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Advanced materials for a damage resilient divertor concept for DEMO: Powder-metallurgical tungsten-fibre reinforced tungsten

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HIGHLIGHTS

- For PM-W_f/W it can be said that a potential manufacturing path for W_f/W has been opened.
- W_f/W on its own can't solve the issues of heat-exhaust in the divertor of a future fusion power plant.
- Improvements of the copper cooling structure needs to be considered.
- Prototype components should be available within 5 years for application.

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ABSTRACT

Material issues pose a significant challenge for future fusion reactors like DEMO. When using materials in a fusion environment a highly integrated approach is required. Damage resilience, power exhaust, as well as oxidation resistance during accidental air ingress are driving issues when deciding for new materials. Neutron induced effects, e.g. transmutation adding to embrittlement is crucial to material performance. Here advanced materials, e.g. W_f/W or W/Cu, W_f/Cu composites allow the step towards a fusion reactor. Recent developments in the area of multi-fibre powder-metallurgical W_f/W mark a possible path towards a component based on standard tungsten production technologies. Field assisted sintering technology is used as production route to achieve 94% dense materials. Initial mechanical tests and micro-structural analyses show potential for pseudo-ductile behavior of materials with a reasonable (30%) fibre fraction. In the as-fabricated condition samples showed step-wise cracking while the material is still able to bear rising load, the typical pseudo-ductile behavior of a composite. Yttria is used as the interface material in order to allow the energy dissipation mechanisms to become active. W_f/W as plasma facing material contributes here to advanced material strength and crack resilience even with a brittle matrix embrittlement, while W/Cu, W_f/Cu composites at the coolant level allow for higher strength at elevated cooling temperatures. In addition to the use of pure tungsten it is demonstrated that tungsten-based self-passivating alloys can also be used in the composite approach.

1. Introduction

Tungsten (W) is currently the main candidate material for the first wall and in particular for highly loaded components of the divertor of a reactor as it is resilient against erosion, has the highest melting point, shows rather benign behavior under neutron irradiation, and low tritium retention. Extensive work has been done

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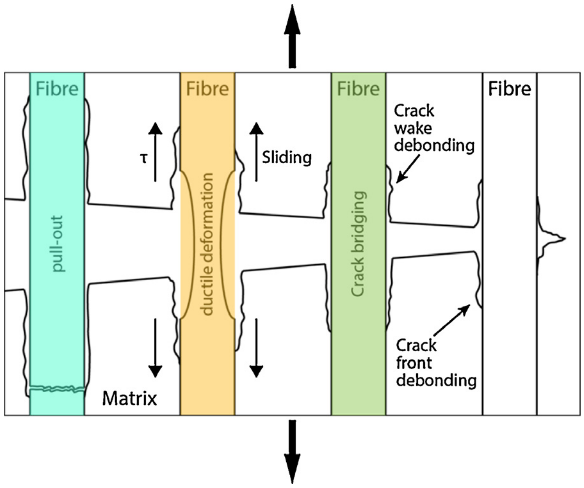


Fig. 1. Energy dissipation mechanisms typically considered in W_f/W and other fibre-reinforced composites (based on [11]).

to qualify current materials with respect to these issues for ITER, especially for W as first wall and divertor material [1,2]. For the next step devices, e.g. DEMO, or a future fusion power plant the limits on power exhaust, availability, lifetime and not least on fuel management are quite more stringent. Extensive studies and materials programs [3–8] have already been performed hence it is assumed that the boundary conditions [9] to be fulfilled for the materials are in many cases above the technical feasibility limits as they are set today [1,2].

1.1. Advanced materials

Efforts to establish new advanced plasma-facing material-options are moving forward [2] focussing on crack resilient materials with low activation, minimal tritium uptake, long lifetime and low erosion. The operational gap between materials for cooling structures, e.g. Cu, and the plasma-facing materials needs to be bridged [10,2]. Together W/Cu and W_f/W can bridge the gap between the upper bound for strength of copper ~620 K and the DBTT of W ~850 K.

Many of these materials base their advanced properties on the use of a composite approach. With the incorporation of fibres, energy dissipating mechanisms, like ductile deformation of fibres, fibre pull-out, and crack bridging and deflection are facilitated [12–14]. Fig. 1 shows the typical mechanisms.

An additional difficulty when using W in a fusion power plant is the formation of radioactive and highly volatile W-oxide (WO_3) compounds during accidental air ingress. In order to suppress the release of W-oxides W-based self-passivating alloys can be incorporated into the composite approach [15–19]. Here the focus lies on the powder-metallurgical (PM) W_f/W as plasma-facing-material (PFM).

2. Tungsten-fibre reinforced tungsten

To overcome the brittleness issues when using W, a W fibre enhanced W composite material (W_f/W), incorporating extrinsic toughening mechanisms can be used. Various methods of building and constructing W_f/W composites, either via chemical vapor deposition (CVD) [20,21] or powder metallurgical processes [22,23] are available. Based on the work presented here and previous work [11,20–24], the basic proof of principle for CVD & PM W_f/W has been achieved. It can be expected that when using doped W-wires even at elevated temperatures (above 1500 K) W-fibres will keep their

Fig. 2. W_f/W produced by FAST with random distributed fibre and 2.5 μm and yttria interface between fibres and matrix.

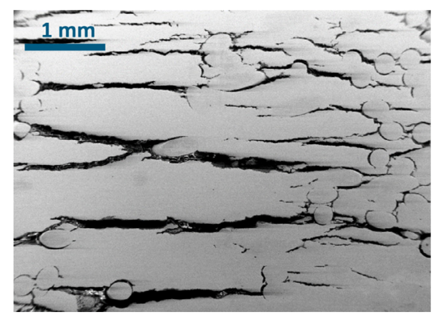


Fig. 3. Microstructure of W_f/W generated by dry pressing and subsequent pressure-less sintering.

ductility [25], hence all mechanisms described above may function [11]. Should the fibres however loose their ductility, due to neutron embrittlement and high temperature [26,27], the pull-out of fibres and the crack deflection should still be able to maintain pseudo-ductility. In W_f/Cu the embrittlement due to high temperature can likely be neglected, neutrons however will still be important.

2.1. Powder metallurgical production

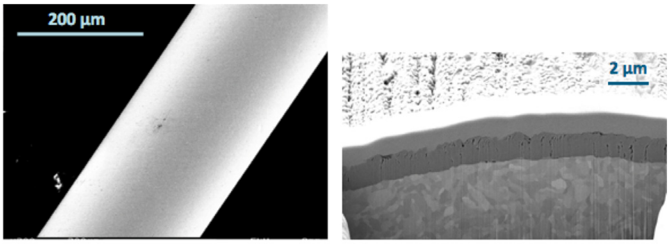
For powder-metallurgical production the homogenous introduction of powder between the fibres is required for good material properties, hence short fibres are used in contrast to, e.g. woven preforms or parallel long fibres.

In Fig. 2 an as-produced PM-W_f/W sample is shown. Based on field assisted sintering technology (FAST) [28] a sample with 40 mm diameter and a height of 5 mm was produced. Potassium doped W-fibres with 150 μm diameter and 1.5 mm length (OSRAM), together with pure W-powders (OSRAM) (average particle size 5 μm) were used as raw materials.

Dry pressing of a fibre/powder mixture and subsequent pressure-less sintering would be the cheapest and simplest process, of which W_f/W would benefit greatly. Therefore our first experiments were conducted in this direction. Using a press with an instrumented cylindrical floating die [29], the fibre/powder mixture has been compacted using a maximum pressure of 700 MPa reaching a relative density of 78%. Subsequently, the resulting green part was sintered in a W-tube furnace under a H_2 atmosphere at 2273 K for 1 h.

The resulting microstructure (cf. Fig. 3) shows distinctive cracking by shrinkage of the compacted powder, whereas the fibres are already at final density. From these results it is evident, that additional external pressure during sintering of W_f/W is required to get a dense and crack-free sample. FAST provides such additional compaction during sintering

The fibres and powders were mixed homogeneously before sintering, in order to produce a W_f/W sample with a random



(a) Surface coating (Y_2O_3) on individual fibre (b) Focused Ion Beam cut - Yttria interface structure - as produced

Fig. 4. The figure shows in (a) the SEM image of a single coated fibre with yttria interface, (b) is a FIB cut showing the yttria interface structure – as fabricated, before consolidation.

fibre distribution and orientation. A density of ∼94% was achieved after applying the sintering process at 2173 K (4 min) and 60 MPa (heating rate 200 K/min). In addition to the large samples, samples with 20 mm diameter for mechanical testing were produced based on the same parameters, but with varying composition. Two kinds of W-powders have been used: Pure W-powder (OSRAM) (average particle size 5 µm) and so called smart W-alloy powders (W–12Cr–0.5Y, provided by CEIT). The fibre size is also chosen differently in this case (240 µm × 2.4 mm). In all cases a fibre-volume-fraction of 30% was used. The samples have been prepared to establish if and how pseudo-ductility can be achieved in the case of a randomly distributed short fibre W_f/W.

2.2. Fibre and interface optimization

As part of the development of W_f/W particularly the choice of the fibre and the interface material can be crucial. With respect to the fibre, the choice of a sag-stabilized potassium doped fibre means that some ductility can be retained [11]. For the interface research on a variety of interlayers and their properties has been performed [30–36], including alumina, erbia and yttria (Y_2O_3). The interface properties, the stability of the interface needs to be established during the powder metallurgical production process. The fibre–matrix interface needs to be chosen as non activating material for fusion applications [2] – here yttria is proposed. Yttria is an ideal candidate as the interface material for the W_f/W composite due to its several advanced properties: good thermal and chemical stability, high mechanical strength and hardness. Yttrium oxide is proposed in W_f/W and is also used for permeation barrier coatings. For the material samples presented here the Y_2O_3 layers were deposited by a Prevac magnetron sputtering system from a yttrium metal target. Oxygen was injected into the argon atmosphere as the reactive gas, so that Y_2O_3 could be formed.

Fig. 4(a) and (b) shows and individual fibre coated with yttria before adding it to the powder for W_f/W production. Various interface thickness have been used during the various development steps of W_f/W. Typically 1 µm was established as a feasible thickness for the CVD Production Route [11,37,38]. For the PM-Route, both FAST and HIP, high pressures and temperatures however have shown [22] that potentially a thicker interface is required. The FAST process adds additional complications as electrical insulation, pressure and temperature on the interface can cause thin interfaces to dissipate [39–41]. Here 2.5 µm thick yttria is needed for a viable interface.

Fig. 5 shows a fibre after consolidation of the W_f/W as described above. The impact of the FAST process can be clearly seen. After FAST the interface is now far thinner and shows the indentation marks of the surrounding powder. Fig. 5 (r) clearly shows that yttria is remaining and hence the interface is intact. Additional interface materials are being tested.

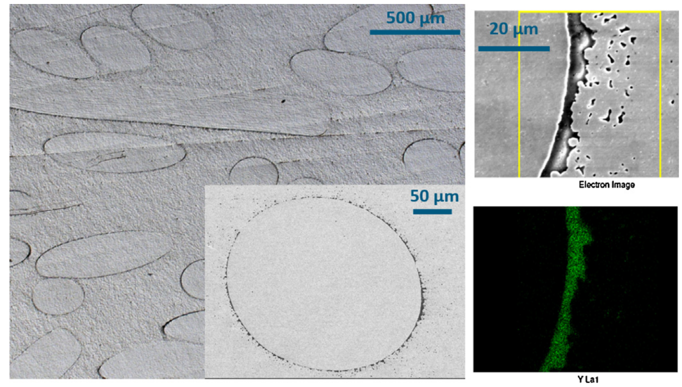


Fig. 5. Yttria interface on W-fibre in PM-W_f/W after consolidation (l) fibre and interface after consolidation (r) EDX map showing yttrium in interface.

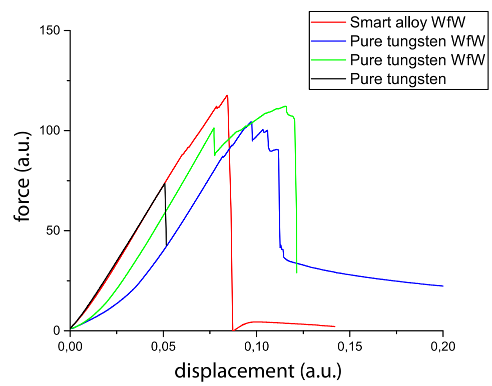


Fig. 6. Force displacement curves – 3pt bending tests of PM-W_f/W.

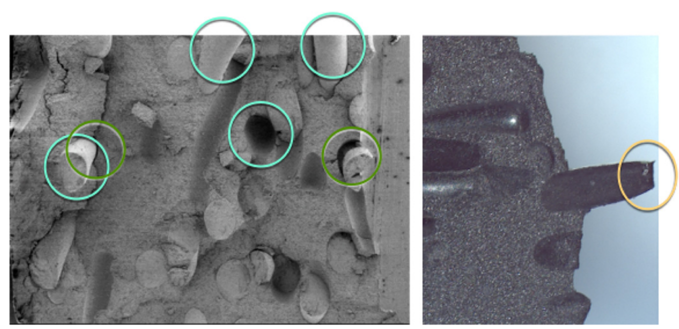


Fig. 7. Fracture surface of W_f/W – for circle colors refer to Fig. 1.

2.3. Pseudo-ductile behavior

The crucial point when considering W_f/W for applications is to establish pseudo-ductile behaviour based on extrinsic toughening mechanisms and eventually show improved mechanical behaviour during operational conditions.

Based on Fig. 1 we would like to identify the three mechanisms in tested material samples. Small (18 mm × 2 mm × 4 mm) three point bending test samples were produced and a pre-notch introduced. Utilizing an Instron 3342 universal testing machine (Instron GmbH) load displacement curves were taken and fracture surfaces produced to establish if the desired behavior can be reached.

Fig. 6 presents four typical load displacement curves. In arbitrary units the behavior of two pure W 2.5 µm yttria W_f/W samples is shown together with one self-passivating (W–12Cr–0.5Y) W_f/W sample measurement. In addition the catastrophic failure of a pure W sample is shown. In all three W_f/W cases crack initiation is

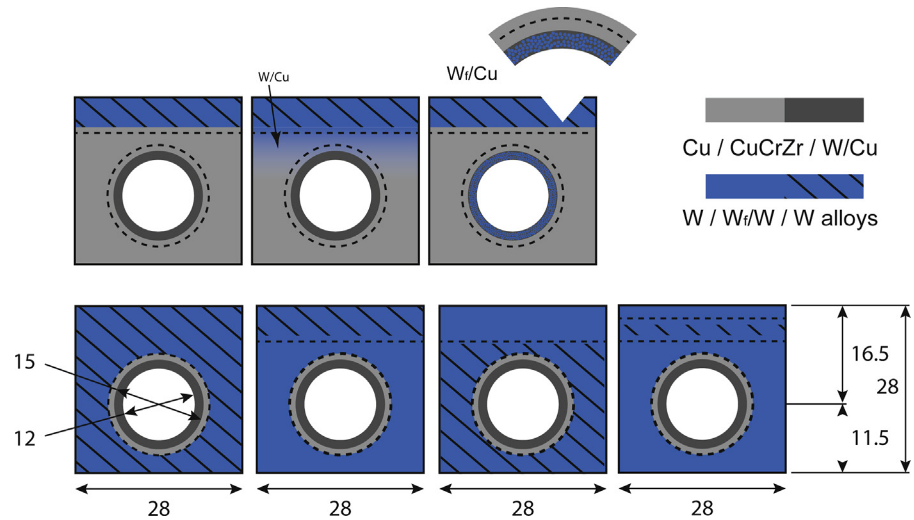


Fig. 8. Component design, incorporating W_f/W and W/Cu solutions at various points in the structure, based on [24,42].

observed after which still an increased load can be handled. This is a clear indication of pseudo-ductility in this simple model-system. Here now material qualification needs to make sure that potential failure modes like cracking [3] can be overcome for future divertor materials and components.

Fig. 7 shows in some detail the crack surface and highlights the individual mechanisms presented before (Fig. 1). All three mechanisms, ductile deformation of fibres, crack deflection and pull-out can be observed. Based on these promising results further materials development needs now to establish the actual material parameters like fracture toughness and ultimate tensile strength.

3. A new divertor component

In the brevity of this contribution mainly the new results on PM-W_f/W are reported. When trying to improve the performance of the divertor, not only the PFM or the armor are important but also the cooling structure and potential joints in the component, hence typically several material concepts need to be combined [2,43]. A component [2,43,44] could comprise of tungsten fibre-reinforced tungsten (W_f/W) [24,11,22,11,23], smart W-alloy as the matrix material [16–18,45], a copper based advanced cooling-tube (e.g. W-reinforced copper, W_f/Cu) [46] and integrated permeation barrier layers (e.g. yttria) [31,47].

Fig. 8 shows only a small variety of potential options that could potentially be used based on conventional ITER-like divertor designs only. The top row assumes a copper cooling structure and a flat tile of W as armour material. The copper tube can be strengthened via introduction of fibres and the mechanical stresses on the copper structure reduced due to introduction of a graded transition between Cu and W. Results on W/Cu new materials are reported elsewhere [4,44,46,48].

It is essential that the exhaust capability of an advanced component is similar to conventional designs and does in addition show resilience against, e.g. embrittlement, failure due to thermal stresses and cyclic loading. We hence propose to utilize the W_f/W composite approach together with W-alloying concepts to maximize the potential of W-based-PFCs on top of the advanced cooling options. The lifetime influenced by erosion, creep, thermal fatigue, and embrittlement, needs to be compatible to the requirements from steady state operation. This means that erosion determined by the top layer needs to be close to pure W. Potentially various options introducing the composite need to be considered. Thermal stress analysis can give hints at locations within the component where a potential application of W_f/W is indicated by high stress and crack probability [3].

4. Conclusion and outlook

Based on the presented tests for PM-W_f/W it can be said that a potential manufacturing path for W_f/W has been opened in addition to the established production via CVD. The presented approach allows now the quick prototyping and testing of new material combinations, fibres, interfaces and alloys. This demonstrates that pseudo-ductile behaviour works in short fibre PM-W_f/W. This paper shows for the first time that all desired mechanisms are active.

W_f/W on its own can however not solve the issues of heat-exhaust in the divertor of a future fusion power plant. Here also the improvement of the typically used copper cooling structure needs to be considered. In combination both can be used to develop a new divertor component. Here rigorous testing and qualification is required with respect to heat-exhaust, thermal fatigue, cyclic loading and plasma wall interaction.

It is planned to have prototype components available within 5 years for application in existing fusion devices. In order to also establish material performance under irradiation PM-W_f/W samples (cf. Fig. 2) are earmarked for irradiation in a nuclear reactor starting in 2017.

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