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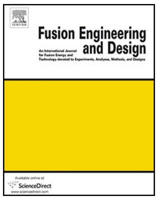

Tensile deformation behavior of tungsten fibre-reinforced tungsten composite specimens in as-fabricated state

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HIGHLIGHTS

- Material qualification of tungsten fibre-reinforced tungsten composite by means of tension tests.
- In the as-fabricated condition samples the material is still able to bear rising load despite multiple matrix cracks.
- Fibre necking as well as fibre pull out was observed leading to the typical pseudo ductile behavior of the composite.
- The description of the mechanical tests will be supplemented by detailed microstructural investigations.

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ABSTRACT

To overcome the inherent brittleness of tungsten, which is a promising candidate for a plasma-facing material in a future fusion device, tungsten fibre-reinforced tungsten composites (W_f/W) have been developed. As a part of the materials characterisation program on W_f/W, we present the results of first tensile tests of as-fabricated W_f/W in this contribution. The results give insight on the ultimate tensile strength properties and reveal the active toughening mechanisms under tension load within the composite. Fibre bridging, fibre necking as well as fibre pull out were observed. This is leading to the typical pseudo ductile behavior of the composite which is characterized by a rising load bearing capability despite multiple matrix cracks accompanied by non catastrophic crack propagation (in the matrix). The description of the mechanical tests is supplemented by detailed microstructural investigations.

1. Introduction

Tungsten is a promising plasma-facing material for future fusion reactors due to its unique property combination such as a low sputter yield, a high melting point and a low activation [1]. The main drawbacks for the use of pure tungsten are its brittleness below the ductile-to-brittle transition temperature [2–4] and the embrittlement during operation e.g. by overheating and/or neutron irradiation [5–7]. These limitations are mitigated by using tungsten fibre-reinforced tungsten composite (W_f/W) which utilizes extrinsic mechanisms to improve the toughness [8–10] similar to ceramic fibre-reinforced ceramics [11]. It was shown that this idea in principle works in the as-fabricated [10] as well as in the embrittled material [12]. The fibres are made of W wire which was characterised in detail by means of tension tests [13–15]. Recently, a layered chemical vapour deposition process was developed allowing the production of large and reproducible samples [16]. This allowed the launch of a material characterisation program in which three point bending tests have been performed in a first step. In Charpy impact tests, it was proven that the toughening effect is still working under high deformation rates [16]. In this paper we are presenting for the first time the behavior of W_f/W under tension load as the next step in this program. Although the amount of tests was restricted to two, the results gave valuable information about the ultimate tensile strength (UTS) of W_f/W as a normalized material parameter. In addition, the detailed microstructural investigations are very helpful for the understanding and further development of W_f/W composites.

2. Materials and experimental procedure

The raw material was produced as a plate with a layered chemical vapour deposition (CVD) process performed at Archer

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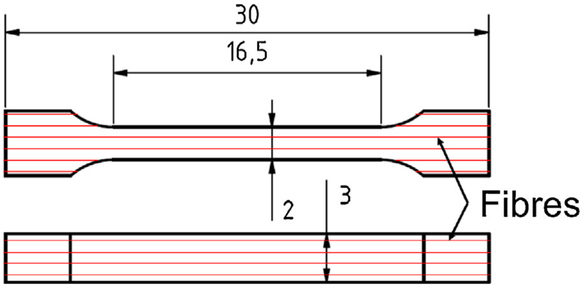

Fig. 1. Dimensions of specimen for tension tests. The (direction of) the fibres are marked in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Technicoat Ltd. (High Wycombe, UK). A detailed process description is given in [16]. Single layer of unidirectional orientated pure tungsten wires with a diameter of 150 μm were used as preforms. These preforms were coated with 1 μm thick interlayer of Er_2O_3 by magnetron sputtering according to the process description given in [17]. The successful use of Er_2O_3 as an interlayer in W_f/W has been demonstrated before [12,17,18]. The CVD process is a layer-wise process consisting of three repeating process steps. At first, the preform is placed on a heating plate inside the process chamber. Secondly, tungsten is deposited until the fibre layer is totally ingrown. Finally, the process chamber is opened to place the next preform layer on top of the already coated solid composite. This process is repeated until the aimed thickness is reached. The fibre volume ratio of the specimens is up to 30% (depending on the distance between the fibre layers) with an overall density of 94% (determined by Archimedes principle) [16]. Material consisting of 10 layers with a total thickness of approximately 3 mm was used in this experiment. Tension specimens were manufactured out of this material with electrical discharge machining (EDM), according to the geometry shown in Fig. 1. The parameters for EDM were chosen to ensure a low surface roughness, hence the specimens were not polished after EDM. The measuring length was 16.5 mm.

The tension tests were performed with a universal testing device (TIRAtest 2820, Nr. R050/01, TIRA GmbH). The load was recorded by a 20 kN load cell. A specially designed holding system was used to avoid stress peaks at the contact surface of the holder and the specimen. Moreover, the holders were mounted with a chain system to the grip of the testing device to ensure self alignment and thus an uniaxial stress-state within the specimen (Fig. 2).

Each specimen was preloaded with 20 N. The test was conducted at room temperature and displacement controlled with a constant displacement rate of 10 μm/s. The strain was calculated with the corrected cross-head displacement and the individual surface area of each specimen was used to determine the stress.

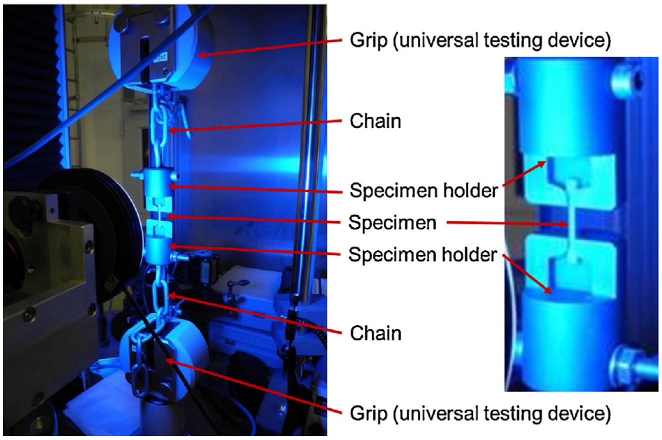

Fig. 2. Experimental setup for tension tests.

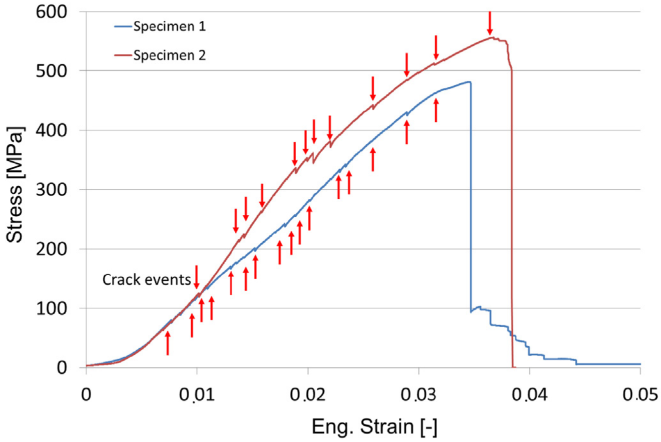

Fig. 3. Stress–strain curves for the specimens 1 and 2.

Afterwards, the fractured surfaces and polished cross sections were investigated by scanning electron microscopy (SEM), confocal laser scanning microscopy (CLSM) and optical microscopy. The different viewing points on specimen 1 are shown in Fig. A1 in the appendix. In total, two samples were tested (specimen 1 and 2).

3. Results

The stress–strain curves of the two tests are shown in Fig. 3. Both stress–strain curves show a very similar behavior. At the beginning, they show a nonlinear behavior due to the setting of the system before the load is fully transferred into the specimen. After linear loading, a first load drop is detected at 80 MPa for specimen 1 and 125 MPa for specimen 2. In total 19 load drops are observed for specimen 1 and 12 load drops for specimen 2, respectively. Each load drop was accompanied with an audible cracking noise. In addition, the crack propagation was observed optically for specimen 2 at which every cracking noise was followed by the appearance of a new crack. Beside these events, the load is rising with ongoing displacement indication a rising load bearing capacity. After reaching the ultimate tensile strength (UTS) a large load drop (slightly delayed in specimen 2) accompanied by a huge crack growth is detected. Specimen 1 can still bear some load whereas specimen 2 is fully fractured. The UTS is 482 MPa (specimen 1) and 557 MPa (specimen 2) respectively.

The fracture surface of specimen 1 is shown in Fig. 4. The fibre layer which was grown first during manufacturing is on the left side of Fig. 4(a). 77 fibres are located in the sample leading to a fibre volume fraction of 22%. The fracture surface has four steps which can be seen in Fig. 4(a) and in the side view (shown in Fig. 5). The first step includes six fibre layers and has the largest area. The second and third step consist of one fibre layer each and the fourth step contains two fibre layers. The height difference from step one to two is 1.23 mm, from step two to three 0.81 mm and from step three to four 5.14 mm. The height of the steps is correlated to the layer (deposition) thickness. In step one, very few pores can be seen and these pores are distributed over the whole area. The pores are located between the deposition layers and have the typical shape caused by premature blocking of gas transport (more details in discussion). The porosity in this area is 2.2% (density: 97.8%). Large pores are located between step three and four which lead to a delamination. The fracture surface of specimen 2 had two steps with a height difference of 1.92 mm which represents the thickness of the layers and 80 fibres are located in the sample leading to

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