Introduction

It has recently been suggested to consider RAFM steel (e.g. EUROFER) as plasma-facing material for the DEMO first wall.

ASDEX Upgrade plans to investigate the plasma performance of solid steel tiles (2 rows of the inner heat shield were exposed in the last campaign, it is planned to expand to 5 rows in the next campaign)

Question:

What do we know about sputtering of steel from past experiments?

Actually, we don’t know very much about steel!

Up to about 3 years ago most assessments compared the behavior of W and Fe. Since then work in the direction of Steel as PFM has been started in various labs (mostly dedicated to H retention).

Sputtering of Fe vs. W

CX sputtering

Calculated with exp. Data from ASDEX, W7-AS, JET [H. Verbeek (1997)]

Sputtering of steel

Preferential sputtering of SS 316 LN

A comparison of the compositions indicates PS2 as the most suitable substitute for EUROFER. The major difference in Mo and W between EUROFER and PS2 should be evaluated in their relevance for the testing.
Steel as first wall material

What do we need to assess the compatibility of RAFM steel as first wall material?

For the primary usability (at least) three different processes have to be considered:
- impurity generation (sputtering) at the first wall (lifetime and impurity source) (this depends strongly on impinging species fluxes and particle energy distributions)
- impurity transport from the wall to the core
- radiation properties in the core

Possible additional aspects (operational limits):
- dynamical inventory (density control)
- impurity accumulation in the centre (Z dependence?)
- impurity flushing

In addition reactor-relevant processes should also be taken into account:
- Total sputtering yield (life time)
- Material transport and redeposition (H inventory, dust, flaking)
- H inventory in the wall material (H inventory)
- H permeation, permeation barriers
- Change of material properties due to H inventory (H embrittlement)
- Neutron irradiation induced damage (and corresponding influence on above effects)
- Transmutation and radiological hazards
- Neutron attenuation in armour material
- Change of material properties due to neutron irradiation

A large number of these questions can be addressed in laboratory experiments.

Hydrogen in EUROFER 97

Release temperatures are relatively high

Thermal release of H from EUROFER

H-induced embrittlement

Preferred sputtering

- sputter yield of different steel components depends strongly on the atom mass (and possibly also on the crystallographic phase)
- not only the yield, but also the threshold energy is sensitively mass dependent
- dynamic state of the surface during sputtering (and also during PSI) depends critically on the mass distribution and energy distribution of impinging species
- in addition this might be influenced by thermally driven diffusion processes
- heavy steel constituents will enrich at the surface
- in steady state, the relative contribution of the different constituents to the sputtering rate (not yield) will be equal to the bulk composition
- but the dynamic state of the surface and accordingly the total sputtering rate will change if PSI parameters change

Preferred sputtering

Maximum energy transfer $T_E$:

$$T_E = \frac{4M_1M_2}{(M_1+M_2)^2}$$

$T_E$ is maximal at $M_1 = M_2$

For D sputtering:

$T_E$ for Fe is 0.133 and $T_E$ for W is 0.0425

Threshold Energy for sputtering: $E_{th} = E_{th}(1-T_E)$

$E_{th}$ (D on Fe) = 37 eV, $E_{th}$ (D on W) = 216 eV,

Highest enrichments expected between 40 and 210 eV

Sputtering of steel

TRIDYN simulation of D $\rightarrow$ Fe + 1%W

Total sputter yields and threshold energies

Preferred sputtering and W enrichment

$E_{th}$, Fe $< E_{th}$, W

No W sputtering @ 100eV $\rightarrow$ 100% enrichment

@1keV both are sputtered $\rightarrow$ enrichment low

Sputtering of steel

Preferred sputtering: TRIDYN simulation

D (150 eV) $\rightarrow$ Fe$_{99}$W$_{1}$ (simulated)
Preferential sputtering: TRIDYN simulation

For parameter scan:
- Compute fluences up to $5 \times 10^{23}$ atoms/m$^2$
- Compute time
- Extrapolate via exponential fit

Scaling law predicts final concentration well, especially for low W bulk concentrations.

Energy (eV)

![Graph showing energy vs. yield for TRIDYN simulation.]

Preferential sputtering: Ion beam analysis

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>Counts</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>2500</td>
<td>3000</td>
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</tbody>
</table>

![Graph showing energy vs. counts for ion beam analysis.]

Further strategy

- Use W doped Fe layers as model system for basic studies on preferential sputtering
- Conduct well-defined sputtering experiments (parameter studies!)
- Characterize W enrichment at the surface
- Compare to SDS/TrimSP simulations (dynamic TRIM)

Relevant parameters:
- $D$ ion energy
- $D$ fluence (dynamic surface evolution!)
- W concentration
- Temperature (diffusion might influence enrichment)

Preferential sputtering: Matrix effect

- Sputtering of Fe overestimated by SDS/TrimSP
- Also: Sputtering of W below 400 eV underestimated
- Leads to overestimation of W enrichments

Energy (eV)

![Graph showing sputter yield vs. energy for matrix effect.]

Sputtering of steel

- Steel is a rather complicated phase mixture & different phases may have rather different properties
- Thermal treatment critical for phase composition
- Surface morphology (dynamic development $\rightarrow$ SEM mandatory)
- Even more complex than for “pure metals” (such as Be and Al, see presentation by RD) [temperature dependence!]

Concluding remarks

- Steel might be an option for some regions of the first wall of DEMO
- A scientific basis (figure of merit) should be developed to assess the fusion plasma compatibility of different types of metals
- This should take into account reactor-relevant processes
- Many of the relevant topics (not all!) can be addressed in laboratory experiments
- A sputtering data base should be compiled and further developed
- Impurity sputtering in plasma experiments must be considered
- Permeation of H isotopes is another important issue