Max-Planck-Institut für Plasmaphysik

IAEA Consultancy Meeting, Vienna, August 2014

PSI issues for steel as plasma-facing material

Wolfgang Jacob

Plasma Edge and Wall Division

Introduction

At present:
W is foreseen as plasma-facing material for a future power reactor

Pros for W:
- H retention in W is low
- Sputtering is low
- High melting temperature

Cons:
- W is expensive
- Joining of W to support structure (e.g., EUROFER) is no-trivial
- Pure W is brittle
- Material properties degrade due to n irradiation

2 strategies:

- **Improve mech. prop. of W by doping ("Advanced tungsten materials")**
- **Use low-activation steel instead of W for the first wall (main chamber wall)**

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:

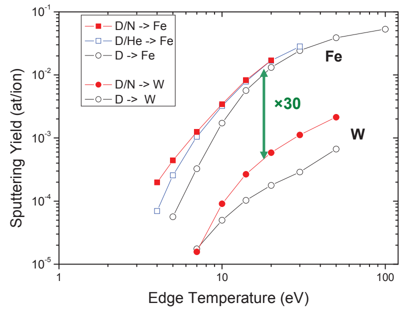
What do we know about sputtering of steel from past experiments?

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

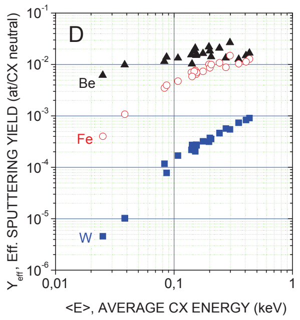
Ion sputtering (pure D and D with 1% impurity)



Maxwell distribution of ions shifted by sheath potential [W. Eckstein (2011)]

Sputtering of Fe vs. W

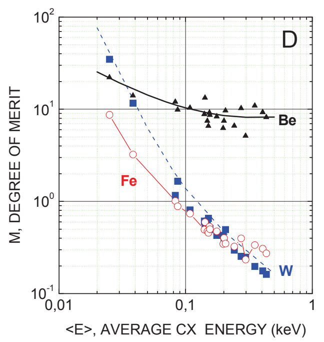
CX sputtering



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

Sputtering of Fe vs. W

CX sputtering, figure of merit



Calculated with exp. Data from ASDEX, W7-AS, JET [J. Roth (2004)]

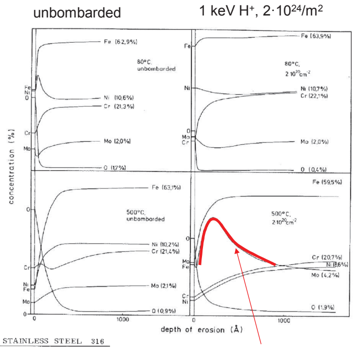
Are the assumptions use to derive this figure of merit still valid?

- Wall fluxes
- Erosion yields
- Boundary layer transport
- Core penetration

Sputtering of steel

Preferential sputtering of SS 316 LN

unbombarded 1 keV H^+, $2 \cdot 10^{24}/m^2$



EROSION AND CHANGES IN SURFACE COMPOSITION OF STAINLESS STEEL 316 AFTER LOW ENERGY LIGHT ION BOMBARDMENT AT TEMPERATURES BETWEEN 50 and 600°C

J. Roth, J. Bohdansky, W. O. Hofer (1976)

Mo enrichment may reduce sputtering yield

Sputtering of steel

Chemical composition (weight %) of AISI 316L(N)-IG, EUROFER97 and P92.

	EUROFER97[1]	AISI 316L(N)-IG[2]	P92 (1.4901)[3]
C	0.09-0.12	0.015-0.030	0.05-0.15
Cr	8.5-9.5	17.0-18.0	8.4-9.6
Mo	<0.005	2.30-2.70	<0.65
V	0.15-0.25	ns	0.12-0.28
N	0.015-0.045	0.060-0.080	0.02-0.072
W	1.0-1.2	ns	1.4-2.10
Fe	balance	balance	balance

Data provided by L. Boccaccini (KIT) 07.02.2011

A comparison of the compositions indicates P92 as the most suitable substitution for EUROFER. The major difference in Mo and W between EUOFER and P92 should be evaluated in their relevance for the testing.

[1] The present reference specification of the EUROFER chemical composition is to be used within the HCLL/HCPB TBS activities. It is extracted from the "*Technical specifications (Annex A) to the contract EFDA-06/1903 – Procurement of reduced activation ferritic-martensitic steel type 9CrWTaV (EUROFER) for the TBM fabrication technology trials and mock-ups*". It shall be noted i) Saarschmiede was able to produce EUROFER within the specification in 2008 (EUROFER 97-3) and ii) this specification is also identical to the one used for production of the EUROFER 97-2.
[2] ITER STRUCTURAL DESIGN CRITERIA FOR IN-VESSEL COMPONENTS (SDC-IC) APPENDIX A (ITER IDM: G 74 MA 8 01-05-28 W0.2)
[3] Composition of P92 from Arcelor (CROMELSO 92) taken from the specification of the KIT Order in 2010.

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

Steel as first wall material

In addition reactor-relevant processes should also be taken into account:

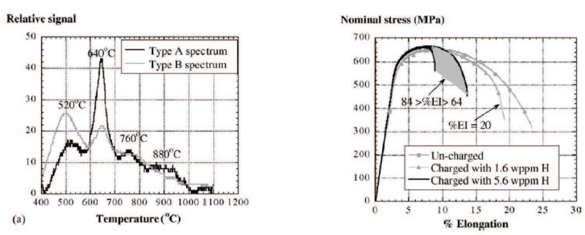
- Total sputtering yield (life time)
- Material transport and redeposition (H inventory, dust, flaking)
- H inventory in the wall material (H inventory)
- H permeation, permeation barriers
- Change of material properties due to H inventory (H embrittlement)
- Neutron irradiation induced damage
  (and corresponding influence on above effects)
- Transmutation and radiological hazards
- Neutron attenuation in armour material
- Change of material properties due to neutron irradiation
- …

Hydrogen in EUROFER 97

Thermal release of H from EUROFER

H-induced embrittlement

M.-F. Maday, L. Pilloni / Fusion Engineering and Design 75–79 (2005) 957–961



Release temperatures are relatively high

H content ≈ 1 resp. 3 $\times 10^{-4}$

Steel as first wall material

Plasma-Material Interaction topics for different types of steel:

- preferential sputtering (sputter threshold)
- dynamic behaviour, fluence dependence (TRIDYN simulations and experiments)
- steady state behaviour
- temperature dependence
- surface morphology development
- sputtering due to impurities (threshold behaviour)
- What are the impinging species fluxes? Particle energy distributions?
- "sputtering data base"? (dependence on species, energies, temperature, …)
- H retention and diffusion

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

Preferential 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

Preferential 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: $E_{thr} = E_{sb}/\{T_E(1-T_E)\}$

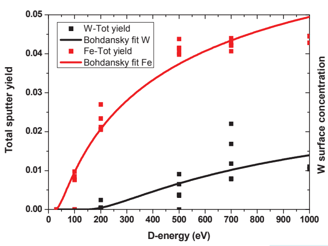
E_{thr} (D on Fe) = 37 eV, E_{thr} (D on W) = 216 eV,

Highest enrichments expected between 40 and 210 eV

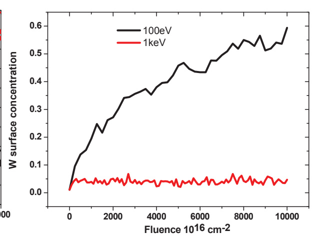
Sputtering of steel

TRIDYN simulation of D → Fe + 1%W

Total sputter yields and threshold energies



Preferential sputtering and W enrichment

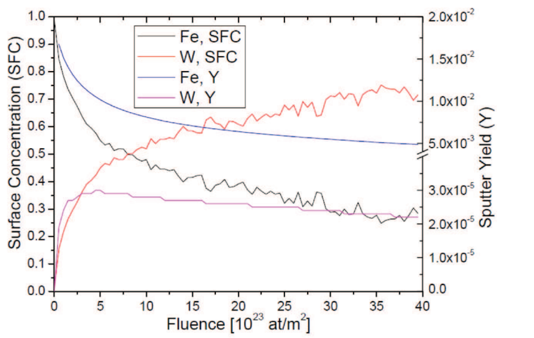


➢ E_{Thres} Fe << E_{Thres} W

➢ No W sputtering @ 100eV → 100% enrichment
➢ @1keV both are sputtered → enrichment low

Preferential sputtering: TRIDYN simulation

D (150 eV) → $Fe_{99}W_1$ (simulated)

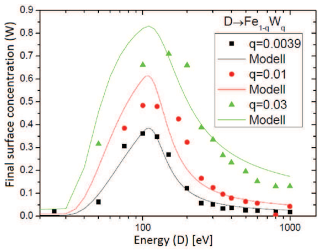


Bachelor Thesis, Malte Kremser, 2013

Preferential sputtering: TRIDYN simulation

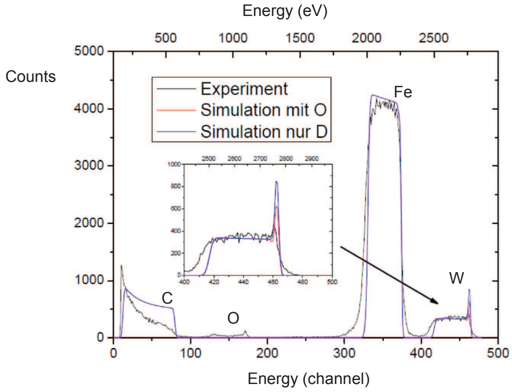
For parameter scan:
Only Fluences up to 5x10^{23} at/m^2
→ computation time
→ extrapolating via exponential fit

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



Bachelor Thesis, Malte Kremser, 2013

Preferential sputtering: Ion beam analysis



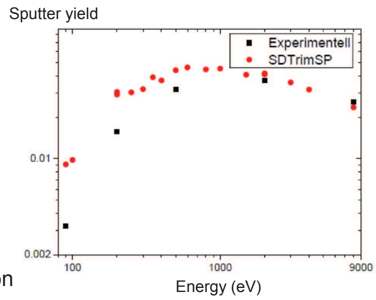
Preferential sputtering

But:

Sputtering of Fe overestimated by SDTrimSP

Also: Sputtering of W below 400 eV underestimated

⇒ leads to overestimation of W enrichments



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

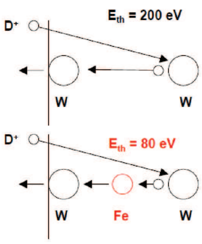
Compare to SDTrimSP simulations (dynamic TRIM)

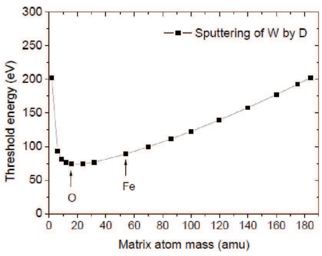
Relevant Parameters:

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

Preferential sputtering: Matrix effect

Analytic calculation:
Threshold energy for the simplest sputtering process:





The threshold energy for sputtering of W in a Fe matrix is reduced from about 200 eV to about 100 eV.

J. Roth, Wall Forum 17.7.2013

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 → 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 asses 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