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Evaluation of heat transfer by sublimation for the application to the divertor heat sink for high fusion energy conversion

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ABSTRACT

Thermal and structural responses of divertor target were evaluated by using finite element method. High heat flux simulating ELMs at the level of 100 MW/m^2 was assumed onto the tungsten armor, and surface temperature profile was obtained. When dynamic heat load over 100 MW/m^2 was applied, the maximum surface temperature exceeded 1300 °C, and it caused recrystallization of tungsten regardless of the heat transfer below it. The result was used to conduct dynamic heat load experiment on tungsten, and material behavior of tungsten was evaluated under dynamic heat load. This study also proposed new concept of divertor heat sink which can distribute high heat flux and transfers the heat to high temperature medium. It consists of tungsten armor, composite enhanced with high thermal conductivity fiber, and heat transport system applying phase transition. High heat flux simulating ELMs was also applied to target surface of the divertor, temperature gradient, thermal stress of tungsten and composite were evaluated. Based on the results of analysis, thermal structural requirement was considered.

1. Introduction

Target surface of divertor takes high heat flux by plasma, high energy particles and radiation. In the case of ITER divertor, assumed heat flux to target surface is postulated to be average of 10 MW/m^2, peak of 20 MW/m^2 as design criteria [1]. However, transient high heat flux, 100 MW/m^2 order, is anticipated to the target surface at a few milliseconds intervals by edge localized modes (hereafter, ELMs) [2–4]. Tungsten is expected to have minimal sputtering damage due to tungsten's higher sputtering threshold energy compared to that of carbon, as well as good heat tolerance. In this study, transient response of plasma facing materials (hereafter, PFMs) of divertor particularly tungsten is considered. Although the integrated heat load may not be dominant, ELMs could cause melting, recrystallization, thermal stress and thermal fatigue in localized area of tungsten armor, and it leads to fracture of tungsten armor. Therefore, it is important to evaluate heat-structural response of divertor under dynamic heat load like ELMs. ITER mono block consists of tungsten or CFC tile and CuCrZr coolant pipe. Its heat sink is only the upper half of coolant pipe and tungsten block. Large temperature gradient occurs, and it would also cause large thermal stress in mono block. The authors have proposed a new concept of divertor heat sink which can not only distribute high heat flux, but also collect high temperature thermal medium. Fig. 1 shows schematic diagram of new concept of divertor. It consists of tungsten armor, unidirectional fiber composite enhanced with high thermal conductivity, and heat transport system applying phase transition of sublimating medium [5]. The coefficient of heat transfer with the phase transition is much larger than that of general convection, approximately, 170 kW/m^{2}K [8]. Heat sink area of new concept of divertor is larger than that of mono block, and it could reduce temperature gradient and thermal stress compared with mono block.

2. Dynamic heat load analysis on tungsten armor

2.1. Analysis method

Thermal response on tungsten surface was analyzed by using finite element method to simulate experiment by laser irradiation. Fig. 2 shows schematic of analysis model. Original size of tungsten specimen is 3 mm × 3 mm × 2 mm, but only 1/4 model of original size was used as analysis model. Heat flux of pulse shape with 10 ms width was applied to the top surface of tungsten target as shown in Fig. 2, and its value was 10–500 MW/m^2. Diameter of the laser was 1.2 mm. Emissivity of tungsten was assumed to be 0.39 and

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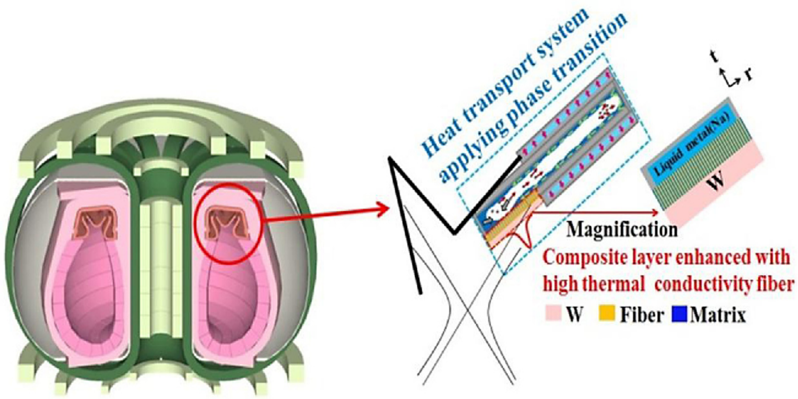

Fig. 1. Schematic diagram of new concept of divertor.

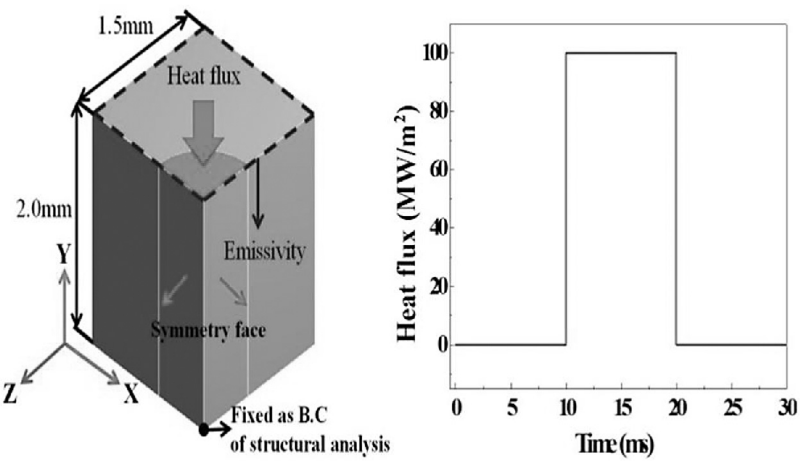

Fig. 2. The schematic diagram of analysis model and heat flux. (For interpretation of the references to color near the citation of this figure, the reader is referred to the web version of the article.)

constant, however actual emissivity would be changed with various conditions such as surface color, roughness, wavelength of laser. Table 1 summarizes the used data of thermal properties of tungsten: density, specific heat, and thermal conductivity. At first, thermal analysis was analyzed, heat flux of 10–500 MW/m^2 was applied to tungsten surface as a single pulse.

Surface temperature profile was investigated for considering recrystallization temperature of tungsten which is 1300 °C, as a criterion of recrystallization of tungsten. After conducting thermal analysis, structural analysis was carried out. Entire temperature distribution obtained from thermal analysis was applied to the analysis model as heat load, and a vertex of bottom surface was fixed on *x*–*z* axis direction. Red arrow expresses symmetry face. Symmetry boundary condition was applied on each symmetry face.

Table 1
Thermal properties of tungsten.

Temperature (°C)	Specific heat (J/kg K)	Thermal conductivity (W/mK)	Density (kg/m^3)
27	133	178	19,250
327	140	139	19,170
527	145	128	19,120
727	150	121	19,060
927	155	115	19,000
1500	160	106	–
2000	168	102	–

3. Results of analysis

Fig. 3 shows temperature distribution of tungsten when heat flux of 380 MW/m^2 was applied to the surface. The surface temperature was about 1400 °C, and it exceeded recrystallization temperature of tungsten, 1300 °C. Table 2 shows the maximum surface temperature with heat flux from 100 to 500 MW/m^2. The heat flux from 100 to 500 MW/m^2 is not sufficiently high to melt the tungsten surface. However, heat flux with 380–500 MW/m^2 elevated surface temperature to above 1300 °C that could cause recrystallization of tungsten.

Fig. 4 shows thermal stress of tungsten when heat flux of 350 MW/m^2 was applied to the surface. Temperature of tungsten surface was 1275 °C, and it was lower than the recrystallization temperature of tungsten. However, very large thermal stress occurred at the tungsten surface. The value was above 1 GPa, and it exceeded ultimate stress and allowable stress of tungsten. This is because heat flux was applied to localized area of tungsten surface.

Table 2
The maximum surface temperature with heat flux.

Heat flux (MW/m^2)	Input heat (J)	The max temp. (°C)
100	1.13	321
350	3.96	1275
380	4.29	1399
400	4.52	1483
500	5.65	1908