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Experimental study of surface tension, specific heat and thermal diffusivity of liquid and solid titanium

K. Zhou, H.P. Wang, J. Chang, B. Wei*

MOE Key Laboratory of Space Applied Physics and Chemistry, Department of Applied Physics, Northwestern Polytechnical University, Xi'an 710072, PR China

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ABSTRACT

The thermophysical properties of liquid and solid titanium such as the surface tension, specific heat and thermal diffusivity have been investigated over a wide temperature range. By using electromagnetic levitation and oscillating drop method, the surface tension of liquid titanium was measured in the temperature range of 1802–2188 K. The viscosity and density of undercooled liquid titanium were calculated by some well-known models using the measured data as input. In addition, the specific heat of liquid titanium was determined over the experimental range using electromagnetic levitation and drop calorimetry obtaining the value of 33.64 J mol^{-1} K^{-1}. In addition, the thermal diffusivity of solid titanium was measured by laser flash method in the temperature range of 171–1080 K.

1. Introduction

The thermophysical properties of metals and alloys have attracted widespread research interest, especially for undercooled liquid melts [1–10]. Surface tension is a key parameter in liquid phase processes [4], such as casting and joining processes [6], specific heat has a significant effect on heat transfer and solidification process [8,9], and thermal diffusivity, as a combination of conductivity, density and specific heat, is important for the heat and mass transfer phenomena [10]. Until now, the experimental data on the above-mentioned thermophysical properties for normal liquid, i.e. with a single liquid phase, undercooled liquid and solid metals, obtained over a wide temperature range are still limited or lacking owing to experimental difficulties associated with measurements at high temperatures as well as elevated costs of undercooling experiments. Fortunately, in many cases, the electromagnetic levitation technique can provide containerless environment and obtain substantial undercooling [6,8,9]. In addition, the oscillating drop method [6] and drop calorimetry [8,9] are quite suitable for the measurement of surface tension and specific heat of normal and undercooled liquid melts, respectively. Meanwhile, the thermal diffusivity of solid metals can be accurately determined by laser flash method, which is by far the most frequently used method to measure the thermal diffusivity for materials [10].

Titanium and Ti-based alloys are widely used in aerospace, marine and other areas, because of their excellent mechanical properties, such as low density, high strength and good specific stiffness [8,9,11,12]. The measurements of thermophysical properties are very important in the development of titanium databases and for the modeling of solidification aiming to optimize existing and/or to design new Ti-based alloys [11,12] or other alloy systems [13]. The objective of this letter is to determine the surface tension and specific heat of normal and undercooled liquid titanium by the oscillating drop method and drop calorimetry together with electromagnetic levitation technique. Moreover, the thermal diffusivity of solid titanium is also measured by the laser flash method over a broad temperature range.

2. Experimental method

Titanium samples were prepared from 99.999% purity titanium, and the mass of each sample was about 0.5 g. The undercooling experiments of liquid titanium were performed in an electromagnetic levitation apparatus, which was evacuated to 10^{-5} Pa and back filled with argon gas. During the experiment, the sample was levitated and melted by radio frequency induction heating facility. Then, inert helium gas blew toward the sample in order to achieve substantially undercooled state. When ideal undercooling was achieved, the gas flow rate was properly regulated to preserve the liquid melts at this undercooling for 10–30 s. The temperature was measured by an infrared pyrometer, and in the same time the surface oscillations recorded by a photodetector at a sampling rate of 800 Hz. By the fast Fourier transformation technique, the

* Corresponding author.
E-mail address: bbwei@nwpu.edu.cn (B. Wei).

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oscillation frequency was obtained. At various temperatures, different spectra were derived and hence the temperature dependence of the surface tension could be obtained. After recording the oscillation signal, the power was switched off and the levitated sample dropped into an adiabatic copper calorimeter.

The thermal diffusivity of solid titanium was measured by Linseis LFA 1000 laser flash diffusivity apparatus, which is commonly used for the measurement of thermal diffusivity because of its excellent properties, such as high accuracy, good repeatability, and wide temperature range. The sample thickness was 2.93 mm and the sample diameter was 12.69 mm. To stabilize the absorption of the incident energy, graphite was sprayed on the surface of the sample. The temperature was raised to each test temperature with a heating rate of 2 and 5 K/min for below room temperature and above room temperature, respectively. The maximum temperature of the rear surface of the sample was measured by thermocouple and infrared temperature sensor. The flash heating for the thermal diffusivity tests was applied to backside surface, and transient temperatures were subsequently measured on a front surface. The thermal diffusivity data were obtained from three measurements, and the standard deviation in the measurements of thermal diffusivity is estimated to be 5%. Meanwhile, Netzsch 404C differential scanning calorimeter was used to determine the specific heat of solid titanium.

3. Results and discussion

3.1. Surface tension

The surface tension can be determined by the oscillating drop method. Figure 1a shows the measured surface tension as a function of temperature. In the experiments, the max undercooling of 141 K is achieved. Based on the high undercooling, the surface tension of normal and undercooled liquid titanium is determined in the temperature range of 1802–2188 K. In the temperature range investigated, the surface tension of liquid Ti obeys a linear law:

$$\sigma_L = 1.64 - 2.38 \times 10^{-4}(T - 1943)\,\mathrm{N\ m^{-1}}. \quad (1)$$

According to Eq. (1), the surface tension of liquid titanium is determined to be 1.64 N m^{-1} at the melting temperature of 1943 K, and its temperature coefficient is -2.38×10^{-4} N m^{-1} K^{-1}.

For convenience of comparison, the surface tension values of liquid titanium in literature are presented in Figure 1a. The new surface tension experimental value measured at the melting temperature is lower than the values reported by Mills and Su [14] and Allen [15], but it is higher with respect to those of Vinet et al. [16] and Paradis et al. [17]. However, the temperature coefficient values are similar with each other. Over a wide temperature interval of measurements, the value at the melting temperature obtained in the present work is higher, while the surface tension temperature coefficient is lower than the corresponding data reported by Amore et al. [11].

The viscosity and density are also important thermophysical properties of metallic melts. On the basis of measured surface tension data, these properties can be calculated by using some well-known theoretical models.

The viscosity η_L can be derived from the following model, which is inferred by Egry [18]

$$\eta_L = \frac{16}{15}\sqrt{\frac{M}{kT}}\,\sigma_L, \quad (2)$$

where k is the Boltzmann constant equal to 1.38×10^{-23} J K^{-1} and M the absolute atomic mass. According to Eq. (2), the viscosity of titanium is obtained as a function of temperature, as shown in

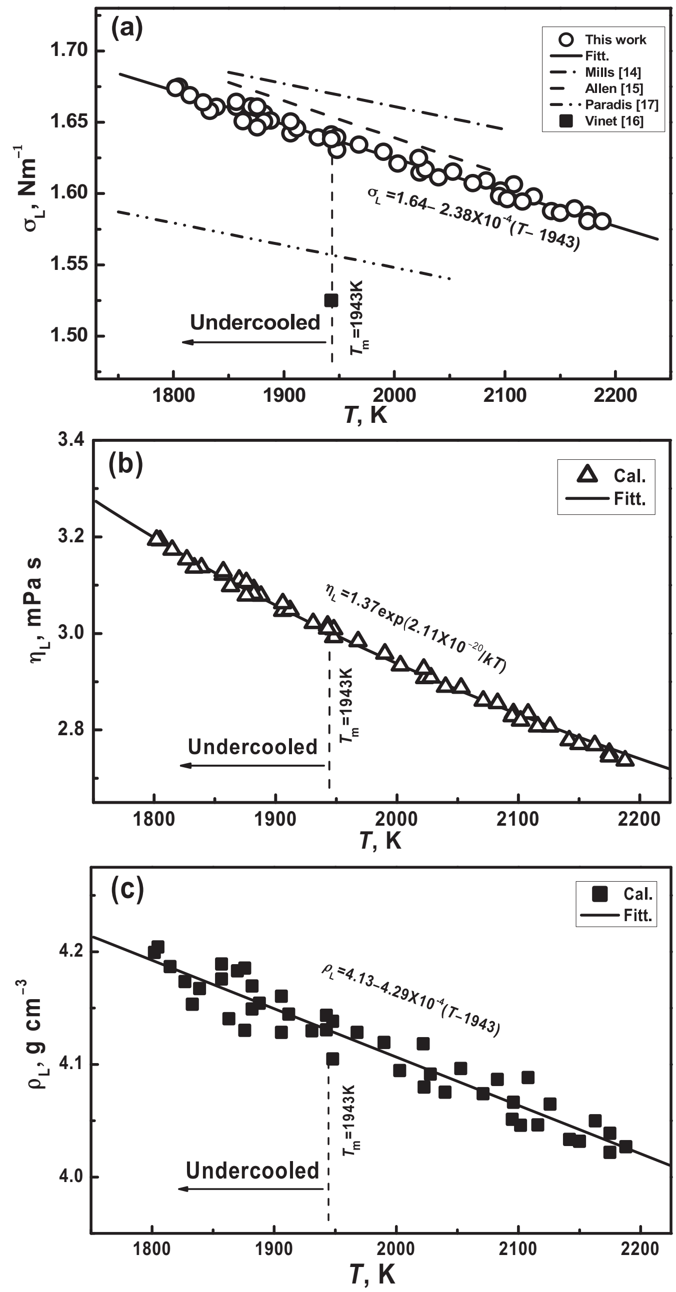

Figure 1. Measured surface tension and calculated relevant properties of undercooled liquid titanium versus temperature. (a) Surface tension, (b) viscosity, (c) density.

Figure 1b. Exponential regression of the derived data shows that viscosity is related to temperature as follows

$$\eta_L = 1.37\ \exp\left(\frac{2.11 \times 10^{-20}}{kT}\right)\ \mathrm{mPa\,s}, \quad (3)$$

the viscosity constant of titanium is equal to 1.37 mPa s.

Comparing the calculated viscosity with the experimental values at the melting temperature, it is evident that the calculated viscosity is larger than that reported by Agaev et al. [19], but lower than those of Paradis et al. [17] as well as of the reference data [20].