Thermal properties of pure tungsten and its alloys for fusion applications

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ABSTRACT

Tungsten is a promising candidate for plasma-facing materials in a fusion reactor, and several research studies have been conducted to improve the mechanical properties of pure W. However, the thermal properties are also important characteristics of plasma-facing materials. In this study, the thermal properties of pure W and its alloys were measured, and the effect of alloying on the thermal properties of pure W was investigated. Potassium-bubble (K-bubble) dispersion, which is one of the major methods utilized to improve the mechanical properties of W, did not affect the thermal diffusivity and conductivity of pure W. On the other hand, the presence of rhenium, which is major alloying element of W, affected the absolute values and the temperature dependence of thermal diffusivity and conductivity. The effect of alloying on specific heat and the anisotropy in thermal diffusivity of pure W and its alloys were also investigated. Measurements of the specific heat showed that K-bubble dispersion and Re addition had insignificant effects on the values obtained for pure W. Anisotropy in thermal diffusivity was not observed, and the effect of anisotropic grain structure and alloying was insignificant.

1. Introduction

Tungsten has attracted much attention as a plasma-facing material (PFM) for in-vessel components such as divertors and blankets in a fusion reactor because of its high melting temperature, high thermal conductivity, low tritium retention, and low sputtering yield. However, its inherent brittleness at low temperature and the embrittlement due to recrystallization and neutron irradiation are major concerns regarding the use of W in fusion reactor applications. To overcome these drawbacks, several efforts have been made to modify W through grain refining, alloying, dispersion of secondary phases, and formation of composites [1–7]. One of the important functions of the divertor in a fusion reactor is the removal of high heat flux. When used as a PFM, W is exposed to high heat loads that are typically ~10 MW/m² in the steady state and > 20 MW/m² in the non-steady state; the thermal properties of W play an important role in maintaining the integrity of the material itself as well as the reactor component. Although the modifications mentioned above can improve the mechanical properties of W, these changes may also lead to degradation of the thermal properties. For example, it is well known that a higher rolling ratio improves the ductility of a W plate or sheet. However, Zhang et al. measured the thermal conductivity of pure W prepared with different rolling-reduction rates, and lower thermal conductivities were obtained in pure W samples that were subjected to higher and lower rolling-

reduction rates [8]; they reported that the decrease in thermal conductivity was probably due to the presence of large defects such as pores and cracks, as well as microscale defects such as dislocations and boundaries [8].

We evaluated the material properties of W alloys in our previous studies, and we reported that W with a small amount of added rhenium or dispersed potassium bubbles (K-bubbles), or both Re and K-bubbles, showed higher grain structure stability and better mechanical properties than pure W [9,10]. The objective of this study is to evaluate the thermal properties of pure W and its alloys, and to investigate the effect of material modification (i.e., secondary-phase dispersion and Re addition) on the thermal properties of pure W.

2. Experimental

The materials examined in this study were pure W, K-doped W, W–1%Re, W–3%Re, K-doped W–3%Re, and La-doped W–3%Re (the percentages represent the nominal mass ratio of Re in the alloys). Both single-crystalline and polycrystalline materials were used for pure W. The single-crystalline pure W used in this study was prepared by secondary-recrystallization heat treatment of polycrystalline pure W. The dimensions of the examined original plates were ~85 × ~80 × 5 mm, where 5 mm corresponds to the plate thickness. Detailed descriptions of the materials, such as the fabrication process and chemical

composition, are provided in the literature [9,10]. The W–1%Re and La-doped W–3%Re were fabricated by the same process as other polycrystalline materials. The reduction ratios of these materials were 80 and 60%, respectively. The final heat-treatment temperature of materials except single-crystalline pure W was 900 °C for 20 min. The thermal diffusivity and specific heat of pure W and its alloys were measured in this study to investigate the thermal properties; the thermal conductivity was calculated using the densities of materials obtained from the literature and the measured values of thermal diffusivity and specific heat.

The thermal diffusivity was measured with a laser flash apparatus, LFA-457 MicroFlash (NETZSCH GmbH, Germany), and the values between room temperature (RT) and 1080 °C were measured in an Ar atmosphere; three measurements were obtained at each temperature. Pulse-length correction and non-linear regression for the Cowan fit were applied to correct the raw data. Disk-shaped (10 mm (φ) × 2 mm (t)) and plate-shaped (5 mm (l) × 5 mm (l) × 1 mm(t)) samples were prepared for these measurements; the plate-shaped samples were used only for investigation of the anisotropic thermal diffusivity owing to the limitation of the original plate thickness (5 mm). The specific heat was measured by using two differential scanning calorimeters, DSC 204 F1 Phoenix (NETZSCH GmbH, Germany) and STA 449 F3 Jupiter (NETZSCH GmbH, Germany), for the low-temperature (10–100 °C) and high-temperature (100–1400 °C) measurements, respectively, in an Ar atmosphere. The heating rates for the low- and high-temperature measurements were 10 and 20 °C/min, respectively, and disk-shaped (5 mm (φ) × 1 mm (t)) samples were used.

The specimens for the measurement of thermal diffusivity and specific heat were cut by electro-discharge machining from the plate materials, and the surface of each specimen was mechanically polished with up to #3000 mesh before the measurements. To analyze the effect of microstructure on the thermal properties, the microstructure of the selected materials was observed using a digital microscope (VHX-200, Keyence Corp., Japan) and a scanning transmission electron microscope (STEM, JEM-ARM200F, JEOL Ltd., Japan).

3. Results

Fig. 1 shows the temperature dependence of the thermal diffusivity in pure W and its doped W–Re alloys (i.e., K-doped W, K-doped W–3%Re, and La-doped W–3%Re), measured using disk-shaped samples (10 mm (φ), 2 mm (t)) cut from the RD–TD plane (RD: rolling direction; TD: transverse direction) of the plate materials. The thermal diffusivity of the examined materials decreased with increasing temperature, and this trend was especially prominent in pure W and K-doped W: pure W (both single-crystalline and polycrystalline samples) and K-doped W
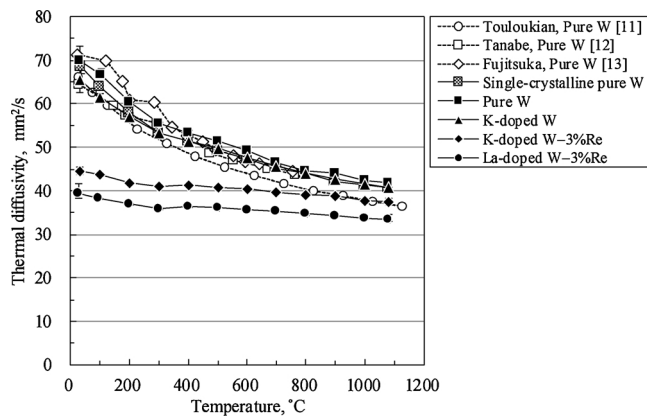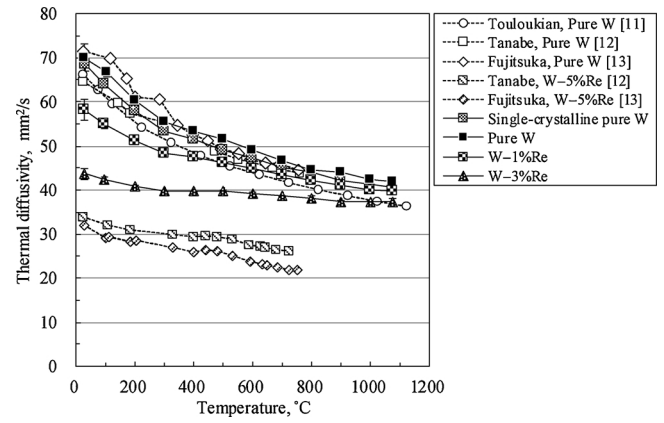

Fig. 2. Measured thermal diffusivity of pure W and non-doped W–Re alloys. The values of thermal diffusivity reported in the literature are also shown in this figure [11–13].

showed almost the same thermal diffusivity in the temperature range of RT–1080 °C; K-doped W–3%Re and La-doped W–3%Re showed lower thermal diffusivity than other samples, especially in the intermediate temperature region (below ~800 °C). The temperature dependence of thermal diffusivity was insignificant in these materials.

Fig. 2 shows the thermal diffusivity of pure W and non-doped W–Re alloys in the temperature range of RT–1080 °C. It can be clearly seen that the thermal diffusivity decreased with increasing Re concentration, especially at temperatures below ~800 °C. W–1%Re and W–3%Re showed values that were approximately 18 and 23% lower than that of pure W at 100 °C, although these differences were less than 10% at temperatures above 900 °C, as shown in Fig. 3.

Fig. 4 shows the results of specific heat measurements for pure W and its alloys. Pure W showed relatively lower specific heat at elevated temperatures (> 700 °C), although the difference in values was less than 3% and there was no significant difference among the examined materials. The reference specific heat increased with increasing temperature, although the measured values decreased at approximately 900 °C. The thermal conductivity of the examined materials was calculated by using the following equation:

$$\lambda = \alpha \cdot c_p \cdot \rho,$$

where α and c_p are the thermal diffusivity and the specific heat, respectively. The values of density, ρ, reported in the literature were used to calculate the thermal conductivity at each temperature [14]. The thermal conductivities calculated for pure W and K-doped W were
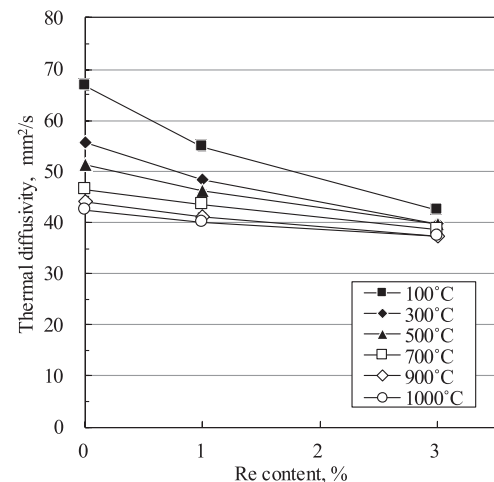

Fig. 1. Measured thermal diffusivity of pure W and its doped W–Re alloys. The values of thermal diffusivity reported in the literature are also shown in this figure [11–13].

Fig. 3. Effect of Re addition on thermal diffusivity of pure W at selected temperatures.