Fabrication and High-Heat-Flux-Testing of W/Cu-divertor modules with a graded interface

Research-project of the “Friedrich-Schiedelstiftung für Energietechnik”
# Actively cooled divertor test modules

<table>
<thead>
<tr>
<th>Mock-up Type</th>
<th>HHF Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>W macrobrush mock-up</strong></td>
<td>1000 cycles @ 18 MWm(^{-2}) without failure</td>
</tr>
<tr>
<td>• coating of W-tiles with OFHC-Cu</td>
<td></td>
</tr>
<tr>
<td>• e-beam welding to CuCrZr heat sink</td>
<td></td>
</tr>
<tr>
<td><strong>PS-W mock-up</strong></td>
<td>1000 cycles @ 5.5 MWm(^{-2}) without failure</td>
</tr>
<tr>
<td>• vacuum plasma spraying of tungsten</td>
<td></td>
</tr>
<tr>
<td><strong>W monoblock (monolytic type)</strong></td>
<td>1000 cycles @ 18 MWm(^{-2}) without failure</td>
</tr>
<tr>
<td>• drilling of W-La(_2)O(_3) monoliths (d = 4 mm)</td>
<td></td>
</tr>
<tr>
<td>• casting with OFHC-Cu</td>
<td></td>
</tr>
<tr>
<td>• HIPing (700°C, 3 hrs.)</td>
<td></td>
</tr>
</tbody>
</table>
Flat Tile Concept with and w/o W/Cu-Gradient

Reduction of residual and thermal stresses at the interface
\((\Delta \alpha_{\text{W/Cu}} \approx 12 \times 10^6 \text{ K}^{-1})\) \(\Rightarrow\) reduced delamination effects

\(\Rightarrow\) INCREASE OF LIFETIME
Fabrication methods for W/Cu-FGMs

Investigated methods:

- Vacuum Plasma Spraying
- Water Stabilized Plasma Spraying
- Direct Laser Deposition

Other methods:
Electrochemical infiltration, Sintering, Spark Plasma Sintering,…
Vacuum Plasma Sprayed W/Cu-Composites

Parameters

- 2 powder feeders
- Transferred Arc Cleaning

Powder

W [< 10 \( \mu m \)] + 
Cu [40 - 50 \( \mu m \)]

I) W-Cu26
II) W-Cu43
III) W-Cu52
IV) W-Cu78

20 \( \mu m \)
Finite Element Simulations

Parameters

- **optimal bonding at the interfaces**
- **stress-free state at 500 °C**
- **loading:** 5-20 MW/m²
- **cooling:** T = 100 °C, p = 4 MPa twisted tape
Finite Element Simulations - Stresses

x-directional stresses; P = 5 MW/m²

- σ [MPa]
- d [mm]

- Tungsten
- OFHC-Cu
- CuCrZr

- FGM
- FGM + brush
- brush – w/o FGM
Vacuum Plasma Sprayed W/Cu-Gradient

- theoretical
- measured

![Graph showing the variation of vol% W with d (mm)]

- 0 500 1000 1500 2000 2500 d [mm]
- 100 90 80 70 vol% W

Forschungszentrum Jülich
in der Helmholtz-Gemeinschaft
Fabrication of Actively Cooled Components

I. Cu-coating on the FGM
II. Ni-coating on OFHC-Cu (both sides)
III. Mounting of CuCrZr, OFHC-Cu and W+FGM in a Cu-can (vacuum)
IV. HIP cycle: 3h, T = 550°C
    1h, T = 450°C

Castellation
module A: 24 x 24 mm²
module B: 4.5 x 4.5 mm²
cutting width: ~0.35 mm
Porosity in the Gradient

![Graph showing porosity percentage (Porosity [%]) against distance (d [mm]) before and after HIP process. The graph displays data points for different distances, with markers indicating changes before and after HIP.](image)
Interface Ultrasonic Inspection

Module A
CuCrZr-OFHC-Cu interface

Module B
OFHC-Cu-FGM interface
Screening Tests (1)

Electron beam loading: JUDITH (FZJ)

8 MW/m$^2$: failure: brick 3
19.2 MW/m$^2$: failure: brick 1
Thermal Fatigue Tests (1)

Electron beam loading: JUDITH (FZJ)

14.8 MW/m²: 1 cycle, failure: brick 2

W-Oberfläche

1

2

3

A = 583 mm²
Screening Tests (2)

Electron beam loading: JUDITH (FZJ)

23.8 MW/m²: no degradation
Thermal Fatigue Tests (2)

Electron beam loading: JUDITH (FZJ)

20 MW/m²: 100 cycles + 50 cycles
10 s loading, 20 s cooling degradation at the edges

W- Oberfläche

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

A = 694 mm²
Failure Analysis

After Screening Test

After Thermal Fatigue Test
Surface Modification
Temperature monitoring

Infrared camera
point 1
point 2
point 3
point 4

Pyrometer

Cycle Number

T [K]

0  15  30  45  60  75  90  105  120  135  150

2400 2200 2000 1800 1600 1400 1200 1000
Thermal Fatigue Test – Infrared Pictures

1. cycle

50. cycle

100. cycle

150. cycle
Thermal Fatigue Test – Temperature Graphs

1. cycle

50. cycle

100. cycle

150. cycle

T [°C]
- 1980-2010
- 1950-1980
- 1920-1950
- 1890-1920
- 1860-1890
- 1830-1860
- 1800-1830
- 1770-1800

T [°C]
- 1970-2000
- 1940-1970
- 1910-1940
- 1880-1910
- 1850-1880
- 1820-1850
- 1790-1820
- 1760-1800

Forschungszentrum Jülich
in der Helmholtz-Gemeinschaft
**Conclusion**

Vacuum plasma sprayed W/Cu-gradient: *W-content > 75vol%*

*Castellation* of the plasma facing material still necessary

*High performance* of test component: *150 cycles at 20 MW/m²*

Full potential not yet reached

*Problem*

Castellated structure: *critical joint between gradient and OFHC-Cu → not yet optimized*