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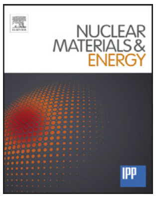

Chemically deposited tungsten fibre-reinforced tungsten – The way to a mock-up for divertor applications

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ABSTRACT

The development of advanced materials is essential for sophisticated energy systems like a future fusion reactor. Tungsten fibre-reinforced tungsten composites (W_f/W) utilize extrinsic toughening mechanisms and therefore overcome the intrinsic brittleness of tungsten at low temperature and its sensitivity to operational embrittlement. This material has been successfully produced and tested during the last years and the focus is now put on the technological realisation for the use in plasma facing components of fusion devices. In this contribution, we present a way to utilize W_f/W composites for divertor applications by a fabrication route based on the chemical vapour deposition (CVD) of tungsten. Mock-ups based on the ITER typical design can be realized by the implementation of W_f/W tiles. A concept based on a layered deposition approach allows the production of such tiles in the required geometry. One fibre layer after the other is positioned and ingrown into the W-matrix until the final sample size is reached. Charpy impact tests on these samples showed an increased fracture energy mainly due to the ductile deformation of the tungsten fibres. The use of W_f/W could broaden the operation temperature window of tungsten significantly and mitigate problems of deep cracking occurring typically in cyclic high heat flux loading. Textile techniques are utilized to optimise the tungsten wire positioning and process speed of preform production. A new device dedicated to the chemical deposition of W enhances significantly, the available machine time for processing and optimisation. Modelling shows that good deposition results are achievable by the use of a convectional flow and a directed temperature profile in an infiltration process.

1. Introduction

The so called DEMOnstration power plant DEMO will be the first fusion reactor producing electricity and is therefore the next step towards realizing fusion based energy systems [1,2]. If considering such a fusion based power plant a combination of multiple issues needs to be evaluated [3,4]. Currently such a reactor only exists in the form of early design studies where detailed operational requirements are just now being developed [5,6].

For the first wall material of DEMO unique challenges require complex features in areas ranging from mechanical strength to thermal properties. The main challenges include wall lifetime, erosion, fuel management and overall safety. For the lifetime of the wall material, considerations of thermal fatigue as well as transient heat loading are crucial as typically 1×10^9 (30 Hz) thermal transients (ELMs) during one full power year of operation are to be expected. For next step devices, limits on power exhaust, availability and lifetime are far more restraint than for current research-use-only reactors [6]. The development of advanced materials especially having high temperature strength and high fracture resistance/damage tolerance is therefore essential for a future fusion power plant [7].

Tungsten (W) is currently the main candidate material for the first wall of a fusion reactor due to its unique property combination e.g. the high melting point and the high temperature strength as well as an excellent erosion resistance and a low

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tritium retention [7]. For this reasons a solution based on actively cooled tungsten components has been developed for the divertor of the next generation device, ITER [8].

However, as a typical bcc metal, tungsten exhibits a so called ductile-to-brittle transition (DBT) [9]. Below a certain temperature, the DBT temperature (DBTT), these materials show brittle behaviour. The transition temperature is very much dependent on the composition, the fabrication process, and the pre-treatment as well as the testing method. It lies typically between 500 K and 600 K [10] and goes up to above 1200 K for tungsten annealed at high temperature [11]. W is susceptible to embrittlement, i.e. the DBTT is rising by grain coarsening [12] or/and neutron irradiation [13,14].

Tungsten fibre-reinforced tungsten composites W_f/W utilize extrinsic mechanisms to improve the fracture toughness. The brittleness problem of W is thereby mitigated and an application as a plasma facing material under thermal transients and neutron bombardment becomes feasible. A similar approach has been successfully applied to ceramic materials reinforced by ceramic fibres for many years [15].

W_f/W composites consist of tungsten fibres made of commercially available tungsten wire embedded in a tungsten matrix produced either by a chemical process [16,17] or by powder metallurgy [18]. In the past years, it has been shown at the Max-Planck-Institute for Plasma Physics, Garching (IPP) that extrinsic toughening can be achieved in such composite systems [19,20]. Being a key factor for the effective operation of this toughening mechanism the interface between fibre and matrix was investigated in a first step [21,22]. Engineered layers provide a stable interface during production and operation. Model systems consisting of a single W fibre embedded in a chemically deposited tungsten matrix were used to prove the feasibility of the toughening effect. It was shown that various extrinsic toughening mechanisms, e.g. fibre bridging, fibre pull-out etc. are active in the as-fabricated case as well as after embrittlement of the fibre by recrystallization and grain growth[1] [20]. In addition it was shown that the plastic deformation of the fibre makes an important contribution to the toughening in the as-fabricated state [23]. In a further development step a fabrication method for bulk material based on the chemical deposition of W was developed and first samples were produced. Mechanical tests on these samples revealed an intense toughening at room temperature and active toughening mechanisms in embrittled conditions. Based on these results the material was chosen as risk mitigation plasma-facing component and high heat flux material in the EU Fusion roadmap [2,3].

In [24] we presented a development approach towards the use of W_f/W in a future fusion reactor. As a first step components will be fabricated and tested under high heat flux conditions. The components will be designed according to the ITER reference design of small-scale divertor mock-ups [25]. High heat flux testing of small scale mock-ups is a well-established method to qualify material for the use in a fusion divertor and is for example used in the ITER qualification program. Two designs are very common: a so-called monoblock design where the whole component consists of the plasma facing material connected to a cooling tube in the central region, and a flat tile design where a plate of this material is connected to a larger cooling structure [26].

In this article we present a way to utilize W_f/W composites for divertor applications by a fabrication route based on the chemical vapour deposition (CVD) of tungsten. A technique to produce W_f/W material which can be used for producing monoblock or flat tile mock-ups is introduced and mechanical test results of such material showing increased fracture energy are shown. In addition we address the benefits of such a material system and present new techniques/methods for improving the manufacturing process.

2. Divertor mock-up components made of W_f/W

Based on the mock-up design presented by Hirai et al. [25] a possible W_f/W mock-up is shown in Fig. 1. The mock-up is made of 5 segments attached to a CuCrZr cooling tube. The single segments consist either of W_f/W only (monoblock) or of a W_f/W plate attached to a *Cu* structure. In the following we present a possible fabrication approach for such mock-ups together with first results. For a flat tile design W_f/W tiles with a thickness of 5 mm are needed. For a monoblock design tiles with a thickness of 12 mm are used in an upright position. The geometry including the necessary hole in the monoblock case are produced by spark erosion. In the case of the flat tile concept the W_f/W parts are connected to the Cu structure by brazing [27]. Finally the segments are joint with the cooling tube by hot radial pressing [28] (monoblock) or again brazing (flat tile). In both cases the W_f/W tiles are arranged in a way that the fibres will be orientated parallel to the surface.

2.1. W_f/W tile by layered deposition process

First W_f/W tiles have been produced utilizing a layered deposition procedure. In this process the tile is produced by successive chemical vapour deposition (CVD) of W on single layers of equally distanced and unidirectional orientated tungsten wire with a diameter of 150 μm (similar wire has been used for the chemical infiltration experiments performed in [16]). These layers are produced in a multi step process. First the wire is wound around a frame consisting of two fine threaded top ends in a way that the distance between the wire is determined by the pitch (500 μm in this case). This results in a top and bottom layer of wire pieces (called fibres in the following) with a free distance of 350 μm between each other. By a vertical adjustable clamping system the two layers are brought into one plane and the distance of the fibres is adjusted to the final distance of 100 μm.

To form the composite a fibre layer is placed on a heated surface where the applied process gas (WF_6 and H_2) reacts in a surface reaction to form W deposit which starts to ingrow the layer. After reaching the required thickness for the desired vertical layer distance the already ingrown layer is cut free of the frame. Then a second fibre layer is placed on top and is ingrown again. This procedure is repeated until the desired sample height is reached. By this procedure a vertical distance of the fibre layers slightly above 100 μm is achieved. The footprint of the final sample is determined by the size of the used fibre layer and the height is determined by the number of layers put on top of each other. The resulting fibre volume fraction is up to 30% (depending on the vertical distance between the individual fibre planes). To provide a stable interface to the matrix the fibres are typically coated by magnetron sputtering e.g. by an Er_2O_3 interface layer with a thickness of 1 μm (see [19] for details of the process) prior to the matrix production.

Samples with a footprint of 50 by 50 mm^2 containing up to 10 fibre[2] layers have been produced so far (see Fig. 2). The samples thickness varied between 3.5 and 4 mm and the density reached 94% (determined by Archimedes principle). Microstructural investigations revealed that the deposition itself was very dense (no micropores) and that large pores were formed in between the fibres by premature stopping of the deposition due to pore blocking. This was especially a problem if the fibres were not well arranged and thus a large variety of different distances between the fibres was

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[1] This condition is called “embrittled” in the following.

[2] The fibres were coated by an Er_2O_3 interface layer with a thickness of 1 μm.

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