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The effects of heat treatment at temperatures of 1100 °C to 1300 °C on the tensile properties of high-strength drawn tungsten fibres

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ABSTRACT

The design and manufacture of highly heat loaded plasma-facing components (PFCs) represents a major challenge for the realisation of thermonuclear magnetic confinement fusion. The performance of such PFCs is essentially related to the properties of the materials that are used for their design. Currently, tungsten fibre-reinforced metal matrix composites (MMCs) are regarded as promising advanced materials for PFC applications. In this respect, tungsten fibre-reinforced tungsten is being investigated as an advanced pseudo-ductile plasma-facing material while tungsten fibre-reinforced copper is being developed as an advanced heat sink material. The essential ingredients for the abovementioned MMCs are the fibrous reinforcements which are commercially available drawn tungsten fibres.

An important aspect regarding the development of the abovementioned MMCs is the effect of the composite material manufacturing process on the properties of these high-strength reinforcements. During composite material manufacturing experiments it has been found that the mechanical properties of the used W fibres can be deteriorated significantly already at process temperatures of approximately 1200 °C.

Against this background, dedicated investigations have been conducted on drawn tungsten fibre samples. In more detail, single fibre tensile tests, microstructural investigations as well as chemical composition analyses have been conducted. All in all, the performed investigations indicate that impurities incorporated into the tungsten fibre material are the underlying reason for the observed deterioration of the mechanical properties.

1. Introduction

Highly loaded plasma-facing components (PFCs) of future thermonuclear magnetic confinement fusion devices have to withstand enormous particle fluxes that in turn lead to high heat fluxes which have to be dissipated reliably [1,2]. The performance of highly loaded PFCs is most closely linked to the properties of the materials from which such components are manufactured.

In this respect, tungsten (W) fibre-reinforced metal matrix composites (MMCs) are regarded as potentially advanced materials that can enhance the performance of PFCs [3]. Examples for such fibre-reinforced MMCs currently under development are the following two: W fibre-reinforced W (W_f-W) [4] as well as W fibre-reinforced copper (Cu) (W_f-Cu) [5,6].

W_f-W is a composite material with a pseudo-ductile behaviour and hence considered to be able to overcome the issue of inherent brittleness of bulk monolithic W. W_f-Cu MMCs are being developed as advanced heat sink materials that exhibit potentially superior mechanical properties compared to Cu alloys which are currently regarded as state-of-the-art PFC heat sink materials.

The preferred reinforcing fibres for the abovementioned MMCs are commercially available high-strength drawn potassium (K) doped W fibres.

These fibres exhibit very beneficial mechanical properties. On the one hand, a tensile strength of about 2700 MPa for material with a nominal diameter of 150 µm in an as-fabricated state and tested at room temperature (RT). On the other hand, a ductile fracture behaviour even after heat treatment at temperatures of up to 1900 °C. In Figs. 1 and 2, these benign properties are illustrated. Fig. 1 shows typical single fibre tensile curves of as-fabricated and heat treated K doped W fibres [7]. Fig. 2 shows a typical fracture surface of a drawn K doped W fibre after heat treatment at 1900 °C for 30 min [7]. The picture illustrates that the

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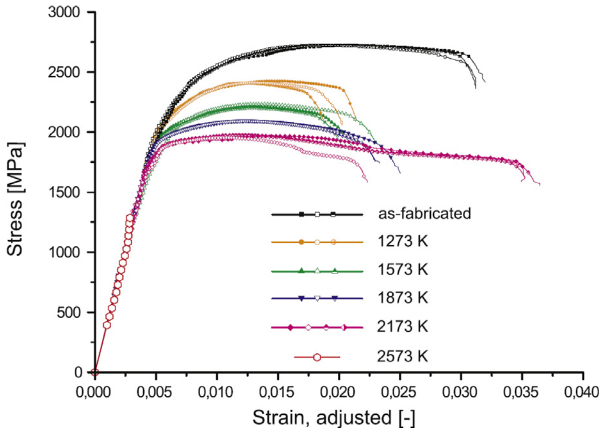

Fig. 1. Typical stress-strain curves for single fibre tensile tests at room temperature (RT) of as-fabricated and heat treated drawn K doped W fibres with a nominal diameter of 150 µm [7].

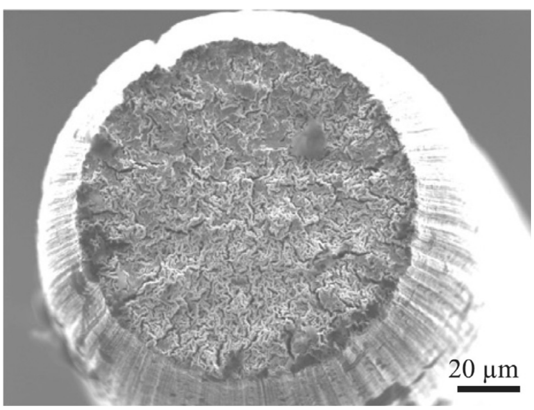

Fig. 2. Typical fracture surface of a drawn K doped W fibre after heat treatment at 1900 °C for 30 min illustrating the ductile fracture behaviour [7].

specimen fractured with local necking in a ductile manner even after heat treatment at this considerably high temperature.

Regarding material developments for PFCs of future thermonuclear fusion reactors industrially viable manufacturing is an important consideration. In this context, manufacturing trials have been performed for W_f-Cu materials in an industrial environment (Louis Renner GmbH, Germany). During these investigations, it has been found that the mechanical properties of the used W fibres were deteriorated significantly already at heat treatment temperatures considerably lower than the abovementioned 1900 °C.

In order to investigate these contradictory findings, dedicated experiments have been performed on W fibre samples within the present work. In more detail, single fibre tensile tests, microstructural investigations as well as chemical composition analyses have been conducted on as-fabricated and heat treated W fibre samples as is described in the following sections.

2. Material and heat treatments

As raw material for the investigations reported herein drawn K doped W wire with a nominal diameter of 150 µm has been used (OSRAM GmbH, PN 102045280000).

Various heat treatments relevant with respect to a W_f-Cu composite material manufacturing process have been performed in different furnaces and for different W fibre sample arrangements both in a laboratory (Max-Planck-Institut für Plasmaphysik) as well as an industrial environment (Louis Renner GmbH). The heat treatments have been performed with temperatures in the range of 1100 °C to 1300 °C and

Table 1
Details regarding the furnaces used for the heat treatments on W fibre samples within the present work.

Environment	Atmosphere	Purity/pressure
Laboratory	He 5.0	≥ 99.999%
Industry	H_2 3.0	≥ 99.9%
Industry	High vacuum (turbomolecular pump)	≈ 10^{-5} mbar
Industry	High vacuum (oil diffusion pump)	≈ 10^{-5} mbar

dwell times in the range of 1 h to 8 h. In Table 1, an overview regarding the used furnaces is given.

3. Tensile tests

In order to investigate the mechanical performance of the W fibre samples uniaxial single fibre tensile tests have been performed with an electromechanical universal testing machine (TIRA Test 2820) that was equipped with a 200 N load cell. The tests were conducted at RT with a constant cross-head displacement speed of 5 $\mu m/s$. The specimens had a gauge length of 3 cm and the fibres were clamped with glued ends in order to improve the grip and to protect the samples from damage by clamping. Such an arrangement is exemplarily illustrated in Fig. 3. For each sample type ≥ 15 tensile tests were performed.

In Fig. 4, measured ultimate tensile strength (UTS) values of all tested heat treated W fibre samples are shown. In principle, it can be seen that there is some noticeable variety in the data. For the sake of clarity, the boundaries of the tensile performance of the samples in terms of mean UTS are highlighted. The *blue (round)* data points correspond to the samples exhibiting the best tensile performance with $UTS = 2356 \pm 23.6$ MPa. The *orange (triangle)* data points correspond to the samples exhibiting the worst tensile performance with $UTS = 1909 \pm 196.6$ MPa.

Furthermore, the *purple (diamond)* data points correspond to samples that underwent nominally the same heat treatment as the orange (triangle) samples in terms of maximum temperature and dwell time but exhibit a tensile performance of $UTS = 2288 \pm 62.9$ MPa. The horizontal dashed lines within Fig. 4 indicate the mean UTS values of the three highlighted sample types. The *grey (cross)* data points correspond to measured UTS values of all other W fibre samples – heat treated as specified within Section 2 – and are shown in order to illustrate the overall amount of investigated samples.

The heat treatment corresponding to the blue (round) data was the following:

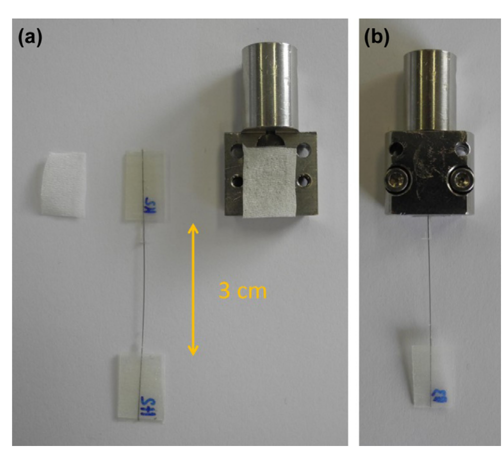

Fig. 3. (a) Single W fibre sample with a gauge length of 3 cm prepared for tensile testing with glued ends next to clamping holder; (b) tightened clamping with inserted W fibre sample.