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Aiming at understanding thermo-mechanical loads in the first wall of DEMO: Stress–strain evolution in a Eurofer-tungsten test component featuring a functionally graded interlayer

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ABSTRACT

For the future fusion demonstration power plant, DEMO, several blanket designs are currently under consideration. Despite geometric and operational differences, all designs suggest a first wall (FW), in which tungsten (W) armour is joined to a structure made of Reduced Activation Ferritic Martensitic (RAFM) steel. In thermo-mechanical analyses of breeding blankets, this joint has received limited attention. In order to provide a basis for better understanding of thermally induced stresses and strains in the FW, the thermo-mechanical behaviour of a water-cooled test component is explored in the current contribution. The model aims at providing a simple geometry that allows straightforward comparison of numerical and experimental results, while trying to keep boundary conditions as realistic as possible. A test component with direct RAFM steel-W joint, and a test component with a stress-redistributing, functionally graded RAFM steel/W interlayer in the joint is considered in the current contribution. The analyses take production- and operation-related loads into account. Following a detailed analysis of the evolution of stress components and strain in the model, a parameter study with respect to geometric specifications and loads is presented.

The analyses show that, even in a small test component, a direct RAFM steel-W joint causes enormous plastic deformation. The implementation of a functionally graded interlayer reduces stresses and strains significantly, but vertical normal stresses at the joint's circumference remain considerable. With the component geometry considered here, the graded interlayer should be at least 1 mm thick and contain 4 sublayers to appropriately redistribute stresses. Beyond a component width of 14 mm, stresses increase strongly, which may pose a risk to the applicability of large-scale FW components, too.

1. Introduction

The first wall (FW) of future fusion reactors like DEMO will likely be realized of mixed-material components. While tungsten (W) is a promising plasma facing material due to its thermal and physical properties [1], a high neutron capture cross section and long cooling down time, required before maintenance, limits its thickness to a few millimetres [2]. Suitable FW structural materials, that the W armour is attached to, are summarised as the group of Reduced Activation Ferritic Martensitic (RAFM) steels, among them Eurofer and F82H [3]. Due to the discrete transition of material properties accompanying a macroscopically direct RAFM steel-W joint, localised loads at the interface are generated in production and operation. In particular, these loads are thermally induced macroscopic stresses and strains arising from different coefficients of thermal expansion, α. Thermally induced stresses and strains may either spontaneously or in the long term yield premature failure of the FW component requiring feasible ways to reduce the loads [4,5]. For W and Eurofer (representing the class of RAFM steels here), α is given in Tables 1 and 2 along with other temperature dependent materials properties used in this work.

Several approaches to create resilient RAFM steel-W joints are currently being investigated. Implementing a vanadium foil ($\alpha_V \approx 8.4 \times 10^{-6}\,\mathrm{K}^{-1}$) in the joint could reduce the mismatch of thermal expansion between RAFM steel and W, and make the production technique (uniaxial hot pressing) possible at fairly low temperatures (700 °C) [6–10]. However, this results in formation of the brittle σ phase FeV during subsequent ageing [10]. An additional Ti foil ($\alpha_{Ti} \approx 8.6 \times 10^{-6}\,\mathrm{K}^{-1}$) in between the RAFM steel part and the V foil delivers favourable properties at the V side and is an effective diffusion barrier preventing the formation of FeV [10–12]. Yet, in this layered

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Table 1
Tungsten properties used for the FE simulation [44,45].

Temperature °C	Young's modulus GPa	Poisson number –	Yield stress MPa	Coeff. of thermal expansion $10^{-6}\,\mathrm{K}^{-1}$	Th. cond. $\mathrm{W\,(m\,K)^{-1}}$	Heat capacity $\mathrm{J\,(kg\,K)^{-1}}$	Density $\mathrm{g\,cm^{-3}}$
20	397.9	0.3	1360.46	4.4	161.53	131.45	19.3
200	397.3	0.3	1154.17	4.4	149.34	135.2	19.3
400	394.5	0.3	947.47	4.4	137.79	139.36	19.3
600	389.5	0.3	746.79	4.4	128.14	143.29	19.3
700	386.2	0.3	681.67	4.4	123.96	145.28	19.3
900	378.0	0.3	531.74	4.4	116.76	149.39	19.3
950	375.6	0.3	497.57	4.4			19.3
1000	373.1	0.3	464.69	4.4	113.7	151.56	19.3
1050	370.4	0.3	433.09	4.4	109.2	152.6	19.3

Table 2
Eurofer properties, representing the class of RAFM steels, used for the FE simulation [44,45].

Temperature °C	Young's modulus GPa	Poisson number –	Yield stress MPa	Coeff. of thermal expansion $10^{-6}\,\mathrm{K}^{-1}$	Th. cond. $\mathrm{W\,(m\,K)^{-1}}$	Heat capacity $\mathrm{J\,(kg\,K)^{-1}}$	Density $\mathrm{g\,cm^{-3}}$
20	217.3	0.3	545.67	12.0	28	472	7.8
200	207.3	0.3	483.62	12.0	30	522	7.8
400	197.1	0.3	446.99	12.0	29	541	7.8
600	177.6	0.3	298.32	12.0	29.7	546	7.8
700	161.0	0.3	134.79	12.0	29.7	549	7.8
900	55.8	0.3	50	12.0	29.7	552	7.8
950	43.9	0.3	36.7	12.0	29.7		7,8
1000	33.8	0.3	29.0	12.0	29.7	553	7.8
1050	30.0	0.3	23.0	12.0	29.7		7.8

system, other brittle intermetallic precipitates like $\mathrm{Fe_2Ti}$- and FeTi establish during uniaxial hot pressing [11,12] and hot isostatic pressing [13–15]. Weakening intermetallic precipitates were also observed for other approaches, e.g. replacing the Ti foil by Ni [16] or using only a Ni interlayer [17]. Cu based interlayers ($\alpha_{\mathrm{Cu}} \approx 16.5 \times 10^{-6}\,\mathrm{K}^{-1}$), e.g. realized by Cai et al. and Pintsuk et al. [18,19], show good bonding to steel and W, but may be unsuitable for high FW heat loads due to low solidus temperatures and high plastic strains, causing failure upon cyclic loading. Brazing of fusion relevant components is generally problematic as most investigated brazes based on Cu, Ag, or Ni develop long-living radionuclides under fusion relevant neutron loads. Work done by Chehtov, Kalin and Ma [20–23] in addition reveals weak features like partial recrystallization of the steel, intermetallic precipitates or pores along the joints.

Summarising the aforementioned aspects, none of the named interlayer systems is technologically reliable yet to join RAFM steel and W, and effectively reduce stresses and strains within a FW component. Functionally graded RAFM steel/W materials (in the following: FGMs) are another promising interlayer option. The class of materials exhibits a compositional grading across the material's height. Given this, RAFM steel/W FGMs are able to gradually approximate homogenized materials properties, such as the coefficient of thermal expansion, across the FGM layer's height and, thus, smoothly re-distribute macroscopic stresses. The combination of W and Fe base materials may be accompanied by the formation of brittle intermetallic phases, $\mathrm{Fe_7W_6}$ and $\mathrm{Fe_2W}$ [4,24], similar as to the above named interlayer developments. Yet, to date these phases do not seem to harm the joint more than precipitates observed in the other interlayer developments while favourably simplifying the material mix within the FW component. The latter may in particular be interesting for recycling of activated and transmuted FW components. Moreover, FGMs may re-distribute and level macrostresses more smoothly compared to homogeneous interlayers. Localised microstress peaks may still be present, particularly in powder metallurgically produced FGMs, containing both pure RAFM steel and W volumes. However, microstresses abate within very short distances, e.g. the mentioned pure volumes, instead of superposing along the macroscopically flat interface of a direct RAFM steel-W joint like macrostresses do.

Several studies on the processing and the impact of FGMs for Cu-W and RAFM steel-W joints of different divertor designs, e.g. the thin-walled finger module design, were already carried out with experimental [7,19,25–32] and numerical [33–35] approaches. In contrast, FGMs particularly used for larger-area RAFM steel-W joints of the FW have received less consideration, only by Qu [36–38] and Emmerich [39]. Qu introduced a 2D model (plane strain) of a rectangular piece of the FW with variable FGM thickness. The model takes elasto-plastic and elasto-viscoplastic material properties into account, but neglects cooling and assumes a homogeneous temperature field [36]. Emmerich further developed the aforementioned model towards a more realistic geometry of the FW. While a greater plate with several cooling pipes allows the consideration of an inhomogeneous temperature field across the FW, the model does not include an FGM thickness variation [39]. Both models take fabrication-related loads into account, but they apply fixed temperatures as boundary conditions (decoupled from operational heat loads) and focus on von Mises stresses and plastic deformations of the W-FGM-Eurofer joint in a central region of the FW (away from edges) over the FW lifetime.

The present contribution tries to support the understanding of DEMO FW loads by filling a gap between the two described models. For that, a test component, similar to a divertor monoblock, which is in between the complexities of the named models, is considered. This design allows straightforward comparison of the numerical results to experimental data of a simple test component, meaningful variation of geometric boundary conditions (FGM thickness, number of FGM sublayers, component size) and dedicated consideration of the edge effect of the W-FGM-Eurofer joint. With respect to the latter, the selected geometry is analysed with and without FGM, and the discussion of the von Mises stress evolution over the lifetime is supported by normal and shear stresses. Temperatures are related to different heat fluxes and to water cooling capabilities.

Modelling in the present work is carried out in three steps. First, suitable FGM properties models are selected, secondly, relevant stress components and the equivalent plastic strain of the first load cycles within the test component are analysed in detail. Lastly, parameter