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The measurement of thermal conductivity variation with temperature for solid materials

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ABSTRACT

An apparatus was designed to routinely measure the thermal conductivity variation with temperature for solid materials. The apparatus was calibrated by measuring the thermal conductivity variations with temperature for aluminum, zinc, tin and indium metals. The variations of thermal conductivity with temperature for the Zn-[x] wt.% Sb alloys (x = 10, 20, 30 and 40) were then measured by using the linear heat flow apparatus designed in present work. From experimental results it can be concluded that the linear heat flow apparatus can be used to measure thermal conductivity variation with temperature for multi component metallic alloys as well as pure metallic materials and for any kind of alloys. Variations of electrical conductivity with temperature for the Zn-[x] wt.% Sb alloys were determined from the Wiedemann–Franz (W–F) equation by using the measured values of thermal conductivity. Dependencies of the thermal and electrical conductivities on composition of Sb in the Zn–Sb alloys were also investigated. According to present experimental results, the thermal conductivity and electrical conductivity for the Zn-[x] wt.% Sb alloys decrease with increasing the temperature and the composition of Sb.

1. Introduction

In the experimental determination of the thermal conductivity of solids, a number of different methods of measurement are required for different ranges of temperature and for various classes of materials having different ranges of thermal conductivity values. A particular method may thus be preferable over-others for a given material and temperature range.

The various methods for the measurement of thermal conductivity fall into two categories: steady state and non-steady state methods. In steady state methods of measurement, the specimen is subjected to a temperature profile that is time invariant; after equilibrium has been reached; the thermal conductivity is determined directly by measuring the rate of heat flow per unit area and the temperature gradient. In non-steady state methods of measurement, the temperature distribution in the specimen varies with time, and the measurement of the rate of temperature change, which normally determines the thermal diffusivity, replaces the measurement of the rate of heat flow. The thermal conductivity is then calculated from the thermal diffusivity with a further knowledge of the density and specific heat of the materials [1].

Many attempts have been made to determine the thermal conductivity values of solid and liquid phases in various materials by using different methods. One of the common techniques for measuring the thermal conductivity of solids is the longitudinal heat flow method. In the longitudinal heat flow methods, the experimental arrangement is so designed that the flow of heat is only in the axial direction of a road specimen. Under steady-state condition and assuming no radial heat loss or gain, thermal conductivity is determined by the following expression from

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one-dimensional Fourier–Biot heat conduction equation [1,2]:

$$K = -\frac{Q}{A}\frac{\Delta T}{\Delta X} \quad (1)$$

where K is the thermal conductivity of solid, Q is the rate of heat flow or input power flows through to specimen, A is the cross-sectional area of the specimen, $\Delta X = X_2 - X_1$ is the distance between points of temperature measurements for T_1 and T_2 and $\Delta T = T_2 - T_1$ is the temperature difference between X_2 and X_1 points.

There are several different types of apparatus, all employing the longitudinal heat flow methods. The longitudinal heat flow methods are a steady state methods and the classification is mainly based upon: absolute or comparative methods. Rod method is one of the most common absolute methods and suitable for good conductors. The specimen is in the form of a relatively rod so as to produce an appreciable temperature drop along the specimen for precise measurement. In this method, a source of heat at a constant temperature is supplied at the one end of the rod and flows axially through the rod to other end, where a heat sink at a lower constant temperature is located. Radial heat loss or gain of rod should be negligible. In order to determine the thermal conductivity from Eq. (1), it is necessary to measure the rate of heat flow into and/or out of the rod, cross-sectional area, the temperatures of at least two points along the rod and the distance between points of temperature measurements. For measurements at lower (cryogenic) temperatures, radial heat loss does not constitute a serious problem, and thermal insulation and guard heaters are normally not necessary [3–5]. For measurements at higher temperatures, radial heat loss becomes serious problem because radiant heat transfer increases rapidly with temperature. This method, as used for measurements at higher temperatures has been reviewed and discussed by Laubitz [6] and Flynn [7]. Measurements of thermal conductivity at higher temperatures have been made for different kind of materials [8–15].

Recently, we have embarked on research pertaining to the measurement of thermal conductivity variation with temperature of metals and multi-components of metallic alloys. So attention is given to the thermal conductivity and electrical conductivity at high temperature required as input data in heat transfer and solidification simulators. The aim of present work was to modify the rod method to measure thermal conductivity variation with temperature. For this purpose, a linear heat flow apparatus was designed and calibrated by measuring the thermal conductivity variation with temperature for the aluminum, zinc, tin and indium metals. Then, the thermal conductivity variations with temperature for the Zn-[x] wt.% Sb alloys (x = 10, 20, 30 and 40) were measured with the linear heat flow apparatus designed in present work. The variations of electrical conductivity with temperature for same alloys were also determined from the Wiedemann–Franz (W–F) equation by using the measured values of thermal conductivity. Dependencies of the thermal and electrical conductivities on composition of Sb in the Zn–Sb alloys were also investigated.

2. Experimental procedure

2.1. Experimental apparatus

As mentioned above, a linear heat flow apparatus was designed to routinely measure the thermal conductivity variation with temperature for solid materials. The linear heat flow apparatus consists of hot stage, cold stage and sample holder as shown in Fig. 1.

The hot-stage is comprised of two brass plates which are resistively heated by NiCr wires, insulated in alumina tubes and integrally threaded through the plates of the hot stage. A total of 1000 mm of heater wire, 0.5 mm in diameter was used in the hot-stage, providing a maximum power of 4500 W at 220 V AC. To maximize the thermal stability of the hot-stage, a transformer was placed in the supply circuit, stepping the maximum current down to 4 A. A fully proportional thermistor-based control system was implemented, employing a control thermocouple within the hot-stage. The temperature of the hot-stage was controlled to an accuracy of ±0.01 K with a Eurotherm 2604 type controller. The hot stage can be operated up to 773 K degrees.

The cold-stage design is similar to that of the hot-stage. However, cooling is achieved by using a Poly Science digital 9102 model heating/refrigerating circulating bath containing an aqueous ethylene glycol solution. The temperature of the circulating baths was kept constant at 278 K with an accuracy of ±0.01 K.

To get linear temperature gradient into specimen, the distance between the hot stage and cold stage was kept typically 10 mm. Hot and cold stages were placed with a space of 10 mm on an insulating plate and the insulating plate was then vertically fixed as the hot stage is at top of the insulating plate and the cold stage is at bottom to prevent convection effect on heat conduction into specimen and get a constant linear temperature gradient into specimen as shown in Fig. 1.

Sample holder consists of two copper plates as shown in Fig. 2. Two holes in 10 mm depth and 8 mm diameter were drilled at cross sections of cold and hot copper plates to place the specimen between the hot and cold stages and get good heat conduction trough to specimen. At the same time, a hole in 3 mm diameter through bottom cold copper plate was also drilled to insert the measurements thermocouples into specimen. The ends of specimen were tightly fitted into holes at the cold and hot copper plates. Thermocouples were then placed into specimen by inserting thermocouples through hole at the cold plate as shown in Fig. 1. Then, top and bottom copper plates include the specimen were placed together into hot and cold stages.

2.2. Specimen preparation and processing

A thin-walled graphite crucible, 12.0 mm OD × 8.0 mm ID × 50 mm in length was made by drilling out a graphite rod of 12 mm in diameter and 250 mm in length. A hole, 1.2 mm in diameter was drilled at the bottom of crucible for thermocouple's alumina tube as shown in Fig. 3.

Zn–Sb binary system shows an eutectic phase equilibria in the range of compositions 0–57 wt.% Sb. The eutectic