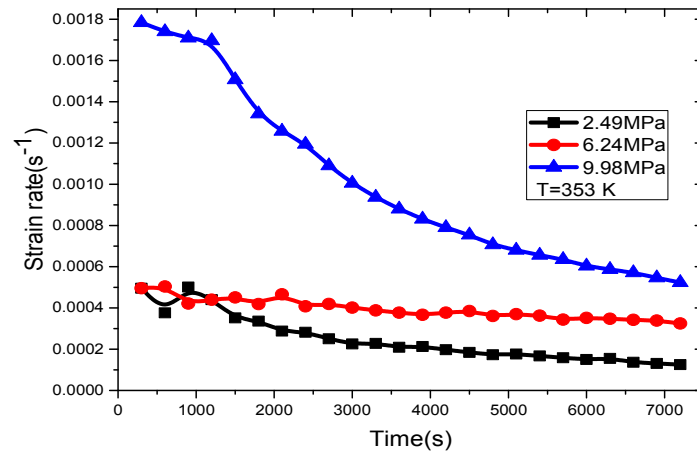


Fig. 2.c. Creep rate – time (0-7200s) curves at constant temperature T=353K, for Sn5wt%Sb, & different stress 2.49MPa, 6.24MPa, 9.98MPa

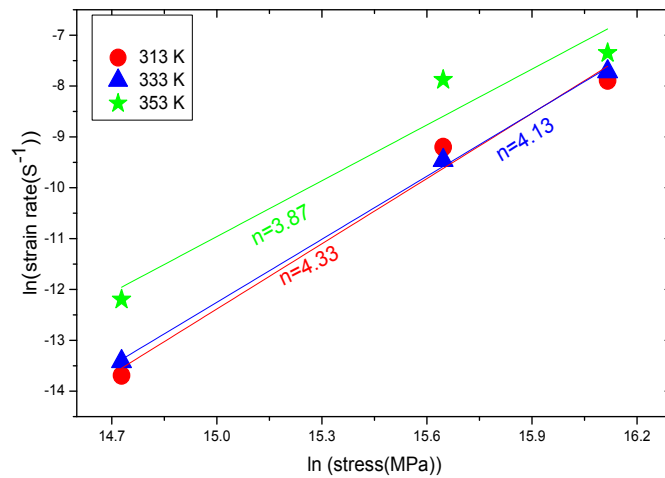


Fig. 3. Stress exponent sensitivity at different temperature

The contribution of this mechanism decreases as the SR decreases and the DT increases. This is attributed to grain growth under these deformation conditions [19]. These curves illustrate the change in creep rate that occurs during the creep test. The variation in strain rates is the result of changes in the internal structure of the material with creep strain and time. During the strain hardening process, the dislocation density gradually increases leading to a decreasing creep strain rate as dislocation mobility is impeded.

Then is work hardening exponent, which characterizes the work hardening ability of materials. The larger the  $n$  value, the stronger the work hardening ability, while the strain distribution of materials is more uniform. This parameter is calculated using the following relation [20].

$$n = \frac{1}{m} = \frac{\partial(\ln \dot{\epsilon})}{\partial(\ln \sigma)}$$

“where  $n$  is the stress exponent,  $m$  is the strain rate sensitivity,  $\sigma$  is the stress, and  $\dot{\epsilon}$  is the strain rate”

It can be observed from Fig. (3), The  $n$  value also decreases with temperature increasing, which shows that a higher strain rate and temperature would reduce the work hardening ability and make a non-uniform strain distribution of alloy during elevated temperature.

The decreases significantly with increasing testing temperature. This signified that the reinforcement strengthening effect was greater at lower testing temperature and high stress regime. Furthermore, creep resistance was more evident at lower testing temperatures. The  $n$  values are change with increasing temperature. From the steady state stage, the values of the stress exponent  $n$  between 3.89 and 4.3 well within the range for dislocation climb controlled creep. However these exponents are typical of dislocation climb-controlled creep [21,22,23] where is the stress exponent ( $n_{creep}$ ) is parameter of the material that could give useful information on the creep controlling mechanisms is in the rang (3 - 8) this agreement with Harry Schoeller, et al. [24]. The decrease of  $n$ -value with increasing temperature is a well-known phenomenon that is attributed to the instability of microstructure at elevated temperatures. Softening and dissolution of second phase particles are possible causes for the observed

instability. This means that the stress exponent becomes temperature dependent for the alloy.

#### 4. CONCLUSIONS

1. The deformation modes in the stress–strain curves, characterized by work-softening and work-hardening with a steady-state, are observed in Sn–5wt%Sb solder alloy.
2. Strain-time curves were examined during creep deformation. The obtained results indicate that the tensile strength of the Sn–5wt%Sb alloy increases with decreasing DT and increasing SR.
3. Results indicate that a drastically changed creep strain rate corresponding to higher stress is observed comparing to that at lower stress level.
4. A higher strain rate and temperature will reduce the work hardening ability and work-hardening rate during elevated temperature.
5. Based on the experimentally determined stress exponent, the rate controlling creep deformation mechanism in 95Sn-5wt%Sb is dislocation climb

#### COMPETING INTERESTS

Authors have declared that no competing interests exist.

#### REFERENCES

1. Chen X, Zhang L, Sakane M, Nose H. Tensile stress–Strain curves modeling of four kinds of solders with temperature and rate dependence. Key Eng. Mater. 2005;297–300,905–911.
2. Kanchanomai C, Miyashita Y, Mutoh Y. Low cycle fatigue behavior and mechanism of a eutectic Sn–Pb solder 63Sn/37Pb. Int. J. Fatigue. 2002;24:671–683.
3. McCormack M, Jin S, Kammlott GW, Chen HS, Appl. Phys. Lett. 1993;63:15.
4. Kamal M, Gouda ES. Cryst. Res. Technol. 2006;41:1210.
5. McCormack M, Jin S, Electron J. Mater. 1994;23:635.
6. Abtey M, Selvaduray G. Mater. Sci. Eng. Rep. 2000;27:95.
7. El-Daly AA, Abdel-Daiem AM, Abdel-Rahman AN, Mohammed SM. Effect of Zn-addition and structural transformation on the creep behavior of Pb–10wt%Sn alloy. Mater. Chem. Phys. 2004;85:163–170.

8. Banks DR, Bunette TE, Gerke RD, Mammo E, Mattay S. Multichip modules. *Process. Int. Conf.* 1994;529–534.
9. Hwang J. *Electronic packaging and interconnection handbook*, McGraw-Hill, New York; 1991.
10. Kamal M, Gouda ES. *Matter. Manuf. Proc.* 2006;21:736.
11. Mochizuki A, et al. Influence of antimony on reliability of solder joints using Sn-Sb binary alloy for power semiconductor modules. *Transactions of The Japan Institute of Electronics Packaging.* 2015;8:8-17.
12. Murty KL, Haggag FM, Mahidhara RK. *J. Electron. Mater.* 1997;26:839–846.
13. McCabe RJ, Fine ME. *Metall. Mater. Trans.* 2002;33A:1531–1539.
14. Mahmudi R, Geranmayeh AR, Bakherad M, Allami M. *Mater. Sci. Eng. A.* 2007;457:173–179.
15. Mathew MD, Yang H, Movva S, Murty KL. *Metall. Mater. Trans.* 2005;36A:99–105.
16. Mahmudi R, Geranmayeh AR, Rezaee-Bazzaz A. *Mater. Sci. Eng. A.* 2007;448:287–293.
17. Mahidhara RK, Sastry SML, Turlik I, Murty KL. *Scripta Metall.* 1994;31:1145–1150.
18. Lin YC, Chen MS, Zhong J. Effect of temperature and strain rate on the compressive deformation behavior of 42CrMo steel. *J. Mater. Process. Technol.* 2008;205:308–315.
19. Takasugi T, Watanabe Y, Inoue H. Dynamic recrystallization and super plastic deformation. *Scripta Mater.* 2000;43:485–490.
20. Edington W, Melton KN, Cutler CP. “Superplasticity” Department of Metallurgy and Materials Science, University of Cambridge, Pembroke Street, Cambridge, U.K; 1976.
21. Kerr M, Chawla N. *JOM.* 2004;65:50.
22. Choi S, Lee J, Guo F, Bieler T, Subramanian K. J. Lucas, *JOM.* 2001;53:22.
23. Huang M, Wu C, Wang L. *J. Electron. Mater.* 2005;34:1373.
24. Harry Schoeller, Shubhra Bansal. ASME International Mechanical Engineering” Congress and Exposition. United States; 2008.

© 2019 Khoreem et al.; This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

*Peer-review history:*

*The peer review history for this paper can be accessed here:*  
<http://www.sdiarticle4.com/review-history/42127>