Solid State Sciences 46 (2015) 107–115

Contents lists available at ScienceDirect

Solid State Sciences

journal homepage: www.elsevier.com/locate/ssscie

The electrical, thermal conductivity, microstructure and mechanical properties of Al–Sn–Pb ternary alloys

C. Alper Billur [a, *], E. Gerçekcioglu [b], M. Bozoklu [a], B. Saatçi [a], M. Ari [a], F. Nair [b]

[a] Department of Physics, Erciyes University, Kayseri, Turkey
[b] Department of Mechanical Engineering, Erciyes University, Kayseri, Turkey

ARTICLE INFO

Article history:
Received 23 August 2014
Received in revised form
25 May 2015
Accepted 12 June 2015
Available online 15 June 2015

Keywords:
Electrical conductivity
Thermal conductivity
Mechanical properties
Micro-hardness
Crystal structure

ABSTRACT

The structural, thermal, electrical and mechanical properties and micro-hardness of four different samples of Al–Sn–Pb ternary alloys (Al-[x] wt. % Sn-10 wt. % Pb) (x = 40, 30, 20 and 10) with constant lead concentrations were investigated for four different samples. Electrical resistivity and conductivity were measured by using (four-point probe measurement techniques) 4PPT techniques. The variations of thermal conductivity were determined by Wiedemann–Franz law (W–F) and Smith–Palmer (S–P) equation using the data obtained from electrical properties. The mechanical properties of the same alloys were obtained by the tensile test and the Vickers micro-hardness test.

1. Introduction

There are many industrial applications by using the bush materials such as the automobile industry. High-speed and long-life of the new bush materials are preferred in this industry. The Al–Sn binary alloys are various bush materials, which supplies a good combination of strength and surface properties. The fatigue strength of Al–40% Sn alloy is more superior than tin-based white metal, and Al–Sn alloys show good mechanical properties, as well. Al–Pb alloys can be an alternative to Al–Sn alloy because of the low cost [1,2]. The solubility of tin in aluminium in the liquid state is limited in Al-30% Sn. So, the Al–Sn alloys are used as an antifriction material. If a part of the Sn in an Al–Sn alloy is replaced by Pb, the Al–Sn–Pb alloy has a lower friction factor and a higher wear resistance because the solubility of Pb is less than Sn in its liquid state [3,4].

In previous studies, issues such as the thermodynamic parameters, the microstructure and tribological properties, heat treatments on microstructures, and interfacial microstructures in Al-based binary and ternary alloys, and Al–Sn–Pb nanocrystalline alloys have been studied by many researchers [1–10]. This present work is different from other studies because the crystal structure, the cell parameters, the grain sizes, the specific heats, thermal, electrical and mechanical properties and micro-hardness of four different Al–Sn–Pb ternary alloys (Al-[x] wt. % Sn-10 wt. % Pb) (x = 40, 30, 20 and 10) with constant lead concentrations have been investigated.

The crystal symmetry, the cell parameters and the grain sizes of the alloy samples were determined with the help of XRD patterns. The specific heats of the Al–Sn–Pb ternary alloys (Al-[x] wt. % Sn-10 wt. % Pb) (x = 40, 30, 20 and 10) were also measured. The electrical conductivity measurements of the samples have been determined by a standard 4 PPT. The thermal conductivity values were deduced by using the electrical conductivities values which were measured with 4 PPT.

In addition, the microstructure properties, surface morphology and chemical compositions of the samples were determined by using the X-ray Diffraction (XRD), Scanning Electron Microscope (SEM), and Energy Dispersive X-ray Analysis methods, (EDX) respectively.

Finally, the mechanical properties for each component of the Al–Sn–Pb ternary alloys were obtained at room temperature with a strain rate of 20 mm/min. The obtained mechanical properties are particularly important, and the application areas of Al–Sn–Pb alloys by obtained mechanical data can be expanded because the information about the mechanical properties of this ternary alloys in the literature for these compositions is insufficient.

* Corresponding author.
E-mail address: cananbillur@erciyes.edu.tr (C. Alper Billur).

http://dx.doi.org/10.1016/j.solidstatesciences.2015.06.005
1293-2558/

2. Experimental procedure

2.1. 1. Sample preparation

The details of the apparatus used for the preparation of the Al–Sn–Pb ternary alloy samples with constant lead concentrations are given elsewhere [for details see refs 11–15]. Sufficient amounts of metallic materials were melted in a vacuum furnace to produce a cylinder approximately 6 cm in length and 1 cm in diameter for use in mechanical properties, and to produce an ingot approximately 2 cm in length and 3 cm in diameter for use the other physical parameters by using 4 N pure Al, Sn and Pb.

2.2. Microstructure measurements

The obtained samples were grounded and polished using standard techniques and the SEM and EDX measurements were then carried out. From the XRD patterns, the crystal symmetry and cell parameters of the samples were determined [16–21].The microstructures of the samples were characterized using a LEO 440 SEM equipped with an EDX spectrometer as well as a computer-controlled image analyser. The Al, Pb, and Sn compositions of the samples were determined using the EDX technique. After each electrical measurement, the chemical compositions of the samples were determined by using the EDX spectrometer with a possible error of up to 1%.

The crystal structure and lattice parameters were determined by using a computer-interfaced Bruker AXS D8 advanced diffractometer, operated in Bragg-Brentano geometry (CuK_α radiation, graphite monochromator, 40 kV and 40 mA) over $10^\circ \leq 2\theta \leq 90^\circ$ angular ranges. The diffractometer had a divergence and receiving slit of 1 mm and 0.1 mm, respectively. The diffraction patterns were scanned in 0.002° (2θ) steps and the diffracted beams were counted with a NaI (Tl) scintillation detector. The samples were grounded with 180–2400 grit SiC paper and polished, and then the X-ray measurements were carried out. The XRD patterns were thus measured quickly and easily, and compared with the reference data by using DiffracPlus EVA and WinIndex software. The indexing of the XRD patterns of the Al, Sn, and Pb samples were carried out using the DICVOL 91 computer program.

The size of the grains in the samples, t, was calculated using the Scherrer Formula given below [22,23] applying the DiffracPlus EVA computer program:

$$t = \frac{0.9\lambda}{\mathrm{B}\cos\theta} \tag{1}$$

Where B is the half width of the peak with maximum intensities of (111), (200), (220), (311), (222)θ is the Bragg angle, λ is the wavelength of the light used (λ = 1.54056Å, Cu$K_{\alpha 1}$ in the present work). Also, the TOPAS 2 program was used to calculate the average grain size parameter LVol-(IB). The results were given in Table 1.

2.3. Determination of enthalpy and specific heat

The enthalpy of the fusion and the specific heat are very important parameters for industrial applications, and the specific heat is expressed as at constant pressure,

$$C_p = \left(\frac{\partial H}{\partial T}\right)_p \tag{2}$$

The variation of enthalpy, H, with temperature, T, can be obtained from knowledge of the variation of specific heat with temperature.

As we know from the literature, the detailed phase diagram of Al–Sn–Pb ternary alloys is not available yet. In the present work, we used DSC apparatus both to determine precisely the melting temperature in the studied region and to obtain the specific heat. We used DSC (Perkin Elmer Diamond model) thermal analysis which was performed by using about 10 mg sample in the temperature range from room temperature to 947 K with a heating rate of 1 K/min and under a constant stream of nitrogen at atmospheric pressure. The DSC curve was obtained for Al-[x] wt. % Sn-10 wt. % Pb, (x = 40, 30, 20 and 10) ternary alloys.

2.4. Electrical conductivity measurement

The samples were cut transversely into ~3–5 mm long sections and then grounded for the electrical conductivity measurements [16–20]. The temperature of the sample was adjusted by a controllable Nabertherm furnace and measured using a 0.5 mm standard K type thermocouple which was placed very close to the sample and detected with the Keithley 2700 multimeter. Electrical resistivity and conductivity were determined from the detected current and voltage drop using a standard conversion method [5–7]. The temperature dependence to the electrical resistivity of the samples were revealed by using a standard DC 4PPT. By using 4PPT, the measurement errors due to probe resistance, the spreading resistance under each probe, and the contact resistances between the metal probes and material were eliminated [12].The variations in thermal conductivity of the solid phases versus temperature of the same samples were determined by using the measured values of electrical conductivity in the (W–F) law and (S–P) equation.

In addition, the temperature coefficient of resistivity (TCR), α_ρ, of the Al–Sn–Pb ternary alloys was also estimated from the electrical resistivity results obtained in the temperature range 330–430 K by the following equation:

$$\alpha_\rho = \left(\frac{1}{\rho_1}\right)\left(\frac{d\rho}{dT}\right) = \left(\frac{1}{\rho_1}\right)\left(\frac{\Delta\rho}{\Delta T}\right) \tag{3}$$

where α_ρ is the TCR in the temperature between $\Delta T = T_2 - T_1$ and $\Delta\rho = \rho_2 - \rho_1$, ρ_1 is the resistivity at T_1 and ρ_2 is the resistivity at T_2.

2.5. Determination of thermal conductivity

The thermal and electrical conductivities of pure metals are proportional to the temperature; increasing temperature increases the thermal conductivity while it decreases the electrical conductivity. Such behaviour is known as the Wiedemann-Franz law (W–F), which is expressed by the following equation,

$$L = \frac{\kappa}{\sigma T} = \frac{\pi^2 k^2}{3e^2} \tag{4}$$

where k, e, κ, σ, T, and L represent the Boltzmann constant, elementary unit charge, thermal conductivity, electrical conductivity, temperature, and Lorenz number, respectively. When the W–F law is applied to the prediction Lorenz number, the value of L ($=2.45 \times 10^{-8}$ WΩ/K^2) is derived by using the free electron model [13] and experimental results of L which have temperature dependence even for some pure metals [14]. Quantitatively, this relationship is based upon the fact that the heat and electrical transport both involve the free electrons in the metal. According to equation (5), the value of L seems to be constant and does not depend on the properties of materials. At the same time, in the literature, this value depends on the properties of materials. The values of L are well known for pure materials but are unknown for