Contributions of tungsten-fibre reinforced tungsten composites to divertor concepts of future fusion reactors

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Tungsten as Plasma-Facing Material

- Oxidation: Oxide Stability, Oxidation Mechanism
- Mechanics: DBTT, Fracture Mechanics
- Thermal Properties: Thermal Conductivity, Heat Capacity
- D/H/T Interaction: Retention, Diffusion
- Sputtering: Net Erosion, Surface Composition Change
- Transmutation/Activation: Nuclear Decay Heat, Nuclear Safety

**motivation for W from PWI**

J.W. Coenen PFMC 2015
Content

- $W_f/ W$ materials state of the art and development
  - K-Doped $W$ wires
  - As-fabricated state
  - Embrittled state

- Aspects for future divertor concepts
  - Toughening
  - Temperature window
  - PWI

- Summary
$W_f/W$ – state of the art

- **Theory**

  ![Image of stress-strain curve and fibre-matrix interaction](image)

- **Synthesis**
  - Wound fibre preform (drawn W wire) + CVI (dual step)
  - **Model system**
    + small bulk samples
    (2.5x3x25 mm)

[based on Chawla 1993]
• Manufacturing technique identified + first samples
• Enhanced toughness at room temperature – shown for bulk samples
• Toughness mechanisms after embrittlement – shown for model systems
→ **Proof-of-principle – TRL 2**
→ **Ranked as risk mitigation PFC/HHF material in EU Fusion roadmap towards DEMO**
W_f / W – Materials Development

Address all constituents + all aspects of synthesis

- Fibre studies
  - Strength: influence of diameter
  - Thermal stability
- Interface studies
  - Thermal stability
  - Optimisation of adhesion
  - Activation behaviour
- Matrix synthesis
  - Optimisation: layered CVD / CVI
  - Alternatives: powder metallurgical W_f / W
- Composite studies
  - Investigate mechanical properties
  - Understand embrittlement issues
    embrittlement by overheating
    embrittlement by neutron irradiation
Thermal Stability of K-Doped W wires

Single fibre tension tests on as-fabricated and annealed samples

- W doped with 60-75 ppm K (producer: OSRAM GmbH)
- Diameter: 150 µm, Fiber Length: 80 mm
- Annealing time: 30 min
- Annealing temperatures

\[ \approx 2400 \text{ K: } \text{abnormal grain growth}^{2)} \]

<table>
<thead>
<tr>
<th>Temp [K]</th>
<th>As-fabricated</th>
<th>1273</th>
<th>1573</th>
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- 50 µm
As-produced

2173 K

2573 K
Extensive grain growth

2) [Pink et al. 1989]
Tensile Tests of 150 µm W wires

Stress-Strain curve of as produced and heat-treated fiber

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Tensile strength of pure W: ≈ 2900 MPa

J. Riesch, PFMC 2015
Thermal Stability of K-Doped W wires

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Tensile strength of pure W: $\approx 2900$ MPa

J. Riesch, PFMC 2015
Brittle

Tensile Tests of 150 µm W wires

Tensile strength of pure W: ≈ 2900 MPa

Stress-Strain curve of as produced and heat-treated fiber

Embrittlement of pure W

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No embrittlement below 2200 K

J. Riesch, PFMC 2015
Production of multi-fibre samples by CVI & CVD

- 10 Layers a 220 fibres (pure), fibre volume fraction ≈ 0.3, unidirectional
- 62 x 57 x 3.5-4 mm³, 194 g
- 93 – 98 % depending on location, 94.2 % overall density (Archimedes)
- Er₂O₃ interface

First bulk W₇f / W for extended testing
Mechanical Properties of $W_f / W$

- Multi-fibre composite
  - W-CVD layered deposition
  - Polished
  - 2.2 mm x 3 mm
- As fabricated and Embrittled (2000 K, 30 min) $W_f / W$
- Stepwise 3-point bending + In-situ surface observation in electron microscope (ESI)

**Ductile Fibre (pure)**
Strength 2900 MPa, Fracture strain 2%

**Brittle Fibre (pure)**
Strength 900 MPa, Fracture Strain 0.2%
Mechanical Properties of W_f / W

Bending test of **as fabricated** W_f /W composites

- Controlled crack propagation + rising load bearing capacity → ‘Ideal’ behaviour of composite
Mechanical Properties of $W_f/W$

**bending test of embrittled $W_f/W$ composites**

- **Theory**
  - Controlled crack propagation + rising load bearing capacity
  - Toughening works also after embrittlement

- **Embrittled fibre**

  - Matrix failure = bulk material failure

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R.Neu
Aspects for future divertor concepts
Fibre tests at elevated temperature

Fibre tests after neutron irradiation

Tension tests on recrystallised $W_f/W$

Cracking of tungsten

[M. Wirtz et al., FED 88 (2013) 1768-1772]

Incoperate $W_f/W$

Deep cracking of divertor elements
Electron beam (FE200, France), 10-20 MW/m² up to 1000 cycles, actively cooled
Result of low cycle fatigue (crack initiation) and brittle behavior during cool down


[Pintsuk et al., Fusion Eng Des 88 (2013) 1858–1861]
First results of impact of bridging on J-integrals

No tensile stress concentration at crack tip

Stresses (MPa) in x-direction at the mid-surface

J-integrals for a pre-crack of 3 mm

* The surfaces from depth 1.0 to 1.5 mm and from 2.0 to 2.5 mm are bonded.

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Plasma wall interaction

Tungsten fibre-reinforced tungsten

- Special microstructure
  - Fibre, Matrix
- New materials
  - Interfaces, Doped W wire
- Complicated structures
  - Internal Interfaces, different microstructures

→ Many aspects to be considered if used as plasma facing material e.g.

- Thermal stability
- Activation
- Interaction with hydrogen
- Erosion
- ...

Matrix

Fibre: drawn W-wire

Interface
K doped W wire: activation

K doping of wire: no increase of activation
**Summary & Outlook**

**$W_f / W$ materials development**
- K-Doped $W$ wires show high strength and ductility up to annealing temperatures of 2200 K
- Very high toughness at room temperature due to ductility of fibres
- Toughness after high temperature embrittlement

**$W_f / W$ prospects for future fusion reactors**
- Enhancement of temperature window
- Solution for cracking problem
- Complex PWI issues

**Next steps**
- Fibre tests at elevated temperature
- Optimisation of manufacturing process
  - WILMA
  - PM studies
- PWI studies on constituents and model systems
Thank you for your attention