Max-Planck-Institut für Plasmaphysik

Melt infiltrated W-Cu composites as advanced heat sink materials for plasma facing components of future nuclear fusion devices

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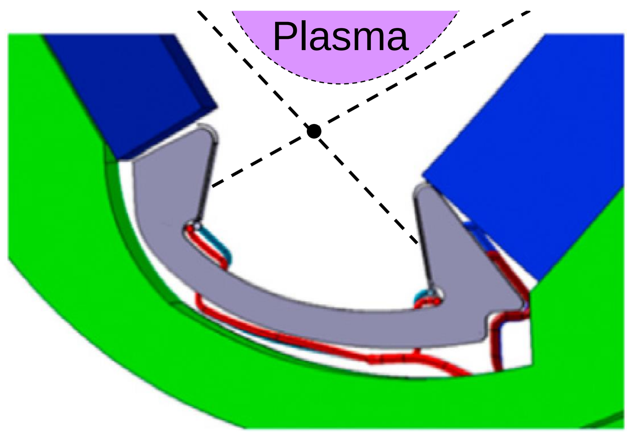
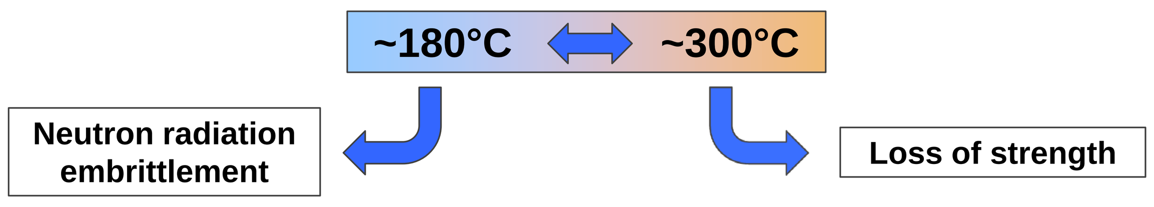
Introduction

- Future magnetic confinement nuclear fusion devices, as e.g. **ITER** or a **demonstration power plant (DEMO)**:
  - ⇒ **Tokamak** with poloidal **divertor** for exhaust of power and particles
  - ⇒ Very challenging nuclear environment for highly loaded **plasma facing components (PFCs)** like the divertor targets
    - Design surface heat flux loads: **≥ 10 MW/m²** [1]
    - Neutron damage levels: **≤ 6-7 dpa/fpy** [2]



- Precipitation hardened Cu alloy **CuCrZr** currently regarded as state-of-the-art **heat sink material (HSM)** for highly loaded PFCs:
  - ⇒ Restricted operating temperature window [2]:



  - ⇒ Combination of **W & Cu** in a PFC:
    - Differing thermomechanical properties, esp. CTE
    - No overlap of operating temperature windows

- Prime **requirements for PFC HSMs** for future magnetic confinement nuclear fusion devices:
  - ⇒ High thermal conductivity (> 200 W/mK)
  - ⇒ High strength at elevated temperatures (≥ 400°C)
  - ⇒ Capability of being produced on industrial scale

- **W-Cu metal matrix composites (MMCs)** as advanced HSMs for highly heat loaded PFCs:
  - ⇒ Material system W-Cu [3]:
    - Constituent materials are readily available
    - No mutual solubility / interfacial reactions
    - Very good wettability of W with Cu melt
    - $T_{m,Cu}$ = 1083°C < $T_{m,W}$ = 3400°C [4]
      - ➢ Fabrication into composites by **liquid Cu infiltration** possible
  - ⇒ Tailoring of macroscopic material properties possible
  - ⇒ High thermal conductivity due to coherent Cu matrix
  - ⇒ High strength at elevated temperatures due to the presence of W inclusions / reinforcements

Conclusions

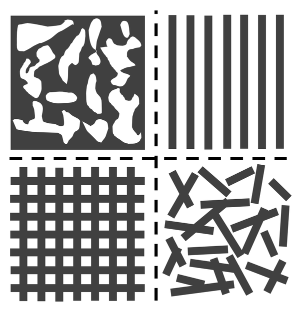
- Future magnetic confinement nuclear fusion devices
  - ⇒ Very challenging environment for materials used for the design of highly loaded PFCs
- Melt infiltrated W-Cu composites are potential HSMs for future PFC applications
  - ⇒ W-Cu composite metals
  - ⇒ W fibre-reinforced Cu
- Future work:
  - ⇒ Manufacturing process optimisation
    - Textile technological processing of W fibres
    - Melt infiltration process in industrial environment
  - ⇒ Continuation of thermophysical and mechanical material characterisation
  - ⇒ High heat flux testing of mock-ups with W-Cu composite heat sink

[1] G. Federici et al., Fusion Eng. Des. 89 (2014) 882-889
[2] D. Stork et al., J. Nucl. Mater. 455 (2014), 277-291
[3] D. L. McDanels, NASA Technical Paper 2924, 1989
[4] Metals Reference Book, 5th Edition, ISBN 978-0-408-70627-8

Manufacturing approach: Melt infiltration

W preform

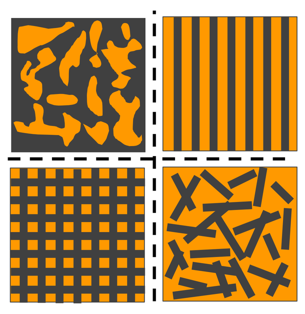
⇒ Reinforcing W phase
⇒ Open porous
⇒ Defined void fraction and/or architecture



Cu melt infiltration

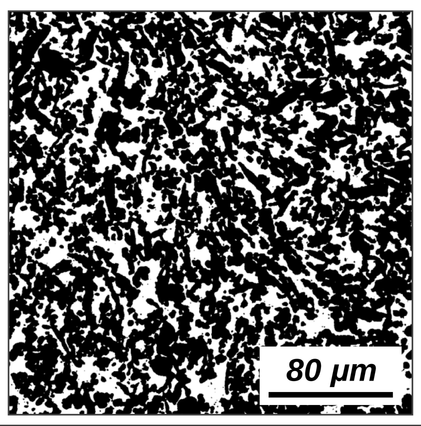
⇒ Process temperature ~1150°C

W-Cu composite



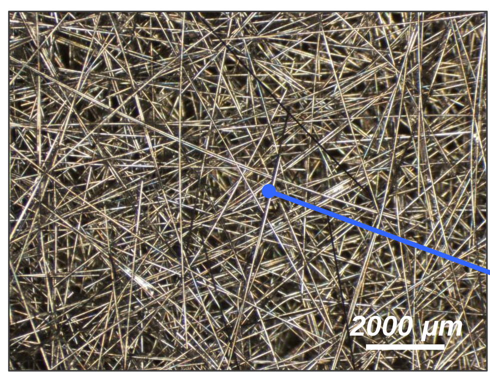
W preforms for Cu melt infiltration

Powder metallurgy



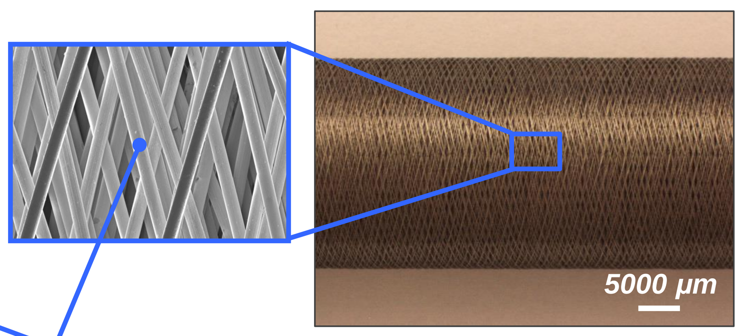
Open porous W preforms can be produced powder metallurgically

Short fibres



Wet-laid W short fibre preform

Continuous fibres



High strength W fibres:
⇒ Ø = 50 µm
⇒ σ_t > 2 GPa
⇒ ε_t ~ 3%

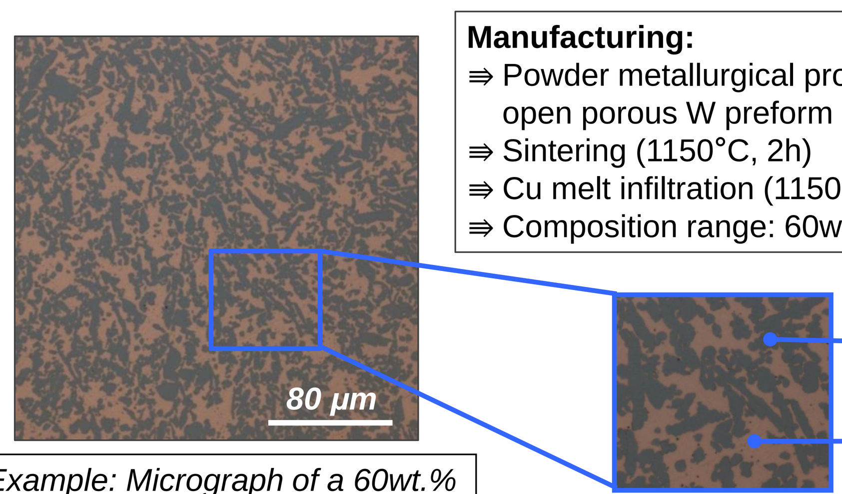
Braided cylindrical W fibre preform

Pattern:

Regular braid – 2/2 twill weave repeat

W-Cu composite metals

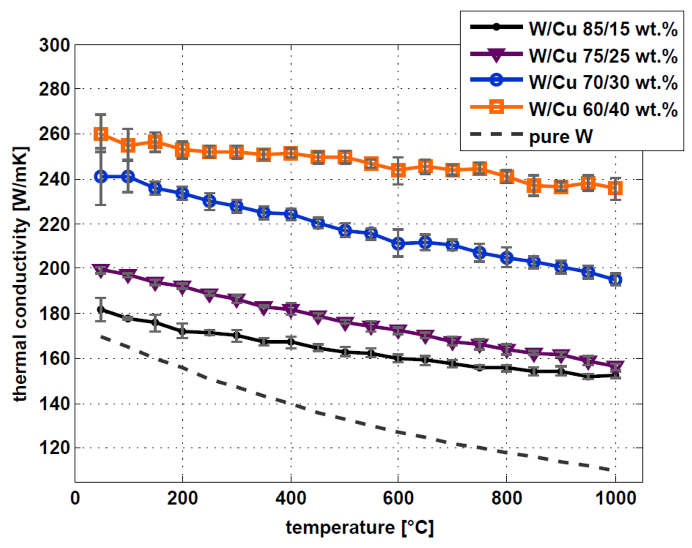
Microstructure



Example: Micrograph of a 60wt.% W – 40wt.% Cu composite metal

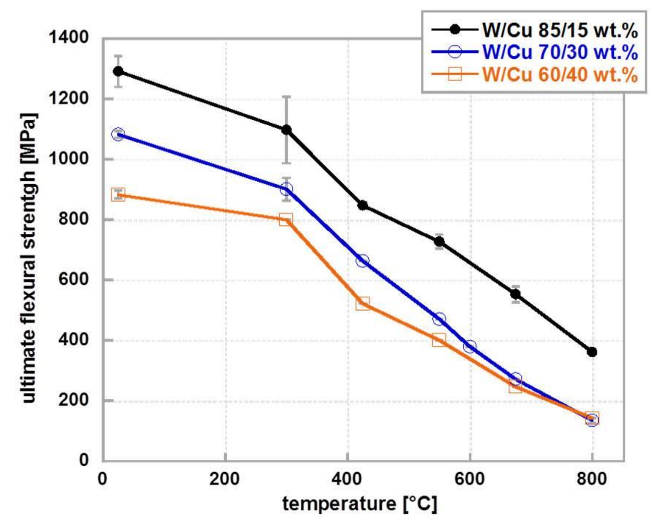
Manufacturing:
⇒ Powder metallurgical production of open porous W preform (cold pressing)
⇒ Sintering (1150°C, 2h)
⇒ Cu melt infiltration (1150°C, 2h)
⇒ Composition range: 60wt.% - 90wt.% W

Thermophysical



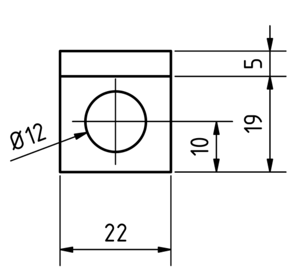
Thermal conductivity of W-Cu composite metals with varying compositions

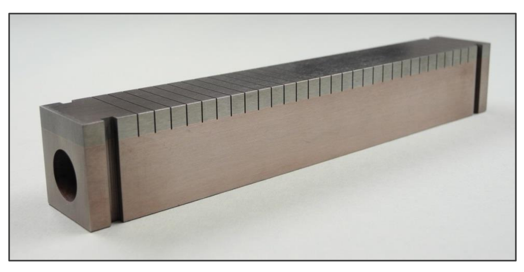
Mechanical

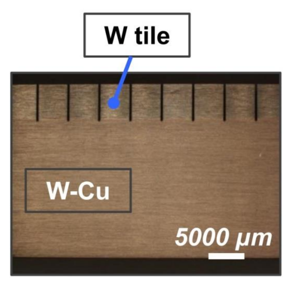


Flexural strength of W-Cu composite metals with varying compositions

Mock-ups for HHF testing



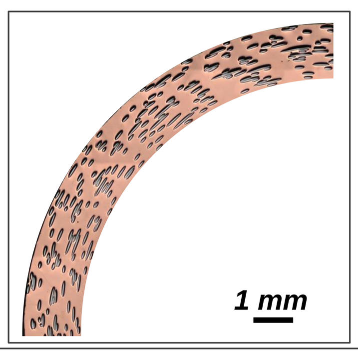




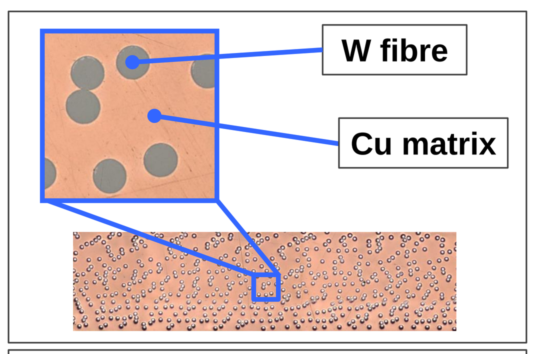
⇒ W-Cu (50/50 vol.%) composite metal heat sink
⇒ W armour tiles bonded to heat sink during Cu melt infiltration

Continuous W fibre reinforced Cu

Microstructure



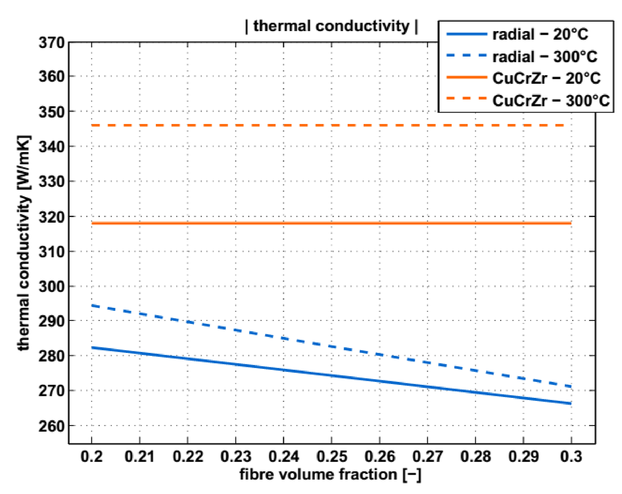
Transversal micrograph of W fibre-reinforced Cu pipe



Axial micrograph of W fibre-reinforced Cu pipe

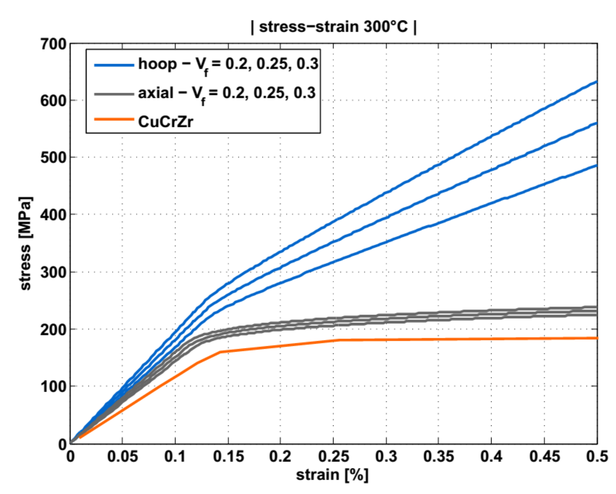
Manufacturing heat sink pipe:
⇒ Textile technological production of cylindrical W fibre preform
⇒ Cu melt infiltration

Thermophysical



Thermal conductivity (radial) of W fibre-reinforced CuCrZr composite predicted by means of mean-field homogenisation (MFH)

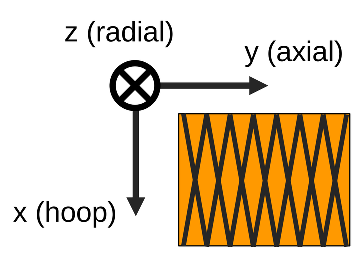
Mechanical



Stress-strain behaviour (hoop & axial) of W fibre-reinforced CuCrZr composite predicted by means of mean-field homogenisation (MFH)

Mean-field homogenisation (MFH)

Relating micro and macro properties by averaging quantities over **representative volume element** (RVE)



- Continuous W fibres (elastic) in Cu matrix (elastoplastic)
- Orientation: +/- 77°

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