HIGH HEAT FLUX MATERIALS: STATUS AND PERSPECTIVES

M. Rieth, J. Linke, Ch. Linsmeier

INSTITUTE FOR MATERIALS RESEARCH
Outline

• Introduction: High Heat Flux Materials

• (I) First Wall Armour Materials
  o Self-passivating alloys

• (II) Divertor Armour Materials
  o Thermal shock & He beam load

• (III) Structural Divertor Materials
  o Design & fabrication
  o Critical properties

• Conclusions
Components and Applications

New Concepts

- R&D
- Materials
- Fusion devices:
  - ASDEX-U
  - JET
  - DEMO
  - ITER

Standard Materials

- Fusion devices:
  - actively cooled PFCs
  - passively cooled PFCs

Heat removal:

- water
- He, liquid metal

Tritium fuel:

- increased T inventory
- n-induced material degradation

Lifetime fluence:

- 0 dpa
- $10^{-9}$ dpa
- 1 dpa
- 100 dpa

Neutrons:

- $10^3$ dpa
Example: ITER Wall Loads

- Neutron induced material degradation
- Disruption
- Irreversible material degradation
- ELM: 1 GWm$^{-2}$, 500 µs, n > 10$^6$
- VDE
- Divertor: 5 MWm$^{-2}$, 450 s, n ~ 3000

ELM: edge-localized mode
VDE: vertical displacement event
General Requirements for High Heat Flux Materials

- high thermal conductivity
- adequate mechanical properties
- low activation/transmutation/damage under neutron irradiation
- compatibility with plasma/coolant
- acceptable costs, (i.e. availability, applicable fabrication processes)
- high melting point
Selection of High Heat Flux Materials for DEMO

Melting Point >2000 K
Thermal Conductivity >50 W/mK

Availability, Cost

Low/Medium Activation

Irradiation Damage

e.g. $T_{RC}$
Materials & Applications

Blanket

Structure
- 316 Stainless Steel
- Ferritic/Martensitic 9% Cr Steel (e.g. Eurofer, F82H)
- Ferritic/Martensitic 9% Cr ODS Steel (e.g. ODS Eurofer)
- Ferritic ODS Steels (e.g. 14% Cr)
- SiC/f / SiC et al.

Armour
- Beryllium
- Tungsten

Divertor

Structure
- CuCrZr
- Ferritic/Martensitic 9% Cr Steels
- Ferritic ODS Steels
- Vanadium Alloys (e.g. V4Cr4Ti)
- Tungsten Materials

Armour
- Tungsten
- SiC/f / SiC
PART I – FW Armour Materials: (A) Self passivating tungsten alloys

- **Accidental loss of coolant:** peak temperatures of first wall up to 1200 °C due to nuclear afterheat
- **Additional air ingress:** formation of highly volatile WO$_3$ (Re, Os)
- **Evaporation rate:** order of 10 -100 kg/h at >1000°C in a reactor (1000 m$^2$ surface) → large fraction of radioactive WO$_3$ may leave hot vessel

Temperature profile in PPCS Model A, 10 days after accident with a total loss of all coolant.


### Development of self-passivating tungsten alloys
Normal operation (600°C):
Formation of tungsten surface by depletion of alloying element(s) due to preferential sputtering

Accidental conditions:
(ai ingress, up to 1200 °C)
Formation of protective barrier layer
Self-passivating tungsten based alloys

Surface composition automatically adjusts to the requested property

Normal operation (600°C):
- TRIDYN numerical simulation of sputter erosion of W-Si-Cr alloy (D ions, 30 eV, fluence $10^{18}$/cm²)

Accidental conditions:
- Cross section of sputter deposited W-Si-Cr film after oxidation at 1000°C for 1h

![Cross section of sputter deposited W-Si-Cr film after oxidation at 1000°C for 1h](image)

F. Koch, IPP
Oxidation Test Results

Arrhenius plot of oxidation rates of tungsten and tungsten alloys

Temperature [°C]

Oxidation rate (k) has been calculated from weight increase versus time, linear fit.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>W</th>
<th>Si</th>
<th>Cr</th>
<th>Zr</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSi8Cr12</td>
<td>46</td>
<td>30</td>
<td>24</td>
<td>-</td>
</tr>
<tr>
<td>WSi3Cr10Zr5</td>
<td>56</td>
<td>13</td>
<td>24</td>
<td>7</td>
</tr>
</tbody>
</table>

Composition in at.%

Linear oxidation rates of W-Si-Cr and quaternary alloys comparable.

Oxidation resistance can be increased by factor 100…1000

F. Koch, IPP
W-10Cr-10Si Bulk Material

FIB, EDX, and XRD analysis

Cr₂WO₆
SiOₓ
CrOₓ, CrWₓOᵧ
WOₓ, SiOₓ, (W, Si)

bulk alloy

F. Koch, IPP
Example: Microstructure of 90W-Cr-Si for the three MA processes after HIP

High densification possible (>97%) by powder metallurgical approach (Milling, HIP)
PART I – FW Armour Materials: (B) Tungsten Coating on Steel

Micro-Tomography

Sample

0.28 mm
0.5 mm

0.28 mm

A. Zivelonghi, IPP
T. Weitkamp, ESRF
VPS-W coating, steel matrix, W particles, pores

Blue: steel
White: W
Yellow: pores in steel

A. Zivelonghi, IPP
T. Weitkamp, ESRF
VPS-W interlayer: W particles, pores

White: W
Yellow: pores in steel

Micro-tomography: quantitative analysis of real 3D microstructure

A. Zivelonghi, IPP
T. Weitkamp, ESRF
Coatings and scales from organic electrolytes (Ionic Liquids)

W on Eurofer

resin

W layer 15 μm

Eurofer

W layer in vertical SEM view

W. Krauss, N. Holstein, KIT

Tungsten layer on Eurofer steel

- Deposited at 120 °C
- Electrolyte (IL) EMIN-Cl + WCl₆
PART I – FW Armour Materials: CONCLUSIONS

• Possible solutions for oxidation problem
• Alternatives coating process
• Fall-back options:
  (1) plating
  (2) plasma controlling 😊

NOT a pressing issue
(compared to other topics)
PART II – Divertor Armour Materials

Testing with JUDITH (thermal shock) and GLADIS (H, He beam)

1. electron beam (EB) gun (200 kW)
2. vacuum chamber
3. cooling circuit (RT & 100 °C)
4. test component
5. diagnostics
6. carrier system
7. alternative flange for the EB-gun

Power: 2 x max. 1.1 MW
Heat load: 1 - 50 MW/m²
Pulse length: 10 ms - 30 s
Repetition rate: ~ 100 /h
## Thermal Shock Tests

### Investigated Tungsten Grades

<table>
<thead>
<tr>
<th>Material</th>
<th>ID-No.</th>
<th>process</th>
<th>composition</th>
<th>deformation</th>
<th>treatment</th>
<th>dimensions</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>pure W</td>
<td>M182</td>
<td>sintering</td>
<td>&gt; 99.97 %</td>
<td>hammering</td>
<td>2 h @ 1000°C</td>
<td>Ø = 12</td>
<td>rods</td>
</tr>
<tr>
<td>pure W</td>
<td>M184</td>
<td>sintering</td>
<td>&gt; 99.97 %</td>
<td>hammering</td>
<td>2 h @ 1000°C</td>
<td>Ø = 12</td>
<td>rods</td>
</tr>
<tr>
<td>pure W</td>
<td>M196</td>
<td>sintering</td>
<td>&gt; 99.97 %</td>
<td>uniaxial forging</td>
<td>2 h @ 1000°C</td>
<td>Ø = 170 d = 30</td>
<td>not tested</td>
</tr>
<tr>
<td>W-UHP</td>
<td>M192</td>
<td>sintering</td>
<td>&gt; 99.9999 %</td>
<td>uniaxial forging</td>
<td>2 h @ 1000°C</td>
<td>Ø = 170 d = 30</td>
<td></td>
</tr>
<tr>
<td>WVMW</td>
<td>M188</td>
<td>vacuum metallizing</td>
<td>W 15 - 40 ppm K</td>
<td>hammering</td>
<td>2 h @ 1000°C</td>
<td>Ø = 15</td>
<td>rods</td>
</tr>
<tr>
<td>WVMW</td>
<td>M193</td>
<td>vacuum metallizing</td>
<td>W 15 - 40 ppm K</td>
<td>uniaxial forging</td>
<td>2 h @ 1000°C</td>
<td>Ø = 170 d = 30</td>
<td></td>
</tr>
<tr>
<td>double forged W</td>
<td>M190</td>
<td>sintering</td>
<td>&gt; 99.97 %</td>
<td>double forging</td>
<td>2 h @ 1000°C</td>
<td>Ø = 144 d = 45</td>
<td></td>
</tr>
<tr>
<td>WTa1</td>
<td>M194</td>
<td>sintering</td>
<td>W 1.0 % Ta</td>
<td>uniaxial forging</td>
<td>2 h @ 1000°C</td>
<td>Ø = 170 d = 30</td>
<td></td>
</tr>
<tr>
<td>WTa5</td>
<td>M195</td>
<td>sintering</td>
<td>W 5.0 % Ta</td>
<td>uniaxial forging</td>
<td>2 h @ 1000°C</td>
<td>Ø = 170 d = 30</td>
<td></td>
</tr>
</tbody>
</table>
Thermal Shock Tests - Summary

- Double forged W (M190)
- W-UHP (M192)
- WVMW (M193)
- WTa1 (M194)
- WTa5 (M195)

- $P_{\text{abs}} / P_{\text{inc}} = 0.46$
- $\Delta t = 1 \text{ ms}; n = 100 \text{ cycles}$

G. Pintsuk et al., FZJ

- no damage
- surface modification
- crack network
- small cracks

Δt = 1 ms; n = 100 cycles
Morphology is dominated by physical sputtering. The erosion patterns depend on the local orientation of each individual grain. Strong surface modification occurs.

Similar results for PM-W and VPS-W in the temperature range 200 – 850°C. Cone and wave structures after high He fluence.

H. Greuner, IPP
Pure He loading PM-W components, Surface Temp. > 2000°C

Surface morphology of PM-W and W-VPS is dominated by a porous structure due to agglomeration of He bubbles. The coral-like structure has a typical thickness of ~2-3 µm.

Note: 0.07 µm calculated He implantation depth only!

H. Greuner, IPP
Influence of surface temperature on erosion at high fluence: \(1 \cdot 10^{25}\) He/m²

- \(T_{surf}=200°C\)
- \(T_{surf}=1000°C\)
- \(T_{surf}=1450°C\)

Low temperature: no bubble formation
Surf. Temp. \(\geq 1000°C\): strong bubble formation dominates erosion pattern

Note: 70 nm penetration depth
Calculated erosion: 5 µm

H. Greuner, IPP
PART II – Divertor Armour Materials: CONCLUSIONS

• Not many degrees of freedom in developing better performing materials
• Much more knowledge about irradiation effects and mechanisms necessary
• Fall-back options: NONE
  → physics dominates material performance

This has a significant impact on the divertor design (possible operation limits)
Fiber-reinforced metal matrix composites

Heat sink applications
- SiC\textsubscript{f} / Cu
- W\textsubscript{f} / Cu

Heat load

T = 550°C

MMC

Heterogeneous W material
- W\textsubscript{f} / W

- controlled crack deflection
- internal energy dissipation
- increased strength by pseudo-ductility

- enhanced high temperature strength
- high creep resistance
- increased fracture toughness

Chawla, 1993
Synchrotron tomography – Results

**W_{f}/W-Single-fibre composite**

- 11 tomography/displacement steps
- Diameter 1.006 mm, Notch depth 0.094 mm
- Maximum load 253 N; Measured displacement 0.1584 mm

**Graph showing stress-strain relationship**

- First crack, fibre intact
- Final rupture

*Artificial notch*

*Fibre (d=150 µm)*

*Interface debonding*

*200 µm*
SiC$_f$ / Cu: Voids in matrix

SiC$_f$ / Cu (20% fibers)

→ ESRF ID-15A: ≤2 µm/pixel, 10 s / scan

3D view of the voids in the Cu matrix
Synthesis Problem: Porosity

Deposition 1: Porosity 20%; Interface WO$_x$; Uniform coating of all fibres (≈50 µm);

Deposition 2: Porosity 14%; Interface Er$_2$O$_3$; Strong gradient in deposition thickness

Deposition 3: „Moving Heater“ – Concept; Interface Er$_2$O$_3$ Porosity 8%; fibre pattern not maintained
PART III – Structural Materials for Divertor Applications

Divertor Concept up to 15 MW/m²

Divertor target plates with modular thermal shield (W/W alloy)

Dome and structure (ODS RAFM)

Inboard

Outboard

Divertor Cassette

9-Finger Module

Finger

He 600°C
10 MPa

P. Norajitra et al., KIT, 2003-2010
Divertor Concepts, 5-10 MW/m²

→ S. Hermsmeyer, S. Malang, 2002
→ A. R. Raffrey, S. Malang et al., 2008
Divertor Concepts, 5 MW/m²

→ K. Kleefeld, S. Gordeev, 2000
→ S. Hermsmeyer, K. Kleefeld, 2001
Divertor Concepts, 10 MW/m²

→ S. Sharafat et al., 2005-2009
Conclusion for ALL Helium Cooled Divertor Concepts

The main divertor part is a pipe-like structure (with open or closed ends) with different cross-sections (rectangular or round) on which the armour can be attached.
Tungsten Material Production Routes

Sintering (H, V) & Forming

- Mass Production
- High Density

+/⁻ Specific, anisotropic microstructure

- Some Alloys WV, WTa only in vac.

Powder-Metallurgy

Mechanical Alloying & HIP/Forming

+ Fine Particles
+ Homogenous Microstructure

- Small Quantities
- Porosity
- (Brittleness???)

Injection Molding & Sintering/HIP

+ Mass Production
+ Nearly Finished Products
+ Homogenous Microstructure

- Porosity
- Severe Brittleness

Melting (EB, Arc)

+ “Real” melting

- Coarse Grains (solidification)
- Expensive
Half-finished Products

Rolling (or Swagging) of Rods
Microstructure Anisotropy

Rolling (or Swagging) of Rods

WL10 Rod, Ø7 mm

W Rod, Ø7 mm

La$_2$O$_3$

2 μm
Microstructure Anisotropy

Rods

Bundle of "Fibres"

Bundle of "Fibres"

Bundle of "Fibres"
Rods: Fracture Characteristics

Charpy Energy, J

Test Temperature, °C

Rod Materials
- W, 6.9 mm
- W, 20 mm
- WL10, 6.9 mm
- WL10, 20 mm

ductile

delamination

brittle
Delamination Fracture in Rods

W1Re1La$_2$O$_3$  WL10opt  WL10  WVM
Half-finished Products

Rolling of Plates

Forging of Round Blanks
Microstructure Anisotropy

Plates: SEM / FIB channeling effect
Microstructure Anisotropy

Plates

Round Blanks

Stack of „Pancakes“
Charpy Tests, Plate Materials

- Plate Materials
  - W, 3.6 mm
  - WL10, 3.6 mm
- Round Blanks
  - W (RW), 30 mm
  - WTa5, 30 mm

Charpy Energy, J

Test Temperature, °C
Delamination Fracture in Plates

(a) Diagram showing delamination under applied force.
(b) Macroscopic image of delaminated region.
(c) Detailed image showing the delamination path.

1.5 mm
Powdermetallurgy

W-1.7TiC

- TEM observations:
- Bimodal grain size distribution:
  mean sizes ≈ 40 and 146 nm
- Bimodal particle size distribution:
  mean sizes ≈ 4 and 40 nm

L. Veleva, N. Baluc, CRPP
The plastic behaviour seems to appear at 1000 °C

DBTT seems to be higher than for W-V alloys

➢ The fracture toughness is a little smaller than for W-V alloys.
➢ In this case the degradation due to oxidation is smaller than in W-V alloys

A. Muñoz, CIEMAT/UC3M/UPM
Significant enhancement of the low temperature ductility of ultra-fine grained (UFG) W–TiC requires sufficient plastic working after consolidation.

H. Kirushita, Tohoku Univ., 2009
W tile manufactured by PIM

Binary powder: 50wt% W1 (0.7 µm) + 50wt% W2 (1.7 µm)
Feedstock mixing ratio powder/binder: 50/50 vol%

Material properties achieved:
Vickers-hardness: 457HV0.1
Density: 98.6 – 99 % TD

*Heat-treatment:
- pre-sintering (1650°C, 2h, H₂) +
- HIP (1600°C, 3h, Ar, 250 MPa)

Metallurgy results (Fig.:real microstructure of the W-tile): no porosity; grain size 5 µm

S. Antusch, KIT, 2010
Main Question for Structural Divertor Materials

How to fabricate pipe-like structures?

Powder metallurgy

Injection Moulding

Mechanical Alloying

Sintering + Forming

Plate Materials

Rods

↓↓↓

↓↓

↓
Pipe Fabrication of Rods

Pipe Impact Test

B. Dafferner, P. Norajitra, KIT

9Cr-Steel
Solution: Composite Materials?

Ductile W-Foil

Sandwich of W-Foils

Fracture Behaviour

J. Reiser, KIT
Pipe Fabrication of Sandwich Material

W-Tube: Charpy Test
PART III – Structural Div. Materials: CONCLUSIONS

- No material available which fulfills all design criteria (strength, heat conductivity, DBTT)
- No DEMO divertor concept ready which is feasible with existing materials
- Lower operating temperature about 800°C (due to irradiation → has to be confirmed)
- Upper operating temperature limit given by loss of strength or recrystallization (depends strongly on material, about 1000-1300°C)
- Water cooling as fall-back option not confirmed yet (many doubts!)

This topic has a critical impact on the DEMO design
Thank you for your interest!

Thanks to all contributors to the following R&D programmes:
- EFDA Topical Group on Fusion Materials
- ExtreMat
- FEMAS-CA

Whenever you see this, remember that tungsten rods are not an option!