Heat Sink Materials for the Plasma-facing Components of Fusion Devices

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contents
• Fusion
• ITER: divertor requirements
  heat sink material: CuCrZr
• Reactor: divertor requirements
• Cu-SiC MMC development
• Conclusions

Part of the work has been supported by the European Commission in the frame of the ExtreMat Integrated Project
Fusion reaction, fusion power

Parameter field for a fusion reactor

- **plasma density** ($n$): $>10^{20}$ m$^{-3}$
- **plasma temperature** ($T$): 18 keV (equ. 200 Mio. deg.)
- **energy confinement time** ($\tau$): $>1$ s
- **plasma volume**: approx. 1000 m$^3$
- **fusion power**: 2 GW
Magnetic confinement, tokamak, stellarator

**principle of toroidal magnetic confinement**

- magnetic field confines ions, electrons
- balances the plasma pressure (10 atm)
- thermal insulation (200 Million K)

Next step: ITER
ITER Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion Power</td>
<td>500 MW</td>
</tr>
<tr>
<td>Plasma Volume</td>
<td>837 m³</td>
</tr>
<tr>
<td>Plasma Surface</td>
<td>678 m²</td>
</tr>
<tr>
<td>Heat flux on Divertor</td>
<td>10 (20) MW/m²</td>
</tr>
<tr>
<td>Pulse length</td>
<td>400 s</td>
</tr>
<tr>
<td>Number of pulses</td>
<td>~ 30,000</td>
</tr>
</tbody>
</table>

ITER goals:

- Show scientific and technological feasibility of fusion energy for peaceful purposes.
- Test essential technologies in reactor-relevant physics and technology environment.
- Demonstrate safety and environmental acceptability of fusion.
Loading of materials in a fusion device

**bulk plasma:**
Impurity tolerance
(<10^{-5} \text{ W}, 10^{-2} \text{ Be}, \text{ C})

**structural materials**
- thermomechanical loads
- electromagnetical loads
- neutron irradiation

**plasma facing materials**

**heat sink materials**

**divertor target:**
- stationary high heat flux 10 (20) MW/m^2
- transient heat loads: e.g. disruptions
- highly loaded surface approx. 50 m^2
- neutron damage: < 0.5 dpa

**tritium inventory:**
- to be kept low (safety)
Materials for the **ITER Plasma Facing Components**

**Plasma facing materials**

- **first wall:** beryllium: *low Z*
- **divertor:** 3d C-C composite: *thermal shock resistance*
- **tungsten:** *high temp. resistance*

→ materials selection driven by T-codeposition and thermal transients

**Heat sink material**

*CuCrZr*
## Loading conditions for the divertor

<table>
<thead>
<tr>
<th></th>
<th>Divertor target</th>
<th>Divertor target</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ITER</td>
<td>Reactor (DEMO)</td>
</tr>
<tr>
<td>Component replacements</td>
<td>up to 3</td>
<td>5 year cycle</td>
</tr>
<tr>
<td><em>av. neutron fluence</em></td>
<td>max. 0.5</td>
<td>30</td>
</tr>
</tbody>
</table>

### Normal operation

- No. of cycles: 10000? < 1000
- Coolant temperature (°C): 100 < 300 (600, He)
- Surface heat flux (MW/m²): 10 (20) 10...15
ITER Divertor cassette

Plasma facing armour:
Tungsten and CFC

25 mm

400 mm

150 mm
ITER: Two designs: „Flat tile“ and „Monoblock“

- W flat tiles
- CFC monoblocks
- Heat sink material
  CuCrZr (ITER)
**CuCrZr alloy:**
- properties depend largely on heat treatment (manufacturing of components).

<table>
<thead>
<tr>
<th>CuCrZr</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHEMICAL COMPOSITION</td>
<td>Detail from Industry</td>
</tr>
<tr>
<td>SPECIFIC HEAT</td>
<td>Generally OK</td>
</tr>
<tr>
<td>THERMAL CONDUCTIVITY</td>
<td>Generally OK, depends on thermal treatment</td>
</tr>
<tr>
<td>THERMAL EXPANSION</td>
<td>Well documented</td>
</tr>
<tr>
<td>ELECTRICAL CONDUCTIVITY</td>
<td>Well documented</td>
</tr>
<tr>
<td>DENSITY</td>
<td>Well documented</td>
</tr>
<tr>
<td>ULTIMATE TENSILE STRENGTH</td>
<td>Generally OK, depends on thermal treatment</td>
</tr>
<tr>
<td>YIELD STRENGTH</td>
<td>&quot; &quot;</td>
</tr>
<tr>
<td>ELONGATION</td>
<td>&quot; &quot;</td>
</tr>
<tr>
<td>REDUCTION OF AREA</td>
<td>&quot; &quot;</td>
</tr>
<tr>
<td>ENGINEERING STRESS-STRAIN</td>
<td>&quot; &quot;</td>
</tr>
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<td>YOUNG'S MODULUS</td>
<td>Well documented</td>
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<td>STRESS RUPTURE</td>
<td>Some data exists</td>
</tr>
<tr>
<td>CREEP AT 1%</td>
<td>Some data exists</td>
</tr>
<tr>
<td>FATIGUE</td>
<td>Some data exists, depends on creep</td>
</tr>
<tr>
<td>FRACTURE TOUGHNESS</td>
<td>Some data, better than DS Cu</td>
</tr>
</tbody>
</table>

Data: ITER Materials Data Handbook
CuCrZr alloy: properties depend on heat treatment (manufacturing of components).

**CHEMICAL COMPOSITION**
Details from Industry

**SPECIFIC HEAT**
Generally OK

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Some data

Data: ITER Materials Data Handbook
**ITER Database – Heat sink materials**

**CuCrZr Alloy, Neutron effects**

- For ITER conditions: no change of thermal properties,
- However, loss of ductility is main concern for ITER (low operation temperature), but should pose no problem for reactor conditions (high operation temperature)

Data: ITER Materials Data Handbook
**ITER Database – Heat sink materials**

**CuCrZr Alloy, Neutron effects:**

- For reactor conditions irradiation induced creep is main issue

![Graph showing yield strength vs temperature for CuCrZr-I, CuCrZr-G, CuCrZr-Ic, and CuCrZr-Ir.](image)

**Data:** ITER Materials Data Handbook

- Dose - 0.3 - 5 dpa, \( T_{irr} = T_{test} \)
Performance of components under irradiation

EUROMAT C33

Tungsten Macrobrush Mock-Ups

Unirradiated
- 1000 cycles x 8 MW/m² – no failure
- 1000 cycles x 14 MW/m² – no failure

200°C, PARIDE 4 (0.5 dpa in tungsten)
- 1000 cycles x 10 MW/m² – overheating
- 1000 cycles x 14 MW/m² – loss of tiles

CFC Monoblock Mock-Ups

Unirradiated
- 1000 cycles x 19 MW/m² – no failure
- 700 cycles x 23 MW/m² – no failure

200°C, 0.2 dpa (in carbon)
- 1000 cycles x 10 MW/m² – no failure
- 1000 cycles x 12 MW/m² – no failure
- screening at 14 MW/m² – surface erosion

Activity: FZ Juelich and HFR, Petten

Data: J. Linke, M. Roedig, FZ Juelich
## Comparison of PH alloys and DS Cu

<table>
<thead>
<tr>
<th>PH Cu alloys</th>
<th>DS Cu alloys</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal stability</strong></td>
<td></td>
</tr>
<tr>
<td>Above ageing temperature overageing: significant decrease of strength. Overageing affects also the thermal conductivity by the dissolution of precipitates.</td>
<td>Inert alumina particles are not prone to coarsening or to dissolution, keeping their hardening effect up to very high temperatures. Properties strongly depend on the production route and are less sensitive to heat treatments.</td>
</tr>
<tr>
<td><strong>Fracture toughness</strong></td>
<td></td>
</tr>
<tr>
<td>FT of unirradiated and irradiated materials decreases with increasing temperature, but remains at a relatively high level.</td>
<td>Very low above 200°C in the unirradiated condition. Fracture toughness of irradiated GlidCop Al25 decreases 2-3 times compared to unirradiated material.</td>
</tr>
<tr>
<td><strong>Isotropy</strong></td>
<td></td>
</tr>
<tr>
<td>Isotropic mechanical properties.</td>
<td>The short-transverse ductility and fracture toughness is less than in the other two directions.</td>
</tr>
<tr>
<td><strong>Weldability</strong></td>
<td></td>
</tr>
<tr>
<td>Can be welded by TIG and EB and then solution annealed and aged without cold work, recovering 50-70% of the full hardened strength.</td>
<td>Not suitable for structural/leak tight fusion welds. Microstructure is completely destroyed in this case, with unrecoverable loss of strength of the joint. Non-fusion weld should be applied (friction, explosion, etc.).</td>
</tr>
<tr>
<td><strong>Neutron irradiation resistance at high temperature</strong></td>
<td></td>
</tr>
<tr>
<td>The PH alloy microstructure is less stable under irradiation, due to radiation enhanced coarsening of the Cr/Zr precipitates. Irradiation induced creep at &gt;350°C.</td>
<td>DS alloys have a higher stability range, but are also expected to show irradiation induced creep at high temperature.</td>
</tr>
</tbody>
</table>
Requirements for reactor PFCs

Most important: efficient energy conversion
- Water cooled divertor: close to PWR conditions, water at 300°C, 10 MPa: new heat sink materials needed

Attractive, higher thermal efficiency:
- **He-gas cooled** W-based divertor: advanced technology (min. 600°C He at 10 MPa) open materials questions
Heat sink materials: ITER – reactor (DEMO)

**ITER - Divertor**
- divertor: 10-15 MW/m²
- coolant: water 80°C
- no energy production
- neutron irradiation ≤ 0.5 dpa
- use of available materials

Heat sink:
CuCrZr
max. operation temperature: 350-400°C

**DEMO - Divertor**
- divertor: 10-15 MW/m²
- coolant: water ≥ 300°C or helium ~ 600°C
- energy production
- neutron irradiation ~ 30 dpa
- development of new materials

Heat sink:
SiC fibre reinforced copper
operation temperature: ~ 550°C
Motivation: Cu-SiC MMCs

aim: composite tensile strength 600-800 MPa at room temperature
important: optimised bonding between the fibre and matrix

- e.g. DLR: titanium matrix composite reinforced with SiC long fibres for aeroplane engines
- interf. shear strength in the range of 70-80 MPa

problem: adhesion between SiC/C and copper

solution: titanium interface layer between SiC fibre and copper matrix
MMC – SiC Fibres

SiC fibre SCS6 (Specialty Materials) Ø 140 µm

- commercially available SiC fibre
- with carbon rich layer at the surface for protection during handling
- optimised for titanium matrix

CMF - Carbon Mono Filament
Processing of MMC - Matrix

Electroplating of copper

- CuSO₄ bath
- room temperature
- 4.5 V
- 8 hours
- fibre volume fraction \( v_f = 20 \% \)

galvanic deposition of a 80 µm thick copper layer as matrix
Processing of MMC – Interlayer

- sputter deposition of titanium interlayer
- layer thickness 100-200 nm
- deposition of copper layer - protective coating (500 nm)
Phase diagrams

Titanium and Carbon

Ti + C → TiC above 350°C

Copper and Titanium

TiC + graphite
coated fibres were consolidated in a copper capsule by hot-isostatic pressing at 650°C for 30 minutes.

- maximum pressure 100 MPa
TEM investigation

- plane pyrolytic carbon substrate (PyC)
- 100 nm Ti + 500 nm Cu
- heat treatment at 650°C/1h

EELS (electron energy-loss spectroscopy)

TEM image of interface (PyC)

- EELS: formation of TiC
- formation of a rough interface
- chemical and mechanical bonding between C and Cu

See also Poster by MPI Halle (Woltersdorf, Pippel, Brendel, Bolt), C11
XRD Investigations

- **PyC+200 nm Ti + 500 nm Cu**
  - with heat treatment at 550°C
  - without heat treatment

- **Cu** (200), (111)
- **Cu_4Ti** (021), (022)
- **Ti** (101), (111)
- **TiC** (200)

- 5 µm thickness

- Substrate PyC
Push-Out Test
Push-Out Test

SiC fibre reinforced copper **without** titanium interlayer

Sample thickness 2.4 mm

Load in N

Displacement in mm

$P_{\text{max}} = 12 \text{ N}$

$P_d = 6 \text{ N}$

SiC fibre reinforced copper **with** titanium interlayer

Sample thickness 0.9 mm

Load in N

Displacement in mm

$P_{\text{max}} = 25 \text{ N}$

$P_d = 29 \text{ N}$
**Push-Out Test**

**Interfacial shear strength**

- **with titanium interlayer**
  - $\tau_d = 6 \text{ MPa}$
- **without titanium interlayer**
  - $\tau_d = 70 \text{ MPa}$

**Interfacial friction stress**

- **with titanium interlayer**
  - $\tau_f = 54 \text{ MPa}$
- **without titanium interlayer**
  - $\tau_f = 4 \text{ MPa}$

Push-Out Test - SEM

**without titanium interlayer**

no plastic deformation of matrix after push-out test

front side after push-out test

**with titanium interlayer**

matrix cracks

plastic deformation of matrix
Push-Out Test - SEM

**without titanium interlayer**
- carbon (fibre)
- copper (matrix)

**with titanium interlayer**
- SiC (fibre)
- carbon (fibre)
- copper (matrix)
- titanium (interlayer)
- sample length 70 mm with thread at the ends
- gauge length 10 mm
- diameter in gauge length 3.5 mm (fibre reinforced zone)
Fibre pull out in the composite without titanium interlayer indicates a weak bonding between fibres and matrix.

Analysis of back scattered electrons shows carbon at the matrix for composites with titanium after tensile test.
Thermomechanics of Cu-SiC FRMMCs

• Open question: plastic stability of the FRMMC under cyclic heat flux loads?

• Investigation issue: determination of loading limit for plastic instability (shakedown / ratchetting)

• Shakedown analysis; SD limit as design criterion?

• Implications on design

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMMC laminate</td>
<td>Tensile strength (MPa)</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>CTE ($\times 10^{-6}$)</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>Young’s modulus (GPa)</td>
<td>398</td>
</tr>
<tr>
<td>CuCrZr</td>
<td>Tensile strength (MPa)</td>
<td>400 at RT</td>
</tr>
<tr>
<td></td>
<td>CTE ($\times 10^{-6}$)</td>
<td>W: 3.9</td>
</tr>
<tr>
<td></td>
<td>Young’s modulus (GPa)</td>
<td>W: 398</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FMMC laminate: 12.4 (//)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CuCrZr: 15.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FMMC laminate: 165 (//=)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CuCrZr: 128</td>
</tr>
</tbody>
</table>
Component thermomechanics under high heat flux loading

Heat flux: 10 MW/m², $T_{sf}$: 550 °C, $T_c$: 250 °C

- perfect plastic
- kinematic hard.

$\Sigma_y$ [MPa] vs. Temperature [°C]

$\Sigma_x$ [MPa] vs. $\Sigma_y$ [MPa]
Alternative design: Composite coolant tubes

- Merits of this design
  - works with CuCrZr tube for cold ITER loading conditions
  - basic component fabrication technology already developed

- Motivation
  - strengthen the tube for coolant temperature up to 320 °C
  - reduce the thermal stress

- Issues:
  - fabrication of fiber-reinforced composite tubes
  - simulation techniques for ‘design by analysis’
Summary: Heat sink materials for fusion

**Divertor** (high thermal conductivity needed):
- CuCrZr: (irrad. data up to 10 dpa)
  - temperature window:
    - 200°C...350°C
    - (<200°C: hardening; >350°C: softening)
- DS Cu similar, max. 400°C

New class of heat sink materials needed
and the respective component technology

- Cu-SiC MMC
- Bonding technologies
- Adequate component design
**Summary: New materials are needed for fusion**

<table>
<thead>
<tr>
<th>JET</th>
<th>ITER</th>
<th>reactor (DEMO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(fusion power 16 MW, 2 s)</td>
<td>(fusion power 500 MW, 400 s)</td>
<td>(fusion power &gt;2000 MW, stationary)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
<th>power reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>relative size</td>
<td>1</td>
<td>1...1.2</td>
</tr>
<tr>
<td>fusion power (MW)</td>
<td>500</td>
<td>2000</td>
</tr>
<tr>
<td>power to He-ions (MW)</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>total thermal power (MW)</td>
<td>2600</td>
<td>1000</td>
</tr>
<tr>
<td>electric power (MW)</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>efficiency (%)</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>neutron damage (dpa)</td>
<td>5</td>
<td>120 in 5y</td>
</tr>
</tbody>
</table>
**Push-Out-Test**

P_d – debonding force

Interfacial shear strength \( \tau_d \)

\[ P_d = \frac{\tau_d}{\alpha} \cdot \frac{2\pi R}{\alpha} \cdot \tanh(\alpha \cdot L) \]

\( \alpha = \sqrt{\frac{2G_i}{b_i RE_f}} \)

P_d, P_{max} – debonding, maximum force

R – fibre radius

L – specimen thickness


\( P_{max} = \frac{\pi R^2 \sigma_0}{k} \left[ \exp\left(\frac{2\mu k}{L} - 1\right) \right] \)

\( \tau_f = \mu \cdot \sigma_0 \)

\( k = \frac{\nu_f E_m}{E_f(1 + \nu_m)} \)

Properties

Load

Displacement

P_{max} - maximum force

Interfacial friction stress \( \tau_f \)
Thermal cycling

Composite without titanium

Fibre displacement

Composite with titanium

Crack between two carbon layers

120 cycles between 350°C and 550°C
Design of Cooling Fingers in He-cooled Divertor Development

- Tile surface 2200 °C
- Cap surface 1450 °C
- EUROFER 610 °C
- W tiles
- W -La₂O₃ cap
- ODS-EUROFER
- He manifolds
- Inlet He, 620 °C
- EUROFER 97 structure
- Detail X: Pin plate with outlet tube
- W plate with integrated pin array
- Outlet He, 720 °C