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Microstructure and tensile properties of tungsten at elevated temperatures

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HIGHLIGHTS

- This work was conducted to support the development of the 5 MW spallation target for the European Spallation Source.
- The effect of fabrication process on microstructure, ductile-to-brittle transition temperature and tensile behaviour was studied with hot-rolled and hot-forged tungsten.
- The tungsten materials were characterized with metallography analysis, hardness measurement and tensile test in a temperature range of 25–500 °C.
- The results indicate that the HR tungsten has better mechanical properties in terms of greater ductility and lower ductile-to-brittle transition temperature.

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ABSTRACT

In order to support the development of the 5 MW spallation target for the European Spallation Source, the effect of fabrication process on microstructure, ductile-to-brittle transition temperature (DBTT), tensile and fracture behaviour of powder-metallurgy pure tungsten materials has been investigated. A hot-rolled (HR) tungsten piece of 12 mm thickness and a hot-forged (HF) piece of about 80 mm thickness were used to simulate the thin and thick blocks in the target. The two tungsten pieces were characterized with metallography analysis, hardness measurement and tensile testing. The HR piece exhibits an anisotropic grain structure with an average size of about 330 × 140 × 40 μm in rolling, long transverse and short transverse (thickness) directions. The HF piece possesses a bimodal grain structure with about 310 × 170 × 70 μm grain size in deformed part and about 25 μm sized grains remained from sintering process. Hardness (HV0.2) of the HR piece is slightly greater than that of the HF one. The ductility of the HR tungsten specimens is greater than that of the HF tungsten. For the HF tungsten piece, specimens with small grains in gauge section manifest lower ductility but higher strength. The DBTT evaluated from the tensile results is 250–300 °C for the HR tungsten and about 350 °C for the HF tungsten.

1. Introduction

Pure tungsten has been widely used as target material at the spallation neutron sources such as LANSCE (Los Alamos Neutron Science Centre) [1,2] and ISIS (neutron source at the Rutherford Appleton Laboratory) [3] and will be applied to the ESS (European Spallation Source) [4] target as well. Due to the high beam power (5 MW), a rotating target has been chosen as the design option at ESS, in order to distribute the beam energy and the radiation damage more uniformly in the spallation volume. Fig. 1 shows the sketch of the ESS target wheel baseline design as of December 2014. The target wheel is 2.58 m in diameter and 11.6 cm in height. The target wheel is divided into 33 segments for structural reasons, and each segment consists of 12 tungsten blocks with varying thicknesses ranging from 12 mm in the beam upstream region with higher volumetric energy deposition to 120 mm in the beam downstream region with reduced heat loads. The tungsten blocks are cooled by helium flow with the mass flow rate 3 kg/s at 1.0 MPa. At 5 MW the operation temperature in the tungsten volume could reach up to 500 °C [4].

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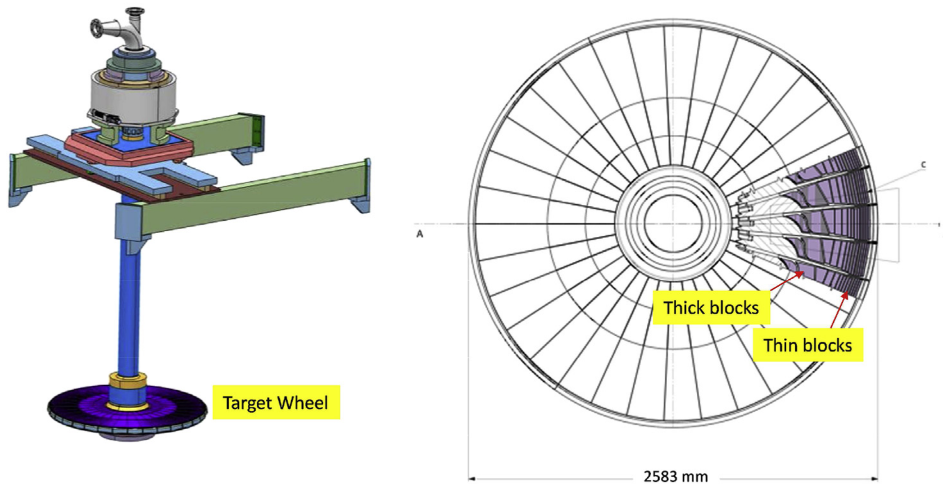

Fig. 1. The snapshot of the ESS target wheel, the baseline design as of December 2014. The left side shows schematically the target. The right side shows schematically some sections of the tungsten target wheel.

Tungsten is normally powder metallurgy pressed and sintered. To increase the density and improve mechanical properties, sintered tungsten needs to be hot-worked, either by hot-rolling or hot-forging. Compared to hot-forged (HF) tungsten, hot-rolled (HR) tungsten usually possesses higher density and better mechanical properties. However, due to difficulties of hot-rolling processing the thickness of HR tungsten plates is limited to 30–40 mm. Therefore, it is considered to use HR tungsten for the first several plates in each section, where the proton and neutron fluxes and heat deposition are high, while HF tungsten for the rear part where thick plates can be applied.

Properties of tungsten materials may vary greatly from one product to another, depending on production route [5–9]. For this reason, a study of HR and HF tungsten materials is necessary for the robust design of the target. In addition, for the typical target operation temperature range, 50–500 °C, very limited published tensile data could be found for commercially available thick (>10 mm thickness or diameter) tungsten plates or rods [6,10]. It should be pointed out that a lot of research work has been done for fusion applications as described in overview papers like [11,12]. However, the most of the publications are on materials development, for example improving tungsten properties with small amounts (normally < 1%) additions (e.g. Ref. [12]) or developing specific processing routes (e.g. Refs. [13,14]). These are, for the time being, not relevant to the ESS application. For the first ESS target, based on the existing knowledge and experience available for LANSCE and ISIS [1–3], just pure tungsten of normal industrial products has been selected as the target material. Due to a great difference in quality and price of commercially available tungsten materials, products of several companies in Europe and China have been pre-selected. Metallography and mechanical tests have been conducted to characterize the materials of the different companies. The final selection will be made based on the results of the characterization and with a compromise of cost. In this work, HR and HF tungsten materials of a Chinese company, Tianlong Tungsten & Molybdenum Co. Ltd., were studied. Tensile, bend and fatigue specimens were fabricated from several HR and HF tungsten pieces of different thicknesses in the interested range relevant to the ESS target have been tested, for the temperature range from room temperature up to 500 °C. The fatigue test results together with few tensile data were published in Ref. [15]. In this paper the results obtained from extensive tensile tests on the HR tungsten with different orientations and HF tungsten will be reported.

2. Experimental

2.1. Material and specimen preparation

The tungsten materials used in this study were purchased from Tian-long Tungsten & Molybdenum Co., Ltd., Beijing, China. A HR tungsten plate of 12 mm thickness and a HF plate of about 80 mm thickness were used for specimen preparation, as illustrated in Fig. 2. The HR plate was rolled five times at temperatures between 1450 and 1650 °C with a 20–25% thickness reduction each time. The HF piece was forged three times in Z-direction at temperatures between 1550 and 1700 °C with a 20–25% reduction each time, during which it was also pressed slightly in X-direction. Miniature type tensile specimens (Fig. 3) were cut from the HR and HF tungsten plates using an electro-discharge machine (EDM). Because of anisotropic structure induced by hot work processing, two different groups of specimens were cut from the HR plate: Group-A tensile specimens with the tensile axis being parallel to the long-transverse direction (X-axis) and the main surface in the *a*-plane; Group-B tensile specimens with the tensile axis parallel to the rolling direction (Y-axis) and the main surface in the *b*-plane (Fig. 2). For specimens of the HF tungsten the tensile axis is perpendicular to the forge direction. After EDM cutting, the specimens were milled to the required thickness of 0.75 mm. In order to study surface effect on mechanical properties of tungsten, a part of the specimens were electro-polished. About 15 microns were removed from surface layer. Fig. 4 presents optical microscopy pictures of specimens in as-milled and electro-polished conditions.

2.2. Metallography observation and hardness measurement

Metallography observation and hardness measurement were performed. The specimens were prepared with fine mechanical polishing and electro-chemical etching at room temperature. The electrolyte was 5% NaOH and 95% H_2O. The microstructural observation was performed with an optical microscope. Most of the images were taken at magnifications of 10 and 20 times. Hardness (HV0.2) was measured with a Vickers hardness tester following ASTM Standard E 92 with 0.2 kg force and 15 s full-loading time. Ten indentations were performed on each measured specimen.