Thermal Shock Behavior Analysis of Tungsten-Armored Plasma-Facing Components for Future Fusion Reactor

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Abstract

In a fusion reactor, plasma-facing components (PFCs) will suffer severe thermal shock; behavior and performance of PFCs under high heat flux (HHF) loads are of major importance for the long-term stable operation of the reactor. This work investigates the thermo-mechanical behaviors of tungsten armor under high heat loads by the method of finite element modeling and simulating. The temperature distribution and corresponding thermal stress changing rule under different HHF are analyzed and deduced. The Manson–Coffin equation is employed to evaluate the fatigue lifetime (cyclic times of HHF loading) of W-armored first wall under cyclic HHF load. The results are useful for the formulation design and structural optimization of tungsten-armored PFCs for the future demonstration fusion reactor and China fusion experimental thermal reactor.

Keywords Plasma-facing components · Thermo-mechanical behavior · High heat flux · Tungsten armor · Fatigue lifetime · Finite element method

1 Introduction

Fusion energy produced by the interaction of high-temperature plasmas is a promising way to solve the human energy crisis. In the thermonuclear fusion reactor, the plasma-facing components (PFCs) are the first barrier to protect the vacuum chamber wall and various internal components from direct high-temperature plasma irradiation [1, 2]. The plasma-facing materials (PFMs) will suffer the irradiation of high heat flux from the plasma up to 5–20 MW/m². In addition, the high-energy ions and neutral atoms escaping from the plasma can lead to severe ablation of the heated PFMs, which will result in the failure of plasma-facing materials and cause plasma contamination [3, 4]. Therefore, the structural integrity of PFMs can affect the service life of PFCs, the stability of the plasma and even the security of the entire fusion reactor. The PFCs are generally composed of PFMs, interlayer and heat sink

materials. Reasonable selection of PFMs and design of PFCs are critical to the realization of controlled thermonuclear fusion power. During the last decades, the most fusion devices with moderate magnetic field and plasma densities have selected low-Z beryllium or carbon-based materials as PFM [5]. However, the main limitations of low-Z PFMs are their heavy erosion under high heat flux (HHF). Therefore, with the further development of fusion reactor, especially the large-scale devices [6], the high-Z materials are selected as alternative candidates, among which tungsten (W) is the most promising one because of its many unique advantages such as high melting point (3420 °C), low sputtering erosion and negligibly small tritium retention, comparatively high thermal conductivity and moderate thermal expansion [7]. Tungsten has been chosen as the main divertor PFMs in international thermal experimental reactor (ITER) and has been foreseen as the most suitable candidate for the first wall in demonstration fusion reactor (DEMO) or future fusion reactors [5, 8]. The CuCrZr alloy with high thermal conductivity and good irradiation resistance has been recommended as the heat sink materials and the oxygen-free high-conductivity copper (OFHC-Cu) is selected as an interlayer material to join the PFMs and CuCrZr heat sink materials for reducing the

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thermal stress caused by large differences of thermal–physical properties of the PFMs and CuCrZr [9–12].

Many numerical simulations or experimental researches on different plasma-facing materials under ITER-relevant high heat flux or other various heat loads have been carried out. Dell’Orco et al. [13] researched the thermal–mechanical calculations for Beryllium first wall (FW) mock-ups under a heat flux of 0.8 MW/m^2 . Hirai et al. [14] calculated the temperature distribution of a tungsten-based PFM under HHF. It demonstrated that in the case of 10-mm-thick W armor, the surface temperature of PFCs reaches about 2500°C at the steady-state heat flux of 20 MW/m^2 . Roeding et al. [15] performed the thermal fatigue experiments on four different tungsten mock-ups for ITER divertor by means of the e-beam facility JUDITH. Different designs of monoblock mock-ups performed as well as a W macrobrush mock-up at power densities at $14\text{--}20 \text{ MW/m}^2$ (absorbed). For two W plasma-sprayed mock-ups, failure will occur when the heat flux barely reached up to 6.5 MW/m^2 . Huang et al. [16] studied the coupled thermal/mechanical calculations for two ITER-like PFMs of Be and functionally graded W–Cu, respectively, under the high heat flux of $1\text{--}2 \text{ GW/m}^2$ for 10 ms and found that heat is mainly deposited on the PFM layer in the thermal shock pulse, causing the complex thermal stress changes and irreversible mechanical damages. Gavila et al. [17] evaluated the performance of W mock-ups and medium-scale prototypes of divertor under HHF using an electron beam test facility.

This work aims to systematically investigate the changing rule and tending of temperature/stress of tungsten-armored FW under different HHF, and to analyze the thermal shock resistance performance of tungsten-armored FW under HHF. Besides, the numerical simulations of thermal fatigue life for tungsten-armored FW are also evaluated. Researches are of great significance for the structural design of PFCs and the formulation of work system of DEMO, China fusion experimental thermal reactor (CFETR) or other future fusion reactor.

2 FE Model

2.1 Geometry, FE Mesh and Materials

The typical ITER-like FW mock-up is shown in Fig. 1 [18]. In this work, the beryllium (Be) armor is replaced by tungsten, and we selected a feature unit from the central area of FW mock-up as the PFC model for simplifying the FE analysis. The 3-D geometric structure, dimensions and constituted materials of the considered PFC model are shown in Fig. 2, and Fig. 3 is the corresponding finite element mesh. The dimension of tungsten armor is

Fig. 1 FW mock-up with hot-isostatic-pressed Be tiles

Fig. 2 Sketch map of the PFC model size and two paths

Fig. 3 Corresponding FE mesh of the mock-up

$15 \text{ mm} \times 20 \text{ mm} \times 10 \text{ mm}$, the thickness of CuCrZr cooling tube is 1 mm, and the inner diameter is 10 mm. There is an OFHC-Cu interlayer between the tungsten

armor and the CuCrZr heat sink layer, which is used to reduce the jointing stress [14, 19].

Thermo-mechanical behaviors of tungsten-armored PFCs under different HHF were analyzed by FE package ANSYS [20–23]. The thermal–physical properties of selected materials in the model are listed in Table 1, and the parameters were referred from ITER material properties handbook [24] and related documents [25–28]. Besides, perfect thermal contacts at the interfaces were assumed.

2.2 Loads and Boundary Conditions

The ITER-relevant cooling condition was selected: ~ 10 m/s, 4.2 MPa and 120 °C [14, 29]. In the analysis of FE, stress and strain distributions of the PFC model were obtained by indirect coupling method, the heat fluxes were uniformly applied to the top surface of the model, and initial temperature of the model is set as 20 °C. In addition, the coefficient of convection heat transfer (CCHF) of the inner wall of the cooling tube and the coolant water is 55,000 W/(m² K), which is derived from the well-known Dittus–Boelter formula [30]. Finally, symmetric boundary conditions (i.e., heat exchange is the state of equilibrium) were applied to other surfaces, and a pressure of 4.2 MPa of the inner surface of cooling tube was applied to simulate the pressure caused by cooling water [31].

3 Steady-State Heat Flux Simulation

3.1 Temperature Fields

The temperature distribution of designed PFC model under different heat fluxes (2–25 MW/m²) was calculated and shown in Fig. 4. It can be found that the temperature field of the model is symmetric to the Y–Z plane which coincides with the axis of cooling tube. Additionally, the temperature gradient of tungsten armor increased gradually as the increase in heat flux. What caused such phenomenon is that the heat of tungsten surface cannot be transferred in time due to the relatively low conductivity of tungsten. Therefore, a large amount of heat will be accumulated at the W-armored layer. Moreover, the decrease in thermal conductivity resulted from the increase in temperature will accelerate the increase in the temperature of W armor. The temperature of W armor will increase to about 3150 °C when the steady-state heat flux goes up to 25 MW/m². To prevent W from melting (the melting point of W is 3420 °C), the maximum heat flux should not exceed about 27 MW/m², which is estimated according to the relationship between the heat flux and surface temperature of W armor.

Path A–A is a hypothetical horizontal path passing through the center point of top surface (Fig. 2). Figure 5 presents the distribution of the temperature along the path A–A at 5 and 25 MW/m². The results indicate that, in the direction of cooling tube axis, the temperature at both sides of tungsten armor is always higher than center area. Therefore, at the edges of tungsten armor, the phenomenon

Table 1 Thermal–physical properties of the considered materials at selected temperatures

Material	Temperature (°C)	Thermal conductivity (W m ⁻¹ K ⁻¹)	Coefficient of thermal expansion (10 ⁻⁶ K ⁻¹)	Young's modulus (GPa)	Poisson's ratio	Yield strength (MPa)	Tangent modulus (GPa)
W	20	173	4.5	398	0.28	1360	1.3
	200	156	–	396	–	1154	–
	500	133	4.7	390	–	854	1
	800	118	–	379	0.29	604	–
	1000	111	5.1	368	–	465	0.8
	1500	101	5.6	333	0.30	204	–
	1800	99	5.8	306	–	103	–
OFHC	20	403	16.7	125	0.34	69	1.5
	200	392	17.2	115		60	1.3
	400	379	17.8	100		48	0.9
	700	360	18.9	70		30	0.6
CuCrZr	20	326	16.7	128	0.32	293	0.9
	250	343	17.2	118	0.42	257	0.7
	500	348	18.2	103	0.52	195	0.6

Fig. 4 Temperature contour plots under different heat fluxes

Fig. 5 Distribution of temperature along the path A-A at different heat flux values: (a) 5 MW/m², (b) 25 MW/m²

of surface roughening or melting induced by the temperature and plastic deformation is much more significant. The simulation results agree with the high heat flux test results at electron beam test facilities conducted by Gavila et al. [17].

3.2 Stress Fields

Figure 6 displays von Mises equivalent stress contour plots under different HHFs. It can be seen that the stress concentration zone (SCZ) formed on the top surface of the W armor, and gradually moved toward OFHC-Cu interlayer with increasing heat flux. Eventually, the SCZ stabilizes at the junction of W-armor layer and OFHC-Cu interlayer, and then the stress value decreased gradually. The reason is

that the Young's modulus of tungsten is very high at relative low temperatures, and the increase in compression stress induced by thermal expansion of this material is larger than the decrease in strength induced by the temperature increase result in the von Mises equivalent stress increase. On the contrary, the Young's modulus significantly decrease as the temperature increases highly, the von Mises equivalent stress will decrease when the increase in the compression stress induced by thermal expansion cannot offset the decrease in material strength. Furthermore, it can be found that the von Mises equivalent stress at the whole tungsten armor layer was almost evenly distributed, when the heat flux is up to 25 MW/m². This phenomenon suggests that the tungsten armor has taken on yield behavior, while the Young's modulus of tungsten has

Fig. 6 Von Mises equivalent stress contour plots under different high heat fluxes

hardly changed with the rise of the temperature. In general, the phenomenon of stress variation is the result of the combination of the Young's modulus change and the yield of tungsten armor.

Path B–B is another horizontal path which passes through the center point of cooling tube. Figure 7a shows the distribution of von Mises equivalent stress along the path B–B at 2–10 MW/m², and Fig. 7b shows the corresponding temperature distribution. The maximum stress value is always on the top surface when the heat flux is less than 3 MW/m² (the temperature on the top surface is about 420 °C), and the Mises equivalent stress is in proportion to the temperature. When the heat flux is larger than 3 MW/m², the SCZ will gradually move toward OFHC-Cu interlayer with increasing heat flux. Moreover, it should be noted that the temperature corresponding to the moving SCZ is about 420 °C. Therefore, we can deduce that the SCZ reached to the junction of W-armor layer and OFHC-Cu interlayer when the heat flux is up to 9 MW/m². In other words, the largest stress difference between the armor layer and interlayer occurred when the heat flux is about 9 MW/m².

Similarly, Fig. 8a shows the distribution of von Mises equivalent stress along the path B–B at 8–25 MW/m², and Fig. 8b shows the corresponding distribution of temperature. It can be found that the top surface of the designed PFC begun to yield at 8 MW/m² (the temperature and stress of top surface is about 1050 °C and 470 MPa), and the thickness of yield layer increased gradually with increasing heat flux. Eventually, the whole tungsten armor layer yielded when the heat flux is up to 25 MW/m². It

Fig. 7 Distribution of von Mises equivalent stress (a), temperature (b) along the path B–B at 2–10 MW/m²

should be noted that the temperatures corresponding to all the yield points all are about 1050 °C.

Fig. 8 Distribution of von Mises equivalent stress (a), temperature (b) along the path B–B at 8–25 MW/m²

4 Fatigue Lifetime Analysis

Thermal fatigue is also a key issue that should be concerned when the PFCs are in service. In this work, HHF load cycles are simulated and each cycle includes 30 s of HHF loading and 10 s of cooling. The initial temperature is 120 °C (cooling water temperature). The duration of the heating period depended on the time span when the heat equilibrium is established [3].

Figure 9 demonstrates the temperature changes at position 2 under different HHF loads (the temperature at position 1 is not showed here due to the similarity). Moreover, the variation of the temperature in each cycle is identical.

The thermal fatigue of tungsten armor is assumed to be a kind of low-cycle fatigue (LCF), and according to the theoretical research at high-temperature LCF [32], the Manson–Coffin equation is adopted to assess the LCF lifetime of tungsten armor. Equation (1) is the “strain-life” equation based on Manson–Coffin equations.

Fig. 9 Temperature variation at position 2 under different high heat fluxes

$$\Delta \varepsilon_t = \Delta \varepsilon_e + \Delta \varepsilon_p = 3.5 \frac{\sigma_b}{E} (N_f)^b + \varepsilon_f^{0.6} (N_f)^c. \quad (1)$$

where $\Delta \varepsilon_t$ is the total strain, $\Delta \varepsilon_e$ is elastic strain, $\Delta \varepsilon_p$ is plastic strain, N_f is the number of cycles to failure, E is the modulus of elasticity, σ_b is the fatigue strength, b is the fatigue strength exponent, c is the fatigue ductility exponent, and ε_f is the fatigue ductility coefficient. As for the LCF, the plastic contribution is dominant, only the plastic term of Eq. (1) was considered in the present analysis of W-armor lifetime. Putting related parameters into Eq. (1) [33], the ultimate assessment equation of LCF lifetime is as follows: (2)

$$\Delta \varepsilon_p = 0.5^{0.6} (N_f)^{-0.6}. \quad (2)$$

In addition, the position of maximum temperature and plastic strain for tungsten armor is located on the top surface of PFC, and fatigue cracks are very likely to initiate from the top surface. Therefore, two reference positions (position 1 and 2) are selected on the top surface to perform thermal fatigue analysis for tungsten armor (Fig. 2).

Table 2 lists the values of the equivalent plastic strain in an HHF load cycle and the calculated fatigue lifetime at position 1 and 2. There is no obvious difference in fatigue lifetime at two reference positions, for the relatively homogeneous temperature distribution on the top surface. In addition, the fatigue lifetime of W armor is exponential decreased with increasing heat flux, and the fatigue lifetime of W armor is about 330 when the heat flux is up to 20 MW/m². However, it should be noted that the armor is very likely to generate cracks during cooling progress because of the high ductile to brittle transition temperature of tungsten [34]. So the actual fatigue lifetime is shorter than the predicted one. Besides, the fatigue lifetime at central area is slightly shorter than that of edges, and the cooling rate at the central area of tungsten surface is also

Table 2 Equivalent plastic strain in an HHF load cycle and the predicted fatigue lifetime at positions 1 and 2

Reference positions	High heat flux (MW/m ²)			
	5	10	15	20
1	0.2942/8285	0.9429/1191	1.4649/571	2.0078/336
2	0.2944/8273	0.9640/1158	1.4991/548	2.0055/325

faster than that of edges. Therefore, the cracks are very likely to initiate in the central area of tungsten surface since the central area will reach to the ductile to brittle transition temperature firstly in the cooling progress. Furthermore, combining the temperature field of W-armored PFC, we can infer that the growth direction of cracks is coincident with the direction of cooling tube axis.

5 Conclusions

1. The heat on the top surface of PFC could not be transferred in time because of relatively low thermal conductivity of tungsten. Therefore, more and more heat would be accumulated at the armor layer with increasing heat flux, and the temperature of tungsten surface is expected to reach the melting point (3420 °C) when heat flux goes up to the 27 MW/m².
2. From the viewpoint of the relationship between the temperature and thermal stress, when the temperature is below 420 °C, the thermal stress of tungsten armor will increase with increasing temperature. The thermal stress will decrease with increasing temperature at 420–1050 °C. Eventually, the thermal stress tends to be stabilized when the temperature on the top surface exceeds 1050 °C. Therefore, it is necessary for reducing the risk of fatigue crack induced by constantly changing thermal stress to control the top surface temperature of PFC at 1050–3420 °C.
3. The SCZ always grows on the surface of tungsten armor when the heat flux is less than 3 MW/m² (stress value is about 940 MPa); and when the heat flux increases from 3 to 9 MW/m², the SCZ will move gradually toward OFHC-Cu interlayer with the increase in heat flux. When the heat flux is more than 9 MW/m², the SCZ is always at the junction between tungsten armor layer and OFHC-Cu interlayer, and the stress concentration phenomenon will fade with the increase in heat flux. Finally, the stress concentration phenomenon will disappear, when the heat flux is up to 25 MW/m². In other words, the whole W armor will yield, when the heat flux reaches 25 MW/m² and the stress value is about 470 MPa.
4. Combining the results of FE simulation and Manson–Coffin equation, we can predict that the fatigue crack is very likely to initiate at the central area of tungsten

surface, and the growth direction of the crack is in the direction of cooling tube axis. Moreover, the fatigue lifetime of W decreases exponentially with increasing heat flux, and the fatigue lifetime of tungsten is about 330, when the heat flux is up to 20 MW/m².

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