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Thermal–stress analysis on the crack formation of tungsten during fusion relevant transient heat loads

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ABSTRACT

In the future fusion devices, ELMs-induced transient heat flux may lead to the surface cracking of tungsten (W) based plasma-facing materials (PFMs). In theory, the cracking is related to the material fracture toughness and the thermal stress-strain caused by transient heat flux. In this paper, a finite element model was successfully built to realize a theoretical semi infinite space. The temperature and stress-strain distribution as well as evolution of W during a single heating-cooling cycle of transient heat flux were simulated and analyzed. It showed that the generation of plastic deformation during the brittle temperature range between room temperature and DBTT (ductile to brittle transition temperature, ~400 °C) caused the cracking of W during the cooling phase. The cracking threshold for W under transient heat flux was successfully obtained by finite element analysis, to some extent, in consistent with the similar experimental results. Both the heat flux factors ($F_{HF} = P \cdot t^{0.5}$) and the maximum surface temperatures at cracking thresholds were almost invariant for the transient heat fluxes with different pulse widths and temporal distributions. This method not only identified the theoretical conclusion but also obtained the detail values for W with actual temperature-dependent properties.

1. Introduction

Tungsten (W) will be used as the divertor target material in ITER and it is also the promising candidate plasma facing material (PFM) for future fusion devices due to its outstanding physical properties [1]. It is expected to withstand the extreme transient heat loads in ITER, which include plasma disruptions (dozens of MJ/m^2 for several ms), vertical displacement events (VDEs, in the order of ~60 MJ/m^2 for ~300 ms) and edge localized modes (ELMs, in the order of ~1 MJ/m^2 for ~0.5 ms in a frequency exceeding 1 Hz) [2,3]. The high transient heat flux in ITER is high enough to cause the material surface deterioration that increased from roughing to cracking [4–7]. Especially, the surface cracking behaviors are related to the mechanical stress-strain by thermal extension and material fracture toughness, in which the former is the driving force for cracking formation, while the later is a material parameter against such destruction [8]. Based on this theory, a theoretical analysis by formula calculation of the thermal stress based on a semi infinite space was roughly estimated the cracking behaviors for W under transient heat fluxes [9]. However, this theoretical method couldn't take into account the temperature-dependent material properties for precise results and only calculated the temperature and thermal stress at some special time points during the whole heating-cooling process. Meanwhile, all the strain components, especially the plastic strain were unclear for the theoretical method. As known, all the thermal and mechanical properties of W are temperature-dependent. With the ability to deal with such kind of analysis conveniently and effectively, the finite element method was proposed to overcome these drawbacks of the theoretical method in this work.

In the present paper, a finite element model was built to realize the theoretical circumstance of a semi infinite space under transient heat flux. It successfully overcame the drawbacks of the theoretical mathematical calculation method. The temperature and stress-strain distribution and evolution of W during one heating-cooling process of transient heat flux were simulated and analyzed. The crack formation mechanism was analyzed and discussed in respect of the balance between thermal-stress distribution and material fracture toughness. In addition, considering different pulse widths and temporal distributions in real high heat flux tests and

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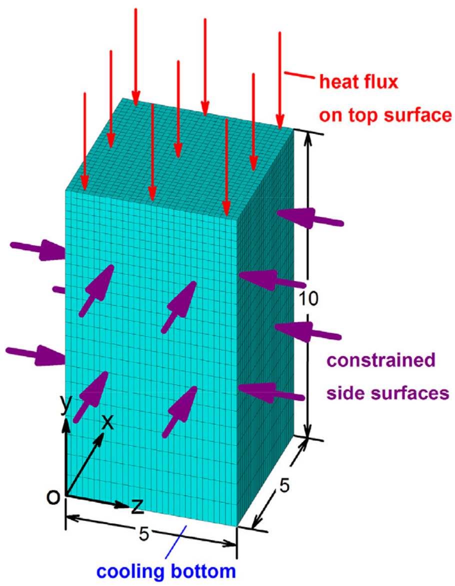

Fig. 1. The simple finite element model to represent the semi infinite space for the transient thermal-stress simulation.

actual fusion devices [6,7,10,11], three kinds of correlated temporal distributions with the pulse widths from 0.01 to 300 ms were used for discussion.

2. Model and materials

A mathematical investigation based on a theoretical model (a semi infinite space) was presented to analyze crack formation of W [9]. However, the theoretical model cannot take into account the temperature-dependent material properties especially the yield strength (σ_y) of W. Thus, a finite element model which can describe the theoretical model based on the mathematical analysis was built, as shown in Fig. 1. Because the pulse width of the transient heat flux is very small, the heat propagation distance (L_p, roughly calculated by the formula $L_p = (2t\lambda/\rho c)^{0.5}$) [12] is very limited (~0.83 mm for W under a heat pulse width of 5 ms), illustrating that the transient heat flux only influence the surface layer and the height of the model should be much higher than the heat propagation distance. Therefore, for both the infinite theoretical model and the finite element model with a bottom, the temperature and stress-strain caused by transient heat flux weren't affected by the cooling bottom. Based on the above analysis, the dimensions of the finite element model were set as 5 mm × 5 mm × 10 mm. In fact, the horizontal dimensions could be random selected. And, the model was heightened if considering longer pulse duration discussed in the following section.

The transient heat load was applied on the top surface, while the bottom was assumed to remain at initial temperature for cooling. It should be noted that the cooling bottom was to make the body temperature return to the initial temperature which was set as the room temperature (RT, 20 °C). Adiabatic boundary condition was applied on the side surfaces, because there is no temperature gradient through horizontal direction for semi infinite space. The surface was assumed to be polished and the emissivity was very low, so the surface thermal radiation had little influence on the temperature field during such short pulse and the thermal radiation can be ignored. In view of the structure analysis, for semi infinite space, any small units didn't have the horizontal displacement during heating and cooling, which means that the finite element model should be applied horizontal constraint, i.e., the XOY side and its facing parallel side were applied z direction constraint ($S_z = 0$), and the YOZ side and its facing parallel side were applied x direction constraint ($S_x = 0$). The bottom side was also applied vertical constraint ($S_y = 0$) to avoid the overall movement of whole body. In addition, it was assumed that the system was stress-free state at the initial temperature.

The mechanical temperature-dependent properties of the ITER-grade W for finite element analysis were listed in Table 1, referencing from the similar work [13–15]. The material was assumed isotropic for simplicity. It should be noted that the commercial W is often rolled so that the material shows anisotropy properties. Noticeably, in spite of the plastic deformation was allowed, the hardening was neglected due to the limited amplitude of W deformation caused by thermal expansion. Similar assumptions were taken in other relevant references [8,9].

The ANSYS transient thermal simulation of ANSYS Mechanical APDL 15.0 was selected for the analysis. A thermal-structure directed couple method was adopted to simulate the distribution and evolution of temperature and stress-strain for the W during fusion relevant transient heat loading and cooling. A twenty-node solid 226 element was used to model such transient heat transfer system. The brick analytical model was meshed for finite element model with mapped meshing using the cuboid element with a smaller size in the vicinity of the surface to ensure the computational accuracy.

This simulation was divided into two phases during one single pulse. At the first loading phase, the transient flux loaded on the surface caused surface temperature rising as well as the body expansion. While at the second cooling phase, the transient heat flux was abolished, thus the body was naturally cooled to the initial temperature for a long time about 10 s.

In order to investigate the influence of different temporal distributions for the transient heat flux on the results, three different temporal distributions, namely uniform, Gaussian and triangular distribution were considered and shown in Fig. 2 with their formulas. The uniform distribution loading pattern represented the temporal feature of the high heat flux experimental facilities such as laser and electron gun [6,7], where F is a constant which equals to the power density of the heat flux. In fact, the temporal patterns were non uniform for the transient heat loads such as the ELMs in fusion experimental devices [10,11]. Thus, the Gaussian distribution were used to describe such patterns, where q is the proportionality coefficient, t is time and $\mu = 3\sigma = 0.0025$ s. In addition, the triangle distribution was also proposed and analyzed for comparison as a simplified form of Gaussian distribution, where H is the peak value of the triangle pattern.

Table 1
Temperature-dependent properties of the ITER-grade W for finite element analysis.

T (°C)	α (10^{-6}K^{-1})	λ (Wm^{-1}k^{-1})	c (Jkg^{-1}K^{-1})	ρ (gcm^{-3})	E (GPa)	σ_y (MPa)	τ (GPa)
20	3.93	173	129	19.3	398	1350	1.3
400	4.15	141	141	19.2	392	945	1.1
1000	4.51	110	158	19.04	368	465	0.8

Where T is temperature; α is coefficient of thermal expansion (CET); λ is thermal conductivity; c is thermal specific; ρ is density; E is Elastic modulus; σ_y is yield strength; τ is tangent modulus.