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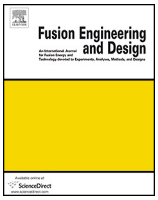

Thermal shock response of deformed and recrystallised tungsten

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HIGHLIGHTS

- Microstructure has a strong influence on the mechanical properties of tungsten.
- Threshold values vary with microstructure by a factor of 2.
- Thermal shock damage patterns depend on the microstructure.
- Cracks parallel to the surface evolve the risk of enhanced erosion and overheating.
- Recrystallisation may lead to enhanced erosion for high pulse numbers.

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ABSTRACT

The thermal shock response of tungsten as a plasma facing material (PFM) strongly depends on its mechanical properties and consequently on its microstructure. In order to characterise this influence, deformed tungsten, both in its stress relieved and recrystallised condition, was exposed to 100 ELM like thermal shock events in the electron beam facility JUDITH 1. The induced thermal shock damages were analysed by scanning electron microscopy, optical microscopy and laser profilometry. Tensile tests at different temperatures show that the mechanical properties such as fracture strength and strain depend on the grain orientation and microstructure. Transmission electron microscope images of the as received and the recrystallised material show that the defect density of the recrystallised samples is decreased. Threshold values such as damage and cracking threshold vary with microstructure by a factor of 2. Also the induced thermal shock damages and surface modifications are strongly depend on the microstructure. Surface roughening due to plastic deformation is more pronounced in the recrystallised state and crack parameters as well as crack propagation is influenced by grain orientation due to preferential crack formation along grain boundaries.

1. Introduction

The response of plasma facing materials (PFMs) to thermal shock loads is a major issue for future fusion devices like ITER and DEMO. Especially in the divertor region, the chosen materials have to withstand severe environmental conditions in terms of steady state (up to 10 MW m^{-2}), slow transient (up to 20 MW m^{-2}) and transient heat loads (up to 1 GW m^{-2} and above). Beside these thermal loads PFMs are also exposed to high particle fluxes of hydrogen, helium and neutron, which will deteriorate the material properties and therefore have an impact on the thermal shock response. Under these conditions, tungsten is one of the most promising materials for application as PFM especially in the divertor region. Its main advantages are a high melting point, high thermal conductivity, low sputtering yield and low tritium retention. But tungsten has also some drawbacks such as the high atomic number and the brittleness at low temperatures [1–4].

Thermal shock damages induced by ELM like events simulated in the electron beam facility JUDITH 1 (Juelich Divertor Test Facility in Hot Cells) comprise surface modifications and crack formation. How pronounced these damages are, depends not only on the test conditions such as absorbed power density and base temperature but also on the material's thermal and mechanical properties as well as on its microstructure. Both are strongly influenced by the manufacturing process of the material in terms of deformation and heat treatment.

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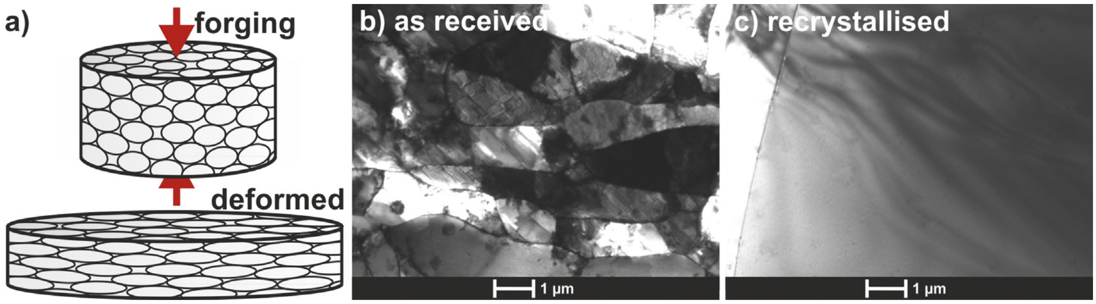

Fig. 1. Microstructure of single forged W-UHP: (a) schematic view of forging process and the resulting grain structure; (b) TEM image of the as received material; (c) TEM image of the recrystallised material.

In order to characterise the influence of a strongly elongated grain structure on the thermal shock response as well as the mechanical properties, deformed, so-called single forged, tungsten was exposed to 100 ELM like cyclic thermal shocks at various base temperatures to address the influence of the brittleness of the material. Additionally, the material was recrystallised and also exposed to the same cyclic thermal shocks to study the influence of recrystallisation, which will take place during the operation of ITER or DEMO.

2. Material properties and experimental settings

The investigated material is W-UHP (ultra high purity tungsten) with a purity of 99.9999 wt% provided by the PLANSEE AG, Austria [5]. The forging of the sintered blank (diameter ca. 80 mm and height ca. 116 mm) was applied in axial direction to increase the density and the mechanical strength of the material and to form round blankets with a diameter of ca. 160 mm and height of 29 mm. Finally, the material was stress relieved for 2 h at 1000 °C. Due to this manufacturing process, the grains are heavily elongated to disc like shape (Fig. 1a). Selected parts of the material were recrystallised at a temperature of 1600 °C for 1 h according to the information given by the manufacturer.

Closer investigation of the material by transmission electron microscopy (TEM) and metallographic means showed that there are significant differences between the as received and recrystallised material. Optical microscope images showed that the grains of the as received tungsten are strongly elongated perpendicular to the forging/deformation direction. After recrystallisation the average grain size is larger (as received: top view (forging direction) 53 µm × 67 µm, cross section (perpendicular to forging direction) 48 µm × 170 µm; recrystallised: top view 76 µm × 126 µm, cross section 74 µm × 147 µm) and the grain structure is more homogeneous. Furthermore, the TEM images in Fig. 1 show that the defects such as dislocations and subgrain boundaries in the recrystallised material (Fig. 1c) are strongly reduced in comparison to the as received (Fig. 1b) one.

The mechanical properties of W-UHP were characterised by tensile tests with a deformation speed of 0.2 mm/min (strain rate ca. $10^{-4}\,s^{-1}$) at elevated temperatures of 300 °C, 500 °C and 1000 °C. In order to quantify the influence of the grain orientation on the mechanical strength of the material, tensile test specimens were manufactured with grains orientated parallel (longitudinal) and perpendicular (transversal) to the loading direction. Additionally, tensile tests of recrystallised longitudinal specimens were performed. One sample for each temperature with the respective microstructure was manufactured (9 in total) with the dimensions: length = 26 mm, width = 8 mm, gauge thickness = 3 mm, gauge length = 15 mm and a curvature radius of 1.5 mm. The results of these tests are plotted as engineering stress–strain curves in Fig. 2.

The focus was on the qualitative analysis of the curves and the comparison of different grain structures rather than the exact values of parameters such as the ultimate tensile strength or the fracture strain. A general expected result is that for higher temperatures the strength of the material decreases while the ductility increases. The comparison of all three grain orientations and structures shows that the longitudinal specimens have the highest strength, the recrystallised specimens have the highest fracture strain and the transversal specimens show brittle behaviour even at 1000 °C. This pronounced anisotropy of the mechanical properties due to the deformation during the production process (longitudinal and transversal) is known as “texture strengthening”. The lower strength but improved ductility of the recrystallised material results from the reduced defect density [6,7].

For the thermal shock tests in JUDITH 1 [8] samples with the dimension 12 mm × 12 mm × 5 mm were cut for all three grain orientations. All samples were polished to a mirror finish to create an undamaged well-defined starting state. The samples were loaded with ELM relevant power densities between 0.16 and 1.27 $GW\,m^{-2}$. These values were calculated by taking an electron absorption coefficient of 0.46 into account. The exposed area (4 mm × 4 mm) was

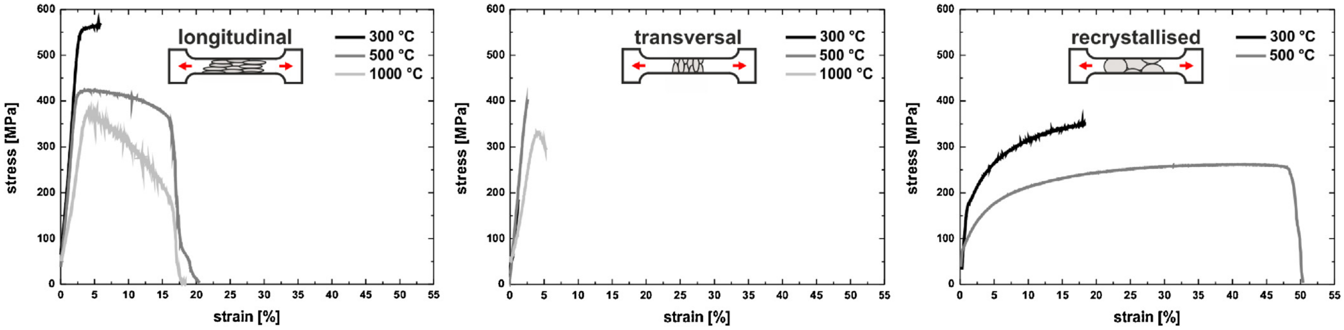

Fig. 2. Stress–strain diagrams for W-UHP at 300 °C, 500 °C and 1000 °C for longitudinal (left), transversal (middle) and recrystallised (right) specimens.

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