Study the interaction of RAFM steel with laboratory and EAST plasma conditions

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Outline

◆ Introduction
◆ Sample preparation & native hydrogen releasing
◆ Deuterium retention in steel related re-deposited layer
◆ Permeation experiments of CLF-1 steel
◆ Summary
Introduction—Participates and research topics

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Institute of Plasma Physics, CAS

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Wang, Peng @ Vienna, First CRP meeting, 09/12/2015
Introduction—Participates and research topics

Lanzhou institute of Chemical Physics, CAS

Institute of Plasma Physics, CAS

BeiHang University

Research topics:

Erosion and D retention of RAFM steel exposed to laboratory plasma—LICP

Erosion of RAFM steel by exposure to ECR plasma source

Deuterium retention in RAFM steel and related re-deposition layer

Performance of RAFM steel exposure to EAST tokamak plasmas—ASIPP

Erosion and D retention of different RAFM steels using MAPES exposure

Simulation the D retention behavior in steel/iron—BeiHang
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### Sample preparation

#### Composition of RAFM steels (in wt.%) (Fe balance)

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Cr</th>
<th>W</th>
<th>Mn</th>
<th>V</th>
<th>Ta</th>
<th>N</th>
<th>P</th>
<th>S</th>
<th>O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eurofer</td>
<td>0.09-0.12</td>
<td>8.5-9.5</td>
<td>1.0-1.2</td>
<td>0.2-0.6</td>
<td>0.15-0.25</td>
<td>0.10-0.14</td>
<td>0.015-0.045</td>
<td>0.004-0.005</td>
<td>0.003-0.004</td>
<td>0.0013-0.0018</td>
</tr>
<tr>
<td>F82H</td>
<td>0.09</td>
<td>7.7</td>
<td>1.94</td>
<td>0.16</td>
<td>0.16</td>
<td>0.02</td>
<td>0.012</td>
<td>0.002</td>
<td>0.002</td>
<td>0.01</td>
</tr>
<tr>
<td>CLAM (CLF-1)</td>
<td>0.11</td>
<td>8.5</td>
<td>1.5</td>
<td>0.5</td>
<td>0.25</td>
<td>0.1</td>
<td>0.02</td>
<td>0.003</td>
<td>/</td>
<td>0.002</td>
</tr>
</tbody>
</table>

CLAM steel from ASIPP (Aug, 2015)  Eurofer from IPP

Wang, Peng @ Vienna, First CRP meeting, 09/12/2015
Sample preparation

Eurofer97/CLAM Steels - Before polishing:
--- Technical finish of samples by the manufacture guaranteed an even thickness of all specimens
--- Ultrasonic cleaning and mechanical removing of possible layer from cutting procedure

Current polishing procedure
--- Polishing with increasingly fine-grained SiC grinding paper (P360-P800 -P200-P2000) (about 5 min each)
--- Nap cloth 20 min with diamond suspension, 2-3 sprayings and polishing
--- Nap cloth with 2.5% NaOH solution (in water) 10min
--- 5 min flushing with water on the Nap cloth
--- ALL 6 sides are polished with a main side polished to a mirror-like surface

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Sample preparation

Eurofer

893 K

1273 K

Fe Ka1
Cr Ka1
W Ka1
C Ka1 2

50μm

50μm

50μm

50μm

Eurofer-900 K

Eurofer-1273

Fe/Cr (110)

Fe/Cr (200)

Cr/Fe (211)

Hardness (HV)

Load (g)

Eurofer steel

Eurofer-893

Eurofer-1273

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Sample preparation

CLAM-L

CLAM-T

893 K

893 K

1273 K

1273 K

Intensity (a.u.)

CLAM-L

CLAM-L-893

CLAM-L-1273

Fe/Cr (110)

Fe/Cr (200)

Fe/Cr (211)

Intensity (a.u.)

CLAM-T

CLAM-T-893

CLAM-T-1273

Fe/Cr (110)

Fe/Cr (200)

Fe/Cr (211)
Sample preparation

CLAM-L

CLAM-T

893 K

893 K

1273 K

1273 K

Eurofer after 1273 K annealing

Hardness (HV)

Loading (g)
Native hydrogen releasing

Magnetron sputtering and Thermal desorption

L chamber: Magnetron sputtering with four targets
M chamber: 10^{-6} Pa base pressure with IR heating (RT-1100 °C)
R chamber: 10^{-8} Pa base pressure with electron beam heating to 2000 °C

Temperature (K)

0 1000 2000 3000 4000 5000 6000
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Oven temperature
Sample temperature

Time (s)

TDS condition: 300 - 893K
Rate: 10 K/min

Hydrogen releasing (10^{-17} \text{ H}_2/\text{m}^2/\text{s})

Mass 2

Eurofer97: 15mm\times12mm
CLAM-L: 15mm\times12mm
CLAM-T: 12mm\times10mm

Temperature (K)

0 300 400 500 600 700 800 900 1000

Oven temperature
Sample temperature

Time (s)

TDS condition: 300K - 1273K
Rate: 10 K/min

Hydrogen releasing (10^{-17} \text{ H}_2/\text{m}^2/\text{s})

Mass 2

Eurofer
CLAM-L
CLAM-T

Temperature (K)

0 300 400 500 600 700 800 900 1000

Oven temperature
Sample temperature

Time (s)
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Deuterium retention in re-deposition layer

Steel used as first wall material will inevitably be sputtered and re-deposited on wall

Fe & Cr layers deposited by magnetron sputtering were used as a model system to study the D retention and releasing behaviors of re-deposited layer

Deuterium implantation
CCP plasma:
Pressure: 1.0 Pa
Bias: -200 V
Substrate T: ~400 K
Flux: $2 \times 10^{18} \text{ D} \cdot \text{s}^{-1} \cdot \text{m}^{-2}$
Fluence: $1.4 \times 10^{23} \text{ D} \cdot \text{m}^{-2}$

Re-deposition layer preparation
Atmosphere: Ar & D$_2$
Pressure: 0.75 Pa
Target: iron and chromium
Deuterium retention in re-deposition layer

Deuterium releasing from Fe, Cr layers before and after deuterium implantation

D releasing from co-deposition layer:
Fe-D: 700 K
Cr-D: 500 K

After implantation:
Fe-D: 700 K
Cr-D: 500 K
600 to 900K
Deuterium retention in re-deposition layer

Total deuterium retention as a function of incident fluence

![Graph showing deuterium retention as a function of incident fluence.]

- No saturation of D retention in Cr re-deposition layer
- D retention in Fe re-deposition layer saturated at a fluence of $10^{22} \text{ D/m}^2$
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Experimental procedure

- **He ions implantation**
  - Energy: 3.5 MeV
  - Flux: $5 \times 10^{11}$ ions/(cm$^2$ s)
  - Temperature: R.T

- **GDP (gas driven permeation)**
  - Sample held by VCR couplings.
  - Temperature: 350-550 °C
  - Driving pressure: $10^3$ Pa-$10^5$ Pa

- **D$_2$ exposure and TDS**
  - Exposure temperature: 350 °C
  - Exposure pressure: $8 \times 10^4$ Pa
  - TDS temperature rate: 1 °C/s
  - TDS temperature range: R.T – 1000 °C

**Chemical composition of CLF-1 steels**

<table>
<thead>
<tr>
<th>Alloy element</th>
<th>Cr</th>
<th>C</th>
<th>W</th>
<th>Ta</th>
<th>Mn</th>
<th>V</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content control</td>
<td>8.5±0.3</td>
<td>0.11±0.015</td>
<td>1.5±0.2</td>
<td>0.10±0.03</td>
<td>0.5±0.2</td>
<td>0.3±0.1</td>
<td>0.02-0.035</td>
</tr>
<tr>
<td>Impurity</td>
<td>S</td>
<td>P</td>
<td>Ti</td>
<td>B</td>
<td>Nb</td>
<td>O</td>
<td>Ni</td>
</tr>
<tr>
<td>Content control</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.01</td>
<td>&lt;0.005</td>
<td>&lt;0.01</td>
<td>&lt;0.005</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Impurity</td>
<td>Cu</td>
<td>Al</td>
<td>Si</td>
<td>Co</td>
<td>As</td>
<td>Sn</td>
<td>Sb</td>
</tr>
<tr>
<td>Content control</td>
<td>&lt;0.01</td>
<td>&lt;0.03</td>
<td>&lt;0.05</td>
<td>&lt;0.01</td>
<td>As+Sn+Sb+Zr&lt;0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reference: P H Wang, report at Chendu, 2013
He ions irradiation

4.5 MV electrostatic accelerator in Peking University

Three groups of irradiated CLF-1 steel samples were got with one sample for permeation experiment and one for D₂ exposure and TDS in one group.

<table>
<thead>
<tr>
<th>No.</th>
<th>DPA Peak value</th>
<th>He implantation ions/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.001</td>
<td>6 × 10^{17}</td>
</tr>
<tr>
<td>2</td>
<td>0.01</td>
<td>6 × 10^{18}</td>
</tr>
<tr>
<td>3</td>
<td>0.05</td>
<td>3 × 10^{19}</td>
</tr>
</tbody>
</table>
GDP results of virgin CLF-1 steel

The permeability (mol·m⁻¹·s⁻¹·Pa⁻¹/²) of the virgin CLF-1 sample can be described by:

\[ P_{\text{clf-1}} = 6.36 \times 10^{-8} \exp \left( \frac{-0.43 \text{[eV]}}{kt} \right) \]

The diffusion coefficient (m²·s⁻¹):

\[ D_{\text{clf-1}} = 3.71 \times 10^{-7} \exp \left( \frac{-0.23 \text{[eV]}}{kt} \right) \]
GDP results of irradiated CLF-1 steel

For each irradiated sample, the GDP experiments were performed from low temperature to high temperature and back to low temperature again.
As the amount of helium implantation is too small, the mess 4 signal in the TDS is only from D₂ gas.

Both the samples show three main peaks, 210 °C, 380 °C, 645 °C.

The irradiated sample shows larger retention than that of virgin sample after exposure to deuterium gas at the same condition.
More work on RAFMs

- Heavy ions irradiation effect on the microstructure and the hydrogen isotope permeation and retention behavior (Ongoing).

- Evaluation of RAFMs as the plasma-facing material by the material and plasma evaluation system (MAPES) in the EAST tokamak (Ongoing).

- Explore the technique to obtain $\alpha$-$\text{Al}_2\text{O}_3$ at low temperature on RAFMs as tritium permeation barrier (Planning)

MAPES on EAST
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Summary

What we have done:
1. Prepare CLAM and Eurofer samples for laboratory plasma exposure
2. Investigate the deuterium retention in steel related re-deposition layer
3. Study the influence of He ions irradiation on deuterium retention and permeation

What we plan to do:
1. Study the erosion and deuterium retention of steel under the laboratory plasma
2. Investigate the performance of different RAFM steel in EAST plasma condition
3. Simulation the D retention behavior in steel/iron
Thank you for your attention!