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

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ABSTRACT

To protect First-Wall components, made of reduced activation ferritic martensitic steel, against the plasma of future fusion reactors, tungsten coatings are a feasible option. The difference in coefficient of thermal expansion between the coating and the steel substrate can be compensated using functionally graded material layers. Such layers were successfully produced by vacuum plasma spraying. This technique reduces, however, the hardness of the substrate surface near zone. Modified spraying parameters moderate the hardness loss. The parameters may, though, affect also the layer bonding toughness which is evaluated in this work by four point bending tests. Furthermore, the layers behavior on First-Wall Mock-ups and under different thermal loads is investigated by finite element simulations.

The measurement of the layer adhesion indicates that the layer adhesion decreases only for modified spraying parameters that do not reduce the substrate hardness. It follows also from the toughness calculation that without layer residual stresses the toughness values depend on coating thickness. In regard to the Mock-up behavior the simulations show that intermediate steps are necessary during heating and cooling to prevent artificial stresses and inelastic deformation. It is, however, not possible to avoid stresses and inelastic deformation completely as they originate from the residual stresses.

1. Introduction

For the protection of First-Wall (FW) structures of future fusion power plants, tungsten (W) is a candidate material due to its favorable thermo-mechanical properties. The difference in the coefficient of thermal expansion (CTE) of the W-coating and steel substrate, made out of the reduced activation ferritic martensitic steel EUROFER, can be compensated by a functionally graded (FG)-layer in between [1]. Such layer systems were successfully created in previous experiments by vacuum plasma spraying (VPS) [2,3]. Tests on these layers showed that they can resist thermal shocks of at least 0.19 GW/m^2 and survive thermal fatigue between 350 and 550 °C for 500 cycles without any damage [3,4]. At 550 °C the layers exhibit satisfactory adhesion and indications of metallurgical bonding to the substrate [3]. Using the VPS-technique it was also possible to deposit FG-layers with a thickness of up to 1.2 mm with W-coatings up to 0.8 mm [3,4]. Such thicknesses are preferred for the later application, as finite element (FE)-simulations indicate that at above 1.2 mm FG-layer thickness especially the maximum creep strain per thermal cycle in the EUROFER substrate strongly decreases [1].

Despite these advantages, the plasma plume of the spraying process heats the substrate significantly up, causing a reduction of the substrate hardness. For instance, the EUROFER substrate hardness of layer system 1 and 2 (Table 1) was significantly reduced [3,4]. These were tests, whether coatings with a specific W/EUROFER gradient and total thickness of up to 2 mm can be produced. On the other hand, for layer system 3–5 the spraying parameters were modified to moderate the hardness reduction of the substrate by VPS. Especially layer system 3 showed no hardness reduction, whereas on layer system 4 and 5 significant and medium hardness loss was measured, respectively [3,4]. The moderated hardness loss implies, though, that there is less interaction of the VPS and the substrate and thus the bonding toughness may decrease. This is investigated in this work performing fracture mechanical four point bending test technique.

Besides the layer development, it is of interest to verify that layers of similar promising quality and properties can also be created on larger sample areas and to investigate how the coated structures will behave under conditions comparable to future fusion reactors. Therefore, it is intended to test these aspects on a First-Wall Mock-up made out of a EUROFER plate with cooling channels. To determine necessary testing

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Table 1
List of tested layer systems.

Layer system number	Ratio W/EUROFER in %	Nominal layer thickness in µm	Modification	Hardness loss
1	25/75	233		High
	50/50	233		
	75/25	233		
	100/0	500		
2	25/75	240		High
	37/63	240		
	50/50	240		
	63/37	240		
	75/25	240		
	100/0	800		
3	25/75	700	Increased spraying distance	None
4	25/75	700	Reduced plasma current	High
5	25/75	700	Increased movement speed of spraying system	Moderate

parameters and to estimate beforehand how the Mock-up will behave non-linear FE-simulations are performed. The simulations are conducted using the Finite Element Code ABAQUS [5] and in form of sequential thermal-stress analyses.

2. Analysis techniques

2.1. Four point bending

Charalambides et al. [6] presented a solution to determine the adhesion of coatings using the four point bending testing technique. A bimaterial beam, consisting of a purely elastic substrate with a comparable stiffer coating, is considered as specimen. Into the coating a central notch is manufactured up to the coating/substrate interface [6]. During bending cracks develop and propagate along the interface, leading to the delamination of the coating from the substrate. The delaminated layer contributes no longer to the stiffness of the beam and thus the strain energy drops at the instantaneous crack growth length. The difference of external applied work and the drop in strain energy equals the required energy for layer delamination [7]. In addition, layer adhesion is influenced by the local plastic deformation at the crack tip, the possible large scale plastic deformation of the substrate and the layer residual stresses [7]. These aspects have been evaluated lately by Forschelen et al. [7] by analytical and numerical analyses. Their results indicate that especially the layer residual stresses change the energy release rate value noticeably. Furthermore, previous analyses of the W/EUROFER layer system showed [1] that significant layer residual stresses are to be expected. Hence, the influence of the residual stresses on interface toughness is also taken into consideration in this work.

The steady-state energy release rate, G, during delamination and influenced by residual stress, σ_R, can be calculated as follows [7]

$$G = 6M^2\left(\frac{1}{\overline{E}_2 h_2^3} - \frac{(\overline{E}_1 h_1 + \overline{E}_2 h_2)}{\xi}\right) + \frac{\sigma_R^2 \overline{E}_2 h_1 h_2 (\overline{E}_1 h_1^3 + \overline{E}_2 h_2^3) + 12\sigma_R M \overline{E}_1 h_1 \overline{E}_2 h_2 (h_1 + h_2)}{2\overline{E}_1 \xi} \quad (1)$$

$M = \frac{Pl}{2b}$ is the bending moment for unity sample width for the force P at which delamination starts, the distance l between inner and outer loading lines and the sample width b. The plane-strain stiffness $\overline{E}_i = \frac{E_i}{(1-\nu_i^2)}$ is calculated out of the Young's modulus E and the Poisson ratio ν, with i = 1, 2 indicating the coating and the substrate, respectively. The parameter ξ represents

$$\xi = \overline{E}_1^2 h_1^4 + 4\overline{E}_1 h_1^3 \overline{E}_2 h_2 + 6\overline{E}_1 h_1^2 \overline{E}_2 h_2^2 + 4\overline{E}_1 h_1 \overline{E}_2 h_2^3 + \overline{E}_2^2 h_2^4 \quad (2)$$

with the respective material thickness h_i.

Four point bending specimens were produced from the layer systems listed in Table 1 with dimensions of $45 \times 3 \times 4$ mm^3 (Length × Width × Height) by electrical discharge machining. In case of specimens with thicker coatings the layer residual stresses caused about 10 µm deflection. The lateral sample faces were prepared using standard metallographic techniques with the last step being 1 µm polish. On some samples the coating surface roughness was reduced by grinding to improve further manufacturing. The coating thickness near the center was measured under a light optical microscope. V-notches were produced by electrical discharge machining into the layers, generally less deep than two thirds of the total coating thickness. Afterwards pre-cracks were created up to the substrate/coating interface using a resonating fatigue machine. Finally, the samples dimensions, the length of the pre-crack and the layer thicknesses were determined before the experiments using a digital caliper and measuring under the light optical microscope, respectively. The caliper has an accuracy of 10 µm and the length of the pre-crack and the layer thicknesses were determined with an accuracy of 1 µm. The values were averaged from at least 4 measurements and in regard to the thickness of the several coating layers even 12. The layer thicknesses were particularly used to determine the plane-strain stiffness of the coating. For each W/EUROFER composition of the coating the Young's moduli and Poisson ratios were respectively interpolated using the values in Table 2. The values for the whole coating were then calculated as weighted average from the individual layer values and their corresponding thicknesses.

The four point bending tests were performed using a testing machine equipped with a 20 kN load cell and a vacuum chamber. The

Table 2
Implemented elastic [8] and plastic [9] material properties for EUROFER and W.

Temperature in °C	EUROFER					Tungsten		
	Young's modulus in MPa	Yield strength in MPa	Ultimate tensile strength in MPa	Failure strain	Coefficient of thermal expansion in K^{-1}	Young's modulus in MPa	Yield strength in MPa	Coefficient of thermal expansion in K^{-1}
20	217,260	545.57	794.61	0.1677	1.20E-05	397,938	1360.46	4.40E-06
200	207,327	483.62	620.71			397,270	1154.17	
300				0.1309				
400	197,123	446.99	576.74	0.1362		394,480	947.86	
500				0.1775				
600	177,589	298.32	509.05	0.2659		389,508	764.79	
700	161,024	134.79	380.32	0.2963		386,210	681.67	
900	55,800	50	220.67			377,970	531.74	
950	43,880	36.7				375,580	497.57	
1000	33,800	29				373,050	464.69	
1050	30,000	23				370,370	433.09	

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