Development of W-coating with functionally graded W/EUROFER-layers for protection of First-Wall materials

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Introduction

To protect First-Wall materials, e.g. reduced activation ferritic martensitic steels, against the plasma of future fusion reactors tungsten (W)-coatings are a feasible option. The difference in coefficient of thermal expansion (CTE) between the W and the substrate can be compensated by functionally graded (FG)-layers in between. Such layer system, with stepwise graded FG-layers, were successfully produced by vacuum plasma spraying (VPS). The fabricated layer system have satisfactory interface toughness with the substrate at 550 °C. Thermo-mechanical tests show that the layer systems can withstand thermal shocks of 0.19 GW/m² and are resistant to thermal fatigue for at least 500 cycles between 350 and 550 °C. Despite these advantages VPS reduces, however, the hardness of the substrate during coating. [1-3]

Interface toughness

Motivation and Objective

The substrate hardness loss, caused by VPS, can be moderated by modified spraying parameters. Layer adhesion tests are performed to investigate the effect of the modified parameters on the interface toughness.

Layer system	Number of layers	Nominal coating thickness in µm	Modification	Substrate hardness loss
1	4	1200		High
2	6	2000		High
3	1	700	Increased spraying distance	None
4	1	700	Reduced plasma current	High
5	1	700	Increased movement speed of spraying system	Moderate

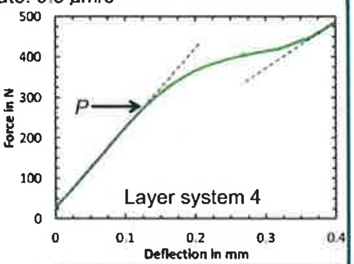
[2, 3]

Determination of interface toughness

- Four point bending testing technique [4, 5]
- Specimens with notch and pre-crack up to coating/substrate interface
- Testing temperature: 550 °C
- Controlled constant displacement rate: 0.5 µm/s

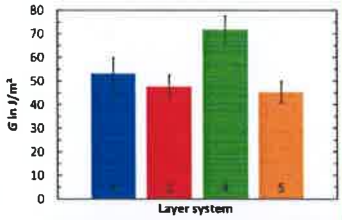
Force-deflection curves

- Plateau in curve
- Not visible for layer system 3 and reference EUROFER
- Decrease in secant stiffness due to layer delamination
- Layer delamination confirmed after testing



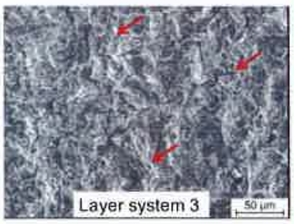
Calculating energy release rate G

- Force P at start of delamination
- Layer residual stresses estimated by FE-simulations
- Comparable G calculated



Layer adhesion

- Fracture surfaces imply ductile fracture, layer system 3 only partially near crack tip
- Except for layer system 3, modified spraying parameters produce coatings with comparable interface toughness



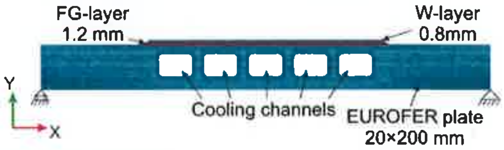
Outlook

- Determine compromise of layer adhesion and hardness loss

Simulation of Mock-up

Motivation and Objective

Based on the promising results at small scale the coatings are transferred to larger scale, with a Mock-Up as first upscaling step. Its behavior, after VPS and during operation, is estimated beforehand by finite element (FE)-simulations in form of a sequential thermal-stress analysis.

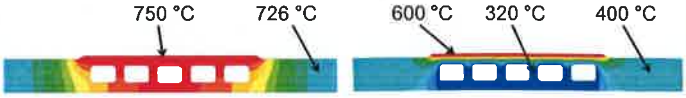


Parameter thermal analysis

- VPS: Layer system 750 °C
- Operation: W-surface 600 °C, cooling channels 320 °C

Parameter stress analysis

- End of VPS as initial stress free state
- Material behavior:
  - W: linear elastic, ideal plastic
  - EUROFER: linear elastic, non-linear viscoplastic, with isotropic hardening
  - FG-layer: W-EUROFER linear interpolation



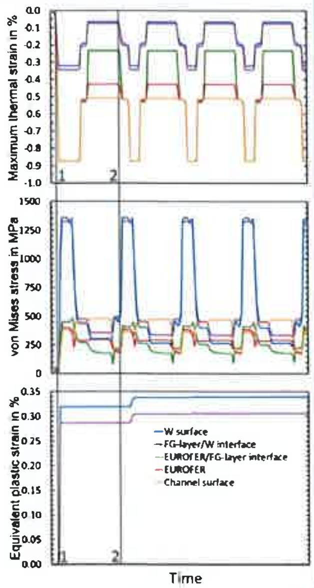
VPS temperature distribution — Operation temperature distribution

Simulated strains and stresses

- Difference in CTE causes residual stresses, deflection of the structure and plastic deformation
- Highest increase of plastic strain after VPS (Line 1)
- Additional plastic strain due to transformation of residual stresses (Line 2)

Influence of temperature loading

- Simultaneous heating without intermediate steps leads to sequential in-/decrease of thermal strains
- Sequential in-/decrease cause thermal induced stresses and inelastic deformation
- Intermediate steps necessary during heating and cooling



Outlook

- Implement layer adhesion in simulation and increase number of simulated operation cycles

References
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[5] P. Forschelen et al., Int J Solids Struct 97-98 (2016) 284–299

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