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Theoretical analysis on the damages for tungsten plasma facing surface under superposition of steady-state and transient heat loads

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ABSTRACT

In ITER and future fusion devices, the plasma facing surfaces are expected to suffer from the superposition of steady-state and transient heat loads. The extreme high transient heat fluxes cause the deterioration of material surface that increases from roughing to cracking even melting. And, the high heat flux tests on pre-heated tungsten implied that the steady-state heat load induced initial surface base temperature would have great influence on the transient heat flux induced damages. The present efforts tried to explain the mechanism of this phenomenon in view of the thermal-mechanical analysis by means of finite element simulation.

The surface temperature and stress-strain distribution and evolution of a cylindrical W/Cu block under superposition of the steady-state heat loads corresponding to base temperature (20–600 °C) and transient heat fluxes (5 ms, 0–900 MW m^{-2}) were successfully simulated. The corresponding relations between stress-strain and temperature are compared with the yield strength-temperature relation to analyze the surface event evolution during the heating and cooling phases, which showed how the base temperature influenced the transient heat flux induced damages. The analysis results theoretically identified that the pre-heating by steady-state heat load indeed influenced the transient heat flux induced damages. Typically, no any crack would be generated even under extreme high transient heat fluxes close to the melting threshold if the base temperature exceeded the ductile to brittle transition temperature, and the surface also showed deterioration from roughing to cracking while then roughing with increasing of transient heat flux under a certain base temperature, which were in good agreement with the experiments results.

1. Introduction

Tungsten (W) will be used as the divertor target material in ITER and it is also the most promising candidate plasma facing material (PFM) for future fusion devices due to its high energy threshold for physical sputtering, high melting point, low tritium retention and other excellent properties [1]. The surface of tungsten plasma facing material and component (PFMC) is expected to suffer from the superposition of steady-state and pulsed transient heat loads, in which the steady-state heat loads continue the entire plasma discharge process, while the transient heat fluxes only occur during the transient events, such as the plasma disruptions, vertical displacement events and edge localized modes (ELMs) [2,3]. Moreover, the transient heat fluxes induced by ELMs cannot be completely avoided during H-mode operation which is the main operational scenario in ITER and future fusion devices [4]. In ITER, the steady-state heat loads are around 10 MWm^{-2} [5,6] at the high heat flux regions, which caused a large temperature rise about 80–100 K per MW m^{-2} on the surface of PFMCs. And the ELM-induced transient heat fluxes can reach up to several MJ m^{-2} in a very short pulse duration (~0.5 ms) [7].

In the last decade, the high heat flux tests on tungsten by means of electron, ion guns and laser have proved that the transient heat fluxes with the power density about several MJ m^{-2} in a very short duration about several millisecond are high enough to cause the material surface degradation that increase from roughing to cracking even melting [8,9]. Although it is not confirmed whether such damages are fatal, the cracking formation and growth of tungsten may lead to the particles ejection, i.e. dust formation, to some extent, certainly influencing the plasma operation stability [10]. Thus, it is important and valuable to understand the generating mechanism of damages. Moreover, according to the results of the high heat flux tests on tungsten with a pre-heating surface, the damage behaviors especially cracking would be significantly influenced by the steady-state heat load induced surface temperature, namely base temperature [11,12]. In addition, when the base temperature exceeded a certain critical value, no any cracks formed even under extreme high transient heat flux that is close to the

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melting threshold. And, the critical temperature seems to be different for different tungsten based materials with different processing, micro structures and components [12]. However, how the base temperature influence the transient heat flux induced surface damages and how to estimate the critical temperature are still unknown. So it is important to elucidate the mechanism and interaction between the two kinds of heat loads for the heat control and the ELM mitigation in fusion devices.

The present view thinks the surface roughing and cracking behaviors are related to the mechanical stress-strain and material fracture toughness, in which the former is the driving force for damages formation, while the later is a material parameter that against such destruction [13]. The temperature and stress-strain distribution and evolution of pure W with initial room temperature under only transient heat fluxes have been described and simulated [14,15]. And, the damage behaviors and mechanism by the stress-strain caused by only transient heat fluxes has been discussed in detail [15]. The steady-state heat loading would lead to a surface temperature rise and thermal stress distribution, which changed the initial state of material surface when the transient heat flux superposed. So, the material surface experienced a different process and shows a different stress-strain evolution with that under only transient heat flux loading. Meanwhile, the tungsten also shows different thermal-mechanical properties and ductile-brittle behaviors at different temperature [13]. So the pre-loading by steady-state heat would certainly influence the transient heat flux induced surface damage behaviors.

In this paper, to find the mechanism of how base temperature influence the damage behaviors, a simplified cylindrical W/Cu block similar to the ITER-like W/Cu mock-up was built for thermal mechanical simulation and theoretical analysis. The temperature and stress-strain distribution as well as evolution of W PFMC under the superposition of steady state heat loads and transient heat fluxes were simulated by means of ANSYS code. The damage behaviors were analyzed in detail and discussed with the experiment results.

2. Model and materials

In fusion devices, the W/Cu PFMC usually contains a piece of tungsten plate with thickness about several millimeters and a bottom copper alloy (i.e. CuCrZr) heat sink with a central cooling channel [16]. A cylinder with diameter of 40 mm and height of 20 mm, consisting 8 mm W on the surface and 12 mm heat sink of CuCrZr with cooling on its bottom surface was built for theoretical simulation and analysis as shown in Fig. 1. It is very convenient for theoretical analysis, and the reason will be discussed as following. Its dimensions were close to an actual W/Cu flat-type structure [16,17], thus it will show similar thermal stress-strain behaviors. Because such cylinder is axisymmetric, it can be represented by a two-dimensional axisymmetric finite element model. The thermal-mechanical temperature-dependent properties of the ITER-grade W and CuCrZr alloy for finite element analysis were listed in Table 1 [18–20]. The DBTT was an important parameter that decided the tungsten behavior. In general, the DBTT is a conventional parameter and the ductile-to-brittle transition is a continuous phenomenon. It is assumed that the ductile-to-brittle transition interval was quite short and the theoretical DBTT was assumed as 400 °C. That was to say the W material showed complete ductile behavior above DBTT, i.e. the material could occur yield and the plastic deformation was allowed, while showed brittle behavior below DBTT, i.e. only elastic deformation was allowed. These implied that the tensile stress exceeding the tensile strength or the plastic deformation changing during cooling phase in brittle temperature range might lead to the material cracking. The material was assumed isotropic for simplicity. It should be noted that the W is often rolled so that the material shows anisotropy properties, so such results can't reflect the completely actual conditions. The hardening was taken into account with the bilinear strain-hardening model. Similar assumptions were applied in other relevant references [13,15].

$$\sigma = E\varepsilon\ (0 \leqq \sigma \leqq \sigma_y)\ \sigma = \sigma_y + \tau\varepsilon_p\ (\sigma > \sigma_y)$$

Where E is elastic modulus, σ_y is yield strength; τ is tangent modulus, ε is strain, ε_p is plastic strain. The combined steady-state heat loads and transient heat fluxes were applied on the top surface uniformly. In spite of the heat load in actual devices and high heat flux test facilities have different spatial distributions [16], the surface of plasma facing materials, especially the W components will be divided into many small elements with 1–2 tens millimeters [21,22]. Thus, for such small sized block tile, the distribution of surface heat loads can be seen as uniform. The bottom was applied to an active water cooling with a heat convection about 15000 W/(m^2 K) for 20 °C, to realize the similar cooling condition in fusion devices [23]. The radiation power on the tungsten surface can be estimated by the Stefan-Boltzmann law: $q = \varepsilon \cdot \sigma_B \cdot T^4$. Where ε is the emissivity of tungsten, which was taken to be 0.3. σ_B is Stefan-Boltzmann constant (5.67 × 10^{-8} Wm^{-2} K^4). T is the temperature. For the transient case, T = 3000 K, q ≈ 1.38 MW m^{-2}. which compared to the several hundred MW m^{-2} transient heat loads, the radiation power can be neglected. For the steady-state case, we assumed T = 1000 K, q ≈ 0.01 MW m^{-2}, the corresponding temperature changes is below 10 K, which also can be neglected compared to several

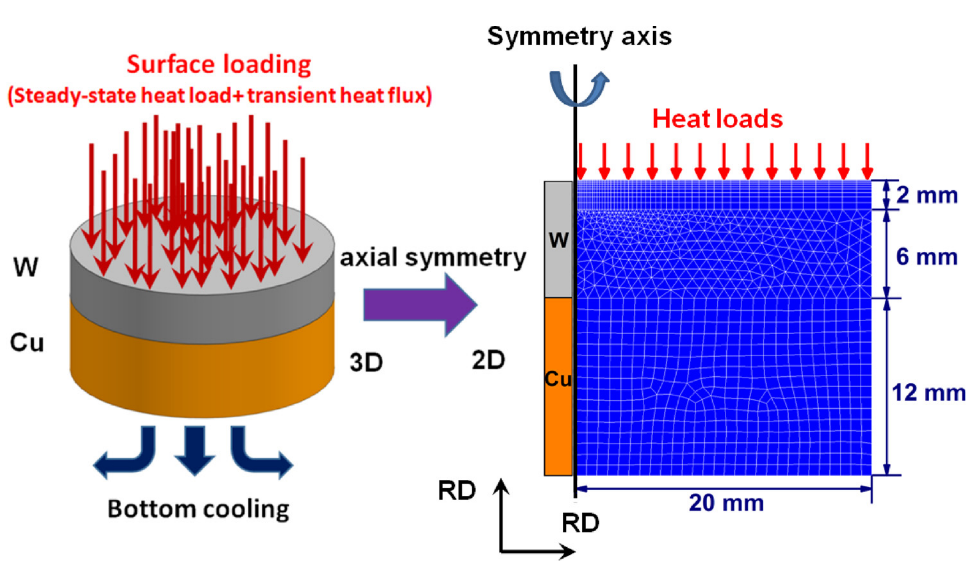

Fig 1. The analytical finite element model as well as its dimension and heating-cooling conditions. RD is radial direction and AD is axial direction.