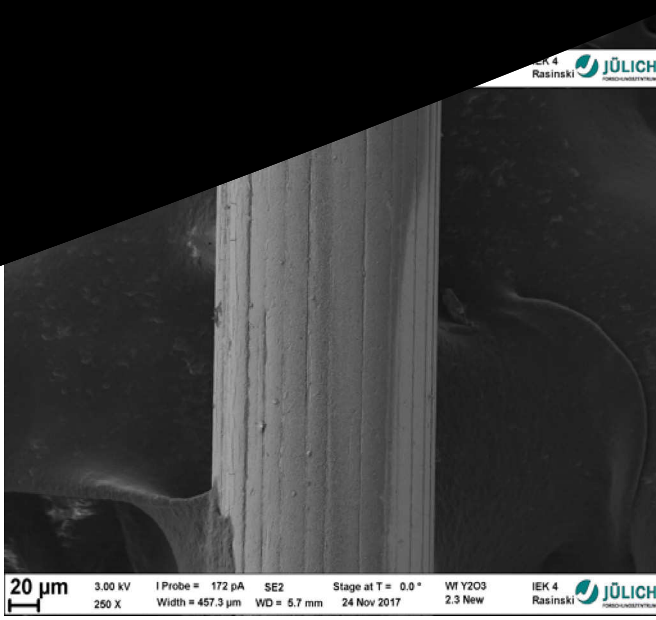

Fig. 1. Short W-fibres coated by 2.5 μ Yttria interface.

metallurgical (PM) production W_f/W as plasma-facing-material (PFM). The influence of the die material used is has been explored. It was shown that the ductile deformation [15] as well as the high strength [16] of the tungsten wire have a significant influence on the overall properties of W_f/W. Mueller et al. [17] show that one of the crucial aspects of the production process of any tungsten fibre composite is to control the amount of impurities e.g. carbon during the consolidation process. Carbon is of particular interested with respect to W and its mechanical properties [18].

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. The short fibres used in this PM version of W_f/W are shown in Fig. 1. Yttria is used as the interface material in order to allow the energy dissipation mechanisms to become active. 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 [8,19]. 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 [15,16,22,24,25], the basic proof of principle for CVD &

...ergy as possible it is ... ductile fibres. Even if the ... of fibres and the crack deflection ... -ductility for a viable material option. ... that when using doped W-wires they will e.g. ... ity even at elevated temperatures (above 1500 K) [15] ... mechanisms necessary for pseudo-ductility will enabled ... ,24,25]. Properties of the fibres might be degraded by various circumstances e.g. by impurities during fabrication, high-temperatures or neutron irradiation during operation [27,28]. In [17] it was found that all fibre samples categorised as brittle exhibit an increased C content compared to the fibres categorised as ductile.? All brittle samples have C content of 0: 0586 wt: % compared to the ductile samples with lower than 0.0013 wt %.

In the following we will describe that one aspect of the production needs to be controlled with particular care to minimise the degradation of the material properties of the fibres.

2.1. W_f/W – Material Production

For powder-metallurgical production of W_f/W as already described in [8,25] 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 as used in the CVD process route. Based on results from [8] pressureless sintering of W_f/W was unsuccessful, additional external pressure during sintering of W_f/W is required to get a dense and crack-free sample. Field Assisted Sintering Technology (FAST) [29] provides such additional compaction during sintering. Details on the consolidation incl. HIP (Hot-isostatic-Pressing) as well as material properties can be found in [8,25].

Potassium doped W-fibres with 150 μm diameter and 2.4 mm length (OSRAM), together with pure W-powders (OSRAM) (average particle size 5 μm) were used as raw materials. The FAST process gives rise to pressure and high temperatures temperature on the interface and can thus cause a thin interfaces to dissipate [30–32]. Here 2.5 μm thick yttria is applied for a viable interface similar to the work given in [25]. The fibres and powders were mixed homogeneously before sintering, in order to produce a W_f/W sample with a random fibre distribution and orientation. A density of $\sim$ 94% was achieved after applying the sintering process at 2173 K (4 min) and 60 MPa (heating rate 200 K/min) [8,25]. In all cases a fibre-volume-fraction of 30% was used.

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 and also which role the interface and impurity content may play. Here the main parameter that was changed in comparison to [8,25] is the addition of a tungsten foil to prevent as much as possible the interaction of the die material with the samples that are being sintered.

In Fig. 3 a sketch of the two different FAST procedures used is given. In one case the powder and die are separated by a graphite foil while in the other case a thin tungsten foil is used. Based on FAST samples with 20 and 40 mm diameter and a height of 5 mm were produced as shown in Fig. 2.

2.2. W_f/W – Material structure

Fig. 4, shows a representative cut though PM-W_f/W after consolidation as described above. The material is dense and a thin interface of yttria remains around the randomly distributed fibres. The difference between

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us studies, a series of tests have been performed without tative values and published in [8,25]. Fracture surfaces were analysed to establish if the desired mechanisms can be observed. In addition to that, small (27 × 2 × 3 mm) KLST type three point bending test samples were produced and a pre-notch introduced. Utilising an universal testing machine (TIRAtest 2820, TIRA GmbH) three point bending tests were performed. With an optical camera system, the accurate sample displacement was measured during the test, so that quantitative load displacement curves were taken. Typical curves are shown in Fig. 6. Here for the first time also quantitative numbers are given.

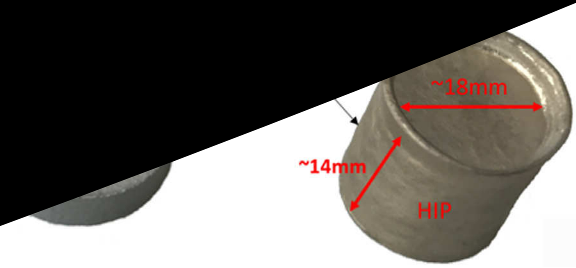

Fig. 2. Large 40 mm FAST W_f/W Sample displayed next to a small 20 mm FAST and HIP samples [25].

microstructure is identical for both consolidation procedures.

For both consolidation procedures shown the microstructure of the fibre was studied also. Fig. 5 shows for both cases similar grain size and structure after FAST. Originally the fibres have a very fine filamented grain structure as given in [33] with (0.3–1.5) μm in the directions perpendicular to the wire axis and roughly 10–90 μ along the axis. After consolidation of the W_f/W samples the average grain size along the original drawing direction of the fibre the is determined to be 2.322, and 2.502 μm respectively while perpendicular to the drawing direction the grains have an extent of around 6.5 μm . The grain size

Even after crack initiation is observed an increased load can still be handled. This is a clear indication of pseudo-ductility in this simple model-system.

In Fig. 6 one major differences for the Wf/W produced with W-foil is the shape of the curve. The fall off in load is far smoother and more steps are visible indicating a different fracture behaviour of both samples.

In Figs. 7 and 8 thus the typical fracture surfaces are depicted to elaborate on the difference in production. Fig. 7 shows the clear brittle fracture of one of the constituent short fibres with a clear intra-granular cleavage fracture.

For the Fig. 8 a ductile behaviour of the fibre is observed allowing for more energy dissipation also indicative from the stress strain curve. The fracture shows fibre necking with knife edges and a sharp fracture surface. This behaviour is in line with the results by Mueller et al. [17]. It was found that carbon when present during the annealing process of

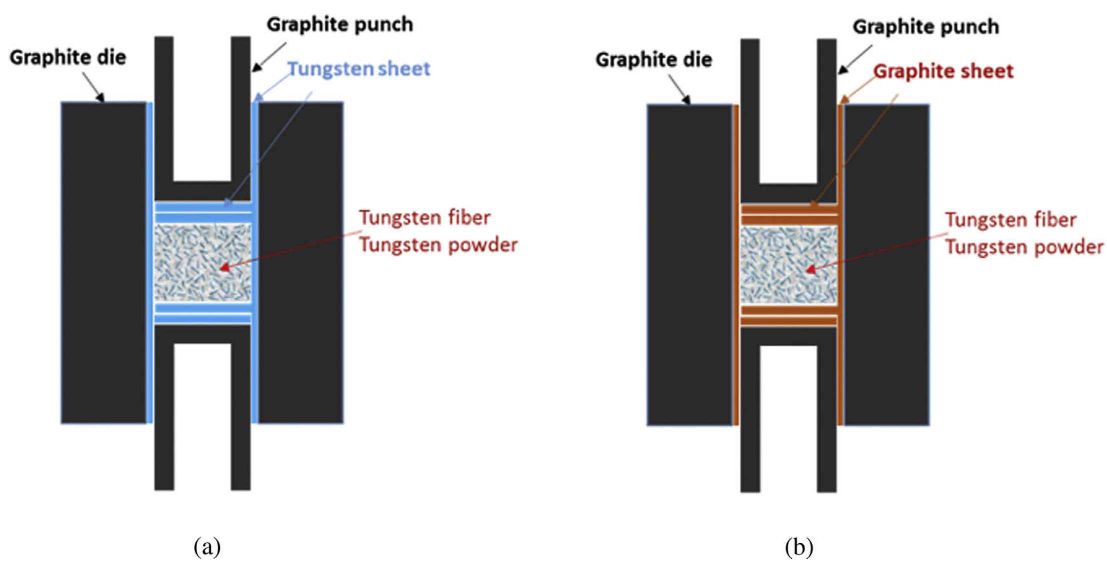

Fig. 3. Two different procedure for consolidation have been used to test the influence of the die material onto the final material properties (a) Tungsten foil as diffusion barrier, (b) graphite sheets for lubrication.

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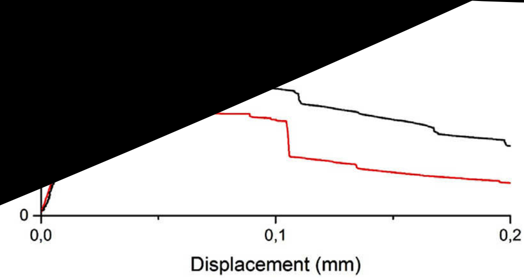

Fig. 6. (red) 3pt bending test results of W_f/W produce via FAST with W-Foil, (black) 3pt bending test results of W_f/W produce via FAST with C-Foil. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

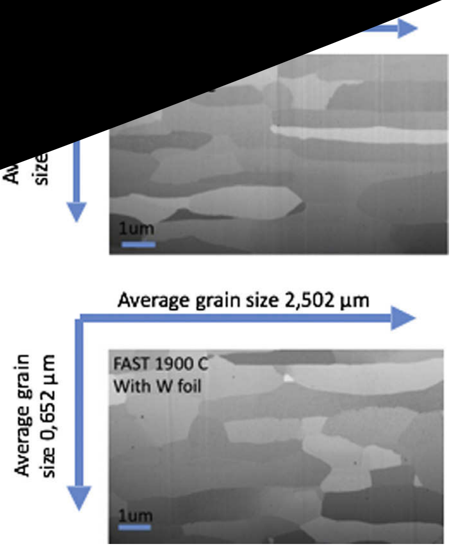

Fig. 5. Grainstucture and grain size of the fibres after sintering.

fibres can embrittle them already when diffusing in small quantities into the fibre. This is in line with findings from literature [18] where a link was established between the interstitial impurities such as carbon and the low temperature tensile properties of tungsten. In the given work above all presented test have been performed at room temperature to represent the worst case scenario for tungsten. Minimisation of the impact of the production process by excluding carbon is one step towards optimisation.

4. Conclusion and outlook

Based on the presented tests for PM-W_f/W with W-foil it can be said that the manufacturing path for W_f/W has been further improved. The presented approach utilising a W-foil mitigates the embrittlement of the constituent fibres during FAST processing.

Based on these results it can be seen that improved pseudo-ductile behaviour can be achieved for PM-W_f/W. It is planned to utilise this new route in developing prototype components 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 neutron irradiation starting in 2018.

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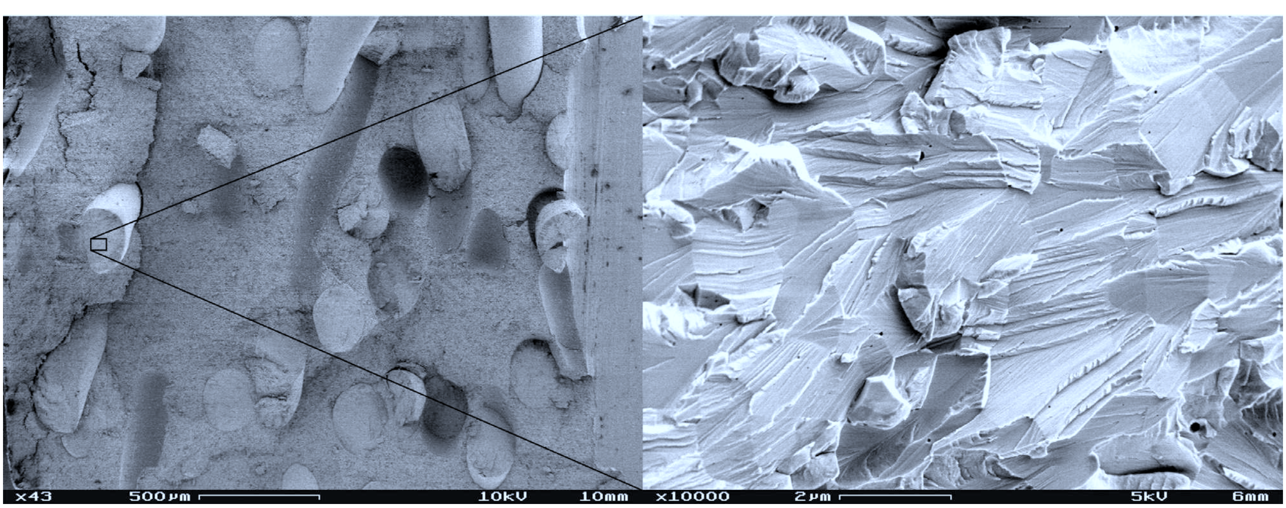
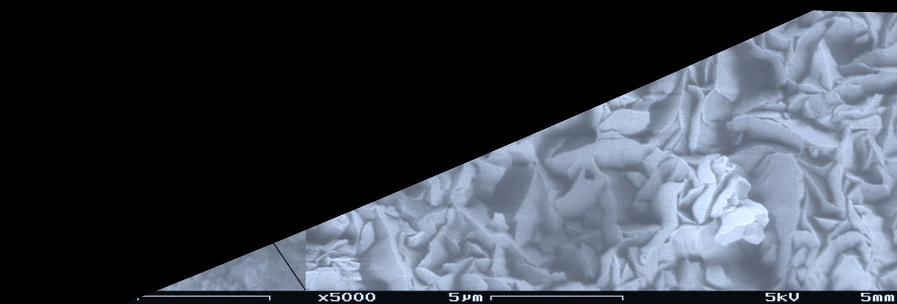


Fig. 7. Fracture Surfaces of a W_f/W samples consolidated with C-foil .



racture Surfaces of a W_f/W samples consolidated with W-foil.

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