Fusion Engineering and Design 137 (2018) 30–34

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Fatigue and fracture analysis on EAST divertor monoblock heat sink in H-mode operation

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ARTICLE INFO

Keywords:
EAST divertor
Heat sink
ELMy H-mode
Creep-Fatigue damage
Crack

ABSTRACT

Currently the most advanced and mature plasma facing unit (PFU) technology is the ITER W/Cu PFU, which is monoblock composed of tungsten, copper and CuCrZr as plasma facing material, interlayer and heat sink, respectively. Fatigue failure in heat sink structural including fracture under H-mode (High confinement mode) operating condition greatly influence the lifetime of divertor target. In this study, to simplify calculation for complex heat load input, the heat load time evolution with ELMs(Edge localized modes) was defined as an equivalent heat flux for steady-state analysis. To investigate the fatigue damage behavior of CuCrZr tube in EAST divertor monoblock, the thermal-stress analysis was performed firstly with regards to EAST operating and cooling condition. The stress and strain distribution on heat sink tube indicates that the risky position is on the upper inner surface of tube. Combined with the strain-life relationship, the fatigue life and creep-fatigue damage of CuCrZr tube was assessed. The fatigue analysis shows that the cumulative fatigue and creep damage on tube meet the requirement under operating condition now available and it is great influenced by steady heat load. The tube also risks cracking and fracture under long pulse operation in future fusion device. The stress intensity factor and J-integral were applied to investigate crack fracture in risky position on heat sink tube that the pre-crack shows no risk of fast fracture but potential for creep at higher operating temperature.

1. Introduction

Divertor is one of the most important components in fusion reactor. The ITER-monoblock structure of divertor is applied in nowadays Tokamak devices. The PFU (Plasma facing unit) consists of tungsten, copper and CuCrZr as plasma facing material, interlayer and heat sink, respectively. H-mode (High confinement mode) is the preferred discharge mode in fusion reactor [1]. ELMs is found in H-mode operation in existed fusion devices, like JET [2], DIII-D [3], ASDEX-U [4],JT60-U [5] and EAST [6], in which Type I ELMs generate higher heat load on divertor PFU than Type II and III ELMs for longer duration [7].Thus Type I ELMs become the main possible factor that affect the thermal load on divertor. The PFU of divertor endure cyclic heat load for long pulse operation in H-mode and the heat sink tube takes risk of fatigue failure. Fracture in view of that crack and water leakage on tube were found in some high heat flux fatigue tests [8,9].In this study, the heat flux of H-mode according to EAST experiment is defined as an equivalent steady state heat load for thermal analysis. Then, the EAST W/Cu divertor PFU structureand corresponding cooling condition are introduced for thermal-mechanical analysis. The position of risk in heat sink tube is located. Fatigue life and creep-fatigue damage are presented by finite element analysis combined with strain-life curve. Assume micro crack caused by fatigue produced in the risky region on heat sink tube, pre-crack finite element analysis is employed to investigate the fracture. The results show that the heat sink structure in EAST divertor PFU is qualified for present stage in fast fracture, but as for fatigue crack propagation, its capacity for heat removal and mechanical strength need to be enhanced for future device of high power and long pulse operation.

2. Monoblock model for analysis

2.1. Geometry and material parameters

The monoblock of EAST W/Cu divertor [10] without twisted tape is shown in Fig. 1. The monoblock is composed of W, Cu and CuCrZr as armour, interlayer and heat sink, respectively.The temperature-dependent physical properties from ITER-SDC [11]. Assume tungsten as

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https://doi.org/10.1016/j.fusengdes.2018.08.011
Received 3 January 2018; Received in revised form 2 July 2018; Accepted 22 August 2018
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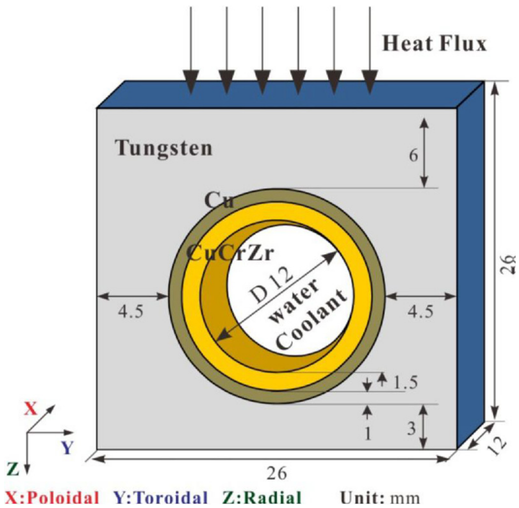

Fig. 1. Dimension of EAST divertor monoblock.

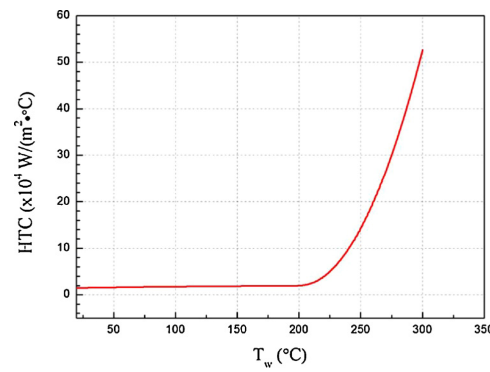

Fig. 2. HTC between the inner wall of the heat sink tube and the coolant water.

elastic material, Cu and CuCrZr as elasto-plastic material use Chaboche model [12] (Table 1).

2.2. Loads, boundaries and cooling conditions

The heat flux bombardment on one monoblock is assumed uniform. The input heat flux loads perpendicular to tungsten surface shown in Fig. 1. Fixed support on the bottom surface of tungsten and remote constraints on tube end faces in direction of rotation.

Active water cooling is applied in EAST W/Cu divertor. The designed cooling water conditions [10] are as follows: inlet temperature of 20 °C, flow velocity of 4 m/s and pressure of 1 M Pa.HTC (Heat transfer coefficient) between water and heat sink tube is calculated using the Sieder-Tate [13] correlation for forced convection regime and the Thom–CEA [14,15] correlation for subcooled boiling regime. Two regimes are divided by TONB(Onset of the nucleate boiling temperature) acquired by empirical formula Bergles-Rohsenow [14,15].Based on the cooling conditions, the calculation formulas above and coolant physical parameters, the relationship between HTC and temperature on inner wall of tube is shown in Fig. 2.

3. Heat flux of H-mode operation

In future fusion devices, long pulse operation of H-mode accompanied with ELMs especially Type I ELMs caused severe fatigue damage on divertor PFUs.

Here, some simplifications are made to describe the long pulse operation process according to Qian [16]. As shown in Fig. 3, the time evolution of one discharge process is divided into 6 parts: Ohmic heating(0–t_1), L-mode(t_1–t_2), L-H transform(t_2–t_3), Type III ELMs and ELMs free (t_3–t_4), Type I ELMs(t_4–t_5), and ending of discharge (t_5–t_6).The main fatigue damage in heat sink tube is caused by periodic heat load. Thus, to investigate the influence of transient event ELMs on temperature in heat sink tube, thermal simulations are employed based on parameters of ELMy discharge in Table 2. These assumed parameters due to that the peak heat flux of Type I ELMs will not exceed 200WM/m2 according to research on H-mode operation of Tokamak devices [18–20], also the rise time and frequency of ELM estimated 350 μs and 10 Hz [6] respectively. The steady heat flux assumed 5 MW/m^2 also based on EAST [6].

The equivalent average heat flux ($q_{\rm equ}$) can be deduced as follows [17]

$$q_{equ} = q_{steady} + f \bullet \int q_{ELMs} e^{\frac{1}{2}} \frac{t}{\tau_{rise}} exp\left(-\frac{t^2}{2\tau_{rise}^2}\right) dt \quad (1)$$

Based on the parameters in Table 3, the q_{equ} in ELMy period is 6.125 MW/m^2.

Three situations of input heat load are employed for finite element analysis on EAST divertor PFU dimensions: (a) defined heat load with full ELMs transient event; (b) heat load without ELMs; (c) Equivalent heat load calculated by Eq. (1).

The temperature response of heat sink tube due to ELMs is shown in Fig. 4 which indicates that the transient wave of ELM have little impact on the tube temperature. In the long enough discharge time, temperature peak on CuCrZr heat sink tube which located at central of its inner surface (coolant side) would reach the quasi-steady state equilibrium; the ELM makes a significant influence on the temperature peak of equilibrium with about 80 °C gradient; the trend of temperature peak in heat sink on the equivalent average heat flux is basically consistent with that on full heat load with ELMs. Therefore, the steady-state load of q_{equ} can be used for the thermal mechanical analysis to investigate the stress and strain caused by heat load in H-mode operation with ELMs.

Table 1
Main parameters of material properties and models [12].

	Tungsten			CuCrZr		Copper	
	20 °C	400 °C	1200 °C	20 °C	400 °C	20 °C	400 °C
Young's modulus(GPa)	389	393	356	115	106	115	95
Yield stress(MPa)	1385	1100	346	273	238	62	33
Heat conductivity(W/mK)	175	140	105	318	347	379	352
Coefficient of thermal expansion(10-6/K)	4.5	4.6	5.3	16.7	17.8	17.8	18.1
Q				−43	−68	76	36
b				6	10	8	25
C				148.575	117.500	64.257	31.461
γ				930	1023	888	952

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