Progress in Developing ITER and DEMO First Wall Technologies at SWIP

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Co-authors:
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1. Background

First wall in operation

Burning Plasma

Charged particle flux

Neutron flux: irradiation damage

 Radiation & charge exchange

Heat transfer

\[ \text{C\text{harged particle flux}} \]

\[ \text{Neutron flux: irradiation damage} \]

\[ \text{Radiation & charge exchange} \]

\[ \text{Heat transfer} \]

\[ \text{ITER First Wall (~3dpa in steel)} \]

\[ \text{DEMO First Wall (>50dpa)} \]

\[ \text{NHF-FW: 2MW/m}^2 \]

\[ \text{EHF-FW: 4.7MW/m}^2 \]

\[ 0.5\text{MW/m}^2 \]
Thermal fatigue is a major concern for the design.


Water cooling:
2 MPa, 70°C, 2 m/sc

J.M. Chen, FEC-26, Poster

4.7MW/m², 15s on/off

Thermal fatigue is a major concern for the design.
ITER EHFW – Thermal fatigue issue

- Assessable thermal fatigue life of CuCrZr and 316L(N) by analysis
- Unpredictable Be/CuCrZr/316L(N) joint interface.
- Test showed thermal fatigue damage of HVT channel & Be tile detachment.

ITER requires FW a fatigue life of 15,000 cycles

Maximal strain in CuCrZr alloy


Water leak at 4.7MW/m²

Be tile detachment

R. Eaton / BIPT-66, Apr 2016
2. Improving ITER FW thermal fatigue performance

(1) To reduce the thermal stress by design optimization

(2) Improving Be/Cu/SS bonding
Fatigue crack may initiate from interface defect.

(3) Improving material properties
Small grain size & high tensile strength
2.1 Design optimization to reduce thermal strain

(1) Adding a groove at the HVT channel bottom
(2) Adding a 0.5mm OF-Cu layer between Be and CuCrZr heat sink
Thermal fatigue life increase by one order

✓ Effect of 0.5mm OF-Cu interlayer

For FW with 16x16mm Be tile

Fatigue life: $4 \times 10^4$ [1] $\rightarrow$ $2 \times 10^5$ cycles

12x12mm Be tile: fatigue life $> 5 \times 10^5$ cycles.
Large Be tile up to $> 16 \times 16$mm is acceptable.

✓ Effect of HVT groove depth & Be tile size

D. GLAZUNOV, ITER BIPT-68, ITER_D_TL78R4

[1] D. GLAZUNOV, ITER BIPT-68, ITER_D_TL78R4
2.2 Improving Be/CuCrZr HIP bonding

(1) Adding a 0.5mm thick OF-Cu accommodation layer
- Significant reduction of residual stress.
- Achieving >90% defect-free EHF FW (previously 0).

Thermal stress (MPa) at Be/Cu interface on Be tile surface

Shear strength: > 190 MPa
Perfect Be/CuCrZr bonding without Cu coating layer

(2) Removing the interfacial Cu coating
- Significantly higher bonding strength.
- No crack at Ti/CuCrZr interface forever.

Cu coating accounts for the 10% failure.

XRD of rupture surface

Crack at Ti/Cu coating interface

Cu coating thickening Cu$_4$Ti layer

Cu$_4$Ti, CuTi & CuTi$_2$ phases

SEM image

Ti/Cu interface--EPMA image

HIPing:
- 590°C
- 150MPa
- 2h

Removing Cu coating
2.3 Strengthening CuCrZr/316L(N) bonding by > 60%

However, Zr and a Cr/Mo segregation layers along interface, may weaken the bonding, shall be further addressed.

By standard tensile testing method, RT

Explosion bonding samples after all thermal manufacturing processes

P.H. Wang, et al, SOFT-29, Poster
2.4 Better CuCrZr than ITER requirement

Eliminating HIP joining SS/Cu at elevated temperature,
Higher strength and smaller grain size

- CuCrZr alloy in 50%CW and 475/3h aging state
- Explosion bonding Cu/SS, followed by SA (970°C/30min)
- HIP bonding Be/Cu treatment: 580°C/150MPa/2h.

Tensile properties

Mean grain size: 98µm
(ITER<200 µm)
2.5 Verify by HHF test_ big effect of Be/Cu defects

- Previous test showed acceptable 12x12mm Be tile for old design.
- Artificial defects by carbon painting on Be surface before Be/Cu HIP joining.
- Acceptable defect: ≤ Φ4 or 3x3mm.

High heat flux (HFF) Testing

- £ 2 Mpa/2 m.s⁻¹/ 70°C water cooling
- £ 4.7 MW/m² for 5000 cycles

Tested at 4.7MW/m². Lifetime decreases with increasing defect size at > ~12 mm².

J.M. Chen et al, ISFNT-12, Poster
Successful HHF test of full-size FW fingers

- 7500 cycle @4.7 MW/m² + 1500 cycle @5.9 MW/m².
- < 24% in local temperature variation and < 11% temperature rising.
- Perfect finger pairs, < 20 μm deformation and < 3.4 × 10⁻¹¹ Pa.m³/s He leakage.

With modified design
CFETR first wall progress

HCCB blanket parameter

<table>
<thead>
<tr>
<th>Parameters</th>
<th>HCCB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Flux, Avg.</td>
<td>0.5 MW/m²</td>
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<tr>
<td>Neutron Wall Loading</td>
<td>2 MW/m²</td>
</tr>
<tr>
<td>Plasma facing mater.</td>
<td>W alloy</td>
</tr>
<tr>
<td>Structural Material</td>
<td>ODS RAFMs</td>
</tr>
<tr>
<td>Breeder</td>
<td>Li$_4$SiO$_4$</td>
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<tr>
<td>Neutron Multiplier</td>
<td>Be</td>
</tr>
<tr>
<td>He Coolant Temp.</td>
<td>300/550 °C</td>
</tr>
<tr>
<td>He Coolant Pressure</td>
<td>12 MPa</td>
</tr>
</tbody>
</table>

Y.X. Wan, Nucl. Fusion, 57 (2017)

FW steel structure

Candidate technologies:
- CVD-W, Brazing & HIP, Low activation design.

W/RAFM steel bonding

1.5GW fusion power

X.Y. Wang, et al, FEC-27, Oral, FTP/1-6
Activities on CVD W/RAFM steel

- Fast CVD W up to 0.5mm/h: dense, columnar structure with high thermal conductivity.
- Fast CVD-W + CVD TiN coating (as T permeation barrier) on RAFMs developed.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Deposition rate</td>
<td>0.3-0.5 mm/h</td>
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<tr>
<td>Purity</td>
<td>99.9999%</td>
</tr>
<tr>
<td>Thermal conduct.</td>
<td>&gt;180 W.m/K</td>
</tr>
<tr>
<td>density</td>
<td>&gt;99%</td>
</tr>
</tbody>
</table>

*X. Liu et al, FEC-25, Oral*  
*L.Z. Cai et al, FEC-27, Poster, FIP/P1-38*
Activities on brazing and HIP Joining W/RAFM steel

ITER-grade W tiles (3mm) and CLF-1 RAFM steel

Results: HIP joints show promising bonding, strongly depending on interlayer metals.

Brazing:
- 0.5mm Fe-base alloy interlayer
- HIP Joining:
  - 980 ℃/150MPa/1h

Shear tested sample

* Fe63.5Cr11.5Si8.3B16.7 (at%) amorphous filler
4. Summary

1. Measures for improving thermal fatigue life of ITER EHF FW were investigated and verified by test.

2. One order increase in fatigue life may allow the using of larger Be tiles in the new FW design, and shall be further verified by test.

3. Strong effect of Be/CuCrZr interface defect on thermal fatigue life of the ITER EHF FW. A thick OF-Cu interlayer is a good solution for defect-free joint.

4. Better CuCrZr properties by explosion bonding instead of HIP bonding CuCrZr/316L(N) joints. Cr and Zr elements segregation maybe an issue and shall be assessed further.

5. Good progress in developing the W/RAFM steel joints for CFETR FW. Further study is required for optimizing the technologies and for high heat flux test evaluation.
Thanks for Your Attention!