Thermal-mechanical analysis on W/CuCrZr plasma facing component with functionally graded material interlayer

D H Zhu1,3, J L Chen1, Z J Zhou2 and R Yan1

1 Institute of plasma physics, Chinese academy of sciences, Hefei 230031, P. R. China
2 University of science and technology Beijing, Beijing 100083, P. R. China

E-mail: dhzhu@ipp.ac.cn

Abstract. Thermal-mechanical analysis is performed on W/CuCrZr plasma facing component with functionally graded material (FGM) interlayer under the steady-state heat load of 5 MW/m² using a finite element method (ANSYS code). The influences of the FGM interlayer on the stress, strain and temperature distribution in the whole component is evaluated and compared to the joint without an interlayer and with OFHC interlayer. It is shown that the inserting of W/CuCrZr FGM interlayer between W and CuCrZr effectively alleviates the thermal stress, whose reduction can reach up to 70% when the W/CuCrZr FGM interlayer thickness exceeds 6 mm. Meanwhile, the optimization of the structure and component distribution for W/CuCrZr FGM interlayer was also carried out. The thermal stress tends to saturate with the layer number exceeding 4. For 6 mm 4-layered FGM interlayer, the preferred component distribution exponent (p) is 1.8.

1. Introduction

Plasma facing component in fusion devices, especially for the divertor target, always faces the extreme conditions with the high heat load in the range 5 - 20 MW/m² [1, 2]. It consists of a plasma facing and a heat sink material, fulfilling the different functions that require different material properties. Tungsten (W) is a promising plasma facing material and is widely used in present tokamaks (EAST, JET, ASDEX, etc) attributed to its high melting point, low tritium retention, low sputtering yield and good thermo-mechanical properties [3 - 6]. Furthermore, W has been selected as the armor material in the activated phase of ITER and currently the most suitable candidate for the first wall in DEMO and future fusion reactors [7, 8]. Meanwhile, copper alloy, i.e. CuCrZr is proposed as the heat sink material because of the high thermal conductivity and other acceptable properties [9]. However, due to the large differences in the coefficient of thermal expansion (CTE) and elastic modulus, the joining of W and CuCrZr results in a high thermal stress concentration at the interface when a W/CuCrZr component is exposed to a quasi-stationary heat load. This stress concentration may lead to the failures in forms of cracking and detachment reducing the lifetime of the components.

In the past decades, a large amount effort has been performed to mitigate the thermal stress when joining of W on CuCrZr to form high heat load component. From the engineering point of view, the solution is to use brush-like or lamellar type of W armor design. The advantage of the brush structure

3 Corresponding author: Zhu Dahuan; Tel: +86-551-5593282; Fax: +86-551-5591310.
is that the single armor elements are free to expand under the heat load deposition, reducing the thermal stress [10]. On the other hand, the insert of an interlayer has also been demonstrated as an effective method to join W armor and CuCrZr heat sink. The interlayer materials are often typically ductile in order to accommodate the dissimilar properties, and it is also preferable that the CTE of an interlayer material is intermediate between W and CuCrZr. If the intermediate interlayer is graded, the stress mitigation would be better than that of a single homogenous interlayer. So W/CuCrZr functionally graded material (FGM) interlayer is the most suitable interlayer when joint W armor material on CuCrZr heat sink material [11].

In this paper, thermal-mechanical simulation was performed on a divertor scaled W/CuCrZr component with FGM interlayer using ANSYS code based on finite element method. The effect of the W/CuCrZr FGM interlayer on the temperature, stress and strain distribution in the entire component is examined and compared to the joint without an interlayer and with oxygen free high conductivity copper (OFHC) interlayer. The interlayer thickness is of special concern in our analysis. In addition, the optimization of the structure and component distribution of W/CuCrZr FGM interlayer was also carried out.

2. Model and materials
To perform the thermal and mechanical simulation a commercial finite element code (ANSYS 10.0) was used. The 2D axis-symmetry geometry analyzed is a divertor scaled model, i.e. a flat-type actively cooled W/CuCrZr mock-up with FGM interlayer as depicted in figure 1. The model contains three pieces of different materials. At the top, the W armor faces to the plasma, providing the protection from the plasma irradiation. At the bottom, the CuCrZr heat sink material with water cooling tube serves to transport heat rapidly, providing the actively cooling of the component. Between the W armor and CuCrZr heat sink, the W/CuCrZr FGM interlayer, i.e. graded layers, is used to join the dissimilar materials. The height of the bottom CuCrZr heat sink and the top W armor are 20 and 2 mm, respectively, while the thickness of the W/CuCrZr FGM interlayer changes from 0 to 6 mm to investigate the effect of interlayer thickness on the stress, strain and temperature distribution. The length of the W/CuCrZr FGM mock-up is 30 mm. The diameter and thickness of water cooling tube are 10 mm and 1 mm, respectively, and the distance between the bottom interface and center tube wall is 8 mm. In our simulation, the model element was described by plane 55 for thermal analysis and plane 42 for structure analysis. The analytical model was meshed for finite element model with mapped and free meshing for different pieces using the quadrilateral-shaped elements. Fine meshing through the thickness was performed to ensure the saturated results. The meshing size near the interfaces was refined to an ultra-fine size to 0.05 mm because this area was under very high stress concentration.

![Figure 1. Schematic of cross section view of flat-type actively cooled W/CuCrZr mock-up with FGM interlayer.](image-url)
The thermophysical and mechanical temperature-dependent properties of the W and CuCrZr for finite element analysis (FEA) are listed in Table 1, referencing from the similar work [12, 13]. The spatial composition of the CuCrZr varies discontinuously and step-wisely from the heat sink substrate to armor material and obeys an exponential function distribution as follows

\[
V_{\text{CuCrZr}} = \begin{cases} 
1 & (y \leq 20) \\
\left(\frac{y-20}{h}\right)^p & (20 \leq y \leq H-2) \\
0 & (y \geq H-2)
\end{cases}
\]  

where the \(V_{\text{CuCrZr}}\) is the volume fraction distribution of CuCrZr through \(y\) axis, the \(p\) is the component distribution exponent to characterize the volume distribution of CuCrZr in the W/CuCrZr FGM interlayer, \(h\) and \(H\) are the thickness of graded interlayer and the whole component, respectively. The Kerner rules are used to calculate the properties of W/CuCrZr mixed composite layers [14].

In the process of numerical simulation, a homogenous steady-state heat load of 5 MW/m² was deposited on the top of W armor surface, while a water velocity of 10 m/s, an average temperature of 50 °C and a water pressure of 1 MPa relevant to actual tokamak cooling condition were applied for active cooling [15]. To simplification, 1/2 part of the axisymmetric model is used, and the isotopic behavior of materials as well as perfect thermal contact at interface were assumed. During thermal stress simulation, the stress free temperature of 50 °C was used as the reference temperature. The center line, i.e. the symmetry axis was to be constrained at horizontal direction, while the origin point was pinned to be restricted at vertical direction in order to avoid the movement of the model. All other edges were free so that the expansion of the model was performed during the heat loading. The maximum von Mises stress was used as the first criterion to evaluate the effect of the W/CuCrZr FGM interlayer to joint W on CuCrZr as compared to the joint with OFHC interlayer and without an interlayer. The auxiliary criterions are the changes of maximum von Mises plastic strain and maximum surface temperature.

### Table 1. Temperature-dependent properties of the W and CuCrZr for FEA.

| Materials | Temperature (°C) | Thermal conductivity (Wm⁻¹K⁻¹) | Coefficient of thermal expansion (10⁻⁶K⁻¹) | Elastic module (GPa) | Yield strength (Mpa) | Tangent modulus (GPa) |
|-----------|------------------|---------------------------------|------------------------------------------|---------------------|---------------------|---------------------|
| CuCrZr    | 20               | 379                             | 15.7                                     | 128                 | 293                 | 0.9                 |
|           | 250              | 355                             | 17.3                                     | 118                 | 257                 | 0.7                 |
|           | 500              | 352                             | 18.6                                     | 102                 | 194                 | 0.6                 |
| W         | 20               | 173                             | 3.93                                     | 398                 | 1360                | 1.3                 |
|           | 500              | 133                             | 4.21                                     | 390                 | 854                 | 1.0                 |
|           | 1000             | 110                             | 4.51                                     | 368                 | 465                 | 0.8                 |

### 3. Result and discussion

#### 3.1. Temperature distribution

The temperature gradient distribution in the vertical direction on the W/CuCrZr mock-up with different interlayer architectures is obtained by applying the heat load at W armor surface and removing heat at the cooling tube in CuCrZr heat sink material. As expected, the maximum surface temperature occurs at the edge corner of W armor surface far from the cooling tube. Figure 2 shows the temperature distribution through the edge line with different architectures, including W/CuCrZr FGM interlayer, OFHC interlayer and sharp joint. The maximum surface temperature is 342 °C for the sharp joint geometry under the analysis condition. For 1 mm OFHC interlayer and W/CuCrZr FGM interlayer with liner distribution, the surface temperature is 351 and 361°C, respectively. The lower
temperature rise for OFHC interlayer as compared to that for FGM interlayer was attributed to its excellent thermal conductivity. If the FGM interlayer thickness increases to 6 mm, the maximum surface temperature reaches to 473°C, which is acceptable for W operation. The thick FGM interlayer leads to the long heat transfer distance and thus the more thermal heat accumulates at surface, causing high surface temperature. So, the surface temperature rise caused by inserting FGM interlayer should be given more concern during operation. It is interest that the temperature distribution shows no significant difference in CuCrZr heat sink with different interlayer architectures, even the vacuum plasma spraying (VPS)-W coating with low thermal conductivity as the armor material. That is to say, the inserting of several millimeters W/CuCrZr FGM interlayer causes negligible influence of the temperature distribution in CuCrZr heat sink substrate. Moreover, the reasonable design of the structure for CuCrZr heat sink as well as the cooling system helps to control the temperature in its operation range.

Figure 2. Temperature distributes through thickness with different interlayer architectures.

![Temperature distributes through thickness with different interlayer architectures.](image)

Figure 3. The peak von Mises stress changes through interlayer (graded layers and OFHC layer) thickness with different interlayer architectures.

Figure 4. The peak von Mises plastic strain changes through interlayer (graded layers and OFHC layer) thickness with different interlayer architectures.

3.2. Stress and strain distribution
For the sharp joint, as expected in the general viewpoint, the peak von Mises stress is found in the singular corner site in the W layer, while the peak von Mises plastic strain is located in the singular corner site in CuCrZr substrate. For different interlayer architectures, the comparison of the maximum von Mises stress and maximum von Mises plastic strain through interlayer thickness is plotted in figure 3 and 4, respectively. Without an interlayer, the maximum von mises stress and maximum von mises plastic strain are 647 Mpa and 0.7308%. However, when several millimeters W/CuCrZr FGM
interlayer is inserted into the joint, the reduction of peak von Mises stress is significant, which can reach up to 70% as compared to that in a sharp joint, illustrating the feasibility of W/CuCrZr FGM interlayer to alleviate the thermal stress, which is largely related to the FGM interlayer thickness. In general, the maximum von mises stress decreases with increasing the interlayer thickness, because the thicker transition distance provide the large stress relaxation. However, for 1-layered W/CuCrZr interlayer, it is found that the maximum von mises stress increases with its thickness exceeding 3 mm. That is not surprise, because the higher thickness results in the high temperature gradient, especially the high temperature at upper interface, resulting in the large thermal expansion. It is concluded that the interlayer poses a critical thickness for minimal thermal stress, above which the thermal stress increases. If the 4 mm 4-layered W/CuCrZr FGM interlayer is used, the decreasing effect of the maximum von mises stress is the same as compared the OFHC interlayer. Moreover, if the 4-layered FGM interlayer thickness increases to 6 mm, the maximum von mises stress decreased to 213 MPa, which is 15% lower than that using 1 mm OFHC interlayer.

As reported in the reference [11], for OFHC interlayer, the reduction of the thermal stress is accompanied with significant plastic strain, and that is why the maximum thermal stress changes little with increasing the interlayer thickness. The large von Mises plastic strain is found in OFHC interlayer as high as 2%, which is 3 times than that in a sharp joint. The plastic strain may further be amplified during many cycled operation, reducing the component lifetime. However, for the joint using W/CuCrZr FGM interlayer, the plastic strain disappeared with FGM interlayer thickness exceeding 0.4 mm. According to the stress mitigation effect and the plastic strain, the W/CuCrZr FGM interlayer seems to be more preferred than OFHC interlayer.

3.3. Optimization of structure and component distribution

Figure 5 shows the change of the maximum von Mises stress with increasing of graded layer number with different interlayer thickness of 3, 4 and 6 mm. The total thickness of graded layers was fixed as constant, and the homogenous thickness of each layer was assumed. The maximum von Mises stress decreases with increasing layer number. For single layer, the maximum von Mises stress is as high as 444 Mpa, however, for 4-graded layers with liner distribution, the maximum von Mises stress decreases to 200 MPa, demonstrating that the graded effect on stress alleviation is significant. The maximum von Mises stress decreases rapidly with increasing the layer number below 4, and then saturates after the layer number exceeding 4, suggesting that the graded layer number should not be less than 4 to most relieve the thermal stress. However, continually increasing numbers of total layers may lead the difficulties of materials processing, enhancing the interface heat resistance which should be of special concern. For example, figure 6 shows the equivalent thermal conductivity of the W/CuCrZr FGM with increasing layer numbers, in which the W/CuCrZr FGM was sintered by resistance sintering under ultra-high pressure method. The theoretic thermal conductivity almost keeps
invariant with increasing of layer number, however, the experiment curve shows a sharp decrease when the layer number exceeds 4 due to the interfaces thermal resistance, illustrating that in actual application, the choosing of the promising graded layers number should balance the thermal stress alleviation and heat transfer ability.

Figure 7 shows the variation of the maximum thermal stress through the exponent distribution (p). For 4-graded layers with total thickness of 6 mm, the maximum thermal stress decreases rapidly with p below 1.2, then seems to saturate with p between 1.2 and 2, and finally increases with p exceeding 2. Such evolution is valid because the FGM interlayer properties diverge from CuCrZr heat sink and close to W armor with increasing of p. Moreover, it is possible to predict that such distribution of maximum thermal stress is very agreement with the results, if the exponent distribution is infinitesimal or infinite (i.e. graded layers degenerate to pure tungsten or CuCrZr material). In addition, it should also point out that the maximum thermal stress is found in the surface W layer near the upper interface with p below 1.2, while in the heat sink material at the bottom interface with p exceeding 1.2. For 4 and 6 mm graded layers, the promising p for minimal maximum thermal stress are 1.8 and 2, respectively. The promising p for minimal maximum thermal stress is not uncertain and depends on the structure of whole component. In a word, the promising p is greater than 1, illustrating the FGM interlayer should be rich in W. Meanwhile, figure 8 shows the temperature evolution with increasing of p. From the curve, we found that the temperature at bottom interface almost keeps invariant, which is consistent with the above discussion in section 3.1. Both the temperature at surface and upper interface increases with increasing p. But the temperature rise seems to be not substantial, which can be ignored. The temperature change is below 30 °C with p in the range 1.2 to 2.

![Figure 7. The maximum thermal stress changes through the component distribution exponent (p) with different architectures.](image)

![Figure 8. The change of surface temperature (T sur.) and interface temperature (T inter. is the temperature at upper interface, and T inter*. is the temperature at bottom interface)](image)

4. Conclusion
Thermal mechanical analysis was carried out on W/CuCrZr component with FGM interlayer under the steady state heat load of 5 MW/m² using a finite element method. The effect of the FGM interlayer on the stress, strain and temperature distribution is evaluated and compared to the joint without interlayer and with OFHC interlayer. The using of W/CuCrZr FGM interlayer with several millimeters thickness can effectively alleviate the stress and decrease the plastic strain in the entire component. The reduction of stress can reach up to 70% with the disappearance of the plastic strain when 6 mm W/CuCrZr FGM interlayer is used. The thermal stress alleviation is largely related to the interlayer thickness. Meanwhile, the use of the thicker W/CuCrZr FGM interlayer causes acceptable temperature rise at W armor surface and negligible influence of the temperature distribution in CuCrZr heat sink substrate.

The optimization of the component distribution and structure for W/CuCrZr FGM mock-up was also carried out. The maximum thermal stress changes rapidly with increasing the graded layer
number initially and then saturates after the graded layer number exceeding 4. The variation of p not only changes the value of thermal stress, but also the thermal stress distribution. The promising p for minimal maximum thermal stress is not uncertain and depends on the structure of whole component. The change of p in the range 1.2 to 2 leads a negligible surface temperature rise. For W/CuCrZr plasma facing component with 6 mm 4-layered FGM interlayer, the preferred component distribution exponent (p) is 1.8.

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