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Numerical assessment of functionally graded tungsten/EUROFER coating system for first wall applications

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HIGHLIGHTS

- Tungsten coatings with W/EUROFER functional graded (FG) interlayers on EUROFER substrates are investigated by means of finite element (FE) simulations as first wall (FW) application.
- The FE simulations consider elasto-perfectly plastic and elasto-viscoplastic material models and the fabrication phase and operation phase.
- The effects of FG-interlayers thicknesses on mitigating the residual stress and inelastic strain are studied.
- Allowable number of cycles is calculated based on creep damage accumulation.

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ABSTRACT

Reduced activation ferritic/martensitic (RAFM) steels, e.g. EUROFER, are to be used as structural material for the first wall (FW) of future fusion power plants. The interaction between the plasma and the FW, especially physical sputtering, will limit the FW lifetime under normal operation. Therefore, a tungsten coating should be selected to protect the FW due to its low sputtering yield, low activation, high melting point and high thermal conductivity. However, the mismatch of thermo-physical properties between W and EUROFER induces large residual thermal stresses and even failure of components. Functionally graded material (FGM) is considered as an appropriate solution to mitigate the high residual stresses.

In this work, W coatings on EUROFER substrates with W/EUROFER FG-layer (the coating system) are investigated by means of finite element (FE) simulations considering elasto-perfectly plastic and elasto-viscoplastic material models. For determining optimal parameters of the coating system the vacuum plasma spraying (VPS) fabrication process and the operation phase of the fusion reactor are simulated. Based on the FE results creep assessment of the coating system is performed demonstrating the gain in lifetime to be expected when using a FG-layer and investigating its dependence on the thickness of the FG-layer.

1. Introduction

Reduced activation ferritic/martensitic (RAFM) steels are selected as structural materials for the first wall (FW) of a demonstration fusion plant (DEMO) and future fusion power plants due to their good resistance to swelling and embrittlement. Because the interaction between the plasma and the FW will limit the lifetime of this component under normal operation phase, due primarily to physical sputtering, a tungsten coating is chosen to protect the FW because of its low sputtering yield, low activation, high melting point and high thermal conductivity.

However, due to the large mismatch of thermo-physical properties a direct bonding of W to EUROFER induces high residual stresses leading to the failure of components. In addition, very brittle Laves phases can be formed at the interface [1]. Commercial brazing alloys or alloys developed in the context of research programs on plasma facing components [2] contain elements such as Ni, Pd or Co which are undesired due to activation under neutron flux. The application of functionally graded material (FGM) is considered to be a good solution. Weber and Aktaa [3] have investigated and compared several methods to fabricate W/EUROFER FGM, for example, vacuum plasma spraying (VPS), magnetron sputtering (MS), and resistance sintering under ultra-high pressure (RSUHP). Among these methods, VPS is proved to be a promising method to fabricate functionally graded layers due to the ability to achieve a full range of graded chemical composition for both materials, as

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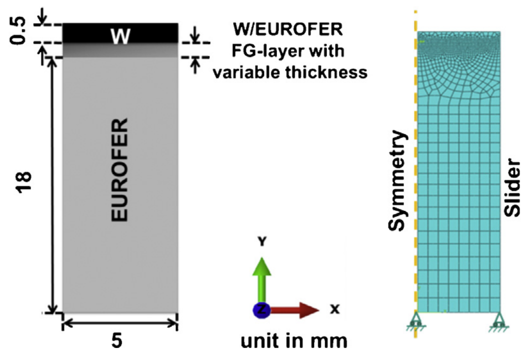

Fig. 1. The sketch and mesh of the FE model.

well as the prevention of oxide formation [4]. Greuner et al. [5] have used W/steel composite as an interlayer to reduce the residual stresses caused by the mismatch between tungsten and steel. The so produced coatings could survive long pulse and cyclic heat load tests up to 2.5 MW/m^2 without any damages. Gareth [6] has studied W/Diamalloy graded coatings with linear and non-linear variations of W fraction and laminar microstructure in his Ph.D. thesis. However, thermo-mechanical properties of the coatings are not investigated.

For FW applications erosion protective W coatings on EUROFER substrates with W/EUROFER FG-layer are investigated performing finite element (FE) simulations in this work. Considering elasto-perfectly plastic and elasto-viscoplastic behavior of the materials, the FE simulation results are evaluated to determine the thickness of the FG-layer and to assess both creep damage and allowable cyclic lifetime during the operating phase.

2. Finite element simulations

The simulations are performed using the finite element code ABAQUS. Thereby, the residual stresses induced in the whole component during the fabrication phase and subsequent operation phase are calculated for determining thicknesses of the W/EUROFER FG-layer.

2.1. Model and boundary conditions

The 2D sketch and mesh of the FE model are shown in Fig. 1. The upper and lower sections consist of a W coating and EUROFER substrate with the thickness of 0.5 mm and 18 mm, respectively. W/EUROFER FG-layer between them has variable thicknesses. Considering the very small thickness and large variability in length and width of the coating system generalized plane strain elements are used. The FG-layer is varied in thickness from 0.1 mm to 4 mm. A field variable *f* ranging from 0 to 1 is used to indicate the gradation level. It has the value 0 for the W side and 1 for the EUROFER side. For *f* values between 0 and 1 the material properties of the FG-layer are interpolated linearly. It was necessary to use adequate meshes for each thickness since the thicknesses of FG-layer range over two orders of magnitude. A mesh with a varying element size is used as shown in Fig. 1, and it is designed in such a way that the highest strain and stress as well as their gradients always lie inside its densest element region, which consists of rectangular elements with a size of 50 μm × 50 μm stapled in *y*-direction. This minimum element size is kept constant along all models to obtain comparable results.

The *x*- and *z*-axis are perpendicular to the symmetry axis ($x = z = 0$), which coincides with the *y*-axis. The two bottom corner nodes are fixed in the *y*-direction so that the model cannot drift away. Slider as a multi-points-constraint of user subroutine is applied on the model as one boundary condition which can simulate one part in the middle of a large plate since the edge effect is well known and is not considered here.

The model is loaded by a homogeneous temperature field that varies over time simulating a cooling down after the hot manufacturing process, where the initial temperature of the whole FE model was set to 750 °C, at which the FE model is considered to be stress free. Thereafter the FE model is loaded by varying the temperature homogeneously over time starting with a linear cooling down to 20 °C within 100 s. After this phase the temperature alternates between 20 °C and 600 °C with a dwell time of 24 h at 600 °C, which corresponds to an operation cycle of the fusion reactor. In reality, there is a temperature gradient instead of a homogenous temperature field during the operation phase. However, the temperature gradient between the surface and the cooling channel is small since only a few millimeters are foreseen in the most designs. In addition, the temperature gradient varies from design to design and thus being not considered in this work. As creep, particularly of EUROFER, becomes significant at least during the long dwell time period at 600 °C, simulation of the operation cycles has been conducted performing non-linear elasto-viscoplastic analyses. The ramping of the temperatures during the operation cycle occurs linearly.

2.2. Material behavior and properties

In the simulations of the first cooling down phase, all the materials are considered to behave isotropic, linear elastic and perfectly plastic. The coefficient of thermal expansion (CTE), Young's modulus and yield strength are assumed to be temperature dependent. Table 1 lists all basic material properties required and used in the simulations [3]. In addition, the properties of the FG-layer are interpolated by the properties of W and EUROFER.

For the simulations of the operation phase Norton power law of creep is taken into account, and the following formula was used, being a likely assumption based on a multiplication of the gradation factor *f* with each material input parameter:

$$\dot{\varepsilon}_{cr} = f \cdot C \cdot \sigma^{f \cdot n} \tag{2.1}$$

Table 1
The basic properties of the materials used in the simulation.

Temp. °C	EUROFER			W		
	E-module MPa	Yield stress MPa	CTE k^{-1}	E-module MPa	Yield stress MPa	CTE k^{-1}
20	217,260	545.57	12×10^{-6}	397,938	1360.46	4.4×10^{-6}
200	207,327	483.62		397,270	1154.17	
400	197,123	446.99		394,480	947.86	
600	177,589	298.32		389,508	764.79	
700	161,024	134.79		386,210	681.67	
900	55,800	50.00		377,970	531.74	