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A Simulation Study on the Thermal Shock Behavior of Tungsten Mock-Up under Steady-State Heat Loads

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In a fusion reactor, due to high heat flux (HHF) loads, the plasma facing components (PFCs) will suffer severe thermal shock. In this paper, the temperature distribution and thermal-stress field of tungsten armor under HHF loads were investigated by the method of finite element modeling and simulating. The orthogonal experiment and range analysis were employed to compare the influence degree of four representative factors: steady-state heat flux; thickness of tungsten armor; inner diameter of cooling tube and the coefficient of convection heat transfer (CCHF) of cooling water, on thermal shock behavior tungsten mock-ups, and then get an optimization model to conduct the transient heat flux experiment. The final simulation results indicated that the steady-state heat flux and the thickness of W armor are the main influential factors for the maximum temperature of mock-ups. Furthermore, the influence of transient thermal shock all mainly concentrates on the shallow surface layer of tungsten (about 500 μm) under different transient heat flux (duration 0.5 ms). The results are useful for the structural design and the optimization of tungsten based plasma facing materials for the demonstration reactor (DEMO) or other future reactors.

1. Introduction

In a fusion reactor, the PFCs are the first barrier to protect the vacuum chamber wall and various internal components from direct high temperature plasma irradiation[1,2]. Typically, the PFC consists of an armor material that directly faces the plasma and a heat sink material that transfers heat loads from the armor to the water coolant. As the components directly exposed to high temperature plasma, the armor or the first wall (FW) materials has to withstand high heat flux load up to 20 MW/m^2 and irradiation of various high-energy particles during the routine operation of the international thermonuclear experimental reactor (ITER) device[3]. The structural integrity of FW not only relates to the service life of materials or components but also affects the stability of plasma and security of device. Therefore, reasonable structure design and material selection of the FW is essential for the realization of controlled nuclear fusion. Tungsten (W) has many unique advantages such as high thermal conductivity, high melting point (3410 °C), low sputtering rate and low tritium retention. Therefore, W has been considered as the most promising candidate for armor materials[4–6]. CuCrZr alloy has been proposed as heat sink material because of its high thermal conductivity[7]. In addition, oxygen free high conductivity copper (OFHC-Cu) is selected as an interlayer jointing the armor material and heat sink material and reducing stress concentration caused by the mismatch of thermal expansion coefficient of these two materials[8,9].

Some numerical simulations and experiments have been carried out to evaluate the performance of different FW materials under various heat loads. Hirai et al.[10] calculated the temperature distribution of a W-armored component under steady-state heat loading by 2D finite element (FE) calculation (ANSYS-code). In case of 10 mm-thick W-armor, the surface temperature reaches around 2500 °C and the interface temperature exceeds 650 °C at the heat flux of 20 MW/m^2. Roeding et al.[11] tested thermal fatigue performance of four different tungsten mock-ups using an electron beam facility. Different designs of monoblock mock-ups as well as a W macrobrush mock-up performed well at power densities between 14 and 20 MW/m^2 (absorbed). For two plasma-sprayed tungsten mock-ups, failure occurred only when the heat flux reached 6.5 MW/m^2. Gavila et al.[12] carried out HHF experiments on W mock-ups and medium scale prototypes to 20 MW/m^2 in the AREVA FE 200 facility. The full W mock-up successfully sustained the thermal shock of 1000 cycles at 15 MW/m^2 and 500 cycles at 20 MW/m^2 respectively. Zhang et al.[13] calculated the distribution of temperature, stress, and strain in different two-dimensional first wall panel models under the combined effect plasma heating and neutron heating

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loadings. Be were selected as the armor layer materials in this work. The maximum temperature (461 °C) occurs at the Be armor. High thermal stress (in the range of 80–200 MPa) are found at the interface between the Be armor and the CuCrZr layer.

Although various models and experiments for the thermal shock of FW were simulated and tested, very few studies were systematically performed to investigate the influence degree of possible factors on the temperature field of first wall and according mock-ups. The aim of this work is to find out the influence degree of four representative factors: steady-state heat flux, thickness of tungsten armor, inner diameter of cooling tube and coefficient of convection heat transfer (CCHF) of cooling water, on maximum temperature of tungsten first wall materials and then get an optimization model to conduct the transient heat flux experiment. It is very useful for the structural design and optimization of first wall to find out the influence degree of various factors on the distributions of temperature.

2. FE Model

2.1. Geometry, FE mesh and materials

The thermophysical and mechanical properties of 9 different types of mock-ups under different thermal loads and cooling conditions were simulated in this work. Fig. 1 shows the 3-D geometric structure, dimensions and constitute materials of the considered mock-ups in this experiment, and Fig. 2 shows the corresponding FE mesh. The other mock-ups have the different thickness (5 mm, 10 mm) of tungsten armor and the inner diameter (8 mm, 12 mm) of cooling tube. The dimensions of mock-ups used here are based on the optimization of the typical ITER first wall qualification mock-ups[10,14,15].

As shown in Fig. 1, the dimensions of tungsten armor is 15 mm × 20 mm × 8 mm, and the thickness of CuCrZr cooling tube is 1 mm, the inner diameter is 10 mm, and the distance from the interlayer to the center of cooling tube is 10 mm. There is an OFHC-Cu interlayer at the brazed bond interface between the tungsten armor and the CuCrZr heat sink layer, which is used to reduce the residual thermal stress.

The finite element method (FEM) has become a significant solution technique in many areas of engineering and physics. In this work, the distributions of temperature and stress for each mock-up was computed and analyzed in FE package ANSYS, which is widely used in many fields for theoretical calculation and practical modeling[16–18]. The properties of the temperature-dependent material adopted in every mock-ups are listed in Table 1, and the data are referred from ITER material properties handbook[19] and related documents[20–23]. It should be noted that all components are bonded to each other perfectly for simplifying the FE analysis.

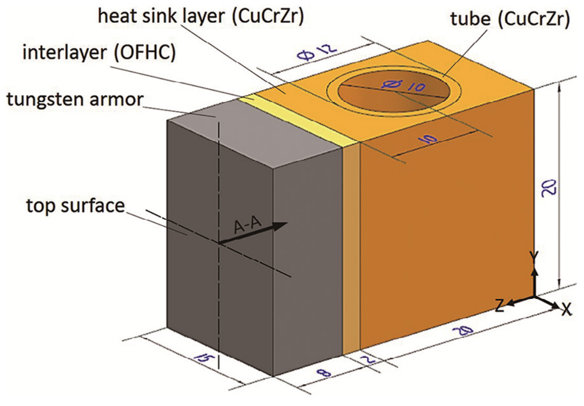

Fig. 1. Sketch map of a mock-up size.

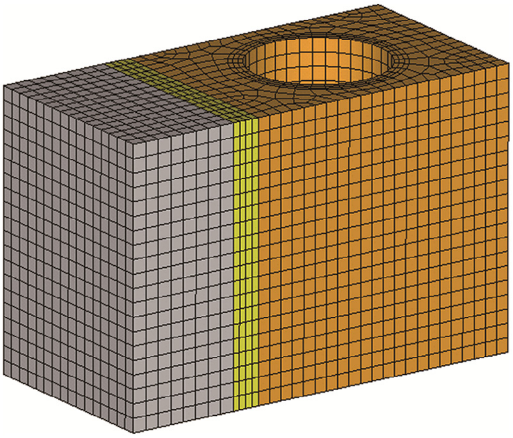

Fig. 2. Corresponding FE mesh of the mock-up.

2.2. Loads and boundary conditions

In order to investigate the temperature field of mock-ups, different thermal loads were applied to the top surface of tungsten armor during thermal analysis. The ITER-relevant cooling condition was selected as ~10 m/s, 4.2 MPa and 120 °C[10,24]; then the CCHF (55 kW/(m^2·K)) could be calculated using the Dittus–Boelter formula[25]. And changing the cooling condition of cooling water could derive the different CCHFs. The thermal conduction between a heated tungsten armor and the neighbor armor is negligible.

Stress distribution of mock-ups was calculated by indirect coupling method, and a two-step procedure was adopted. First, only the thermal loads and boundary conditions were applied to the mock-ups to obtain the temperature field and the initial temperature of the mock-ups is set as 20 °C, and then the elements type was changed from thermal elements to structural elements. Subsequently, displacement constraint was applied to the bottom surface of the model to ensure that no displacement occurs in Z direction (i.e. the bottom surface of model is fixed to the stainless steel structure), and a pressure of 4.2 MPa was applied to the inner surface of cooling tube to simulate the water pressure. Four side surfaces of heat sink layer are applied to be symmetric boundary conditions (i.e. there are same mock-ups in the direction of X direction and Y direction) and the side surface of interlayer and tungsten armor is free. After that, the calculated temperatures were applied to each node of mock-up as an initial condition for the further thermo-mechanical coupling calculations.

3. Orthogonal Experiment

3.1. Simulation methods

As we know, there are a lot of factors influencing temperature field of the first wall, and each factor has many possible values, so it is impossible to test respective or combinational effects of every factor and corresponding values by experiments. However, it is feasible to sample a small but representative in combinations for molding and testing. The orthogonal design method (Taguchi's techniques), which is one of the optimal scientific disciplines to investigate or deal with multifactor and multilevel cases, could be employed for this purpose[26,27]. $L_m(n^k)$ denotes an orthogonal array for k factors and n levels, where "L" denotes a Latin square and m