TUNGSTEN FIBRE-REINFORCED TUNGSTEN COMPOSITE - DEVELOPMENT OF A NEW HIGH PERFORMANCE MATERIAL

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Abstract

Due to its high strength and creep resistance also at high temperature combined with a high thermal conductivity and melting point tungsten would be the ideal high temperature material. However as a typical bcc metal tungsten is brittle up to very high temperature and prone to operational embrittlement. Tungsten fibre-reinforced tungsten composite utilizes extrinsic toughening mechanisms similar to ceramic fibre-reinforced ceramics and therefore overcomes the brittleness problem. In this contribution we present the main characteristics and the manufacturing of this new composite material. We summarize the development approach for its use in a future fusion reactor starting with the proof of principle and the currently ongoing proof of concept. We finally discuss a possible future application in micro gas turbines.

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]. For the first wall material of DEMO unique challenges require complex features in areas ranging from mechanical strength to thermal properties. The development of advanced materials especially having high temperature strength and high fracture resistance/damage tolerance is therefore essential [3]. Tungsten features a high strength and creep resistance also at high temperature combined with a high thermal conductivity and melting point and would therefore be the ideal high temperature material (detailed reviews about the properties of tungsten are found here [4, 5]). These properties and an excellent erosion resistance and low tritium retention makes it the main candidate material for the first wall of a fusion reactor. In this context a solution based on actively cooled tungsten components has been developed for the divertor of the next generation device, ITER [6].

However, as a typical bcc metal, tungsten exhibits a so called ductile-to-brittle transition (DBT) [7]. 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 pretreatment as well as the testing method. It lies typically between 500 K and 600 K [4] and goes up to above 1200 K for tungsten annealed at high temperature [8]. In addition W is susceptible to embrittlement, i.e. the DBTT is rising by grain coarsening [5] or/and neutron irradiation [9].

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Tungsten fibre-reinforced tungsten composites (W_f/W) utilize extrinsic mechanisms to improve the fracture toughness of tungsten. 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 or by powder metallurgy. The fibres are typically coated by engineered layers to provide a stable interface to the matrix. Details are presented in chapter 3.

A similar approach has been successfully applied to ceramic materials reinforced by ceramic fibres for many years [10–12]. In this approach mechanisms are introduced which allow energy dissipation and thereby relaxation of stress peaks at crack tips. The resistance against crack propagation is thereby enhanced and the fracture toughness increased. As these mechanisms are not an intrinsic material property but caused e.g. by introduced reinforcements the mechanism is known as extrinsic toughening.

In this contribution we present the main characteristics and properties of this new composite material as well as two manufacturing routes. We give an overview of the development process so far and the planned next steps. For this we will review and summarize our work published in the past years. Finally we discuss a possible future application in micro gas turbines.

2. Development of W_f/W composites towards a plasma facing material in DEMO

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 the W_f/W composite systems [13, 14]. The interface between fibre and matrix as a key factor for the effective operation of this toughening mechanism was investigated in a first step [15, 16]. 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] [17]. In addition it was shown that the plastic deformation of the fibre makes an important contribution to the toughening in the as-fabricated state [18]. 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 [19, 20]. Mechanical tests on these samples revealed an intense toughening at room temperature and active toughening mechanisms in embrittled condition. 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, 21]. At this stage it has been shown that the idea of extrinsic toughening of W works in principle and the application as highly loaded divertor element has been identified. Thus, level 2 of the so-called technology readiness level (TRL) has been reached (proof-of-principle + application formulated) (explanation of TRL concept in [22, 23]).

The further development approach towards the use of W_f/W in a future fusion reactor is presented in [24]. As a first step components will be fabricated and tested under high heat flux conditions. In [25] a way for the fabrication of such components, so called small-scale divertor mock-ups is outlined. A fabrication route based on the chemical vapour deposition (CVD) of tungsten is used to produce monoblock or flat-tile concepts (details in [26]) and the benefits of such a system are discussed. This will allow to prove that the concept of a W_f/W divertor element works (TRL 3, proof-of-concept). High heat flux tests on such mock-ups are a well established method to qualify material for the use as a plasma facing material [27] and allows to validate the concept under relevant testing conditions (TRL 4, validation). The loading will be performed in a neutron beam [28] and/or electron beam facility [29] and allows the evaluation of the maximum strength, the fatigue strength and the damage tolerance/toughness and thus the conceptual proof in one step. Candidate materials for DEMO however, need to reach TRL 6-8 before being considered for design [30]. TRL 5 is typically associated with the validation in a relevant

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

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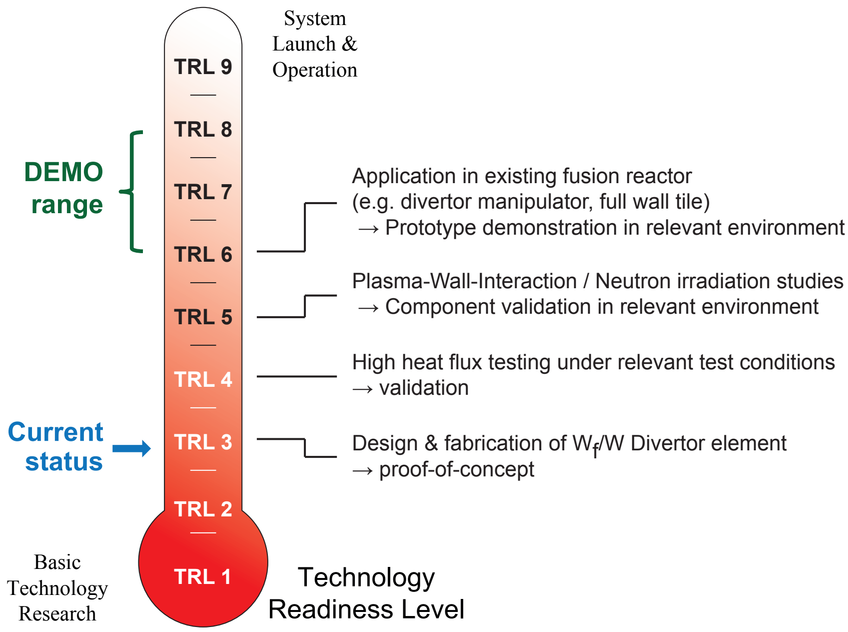

Figure 1: Development of W_f/W composites illustrated in a TRL scheme. The DEMO range is shown according to [30].

environment. In the case of W_f/W this is associated with the fusion plasma interaction, e.g. erosion, hydrogen retention and the behaviour under neutron irradiation have to be taken into account. TRL 6 will be reached by a prototype demonstration in a relevant environment. This can be in wall tiles of existing fusion reactors, e.g. on a manipulator or as a long term wall tile. The development approach in summarized in figure 1.

3. Characteristics and Manufacturing

In the following we give a short summary of the characteristics of W_f/W. A detailed overview is given in [31]. The tungsten fibres used in W_f/W are made of commercial drawn tungsten wire featuring a high strength [24, 32] and a considerable ductility [33, 34]. The used wire has typically a diameter of 150 µm but is commercially available down to a diameter of 16 µm. Pure W wire and wire W doped with several 10 ppm potassium (K) are used. The latter shows due to a grain boundary pinning effect a very beneficial high temperature creep stability (more details in [35]). The first manufacturing step is typically the formation of a fibrous preform which can be done by winding [36],braiding [31] or by a weaving process [25].

The interface system is either applied before this process or on the final preform and has to provide a physical barrier between fibre and matrix and thus maintain the composite structure during fabrication and operation. In addition, the interface must provide the load transfer between fibre and matrix and should in this sense be as strong as possible. On the other hand it is essential that the interface rather than the fibre fails during crack propagation to allow for the toughening mechanisms becoming active (debonding criteria). Several layer types according to interface types described for fibre-reinforced ceramics (see [37]) have been used for W_f/W so far. The layers are typically produced by magnetron sputter deposition. Oxide coatings, i.a. ZrO_2 and Er_2O_3, with different thickness and as multilayer coatings (with W or Zr) as well as pure Er, Cu and C have been used. Fibre push-out tests have been used on single fibre-reinforced model systems, to evaluate the applicability and study the microscopic failure mechanisms [13, 15, 16]. All interfaces fulfil the debonding criteria but also show very little strength.

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Finally the matrix is deposited on the preform to form W_f/W composites. At the moment the most successful processing route for the production of W_f/W is the chemical deposition process which has been readily used for W coatings [38]. In this process tungsten hexafluoride is reduced by hydrogen in a heterogeneous surface reaction and thus solid tungsten is formed. In the case of W_f/W the typical process temperature is between 673 K and 873 K [13, 14]. The main advantages of this process are the comparably low temperature and the force free character which allows to preserve the interface and fibre integrity as well as fibre topology. So far surface deposition processes (chemical vapour deposition CVD) have been used for the production of model systems containing a single fibre (see for example figure [15, 18]) and recently in a step wise approach for the production of bulk material [20, 25]. Infiltration techniques (chemical vapour infiltration CVI) have been successfully used to produce the first bulk material in a dual step process [19].

The preferred manufacturing technique for tungsten is a powder metallurgical (PM) route (70-80 % of total production) [4] leading to highly developed production and processing routes. However, during these processes usually high pressure (200 − 400 MPa) and temperature (2273 − 3273 K) are applied. Such conditions have a huge impact on the fibre properties (e.g. due to recrystallisation/grain growth) and interface integrity (e.g. by thermal decomposition). Jasper et al. [39, 40] started investigations on the applicability of powder metallurgy (PM) for the production of W_f/W with respect to the effect on the fibres and the interface system. Hot isostatic pressing is used to produce model systems of single fibres embedded into a tungsten matrix. It is shown that an Erbia interface can withstand these conditions but that its structure is highly influenced. The pure tungsten wire used in the tests is fully recrystallised during the process. Further approaches to produce bulk material by PM using short fibres in a spark plasma sintering process are ongoing.

Mechanical tests have been conducted mainly in order to investigate the toughess and the respective toughening mechanisms in W_f/W. Tension and bending tests on single fibre model systems as well as on bulk samples have been conducted. As-fabricated samples as well as samples with embrittled fibres were tested. The investigations of the single fibre composites have been combined with in-situ synchrotron tomography to determine active toughening mechanisms qualitatively and quantitatively. By tension tests on single fibre composite samples a high contribution of the ductile fibre deformation on the toughness was proven in the as-fabricated case [18]. In bending tests it was shown that the toughening works in the as-fabricated as well as in the embrittled condition and the contribution of the individual mechanisms to the overall toughness has been determined [17]. Bending tests on bulk samples have been used to determine the total increase of toughness for as-fabricated samples which were produced by a CVI process [19] and for embrittled samples which were produced by a layered CVD process [20]. These tests at room temperature revealed an intense toughening and active toughening mechanisms in embrittled conditions. In both cases stable/controlled crack propagation after crack initiation is observed. With ongoing crack propagation the load bearing capacity of the material increases as well. This is typical for extrinsic toughening as the mechanisms only become active behind the crack tip. Recently charpy impact tests have been conducted at room temperature [25]. An increased energy consumption is measured and almost all fibres fail ductile. The results have been summarized in a Ashby diagram of toughness over Young's modulus [31] (see figure 2)

4. Application of W_f/W in micro gas turbines

As outlined above W_f/W composites have the capability to complement the properties of tungsten by high toughness. The new composite material has the potential to combine the following properties:

- very high melting point and high thermal conductivity

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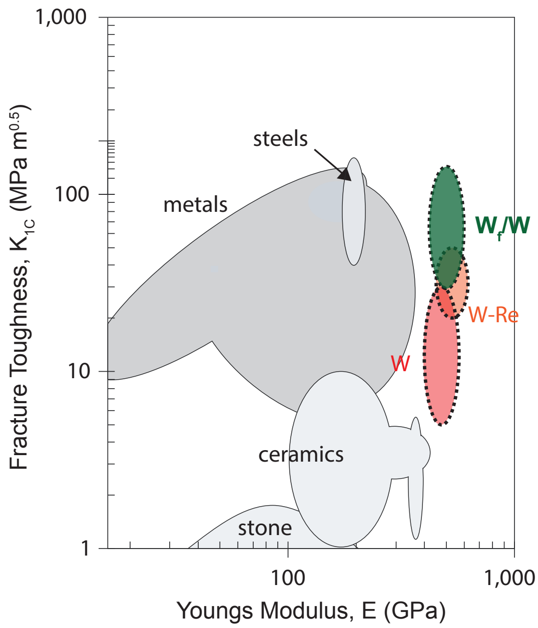

Figure 2: Ashby diagram of fracture toughness over Young's modulus based on [41, 42] and data for tungsten of [43] showing a potential region for W_f/W [31].

- high strength and creep resistance also at high temperatures
- very high toughness and thereby resistance against failure

This makes W_f/W an ideal material for high temperature applications especially for applications in which cyclic loading plays a role. The working temperature and thereby effectiveness could be improved and load and temperature cycles will be possible together with an increased life time.

A possible application could be in micro gas turbines[2] (MGT). Here a rise in the turbine inlet temperature which is between 1200 and 1300 K in current machines (not actively cooled) will allow a rise of the process temperature and therefore the effectiveness. A rise by 250 K will lead to a effectiveness of 34 %, whereas a rise of 450 K will lead to a effectiveness of 37 %. In multiple charged MGT with interstage cooling it should be possible to increase the electric effectiveness to 40 % and more [44]. In addition the large toughness could allow to significantly improve the lifetime in the highly loaded parts. This will be particularly important if MGT are used in combination with renewable energies in a future power network where fast and frequent load changes and starts/stops will be frequent.

The proposed operation temperature window for W_f/W [25] would allow for the anticipated temperature rise. But up to now the lack of comprehensive material data e.g. strength, thermal conductivity, etc. especially at higher temperature and the lack of robust high throughput manufacturing techniques prevent the application. However, it seems that the upcoming development steps within the fusion research program (see chapter 2) could provide such data and techniques for the production of sufficient large amounts of material.

[2]power < 1 MW

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5. Concluding remarks

W_f/W is produced by chemical deposition process and potentially by powder metallurgy. It exhibits a high toughness due to extrinsic mechanisms whereas the plasticity of the tungsten wire has a large contribution. This allows extending the applications of tungsten significantly also for structural applications in a future fusion reactor. The favourable properties could enable its use in other high performance application e.g. in micro gas turbines. In summary the new composite materiel offers a high potential but also large challenges until application in a real structure will be feasible.

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