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Viscous features of single-component melt under horizontal magnetic field

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ABSTRACT

In this paper, the viscosity of Al, In, Sn, and Bi melts under different magnetic field intensities has been investigated by using a torsional oscillation viscometer. The experimental results show that the viscosity curves fit well with the Arrhenius formula under the magnetic field and the viscosity of all melts increases as the horizontal magnetic field intensity enhances. At the same conditions, the viscosity change rates of Al and In are obviously larger than that of Sn and Bi which possess covalent bonds. And the viscosity change rate of the lightest element Al is the largest in the samples.

1. Introduction

Viscosity is one of the important physical properties of metallic melts. It is sensitive to the melt structure [1]. Investigations on the viscosity of metallic melts remain one of the active domains of research in both technical and theoretical fields of condensed matter [2–4]. The viscosity plays an important role in revealing many phenomena related to both materials science and technology. So it is significant to investigate the behavior of liquid metals and one basic parameter for computer simulation. The studies of the viscosity of melts under the traditional conditions have achieved much progress, and the investigations on viscosity under the extraordinary conditions attract more and more attentions. However, the research under the extraordinary conditions mainly focuses on the computer simulations because of the limit of experimental conditions [5].

The magnetic field is one of the important external physical quantities which can change the properties of materials effectively [6]. Some investigations focus on the effects of magnetic field on the nucleation temperature of metals [7,8]. The effects of the magnetic field with high intensity on the alloys have been studied, and it is found that the magnetic field can increase the eutectic line and shift the eutectic point [9].

Despite the magnetic field is widely applied to the materials science, the investigations into viscosity under magnetic field are few. The investigations into viscosity of the metallic melts under magnetic field can help understand the features of melts. In this paper, the viscosity of Al, In, Sn, and Bi melts under different intensities of horizontal magnetic field was investigated by experiments. The viscosity behaviors of the melts were analyzed.

2. Experimental procedure

The device used to measure the viscosity of the melts is a torsional oscillation viscometer for high-temperature melts. The device is shown in Fig. 1(a,b). The viscometer is made up of a suspension system, an oscillation detection system, a heating system and a horizontal magnetic field system. The magnetic system consists of two concentric magnetic rings which are made up of NdFeB. The system could provide horizontal magnetic field intensity from 90 to 2700 G. The heartland of magnetic rings is a static symmetrical horizontal magnetic field [10].The intensity of the horizontal magnetic field could be adjusted manually via regulating the angles of the two rings. The sketch planform about the distribution of the magnetic induction lines is shown in Fig. 1(c). The viscosity of liquid metal could be calculated by measuring the decrement and the time of oscillation. By measuring logarithmic decrement, the kinetic viscosity is calculated using the Shvidkovskiy equation [11]:

$$\nu = \frac{I^2(\delta - T_P\delta_0/T_{P0})^2}{\pi(mR_C)^2 T_P \omega^2} \tag{1}$$

where

$$\omega = 1 - \frac{3}{2}\Delta - \frac{3}{8}\Delta^2 - a - (b - c\Delta)\frac{2nR_C}{H_S} \tag{2}$$

I is the momentum of inertia of the suspended system, δ represents the logarithmic damping decrement, δ_0 is the logarithmic damping decrement for an empty vessel, T_p is the period

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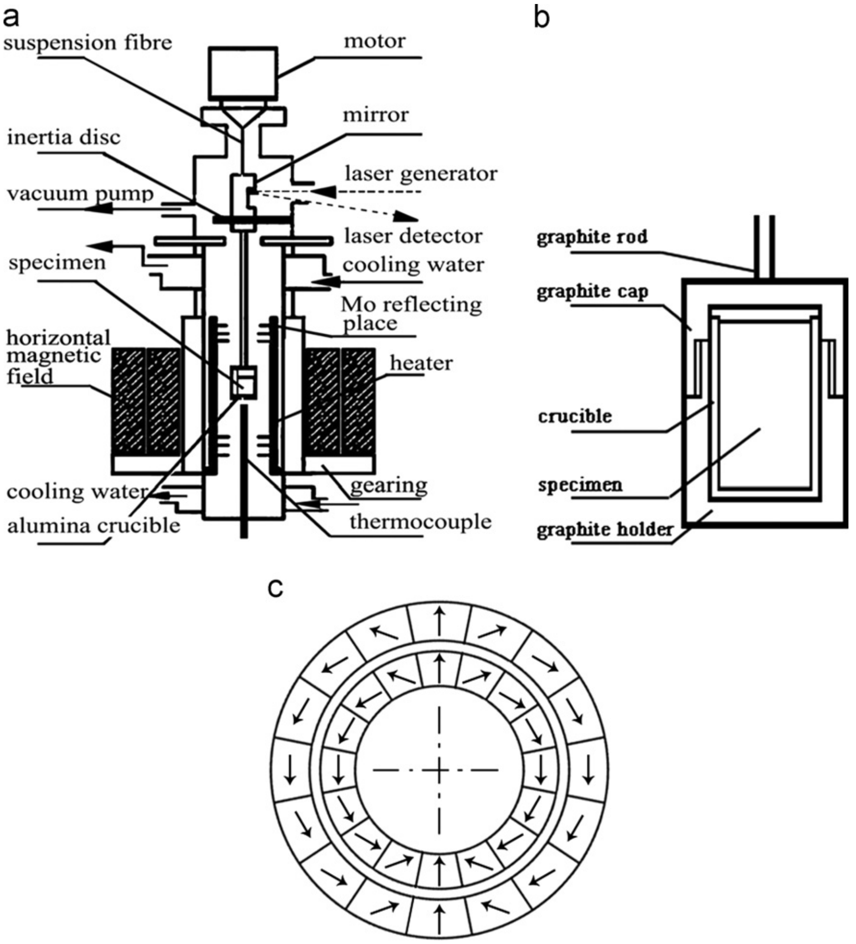

Fig. 1. (a) Schematic diagram of a torsional oscillation viscometer, (b) graphite crucible, and (c) the sketch planform about the distribution of the magnetic induction lines in the magnetic rings.

time of the oscillations, and T_{p0} refers to that of an empty vessel, $\Delta = \delta/2\pi$, m is the mass of liquid sample, R_c represents the radius of the vessel, H_s is the height of the liquid sample in the vessel, and a, b, and c are constants, n is the number of solid planes contacted horizontally by the liquid sample (i.e. in the case of a vessel having the lower end closed and its upper surface free, $n=1$, if the vessel encloses the fluid in top and bottom, $n=2$). The dynamic viscosityη can be calculated using the formula:

$$\eta = \rho \nu \tag{3}$$

in which ρ is the density of sample.

The samples of Al, Sn, In, and Bi used in this work possess a purity of 99.999 wt%. They were melted in an alumina crucible using a high frequency induction electric furnace and cast ingots in a graphite mould. After careful treatment of the surface of the cooled cylinder specimen with a file, the specimen was put into an alumina crucible which reaches 29 mm in diameter and 60 mm in height. The alumina crucible was a non-conductor and its effects on the viscosity measurement could be neglected.

In the experimental process, the crucible was put in the constant-temperature region of the heating furnace. The space of furnace was cleaned to a vacuum of 2×10^0 Pa, and then it was filled with high purity argon (99.99% pure) to 1.3×10^5 Pa to protect the samples from being oxidized. The temperature was controlled by the thermocouples which were placed in the bottom and middle exterior of the crucible. The samples were heated up to a certain temperature at a rate of 8 K/min and held for 30 min at a constant horizontal magnetic field. Certain temperature was 220 K higher than the melting point, namely T_m+220 K (T_m is the melting point of sample). The samples were held for 30 min at this temperature, and then cooled down to the measurement temperature. The first measurement temperature was at the point T_m+200 K. The temperature interval of measurement was every 20 K and every temperature point was held for 30 min before measuring. The last measurement temperature was at the point T_m-20 K. Every temperature point was measured three times and the average values were calculated. The intensities of constant horizontal magnetic field were set at 90 G, 420 G, 760 G, and 1100 G.

3. Results

Fig. 2(a–d) shows the viscosity of molten Al, Sn, In, and Bi under different intensities of the magnetic field (90 G, 420 G, 760 G, and 1100 G) as a function of temperature during the cooling process. It can be found that the viscosity of pure Al, Sn, In, and Bi increases with decreasing temperature under different intensities of magnetic field. The viscosity of the melt is estimated by the following expression [12]:

$$\eta = A \exp\,(E_V/RT) \tag{4}$$

in which η is the viscosity, R is the gas constant, T is the absolute temperature, and E_v is the activation energy.

The logarithm is adopted at the two sides of equal sign in Eq. (4), and then the natural logarithmic form of the formula can