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Tensile and fatigue properties of potassium doped and rhenium containing tungsten rods for fusion reactor applications

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HIGHLIGHTS

- Swaged W-alloy rods as prototype materials for fusion reactor applications.
- W-rods showed better plasticity and fatigue life compared to W-plates.
- Rhenium addition suppressed grain growth successfully after recrystallization.

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ABSTRACT

In this study, large diameter pure tungsten (PW) and potassium doped W (KW) rods fabricated using a swaging process were investigated, in order to develop high performance plasma-facing materials (PFM) for fusion reactor applications. The KW rods show a finer grain size, a more compact [1 1 0] grain orientation, and a more uniform grain size distribution than that of the PW rods. Tensile tests of the KW rods along the axial direction indicated higher tensile strength at each test temperature than what is found in PW rods. On the other hand, both types of rod have nearly identical elongation values. Further comparison of the rods with rolled PW and KW plates indicate that the W rods show larger elongation and lower strength than what is observed in W plates. Meanwhile, the longer fatigue life was observed for the W rods, as predicted by Manson's universal slope method. In addition, a K-doped W rod with 3% rhenium (Re) (KW3Re) was investigated in this study, which featured improved recrystallization and grain growth behavior. Suppression of grain growth after recrystallization was observed in KW3Re rod. High performance PFMs based on these materials can be expected with careful consideration of the fabrication process and additional elements used in their creation.

1. Introduction

Tungsten (W) is considered a primary candidate material for use in high-heat-flux components because of its favorable properties at high temperatures. In this study, large diameter W rods were investigated as prototype materials. In recent years, studies of W wires and small diameter W rods have been primarily focused on their uses in light bulb filaments and electrodes [1–3]. However, evaluation and characterization of large diameter W rods for component materials (which can support enough volume for divertors) is less common [4,5]. Sasaki et al reported that potassium (K)-doping can improve the mechanical properties and low temperature embrittlement in dispersion strengthened K-doped W (KW) plates [6]. Fukuda et al. showed that a rhenium (Re) containing W plate alloy can resist additional recrystallization and grain growth [7]. Therefore, KW and K-doped-3% Re W (KW3Re) rods were fabricated in this study in order to evaluate the effects of K-doping and Re addition, which are expected to improve the mechanical properties, recrystallization and grain growth behavior of the resulting materials. In addition, since a divertor has to withstand high heat loads and periodical intense transient heat loads, cyclic thermal stress is inevitably introduced into the divertor, which might lead to crack formation as a consequence of thermal fatigue. Therefore, the fatigue properties of W structural materials should also be taken into account.

The objective of this study is to investigate the effect of K-doping on the grain structure, tensile properties, and recrystallization behavior of W rods, to estimate the fatigue life of these rods by Manson's universal slope method (with which the fatigue life can be calculated using tensile properties data) [8], and to evaluate the effect of Re addition on the recrystallization and the grain growth behavior of W rods.

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2. Effect of K-doping

2.1. Grain structure

The Pure W (PW) and KW rods, which were fabricated using the same powder metallurgy and swaging processes, were supplied by Allied Material Corp.,. The rod diameters of both PW and KW were 20 mm. The K content ppm in the KW rods was 30. A non-uniform grain size distribution was present due to high deformation of grain structure during the fabrication process, as reported by Inagaki [9]. Therefore, the grain size distribution of swaged PW and KW rods should be discussed. Measurement positions along the radial and axial directions are shown in Fig. 1, and each data point is comprised of three measurements. The results of grain diameter and grain length are shown in Fig. 1. The grain diameter at the middle of the as-received PW was almost 50% larger than at the center and edge along the radial direction. In contrast, the as-received KW showed nearly identical grain diameters along the radial direction. However, along the axial direction, the PW and KW rods showed nearly identical grain lengths (Fig. 1(b)), respectively. The as-received PW rod exhibited significant non-uniformity in its grain size distribution, more so than the KW rod, especially along the radial direction. This is believed to be caused by the die pressure applied in the radial direction, which varies based on the desired diameter. Neighboring grains interact with each other under high reduction ratios in the radial direction, which leads to non-uniformity and deformation during the swaging process. However, uniformity of grain size distribution was observed in the as-received KW rod after K-doping, indicating that the KW rod has more stable grain size distribution than the PW rod.

Compared to the grain size of the as-received PW rods, finer grain structures were observed in the KW rods. One possible explanation for this behavior is that K bubbles were formed on the grain boundary due to volatilization of added K during the sintering and swaging processes. These bubbles exist on the grain boundary and have been shown to suppress grain boundary migration at higher temperatures [10]. Meanwhile, the fabrication process was carried out at temperatures above 1673 K, which induces recrystallization of PW as well as grain coarsening.

Electron backscatter diffraction (EBSD) was used in this study to further investigate the crystal orientation in both the as-received PW and KW rods. Measurement positions were the same as those used in the evaluation of the grain diameter along the radial direction, as shown in Fig. 1(a). Fig. 2 shows the pole figures of the PW and KW rods. The black region was mainly located in the center of circle graphs, indicating a [1 1 0] grain orientation in both types of rod. Similar results were reported by Peck et al. in W wires, and they attributed these observations to the swaging process [1]. However, the black part of PW is more scattered than KW, indicating a disordered [1 1 0] grain orientation in all regions. On the other hand, the middle and edge regions of the KW rods show more compact [1 1 0] orientation.

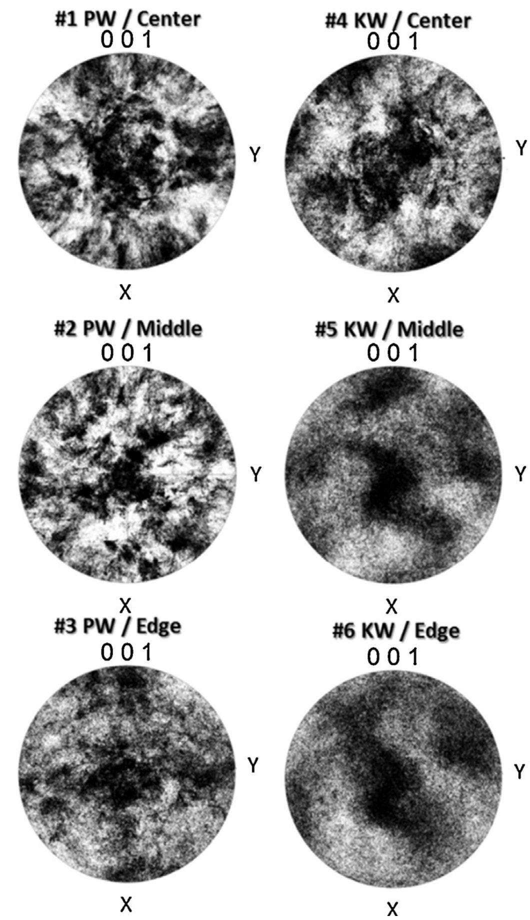

Fig. 2. Radial surface pole figure of as-received PW and KW.

PW and KW rods were heat-treated at 1773 K and 2073 K in order to investigate their recrystallization behavior. The heat treatments were carried out for 1 h under vacuum ($<10^{-4}$ Pa), using an infrared gold image furnace. The results of this treatment are also summarized in Fig. 1. For the heat treatment at 1773 K, a

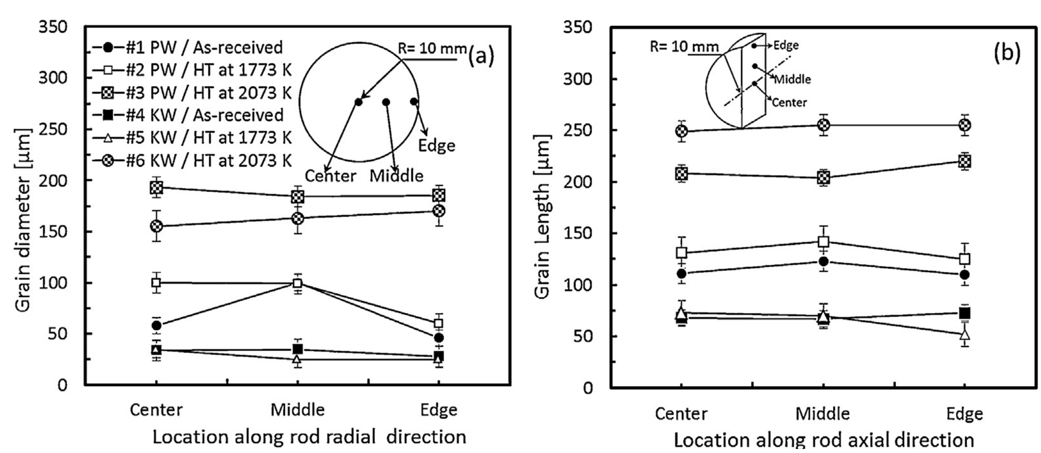

Fig. 1. Grain diameters and lengths of PW and KW, (a) grain diameter dependence of radial direction, (b) grain length dependence of axial direction.