Laboratory measurements of RAFM steel erosion and H retention in RAFM steel

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Content:
• Introduction: Sputtering of mixed materials
• Erosion of EUROFER and model samples
• What do we need?

Introduction

What do we need to answer the question:
Can we use RAFM steels at some areas of the first wall of a future fusion power plant?

Certainly, steel is not an option for areas receiving a high power load and high particle flux.
And probably also not for areas receiving a non-negligible ion (plasma) flux.
Why should we use RAFM (reduced activation ferritic-martensitic) steel at all?

- Blanket modules for the first wall blankets are made of RAFM steel
- Technologically it would be much easier and less expensive
- H retention in RAFM steels is low, even lower than in W

Temperature dependence of D retention in EUROFER and F82H [1] irradiated by D ion / exposed to D plasma under various conditions in HSQ, PlaQ and PISCES-A devices.

Comparison of fluence dependence of D retention between W [2] and RAFM steels (EUROFER and F82H).

[2] ITPA SOLOLv topical group / B. Lipschultz et al., MIT report PSFC/RR-10-4
Why should we use RAFM steel at all?

- Blanket modules for the first wall blankets are made of RAFM steel
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So what is the problem in using steel?

Introduction: Sputter Yields of Fe and W

- Energy dependence of sputtering yield of Fe and W measured by weight loss & RBS (perpendicular ion incidence)
- Data fitted with Bohdansky formula

\[ Y(E) = Q_{SW}^{Fe} \left[ 1 - \left( \frac{E_{SW}}{E} \right)^{4/3} \right] \left( 1 - \frac{E_{SW}}{E} \right)^2 \]

- Open circle: determined by weight loss measurement,
- Closed circle: determined by RBS (Rutherford Backscattering Spectrometry).

- The curve is derived from the fitting by Bohdansky formula.

- Fe has lower sputter threshold and higher yield
- In relevant E region (50 to 1000 eV)
  \[ Y_{Fe} > 10 \cdot Y_{W} \]

\[ \rightarrow Fe \text{ (steel) not useable as PFM} \]
Sputtering of pure Fe (the main component of steel) is too high!

But: steel is not pure Fe

RAFM steels (EUROFER, RUSFER, F82H) contain small amounts (0.4 to 1.0 at.% of W)

Sputter yield of W, \( Y_W \), is much lower than \( Y_{Fe} \)
\[ \Rightarrow \] W enrichment / Fe depletion at the surface

This phenomenon is called “preferential sputtering”

Preferential sputtering will lead to a continuous change of the sputtering behavior
SDTrimSP results: Dynamic Behaviour

- RAFM steels contain W which has a much lower sputter yield than Fe etc.
  - Preferential sputtering leads to W enrichment due to the difference of sputtering yields.
  - Erosion yield is reduced.

### Dynamic surface evolution due to preferential sputtering

#### Preferential Sputtering

The two most important factors for preferential sputtering:
- Max transferable energy for a given projectile/target combination
- Surface binding energy

Energy transfer in binary collisions:

\[ T_{\text{max}} = 4 \cdot \frac{M_1 M_2}{(M_1 + M_2)^2} \]

<table>
<thead>
<tr>
<th>(M_1)</th>
<th>(M_2)</th>
<th>(T_{\text{max}})</th>
<th>(E_{\text{trans}}) at 200 eV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(in eV)</td>
<td>(in eV)</td>
</tr>
<tr>
<td>D on W</td>
<td>2</td>
<td>184</td>
<td>0.043</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>56</td>
<td>0.133</td>
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<tr>
<td>D on Fe</td>
<td>2</td>
<td>184</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>56</td>
<td>26.6</td>
</tr>
</tbody>
</table>

Surface binding energy of W (in W!) = 8.7 eV
Fe (in Fe!) = 4.4 eV
Preferential Sputtering

Preferential sputtering

- Leads to enrichment of one component (transient phase until steady state)
- Reduces total sputter yield
- Effect increases with difference of sputter yield of the 2 components
- Occurs for all energies, but is strongest in the region between the 2 threshold energies

SDTrimSP can simulate the dynamic surface evolution due to preferential sputtering

Experiment: Sample Preparation

Preparation of EUROFER samples (W conc. = 0.42 at%)
- Specimens cut out from a EUROFER sheet (EUROFER 97-2 [heat 993 393])
- Surface polished to mirror-finish and pre-annealed at 800 K.

Preparation of Fe/W binary system layers as “model” of RAFM steel
- Deposition by magnetron-sputtering from Fe and W targets
- Composition variable: Prepared W concentrations: 0.7, 1.5 and 4.2 at%.

Fe/W model layers are used for benchmarking of SDTrimSP simulations.
Experiment: D Irradiation

D ion irradiation & plasma exposure

“High current ion source (HSQ)” ion-beam set-up (IPP-Garching)
- Conditions well-defined:
  - mass-separated mono-energetic D\textsuperscript{+} ion beam
- But relatively low D flux ≤ 10\textsuperscript{19} m\textsuperscript{2}s\textsuperscript{-1}

“PISCES-A” linear plasma device (UCSD) and
Linear plasma device “PSI-2” (FZJ)
- High flux (D\textsuperscript{+}, D\textsubscript{2}\textsuperscript{+}, D\textsubscript{3}\textsuperscript{+}) plasma ~ 10\textsuperscript{21} D\textsuperscript{+}/m\textsuperscript{2}s
- But possible influences of plasma impurities (e.g. O) and redeposition

Experiment: Post-irradiation Analysis

Post-irradiation analysis

- Weight-loss measurement
  - the only applicable technique to determine the sputtering yield of bulk materials, e.g., EUROFER steel
- Rutherford Backscattering Spectroscopy (RBS)
  - with 1 MeV \textsuperscript{4}He\textsuperscript{+}: determination of surface composition and measurement of sputtered amount
- Scanning Electron Microscopy (SEM)
  - Surface morphology examination
Experiment: Post-irradiation Analysis

- Surface composition changes with D irradiation fluence (HSQ exposure).
- W concentration at the top surface increases with fluence (for all D impinging energies).

- HSQ: 200 eV/D → Fe/W 1.5 at.%

RBS spectra obtained from Fe/W 1.5 at.% and EUROFER steel irradiated by 200 eV/D with different fluences: 1.0e22, 1.0e23 and 1.0e24 D/m².

→ Predicted effect of surface enrichment experimentally proven

Erosion of Fe/W Model Layers

- Initial level similar to that for pure Fe ($Y_{Fe}$) (solid lines)
- Clear decrease with fluence (in range of ≥ 10²³ D/m²)
- Yield reduction by 30 to 50% compared with that of pure Fe at 10²⁴ D/m²

Sputtering yield of Fe/W (W ~1.5 at.%) layer by D ion irradiation with different D energies as a function of D fluence (320 K)
Erosion of Fe/W Model Layers

Decrease of sputter yield with increasing fluence

- Initial level similar to that for pure Fe ($Y_{Fe}$) (solid lines)
- Clear decrease with fluence (in range of ≥ $10^{23}$ D/m$^2$)
- Yield reduction by 30 to 50% compared with that of pure Fe at $10^{24}$ D/m$^2$

- Yield reduction depends also on the initial W content in the Fe-W binary layer.

![Graph showing sputtering yield of Fe/W layers with different W content](image)

Erosion of EUROFER

- Yield reduction in the higher fluence range (≥ $10^{23}$ D/m$^2$), as well as for Fe/W layer.
- For 200 eV/D steady state seems to be reached for fluence > ~ $5 \times 10^{24}$ D/m$^2$.
- PISCES-A data\textsuperscript{[1]} at very high fluence and 140 eV/D also indicate steady state for fluence > ~ $5 \times 10^{24}$ D/m$^2$.

![Graph showing sputtering yield of EUROFER steel by D ion irradiation with different D energies as a function of D fluence (320 K)](image)

\textsuperscript{[1]} J. Roth et al., J. Nucl. Mater. 454 (2014) 1
Comparison SDTrimSP – Experiment

- Fe/W binary layers: Experimental data and SDTrimSP result agree within ~30%.

![Comparison SDTrimSP - Experiment](image)

Comparison of sputtering yields between SDTrimSP calculation result and experimental data obtained for Fe/W binary layers with different W content.

Temperature Dependence

- Exposure of EUROFER to low-energy (140 eV/D⁺) / high-flux (~10²¹ D+/m²s) plasma at various temperatures (370 - 870 K).

- Sputtering yield varies within a limited range at <~800 K, while it clearly increases at 870 K.
  - Consistent trend with the numerical prediction.
  - No clear temperature dependence of sputtering in the DEMO FW working temperature range (< 800 K).

![Temperature Dependence](image)

Sputtering yield of EUROFER steel by 140 eV/D⁺ exposure as a function of exposure temperature (measured at PISCES-A)

Surface Morphology

Surface morphology change of EUROFER

- EUROFER surface sputtering is not homogeneous…:
  - grain-dependent erosion.
  - high-Z precipitates.
  - nano-scale roughness.

Irradiation of EUROFER by low-flux (~10^{19} D/m²s) D ion beam in HSQ at several temperatures (320 - 770 K).

- Development of surface topography is strongly affected by the exposure temperature.
Surface Morphology

- EUROFER exposed to PISCES-A plasma: Development of surface topography is strongly affected by the exposure temperature as well.

140 eV/D·, 400 K, 1.3e24 D/m²

140 eV/D·, 870 K, 1.3e24 D/m²

4 μm

Surface Morphology

PSI-2: 555 K, 90 eV, 2.6×10²⁵ D m⁻²

Fe 1.5 at% W

Eurofer-97

Surface

Cross section

IAEA CRP “Steel”, Vienna © W. Jacob, December 2015
Temperature Dependence

- T dependence of sputter yield
- Onset of diffusion (counteracting enrichment?)
- T dependence of surface morphology

Impurity sputtering

- Higher mass $\rightarrow$ higher sputtering of W
- Ions: higher energy due to sheath acceleration

Open questions

Summary

- Erosion of RAFM steel and model systems was investigated in ion beam experiment and in linear plasma devices
- Surface enrichment of W and reduction of sputter yield were experimentally proven
- For the model layers reasonable agreement with theoretical predictions (SDTrimSP)
- Reduction of EUROFER sputter yield by factor up to 8 (at 200 eV)
- Reduction possibly strongly influenced by surface morphology development
- H retention in steel is low (even lower than in W)

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Where could RAFM steel be used?

- First wall in areas without plasma contact
- Impinging flux “only” CX neutrals
- CX neutrals have a very wide E distribution, but dominantly low-E (< 200 eV) hydrogen isotopes
- Under such conditions W enrichment (and the corresponding reduction of the sputter yield) might be effective

Why “no plasma contact”?

- Impurity ions (higher mass and higher energy)
- Higher mass $\rightarrow$ better E transfer $\rightarrow$ higher sputtering of W
- Ions, sheath acceleration $\rightarrow$ higher E $\rightarrow$ higher sputtering
- Under such conditions W enrichment probably not effective

What do we need to answer the question:

Can we use RAFM steels at some areas of the first wall of a future fusion power plant?

What is still needed?

- From lab results: better understanding of T dependence and surface morphology effects
- Improved surface diagnostics
- Influence of impurities
- From the fusion plasma side: mass and energy distribution of impinging particle fluxes