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Recrystallization behavior of hot-rolled pure tungsten and its alloy plates during high-temperature annealing

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ABSTRACT

We aimed to clarify the behavior of change in the grain structure and hardness of hot-rolled pure W and its alloys plates developed for various properties by holding at high temperature for long and short durations in the absence of irradiation. The isothermal annealing was performed at 1100 °C for 10–3115 h. The isochronous annealing was performed for 1 h in a temperature range of 1100 to 2300 °C. After heat treatment, the grain structure was observed using electron backscatter diffraction (EBSD) and the Vickers hardness was measured in the observed plane. Pure W did not recrystallize by the heat treatment for a short duration of 1 h at 1100 °C, while the recrystallization of pure W progressed during the heat treatment for long duration of 3115 h at 1100 °C. The temperature and duration at which the recrystallization occurs increase because of the dispersion of K bubbles and solid solution of Re. Considering the actual operation period of fusion reactors, a temperature of 1100 °C can result in recrystallization. It is necessary to decrease the maximum operating temperature or to use materials having a high recrystallization temperature by alloying.

1. Introduction

Tungsten (W) is one of the most attractive materials for use as the divertor in fusion reactor systems. The divertor in ITER is considered to be exposed to a high heat load, and the temperature of its surface reaches 2000 °C [1], at which the progress of recrystallization of W is expected [2]. Although hot-rolled W materials have favorable mechanical properties after working during the fabrication process, it is well known that grain coarsening by recrystallization causes the increase in the ductile–brittle transition temperature (DBTT) [2] and decrease in strength and toughness, especially at a low temperature. Therefore, the favorable mechanical properties of hot-rolled pure W would be maintained by the suppression of recrystallization.

It is necessary to consider the occurrence of recrystallization in fusion reactor design and in neutron irradiation experiments. In DEMO, the surface temperature of the diverter is designed to be less than the recrystallization temperature of W (< 1300 °C) [3,4]. According to the plan of the Japan-US cooperation project (PHENIX project) for neutron irradiation experiments using the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory, experiments with 3 cycles, where a cycle is approximately 3 months for 1 dpa irradiation, were performed on W materials at three temperatures (500, 800, 1100 °C) [5]. Although these temperatures are less than the recrystallization temperature of pure W, the recrystallization depends on the duration and temperature. It has been reported that pure W was recrystallized by annealing at 1100 °C for a long duration [6]. Therefore, not only the temperature but also the holding duration must be taken into consideration in the design of the fusion reactors and the analysis of the effects of neutron irradiation. It is necessary to grasp the recrystallization behavior of W materials heat treated at the same temperature for the same period in the absence of irradiation.

Several studies have focused on effective methods for the suppression of recrystallization of W materials. Potassium (K) bubble dispersion alloys (K-doped W), in which K bubbles are dispersed as the second phase, have a high recrystallization temperature [7] and excellent creep strength at high temperatures [8]. Rhenium (Re) solid solution alloys (W–Re alloys) also have a high recrystallization temperature [9], in addition to improved ductility at low temperatures (room temperature to 300 °C) [10]. Moreover, it has been reported that irradiation hardening is suppressed at low irradiation magnitudes of approximately 0.1 dpa [11]. We also developed K-doped W-3% Re to investigate the influence of Re generated by nuclear transmutation in the neutron irradiation environment. A superior tensile strength at high temperatures has been reported for this material [12].

The present study aimed to clarify the behavior of change in the grain structure and hardness of hot-rolled pure W and its alloys plates

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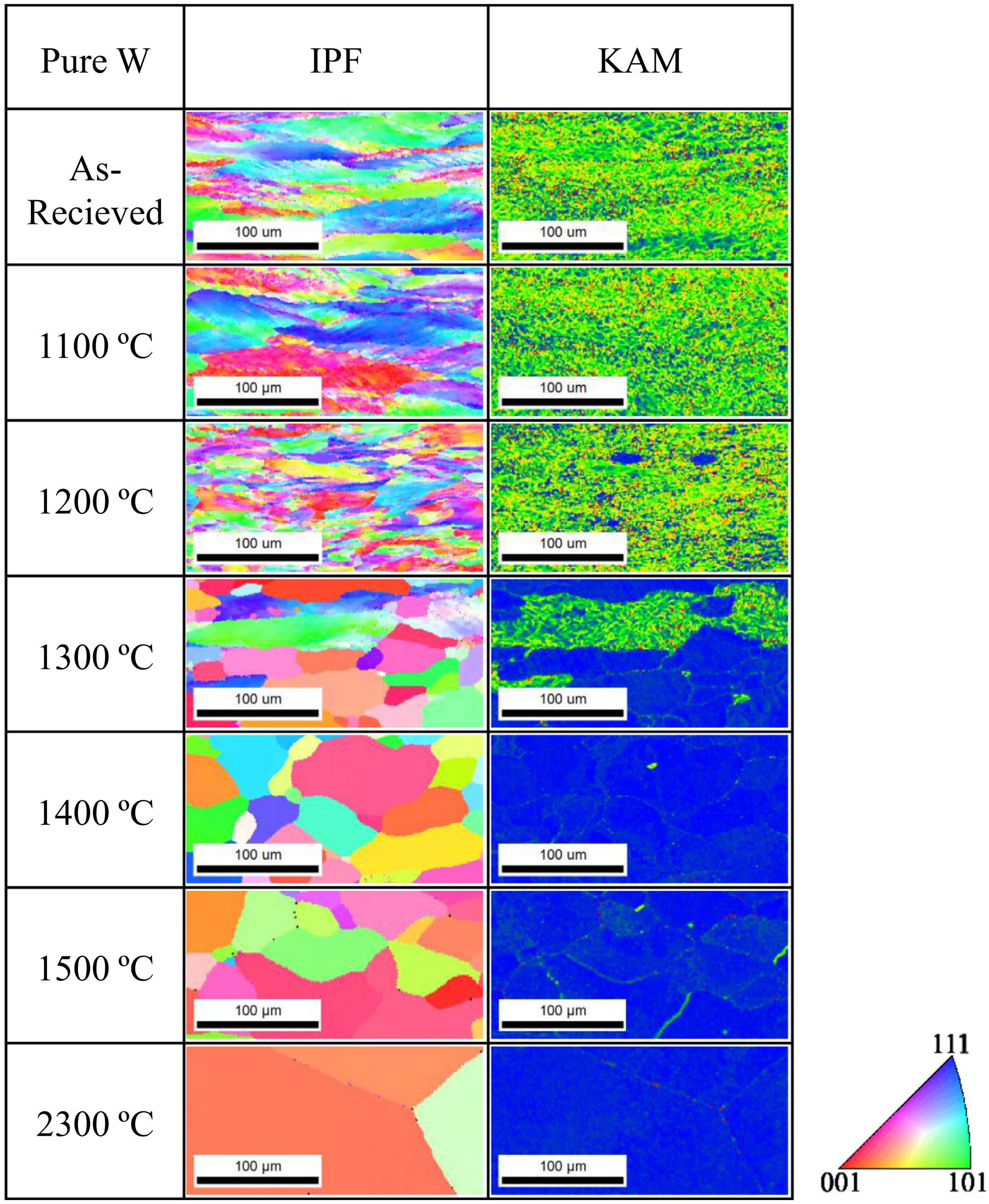

Fig. 1. Change of the grain structure in pure W by isochronous annealing for 1 h.

developed for various properties by holding at high temperature for long and short durations in the absence of irradiation.

2. Experimental

Pure W, K-doped W, and K-doped W-3% Re plates were supplied by A.L.M.T. corp. These materials were fabricated by powder sintering and hot rolling, followed by stress relief heat treatment at 900 °C for 20 min. Interstitial impurities (C, O, N) are less than 10 ppm. Potassium bubbles of 20–30 nm are dispersed in the as-received material [13]. Re is completely solid solved Block-shaped specimens with dimensions of approximately $3 \times 4 \times 5$ mm^3 were cut out from these plates.

Isothermal and isochronous annealing were performed. The isothermal annealing was performed using electric furnaces. The annealing temperature was 1100 °C, and holding durations were 10, 30, 50, 100, and 3115 h. The specimens were vacuum-sealed in a quartz tube. Isochronous annealing was performed using a gold image furnace or high-frequency induction heating furnace. The holding duration was 1 h. The isochronous annealing was performed in a vacuum atmosphere in a temperature range of 1100 to 1500 °C and under argon flow at temperature of 1800 and 2300 °C.

After heat treatment, the grain structure was observed using electron backscatter diffraction (EBSD) using a field-emission scanning electron microscope (FE-SEM) (JIB-4600F, JEOL Ltd). Observations were made on the plane parallel to the rolling direction and perpendicular to the rolled plane. After mirror polishing up to # 4000 on the observation surface, electropolishing with NaOH aqueous solution was conducted. The accelerating voltage and step sizes were 25 kV and 1–1.5 µm, respectively. The observed area was 500×500 µm^2.

The Vickers hardness was measured in the observed plane at room temperature. Surfaces were polished up to #1500. The indentation load and dwell time were 1.961 N and 15 s, respectively. Seven indentations were measured, and the average value of five points excluding the measured maximum and minimum values was taken.

3. Results

The change of the grain structure in pure W caused by isochronous