Institute for Applied Materials
Material Process Technology (IAM-WPT)

Needs and gaps in the development of aluminum-based corrosion and T-permeation barriers for DEMO

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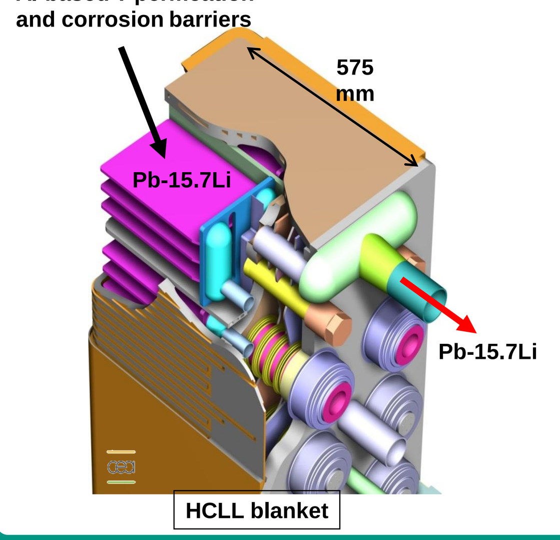
Motivation

Al-based T-permeation- and corrosion barriers



HCLL blanket

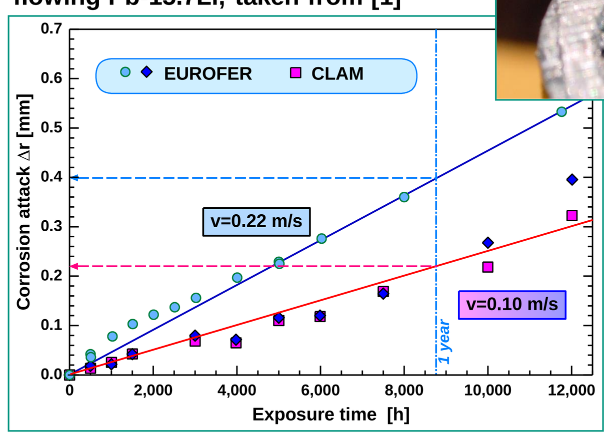
Low-activation-ferritic-martensitic (RAFM) steels are foreseen as structural materials in different blanket designs e.g. HCLL, WCLL, DCLL for DEMO and partly as TBM's in ITER

Steels are in direct contact with flowing Pb-15.7Li (liquid breeder) → Control of corrosion and T-permeation essential for reliable, safe and economic implementation

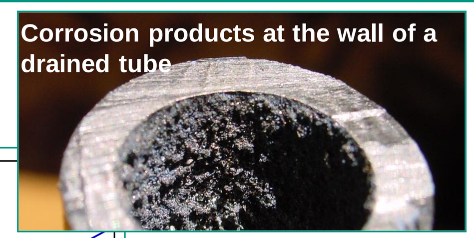
Bare steels suffer from significant corrosion attack of up to 400 µm per year in flowing Pb-15.7Li
► Danger of precipitation of dissolved corrosion products → Plugging of tubings / system failure

Solution: Corrosion and T-permeation barriers on RAFM steels based on aluminum
► Reduction of corrosion attack
► Reduction of T-permeation through the RAFM steel into the coolant

Corrosion attack of RAFM steels in flowing Pb-15.7Li, taken from [1]



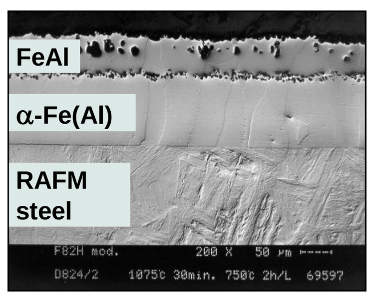
Corrosion products at the wall of a drained tube



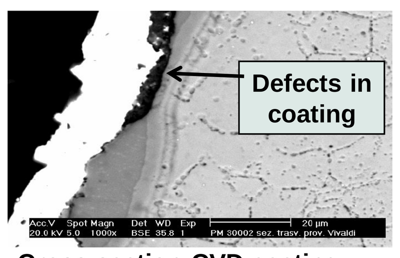
Development of Al-based barriers

10-15 years ago

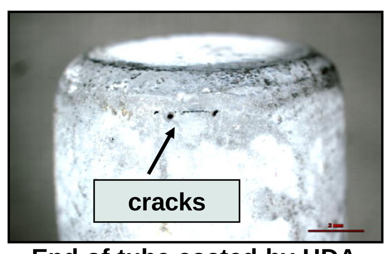
- Vapor plasma spraying (VPS), chemical vapor deposition (CVD), pack-aluminization and hot-dipping (HDA) tested in the beginning
- Corrosion protection potential of Al-based barriers in flowing Pb-15.7Li (v = 0.22 m/s) proved for HDA and VPS
- T-permeation reduction data
  - High T-permeation reduction factors (PRF) at disk shaped samples in H_2 gas
  - Significantly lower PRFs in Pb-15.7Li
  - Ambiguous results depending on sample shape (disk vs. tube), test facility and process
  - Drawbacks: Coating defects induced by the processes, e.g. cracks (HDA), low coverage (CVD) → Problems: Compatibility in Pb-15.7Li (CVD), T-permeation (HDA, CVD), homogeneity



Typ. HDA coating



Cross section CVD coating

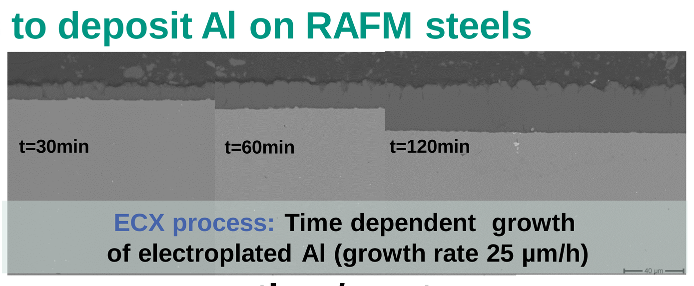


End of tube coated by HDA

Last 5 years – ECA & ECX

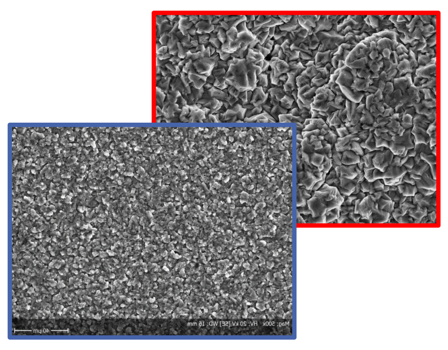
Introduction of electrochemical techniques to deposit Al on RAFM steels

► No reaction with the substrate material
► Adjustable Al thickness (time, j)
► Good adherence to the substrate
► Industrial relevance is given
► Process temperatures <100°C → low energy consumption / costs



Electrodeposition of Al requires water-free electrolytes

1. Toluene-based electrolytes → Adapted for deposition on RAFM steels → ECA process
2. Ionic liquid based electrolytes → More flexibility in using deposition parameters → ECX process



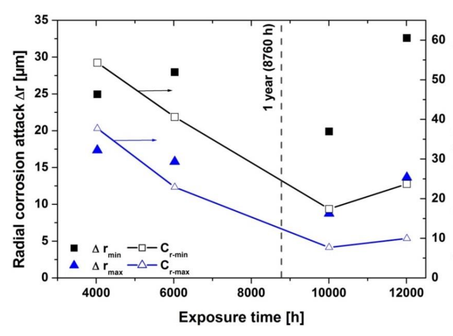
Scale formation through subsequent heat treatment (HT)

► Improved, uniform scales achieved by ECX process due to use of pulse-plating techniques → Improved surfaces
► Homogeneity after heat treatment depends on surface morphology

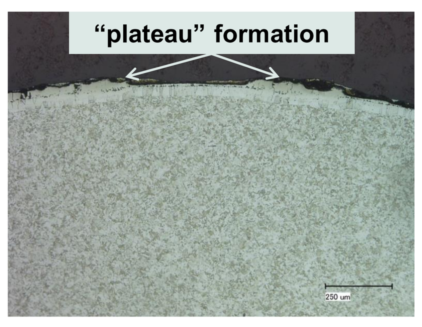
State-of-the-Art

Compatibility in flowing Pb-15.7Li

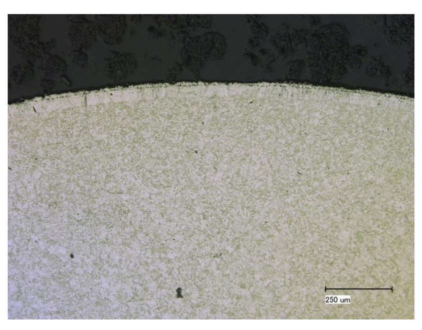
► Long-term compatibility in Pb-15.7Li of Al-based coatings proved for coatings made by HDA and ECA. Partly available for ECX (up to 2,000 h).
► ECA: Corrosion rates 10 times lower compared to bare Eurofer (after 12,000 h)
► Coatings by electroplating thinner than HDA coatings → Low activation
► Plateau formation during exposure in case of ECA → ECX improved surfaces



Corrosion in Pb-Li (550°C, v=0.1 m/s): ECA coated Eurofer, taken from [2]



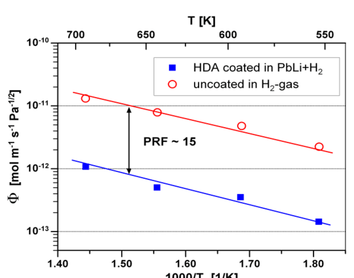
ECA coated Eurofer after corrosion testing in flowing Pb-Li (6,000 h)



ECX coated Eurofer after corrosion testing in flowing Pb-Li (2,000 h)

T-permeation properties

► Significant T-permeation reduction in H_2 gas of Al-based barriers proved in the past (results deviated in the past)
► But: Low values in H_2/Pb-Li → Correlated to fabrication defects (CVD, HDA)
► No data for new coatings made by ECA and ECX

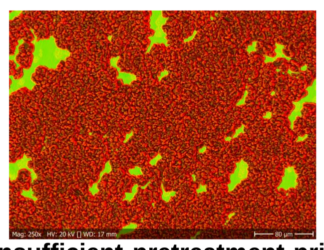


PRFs of coated tube in H_2/Pb-Li (VIVALDI facility)

Gaps in barrier development

Characterization and examination needs

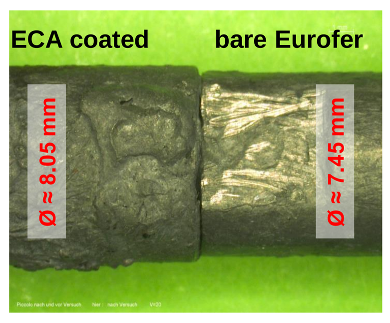
- Optimization of deposition parameters
  - Homogenous plating → More complex shaped parts
  - Further reduction of Al-thickness <12 µm → Lower limit?
- Examination of the influence of pretreatment conditions on:
  - Delamination, coating defects, scale formation and reproducibility
- Optimization of heat treatment conditions
  - Influence of HT atmosphere on scale formation and Al_2O_3 formation in particular
- Testing and examination of recovery properties
  - Behavior of introduced barrier defects in Pb-15.7Li
  - Dependence on impurity amounts in Pb-15.7Li



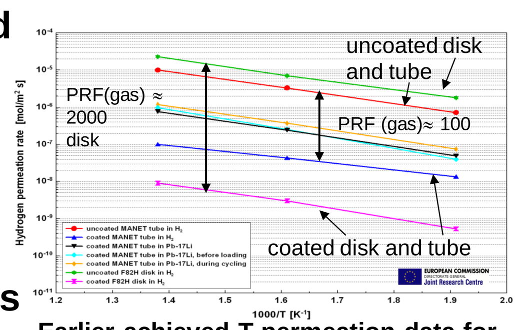
Insufficient pretreatment prior to electroplating

Qualification under fusion relevant conditions needed

- Compatibility in flowing Pb-15.7Li
  - Under TBM relevant temperatures, i.e. at 550°C and at accelerated flow rates (some cm/s)
  - Reliable / reproducible results in limited testing time (worst case)
- Behavior under thermal cycling
  - Test under gas atmosphere: Cycling between expected temperatures of 330°C (cooling gas inlet) and 550°C (neutron heating) → Impact on coatings (cracks, ...?)
  - Cycling in Pb-15.7Li → Impact of liquid metal
- T-permeation testing (in H_2 gas and H_2/Pb-15.7Li)
  - Data urgently needed for ECA and ECX coated samples (as prepared, thermally aged)
  - Testing in H_2 gas should be performed in parallel to further optimization of coating and HT processes
- Irradiation
  - Neutron irradiation tests essential for application as TBM
  - Testing under relevant temperatures, i.e. 330°C and 550°C recommended
- Up-scaling of fabrication process
  - Up-scaling of processes (deposition, HT) is mandatory in the foreseeable future → Aim: Industrial scale processes



Coated and uncoated Eurofer after corrosion testing in Pb-Li (10,000 h)



Earlier achieved T-permeation data for HDA coated disks and tubes

Common metal electroplating facility in industry based on aqueous electrolytes

Conclusions

► Electrochemical processes (ECA and ECX) offer interesting properties for application as fabrication route for Al-based barriers on RAFM steels
► Industrial relevance given for these processes
► Compatibility to flowing Pb-15.7Li proved for ECA coated Eurofer for up to 12,000 hours
► Short-term compatibility tested also for samples with improved surface coated by ECX

► Further characterization of process steps is recommended to ensure development of a reliable fabrication route based on electrochemical plating
► Qualification efforts related to different tasks urgently needed, especially:
  ► T-permeation data: No data available for new coatings made by ECA/ECX
  ► Needed for optimization of coating and heat treatment processes

References:
[1] Konys, J. et al.: Comparison of corrosion behavior of EUROFER and CLAM steels in flowing Pb-15.7Li, Journal of Nuclear Materials 455 (2014), 491-495.
[2] Krauss, W. et al.: Corrosion barriers processed by Al electroplating and their resistance against flowing Pb-15.7Li, Journal of Nuclear Materials 455 (2014), 522-526.