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Modeling of thermal stresses in a graded Cu/W joint

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Abstract

Thermally induced stresses and strains in a CuCrZr alloy–W joint are analyzed using finite element methods. The effect on stress and strain of using different materials as interlayers to join CuCrZr to W is examined and compared to geometries without an interlayer (sharp interface). Oxygen free high conductivity copper (OFHC) and several types of graded structures formed with OFHC and W are used as the different interlayer materials. Temperature dependence of the properties in addition to plasticity and strain hardening are considered in the finite element formulation. The use of an OFHC Cu interlayer results in the maximum reduction of stress compared to the sharp interface, but also in large highly localized plastic strains that increase under operation conditions. The residual stress is slightly higher for OFHC/W graded interlayers, but still significantly lower than for the sharp interface. However, a notable difference for the graded interlayers is that the plastic strain is greatly reduced compared with the OFHC interlayer.

1. Introduction

Cu/W joints are of interest for potential use in divertor assemblies in thermonuclear reactors. W or W-rich composites provide protection from the reactor plasma while Cu or Cu-rich composites serve to transport heat rapidly. Furthermore, Cu and W do not react and are virtually insoluble in one another, providing a chemically stable configuration. The difficulty in joining W to Cu arises from high thermal residual stresses that originate from the difference in thermal expansion coefficient. In addition to thermal residual stresses imposed during joining, the joint experiences thermally induced stresses during divertor operation at elevated temperature ('operation stresses'). The effect of these stresses may become pronounced at stress singularities that typically arise at the interface near the region where the interface reaches the free edge. Delamination and other forms of failure in joints may originate at these sites of stress singularity. Thus, understanding the development of stresses for different interlayer configurations may lead to minimizing failure.

The use of interlayers has been shown to be an effective method to join dissimilar materials [1]. Interlayer materials are typically ductile in order to accommodate the otherwise high thermal residual stresses, and it is usually preferable that the thermal expansion behavior of an interlayer material is intermediate between the materials being joined. If the interlayer is compositionally graded, the stress state and stress singularities would be expected to be different from those for a homogeneous interlayer. The effect of grading the interlayer is examined in this paper.

Previous finite element modeling (FEM) studies of Cu/W joints with an interlayer of oxygen free high conductivity copper (OFHC) showed that reduction in stresses is achieved compared with joints without an interlayer [2,3]. Unfortunately, the reduction in stress may be accompanied by significant plastic strain in the OFHC which may further be amplified during operation conditions in which the joint is cycled between various

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temperatures. Specifically, thermal fatigue may be of concern. It should be possible to optimize the stress and plastic strain distribution in the entire joint by incorporating a compositionally graded interlayer. Graded interlayers have been utilized in a variety of metal/ceramic and glass/metal joints [1]. The present study uses FEM to examine the stress and strain within Cu–W joints that utilize different interlayer architectures.

2. Geometry and loads

The geometry analyzed is a divertor scale model shown in Fig. 1. The divertor is formed by three sections of different materials. At the top, the W armor faces the plasma and limits the radiation damage to the CuCrZr. Joined to the W armor, the CuCrZr heat sink removes heat by means of water flowing through the channel. The heat sink is seated in a 316 stainless steel back piece. Two load cases are analyzed. First the entire piece is cooled down from 550 to 25 °C and the residual stresses from these fabrication conditions are obtained. Next, the operation conditions are modeled, with a load of 5 MW/m^2 applied to the top of the W armor and water flowing through the channel in the CuCrZr at 160 °C, 3.8 MPa and 10 m/s. Stress and strain fields are obtained from the resulting temperature profile.

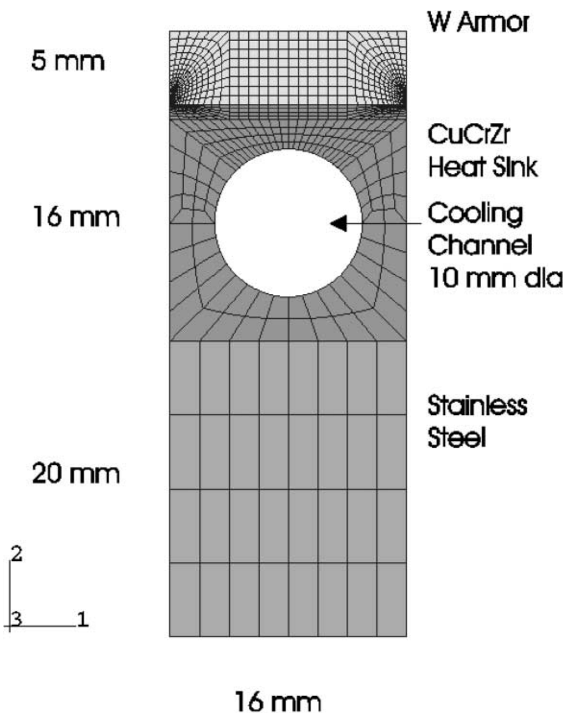

Fig. 1. Geometry of the divertor scale model analyzed.

3. Constitutive relations of graded composites

The different materials modeled to join the CuCrZr and W are listed in Table 1, and shown schematically in Fig. 2. A modified rule of mixtures (ROM) [4–7] was used to estimate the mechanical properties of the different interlayers in this study. In this rule of mixtures the composite is considered isotropic and the stress–strain relation is proportional to the volume fraction of the two constituents according to the following relations:

$$\sigma_c = \sigma_{Cu} V_{Cu} + \sigma_W V_W, \quad (1)$$

$$\varepsilon_c = \varepsilon_{Cu} V_{Cu} + \varepsilon_W V_W, \quad (2)$$

$$q = \frac{\sigma_W - \sigma_{Cu}}{\varepsilon_W - \varepsilon_{Cu}}, \quad (3)$$

where σ and ε are stress and strain, respectively, the subscripts indicate copper or tungsten, V is the volume fraction, and q is the stress–strain transfer coefficient. A more detailed description of this ROM is presented by Suresh [7]. The thermal expansion coefficient (CTE) is estimated also as a function of the volume fraction of the constituents by the Turner equation [8,9]:

$$\alpha_c = \frac{\alpha_{Cu} V_{Cu} K_{Cu} + \alpha_W V_W K_W}{V_{Cu} K_{Cu} + V_W K_W}, \quad (4)$$

where α is the thermal expansion coefficient, K is a weight factor and the subscripts indicate copper or tungsten. The other properties required by the model are approached by a linear rule of mixtures.

The plastic strain is reported in terms of the effective or equivalent plastic strain (PEEQ variable for ABAQUS), where the corresponding stress is the equivalent Mises stress. These are invariants corresponding to the axial normal component stress and strain in a tension test [10]. In terms of the principal directions these are defined as

$$\sigma_{eq} = \frac{\sqrt{2}}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}, \quad (5)$$

Table 1
Different materials and gradient architectures used to model the interlayer joining the Cu and W

Material	Layers	Total thickness (mm)
OFHC	1	1
FGM linear $p = 1$	2	1
	4	1
FGM W-rich $p = 1.5$	4	1
FGM Cu-rich $p = 0.75$	4	1
	4	2
	4	4

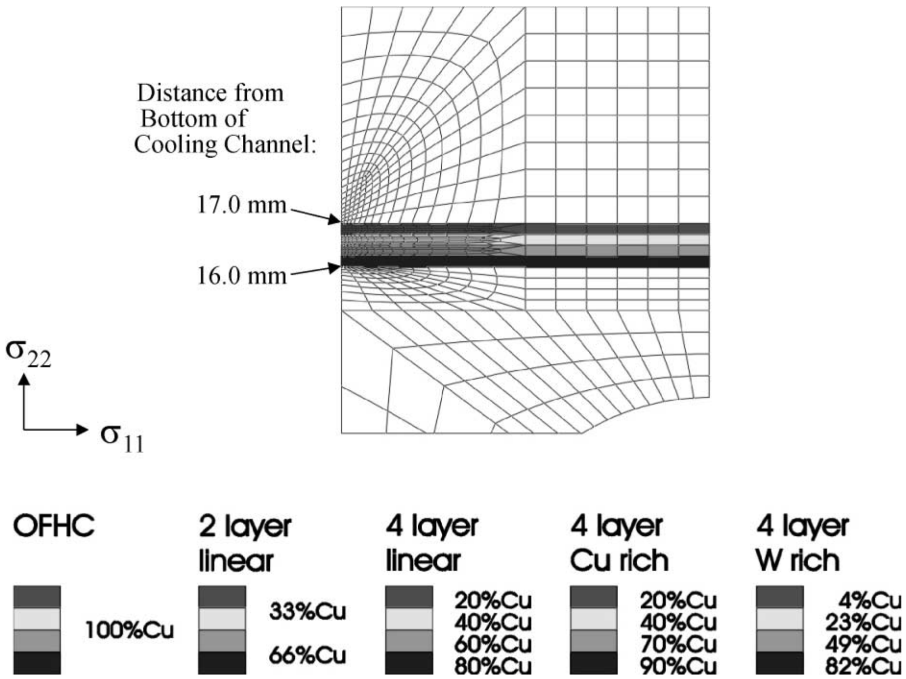

Fig. 2. Different interlayer architectures modeled. Dimensions shown correspond to 1 mm interlayer thickness.

$$\mathrm{PEEQ} = \varepsilon_{\mathrm{eq}}^{\mathrm{pl}} = \frac{\sqrt{2}}{2}\Big[(\varepsilon_1^{\mathrm{pl}} - \varepsilon_2^{\mathrm{pl}})^2 + (\varepsilon_2^{\mathrm{pl}} - \varepsilon_3^{\mathrm{pl}})^2 + (\varepsilon_3^{\mathrm{pl}} - \varepsilon_1^{\mathrm{pl}})^2\Big]^{1/2}, \tag{6}$$

where the subscripts 1, 2 and 3 stand for the principal directions, and the superscript pl indicates plastic strain.

In order to describe the volume fraction gradient along the FGM the following power law equation is applied [11]:

$$V_{\mathrm{Cu}} = \left(\frac{x}{t}\right)^p, \tag{7}$$

where x is the distance from the W interface to the position on the FGM, t is the total thickness of the graded region and p is an arbitrary exponent. The term 'tungsten rich' and 'copper rich' are used for p values greater than 1 and smaller than 1 respectively whereas a value of 1 is used for a linear gradient.

4. FEM formulation

The ABAQUS finite element code is used for the present model [12]. Eight node quadratic diffusive heat transfer elements are used for the heat transfer analysis. Ten node biquadratic generalized plane strain elements are used for the stress analysis. The mesh is refined around the singular corner. Elements of 0.05 mm in size are used in the different models. In the sharp W–CuCrZr interface model, elements of 0.025 mm in size were also used to verify convergence. Only half of the piece is modeled due to symmetry. Boundary conditions constraining the horizontal displacement of the nodes along the vertical centerline of the piece were applied. The vertical displacement is constrained in the first node at the bottom of the centerline. Five different meshes were created to model the sharp and graded Cu/W joints. The graded interlayer thicknesses modeled were 1, 2 and 4 mm. Each interlayer was divided into four different layers and the material property definitions were selectively varied.

5. Results and discussion

5.1. Temperature distribution

Applying the heat load at the top of the W armor and removing heat at the cooling channel results in a vertical gradient in temperature on the divertor. The temperature gradient for the sharp interface is shown in Fig. 3. The maximum temperature occurs on the W surface exposed to the plasma and decreases towards the channel. The maximum temperature on the W surface is 434 °C for the sharp interface geometry. The maximum temperature on the W surface increases to 448 °C when the 1 mm OFHC Cu interlayer is used. The different 1 mm graded interlayer geometries analyzed show an

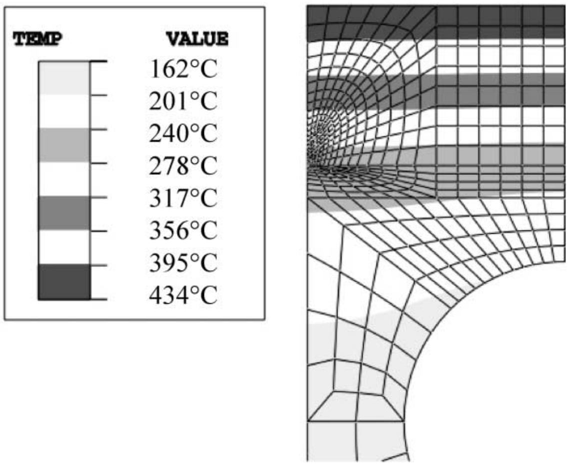

Fig. 3. Distribution of temperature in °C on divertor scale model under operation conditions.

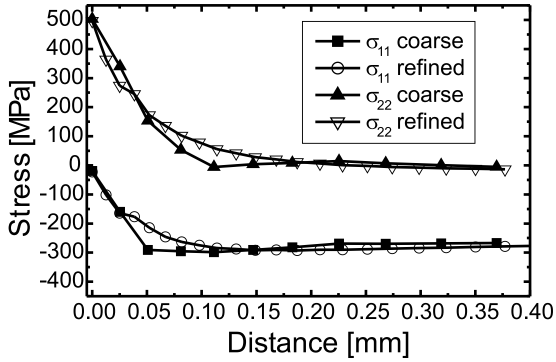

Fig. 4. Comparison of residual stresses on the W armor along the joint as a function of distance from the surface for the sharp interface meshes refined to 0.05 and 0.025 mm. The stress was obtained along the edge of the divertor component.

average maximum temperature of 459 °C. Increasing the thickness of the graded interlayer to 2 and 4 mm raises the average maximum temperature to 484 and to 548 °C respectively.

5.2. Stress and strain distributions

A comparison of residual stresses on the W armor along the joint (i.e., as a function of distance from the free surface) for the sharp interface meshes refined to 0.05 and 0.025 mm is shown in Fig. 4. σ_{ij} indicates a stress acting in plane *i*, with direction*j*. Subscripts 1, 2 and 3 refer to the directions in the orthogonal coordinate system in which the model is based (see Fig. 1). The maximum difference in stress between the coarse and fine mesh is 76 MPa for σ_{11} and 66 MPa for σ_{22}. However, at the edge, the corresponding differences are very small ($\sim$ 1%). Based on the small differences at the edge, a 0.05 mm element size was used around the singular corner for the different architectures analyzed.

The residual stress, σ_{22}, in the singular corner area is larger than any other stress component value at other points of the divertor scale model, with values up to 542 MPa for the sharp CuCrZr–W interface. The minimization of σ_{22} in the singular corner is used as a first criterion to select the optimum interlayer architecture. The second criterion used to select the optimum interlayer is the minimization of the magnitude and distribution of the effective plastic strain (PEEQ) in the interlayer. Table 2 shows a comparison of the peak stresses, σ_{22}, and PEEQ for the different interlayer architectures modeled. In the following, the peak stresses along the edge of the joint are compared.

The maximum reduction in peak stress is obtained using the OFHC layer with a 33% reduction compared to the sharp interface. A comparison of σ_{22} for the sharp interface and for various 1 mm interlayer architectures is plotted in Fig. 5. Residual stress and operation stress distributions are shown in Fig. 5(a) and (b) respectively. The stresses in the interlayers tend to be tensile under residual stress conditions and compressive under operation conditions. Clearly, the optimum stress distribution for the residual stresses in all the interlayers exists for the 1 mm OFHC layer; however, the OFHC interlayer also exhibits the largest operation stresses (approximately −350 MPa). The 1 mm Cu rich graded interlayer shows a 28% reduction of the peak stress; furthermore, the stress is more uniformly distributed throughout the graded interlayer for both residual and operation conditions as compared with the sharper

Table 2
σ_{22} and PEEQ comparison for the different interlayers

Thickness		1 mm					2 mm	4 mm
Architecture variable	Sharp interface	OFHC	FGM linear 2 layers	FGM linear 4 layers	FGM Cu-rich	FGM W-rich	FGM Cu-rich	FGM Cu-rich
σ_{22} (MPa)	542	365	473	422	390	509	372	372
% PEEQ		18.8	4.3	7.6	10.4	8.0	7.9	5.6
% σ_{22} reduction		33	13	22	28	6	31	31

Percent reduction is in comparison to the sharp interface.

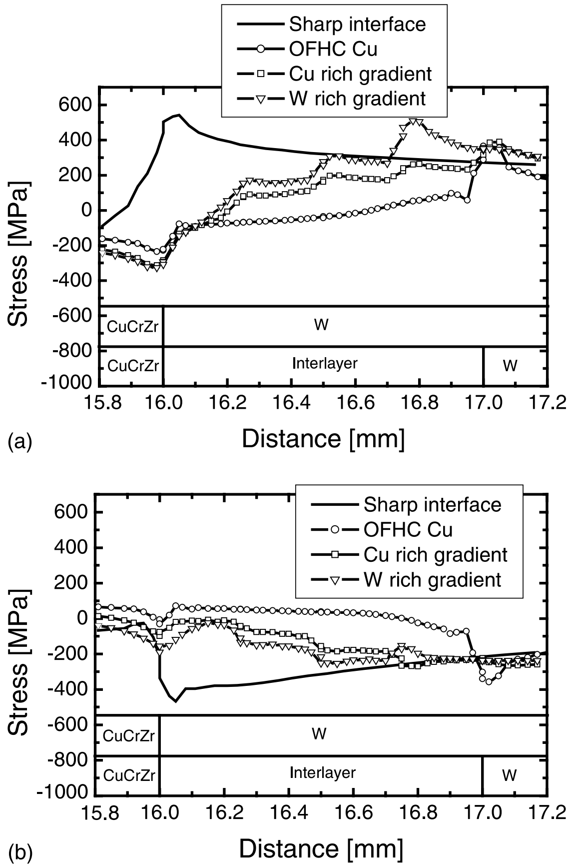

Fig. 5. σ_{22} comparison for sharp interface and various 1 mm interlayer architectures for (a) the residual conditions and (b) the operation conditions. The stress was obtained along the edge of the divertor component.

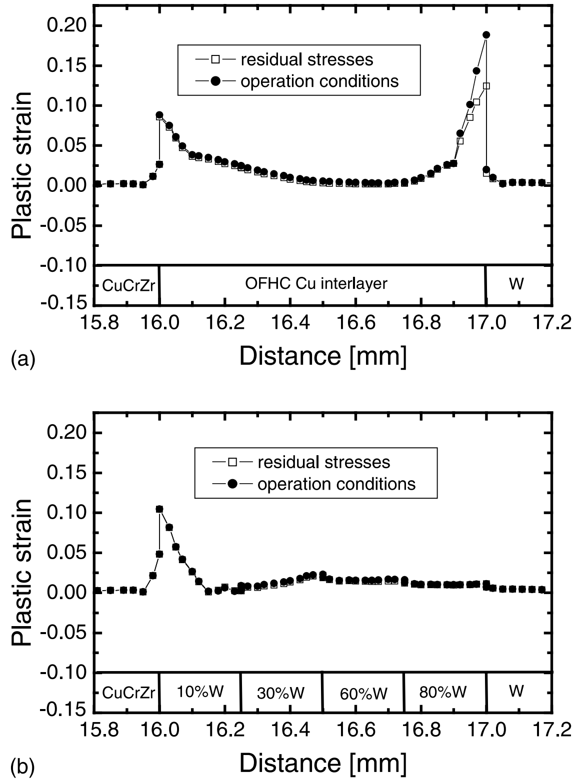

Fig. 6. Equivalent plastic strain (PEEQ) comparison using the OFHC Cu and the Cu rich graded 1 mm thick interlayers for (a) the residual conditions and (b) the operation conditions.

stress gradient in the OFHC interlayer (Fig. 5(a) and (b)). The thermal expansion coefficient mismatch between the OFHC layer and the W is larger than for the graded interlayers, but the lower yield stress allows significant stress relaxation. However, the stress relaxation comes at the expense of plastic strain.

Fig. 6(a) and (b) shows the plastic strain in the OFHC interlayer and the 1mm Cu rich graded interlayer, respectively. The residual stress and operation conditions are shown in each figure. Most of the strain was localized to regions directly adjacent to W and the CuCrZr backing. The largest plastic strain exists in the 1 mm OFHC interlayer, adjacent to W; the strain increases under operation conditions. The large plastic strains suggest that the OFHC interlayer geometry may be susceptible to thermal fatigue. In contrast to the increase in plastic deformation observed in the OFHC interlayer, the 1 mm Cu rich graded interlayer does not show an appreciable change in the amount of plastic strain after modeling the operation conditions (Fig. 6(b)). The plastic strain of the other graded structures analyzed in this study also did not show any increase after modeling the operation conditions.

As shown in Table 2, the Cu rich 1 mm graded architecture resulted in 28% peak stress reduction, accompanied by a plastic strain of 10.4%, significantly lower than that for the 1 mm OFHC Cu layer with the advantage that no further plastic strain occurs during operation. Increasing the thickness of the Cu rich graded interlayer to 2 mm results in further reduction of σ_{22} and plastic strain. No change in stress is observed when the thickness is increased to 4 mm, but lower peak plastic strain is obtained. The changes in stress and strain with thickness suggest that there is an optimum thickness, above which the changes are no longer significant. It is further noted that the changes in stress with joint thickness are consistent with previous work showing that peak stress reduction in graded joints may be accomplished by increasing the joint thickness [11]. The reduction is accomplished because the stress is distributed more uniformly over a larger region of the joint.

6. Conclusions

The use of an OFHC interlayer to join CuCrZr and W results in the maximum reduction in σ_{22} stress when compared to the different FGM structures analyzed. However, the change in magnitude of the stresses after modeling the operation conditions is larger for the OFHC interlayer than for the graded interlayers. An increase in plastic strain on the OFHC layer is also observed when the divertor scale model is analyzed in operation conditions. Use of the 1 mm Cu rich graded interlayer reduces the peak stress to almost the same value to that achieved with OFHC, and the change in stresses between the residual and operation conditions is less severe. The graded interlayers do not show an increase in the plastic strain when the divertor scale model is analyzed in operation conditions, which suggests that OFHC/W graded interlayers are more resistant to thermal fatigue than OFHC. The spatial variation of properties within the graded interlayer effectively redistributes the stresses and strains in larger areas of the gradient, in contrast to the OFHC interlayer where the reduction of stresses is achieved at the expense of sharp stress and strain gradients. The smoother transition in properties decreases the strength of the stress singularities predicted in joints of dissimilar materials. Furthermore, it appears that there may be an optimum interlayer thickness the results in the lowest stress state. Graded interlayers of a specified optimum thickness may be preferred over OFHC Cu when joining W to CuCrZr.

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