Tungsten Fibre Reinforced Tungsten (W_f/W) using Yarn Based Textile Preforms

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Abstract. Material issues pose a significant challenge for the design of future fusion reactors. Tungsten (W) is the main candidate material as it is resilient against erosion, has the highest melting point of any metal and shows rather benign transmutations under neutron irradiation. However, W is intrinsically brittle and faces operational embrittlement. To overcome these issues composites are being developed. W-fibre reinforced W-composite material (W_f/W) incorporates extrinsic toughening mechanisms allowing the redistribution of stress peaks and thus allowing steps towards application in a future fusion reactor.

In this contribution the recent status for the W_f/W production will be given with a focus on the introduction of advanced textile preforms produced from W-yarns [1].

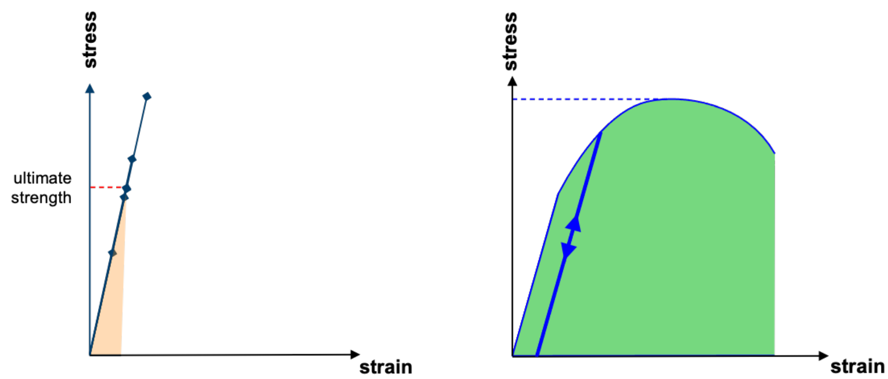
1. Introduction

Solid Tungsten (W) is currently the most viavle candidate for use as plasma facing material in the highly loaded divertor components of future fusion reactors. As tungsten is resilient against erosion , has the highest melting point of any metal, and shows rather benign activation behaviour under neutron irradiation. In addition, low tritium retention is a beneficial property. In recent years many of studies have tackled the issue to qualify current materials with respect to these issues for ITER ‡[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13] and beyond. For a DEMO § type device, or a future fusion power plant the limits are more stringent. It is assumed that the boundary conditions [3, 14] to be fulfilled for the materials are in many cases above the technical feasibility limits as they are set out today [11, 12].

New advanced-options for use as PFCs are being developed (see [15, 9], and references therein) focussing on crack resilient composites with low activation, no or

‡ https://www.iter.org
§ https://www.euro-fusion.org/programme/demo/

low tritium uptake, enhanced lifetime and low erosion. Many advanced materials base their improved properties on the use of a composite approach. Figure 1 visualises the issue with tungsten. In 1(a), the stress-strain behaviour of a fully brittle material is given. Failure occurs in a sudden manner, immediately when UTS is reached. UTS here is statistically distributed and not well defined.



(a) Brittle Material (b) Ductiles / Tough Material

Figure 1: Material behavior for tungsten, when being brittle or ductile (tough)

In 1(b), a material showing well defined material properties , with high toughness and ductility is given. The material, is failure tolerant, with no sudden failure and remaining load bearing capability, beyond UTS , also allowing cyclic loading of the material

In order to improve the mechanical properties of tungsten multiple options had been evaluated including microstructure refinement, alloying or composites [16, 17, 18, 19, 20, 21, 22]. In the following only fibre composites are being considered as they remain among the most promising of the candidates.

2. Tungsten-Fibre Reinforced Tungsten

To overcome the brittleness issues when using W, a W fibre reinforced W composite material (W_f/W), incorporating extrinsic toughening mechanisms as described in [15, 23] can be used. Various methods of building and constructing W_f/W composites, either via Chemical Vapor Deposition (CVD) [24, 25, 26] or powder metallurgical (PM) processes [27, 28, 29, 30, 31] are available. Based on the work presented here and previously in [32, 33, 30, 31, 34, 35, 36, 37, 38], the basic proof of principle for CVD & PM-W_f/W has been achieved. Fully dense material is aimed for and porosity will diminish mechanical properties as much as behaviour with respect to fuel retention.

One of the crucial issues is to maintain as much of the properties of the constituents even after exposing the material to the production cycle and the fusion environment allowing for optimal extrinsic toughening and pseudo-ductile behaviour. Here mainly the adapted interface and the strength of the fibre as well as the preform [33] are important.

Yttria is an ideal candidate as the interface material for the W_f/W composite due to its several advantageous properties: good thermal and chemical stability, high mechanical strength and hardness [39, 40] as well as low neutron activation. To improve the CVD W_f/W material multiple avenues can be pursued - improving the textile preform and improving the CVD matrix production are among the most promising ones. With respect to the constituent properties potassium doped W-wires can mitigate temperature induced embrittlement effects and thus retain their ductility even at elevated temperatures (above 1500 K) [35]. The mechanisms, including ductile fibre deformation, necessary for pseudo-ductility will be retained [39, 36, 38]. Properties of the fibres can however be degraded by various circumstances e.g. by impurities during fabrication [41, 42], high-temperatures or neutron irradiation during operation [43, 44]. To maintain the wires properties also improved fibre types e.g. yarns can contribute by introducing better properties e.g. tensile strength at the point of production. The strength of the 16 μm flament is at 4500 MPa and thus significantly higher than the strength of the 150 μm fibre (∼2500 MPa) (in the as-fabricated state). During the CVD process, the improvement of the W_f/W properties can be realised by optimising the process parameters, fiber sizing, and fiber positioning, with respect to fiber volume fraction, relative density, and WF_6 consumption [26].

In the past, typically monofilamantes with a diameter of 150 μm (OSRAM) have been used to weave textile preforms to facilitate large scale production of e.g. for CVD-W_f/W [33, 23].Recently these preforms have also fund their way into powder metallurgical production.

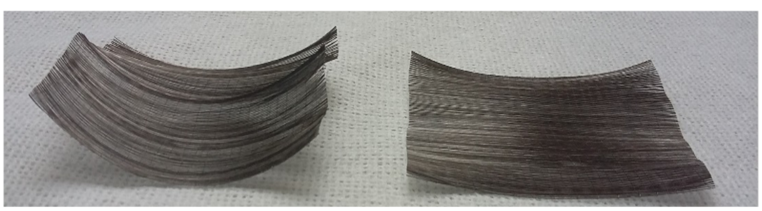
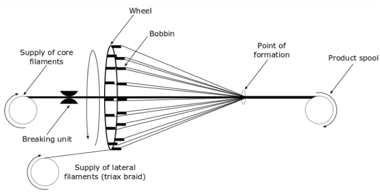


Figure 2: Tungsten weave based on production described in [33]

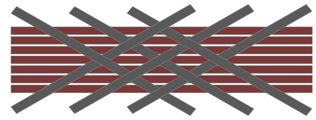
However, the high stiffness of the tungsten fibers with 150 μm diameter often presents some challenges, i.e. positioning of a flat preform during the CVD processes. In Figure 2, a typical weave produced from 150 μm wire is shown. In order to improve these textile prformes or weaves less stiff 16 μm or 25 μm fibres can be used where the strength of the 16 μm fibres is at 4500 MPa [33] and thus significant higher than the strength of the 150 μm fibre.

3. Tungsten Yarn

After the initial success in yarn production [45] a larger amount of triaxial braided yarn with core filaments were industrially produced at Bossert&Kasst and used for weaving of advanced preforms.



(a) Principle of Braiding

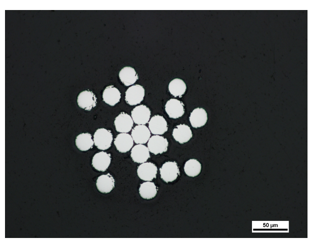


(b) Triaxial braid (sleeve and non-interlaced core filaments

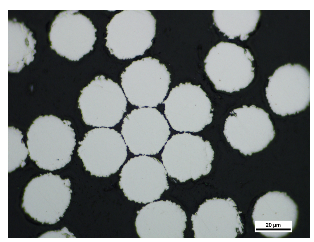
Figure 3: Procedures and braiding.

Braided yarns are based on braiding as a very versatile textile process, that offers various possible variation of the braid and the machine itself. Only the process of radial braiding is relevant for the work presented. Based on the process shown in 3(a) and the selection made in [45] the following yarn type is considered here:Triaxial Braided Yarns with overbraiding of core filaments (16 + 7 Filaments) (cf n Fig. 3(b)).

The braided yarn structures were fabricated based on the study in [45] and manufactured by Bossert&Kast. 16 carriers were used and the braid pattern was selected to "one over two under two" The brading angle was adjusted to 45°.



(a)



(b)

Figure 4: Structures of the individual Yarns, showing both the cores and the sleeve filaments.

In contrast to the previous study $25\mu m$ filaments were used (cf 4) as the acting absolute forces during the braiding process otherwise tore too many filaments. The yarns strcuture otherwise is iodentical to the ones presented in [45]. The diameter of the yarns produced is around $195\mu m$. The filaments were supplied by OSRAM, similar to the weft wire for weaving an dthe original 150 micron wire used in the conventional W_f/W

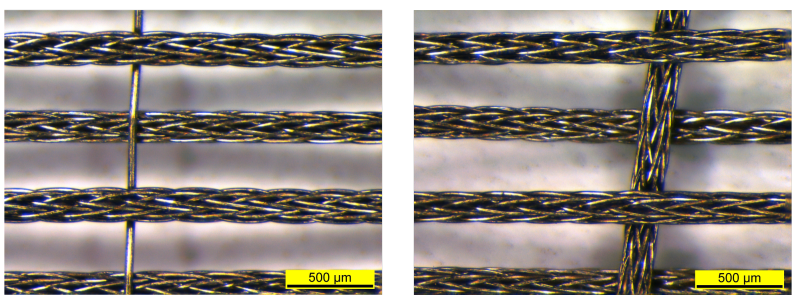
4. Tungsten Weave

The above describesyYarns can then be woven similarly to the conventional process using a single wire.The superior weavability of the yarn allows a much more flexible textile preform to be manufactured, which in turn allows better placement during the production process. Here two types of weaves are being compared: A weave with the warp wire made from yarns and a classical 50 μm tungsten filament in the weft direction and a second one utilising the identical yarn type in both warp and weft direction. Both weaves were based on the triaxial braid with 16 filaments + 7 core filaments.

(a) (b)

Figure 5: Shuttle Loom (a) and Final Weave (b)

A Mageba shuttle loom (type SL 1/80) weaving machine 5(a) was used to produce the weaves 5(b). Both weaves show a good quality with some obvious differences in structure (Fig. 6).

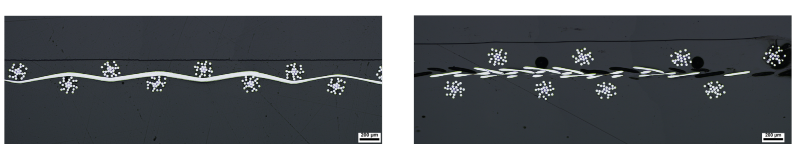


(a) Weave based on Yarn and 50μm weft wire

(b) Weave based on Yarn weft and warp

Figure 6: Tungsten Weaves produced based on the braided tungsten yarn

While the weave with a single weft wire is relative thin (350μ m) (Fig. 7(a)) the yarn only weave is almost 600 μm in thickness (Fig. 7(b)).



(a) Weave based on Yarn and 50μm weft wire

(b) Weave based on Yarn weft and warp

Figure 7: Cuts through textile preforms - two types of weaves

In order to optimise the CVD process these differences will play a role in order to mitigate porosity

5. Summary & Outlook

In summary it can be said that he development of textile preforms utilising yarns was successful and both weaves can now be used for CVD Wf/W production. Based on the work in [26, 33] we know that in order to reach a fully dense material the ratio of distance between the individual wires must be at least as large as the distance between the individual layers during production, as otherwise the gasflow will be restricted and porosity produced. Testing of these weaves in the CVD (W_f/W) production is essential to optimise density and fibre volume fraction.

For the individual yarns already a dense infiltration was observed [45] and needs now to be established for the woven product. Modelling shows that utilising a yarn based weave and thus making the layer placement more accurate, is crucial to allow W_f/W production with optimal density and mechanical properties. In the next steps, CVD coating, and layer wise production will be performed.

Acknowledgements

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