Yttria as a Tritium Permeation Barrier in Fusion Components

J. Engels, A. Houben, M. Rasinski, Y. Mao, and Ch. Linsheimer
Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung - Plasmaphysik, 52425 Jülich, Germany

Motivation

Problems of tritium permeation in fusion vessel:
- Fuel loss
- Tritium accumulation: wall, cooling system, ...
- Radiological hazards
- Prevention of permeation with tritium permeation barrier:
- Material research of thin film barrier layers (Y2O3): porosity, phase, heat load resistivity
- Osmium tritium studies of the barrier layers:
  Required permeation reduction factor is 50...100 for viable power plant – Does Y2O3 film fulfill this?
  Advantage of Y2O3 compared to other candidates (e.g. Al2O3). Favorably low neutron activation behavior of Y:

Barrier layers: Y2O3

Y2O3 film:
- High thermal stability and corrosion resistivity
- Similar thermal expansion coefficients of:
  - Eurofer97 substrate: 12.7·10⁻⁶ K⁻¹
  - Y2O3 thin film: 8·10⁻⁶ K⁻¹
Layer deposition:
- Reactive magnetron sputtering:
  Ar/O2 plasma, power-density: 2.9 W/l
- Change ratio of O2 to Ar inlet flux:
  < 6%: Metallic mode
  > 9%: Reacted mode – Y target is oxidized:
  Deposition rate decreases by factor of ~100
  Porosity is formed

Background

Permeation Studies
Pressure dependence (P pressure): 25 - 800 mbar:
- Permeation control mechanism (J/pressure flux):
  - J/P⁻¹: Diffusion limited regime, dependent on sample thickness
  - J/P: Surface limited regime, independent on sample thickness
- Temperature dependence (temperature: 300 - 550°C):
  - Provides activation energy for diffusion of D2 in sample

Substrate
Eurofer97 - reduced activation ferritic martensitic (RAFM) steel:
- Low content of undesired elements: Nb, Mo, Ni, Cu,
- Sample preparation - wire-cut disks (0.3 mm thickness, 25 mm diameter):
  - Annealing at 550°C: Removal of native hydrogen
  - Mechanical polishing: Defines surface roughness

Barrier layers: Y2O3

Y2O3 film:
- High thermal stability and corrosion resistivity
- Similar thermal expansion coefficients of:
  - Eurofer97 substrate: 12.7·10⁻⁶ K⁻¹
  - Y2O3 thin film: 8·10⁻⁶ K⁻¹
Layer deposition:
- Reactive magnetron sputtering:
  Ar/O2 plasma, power-density: 2.9 W/l
- Change ratio of O2 to Ar inlet flux:
  < 6%: Metallic mode
  > 9%: Reacted mode – Y target is oxidized:
  Deposition rate decreases by factor of ~100
  Porosity is formed

Phase analysis of Y2O3
XRD: Stable cubic phase after annealing

Lattice const.
Metallic Reacted
Not annealed 10.747(5) Å -
Annealed 10.629(5) Å 10.643(5) Å

FIB-cut ➔ SEM analysis of Y2O3 films:
- SEM of thin film cross-section:
  - Metallic mode: Cracks are formed, due to stress during annealing
  - Reacted mode film: Porosity dissipates stress energy
  - No cracks/damages in barrier layer after annealing
  - Perform permeation measurement of this barrier (Possible influence on permeation of Cr2O3 interlayer, formed during annealing)

Comparison of Y2O3 film and substrate:
Pressure dependence: Slope of curve in the diagram equals exponent of D2 pressure P:
- Bare Eurofer97 reference sample: J/P⁻¹⁻⁵⁴ (800°C)
  - Diffusion limited regime
  - Reacted mode Y2O3 barrier layer: J/P⁻⁹⁻¹⁰ (500°C)
  - Barrier performance degraded, probably because of change in Y2O3 grain structure
  - Apparent change of exponent
Permeation reduction factor of oxide layer compared to substrate: ~30 (minimum factor after degradation)

Summary

Y2O3 barrier layer:
- 1 µm layer by reacted mode magnetron deposition process
- Annealing for 15h @ 550°C
  - No crack formation ➔ Accurate permeation measurement possible
  - Cubic phase of the Y2O3 layer after annealing for metallic and reacted mode (XRD)
  - Favorable neutron activation behavior of Y
Preliminary result of D2 permeation measurement:
- Permeation reduction factor: ~30