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Near-surface thermal characterization of plasma facing components using the 3-omega method

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ABSTRACT

Near-surface regime plays an important role in thermal management of plasma facing components in fusion reactors. Here, we applied a technique referred to as the '3ω' method to measure the thermal conductivity of near-surface regimes damaged by ion irradiation. By modulating the frequency of the heating current in a micro-fabricated heater strip, the technique enables the probing of near-surface thermal properties. The technique was applied to measure the thermal conductivity of a thin ion-irradiated layer on a tungsten substrate, which was found to decrease by nearly 60% relative to pristine tungsten for a Cu ion dosage of 0.2 dpa.

1. Introduction

Plasma facing components (PFCs), such as tungsten (W), are expected to be exposed to both steady-state and transient thermal loads [1–7]. The power density of the steady-state heat loads can be as high as 5–10 MW m^{-2}, while that of the transient heat loads is anticipated to be up to 10 GW m^{-2} for short durations of a few ms during plasma disruptions and ~0.5 ms for edge localized modes [2,3]. These large thermal loads inevitably lead to an increased surface temperature rise (T_S) on the PFC, measured relative to the temperature of the heat sink, as shown schematically in Fig. 1(a). For steady-state heat loads, T_S depends on the heat flux (Q_{ss}), thermal conductivity (κ) of the PFC (e.g., W), and the thickness of the PFC (L), namely:

$$T_S = Q_{ss}L/\kappa \quad (1)$$

Eq. (1) shows that the entire thickness of the PFC contributes to the temperature rise for steady-state heat loads.

On the other hand, in the case of transient heat loads (Q_t) with a short duration of 0.5 to a few ms, the thermal penetration depth (L_P) can be significantly shorter than the overall thickness of PFCs. According to one-dimensional heat diffusion equations [8], L_P is defined as

$$L_p \approx \sqrt{2\alpha t} = \sqrt{\frac{2t\kappa}{\rho C}} \quad (2)$$

where α is the thermal diffusivity, ρ is the density, C is the specific heat of the PFC, and t is the duration of the transient heat load. Based on the thermophysical properties of W, for t = 0.5–2 ms, L_P ranges from 200 to 400 μm. As a result, the near-surface regime of PFCs, despite its small thickness, would play an important role in dictating T_S and consequently the thermo-mechanical behaviors.

When subjected to the very high particle fluxes in fusion reactors, the surface of PFCs is well known to experience damages [5–7,9]. On one hand, plasma bombardment can alter the surface material properties such as morphology and could lead to reduced thermal conductivity, which may also consequently cause a higher surface temperature, inducing larger thermal stresses in the near-surface regime of PFCs, especially in the case of large transient heat loads. On the other hand, high energy particles such as 14 MeV neutrons displace W atoms from their original lattice sites and produce radiation damage in the W. The defects associated with the damage sites (interstitials, vacancies or extended clusters etc.) can act as electron and phonon scattering centers to reduce thermal conductivity of the material.

To illustrate the important effect of near-surface thermal conductivity on the temperature distribution in PFCs when subjected to transient heat loads, we modeled the surface temperature evolution of a hypothetical PFC made of W with a thin near-surface regime 10 μm thick, as shown in Fig. 1(a). The transient heat load Q_t is 2 GW m^{-2} with a duration of 0.5 ms, which is typical for

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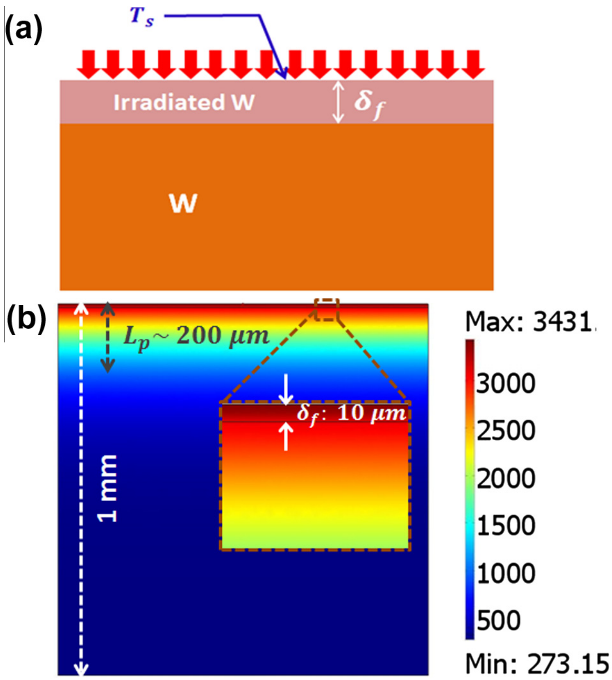

Fig. 1. (a) A schematic of tungsten with irradiation thickness δ_f. T_s represents the surface temperature and the red arrow indicate the heat load. (b) Simulated cross-sectional temperature profile of W under transient thermal loading ($Q_t = 2$ GW m^{-2}) at the end of the heat load duration ($t = 0.5$ ms) when thermal conductivity of the top irradiated layer ($\delta_f = 10$ µm) is half of the W substrate ($\kappa_{film}:\kappa_{bulk} = 1:2$). The color represents the temperature in accordance to the color scale on the right. The majority of the temperature gradient occurs within the thermal penetration depth L_p of about 200 µm. Inset: zoom-in temperature profile near the surface, which shows large temperature gradient across the film. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

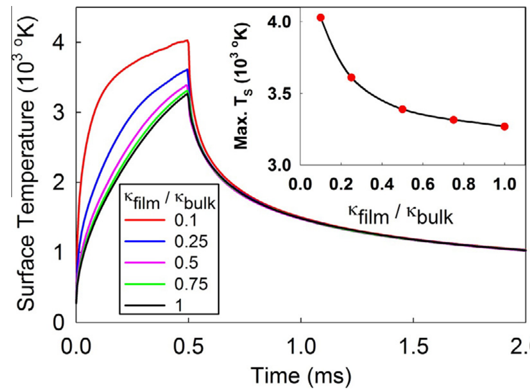

Fig. 2. Time evolution of surface temperature T_s under an applied transient heat flux ($Q_t = 2$ GW m^{-2} and $t = 0.5$ ms) for samples with various κ_{film} values. Inset: Maximum T_s vs. κ_{film} values, showing increasing T_s with lower κ_{film}.

localized edge modes [2,3]. In this model, the substrate of the PFC has the thermophysical properties of bulk W (including temperature dependent thermal conductivity κ_{bulk} and specific heat C_{bulk}), while thermal conductivity of the near-surface regime (κ_{film}) is varied from 10% to 100% of κ_{bulk}. A time-dependent finite-element code was used to compute the evolution of the temperature for different cases. Fig. 1(b) plots the cross-sectional temperature distribution in the PFC at the end of the transient heat flux ($t = 0.5$ ms), for the case with $\kappa_{film}:\kappa_{bulk} = 1:2$. This figure clearly shows that the majority of the temperature gradient occurs within the top 200-µm regime in the PFC, meaning that the transient heat load only penetrates into the PFC by about 200 µm, which is consistent with the result obtained from Eq. (2). The inset in Fig. 1(b) also shows that there is a significant temperature gradient within the 10-µm-thick near-surface regime because of its lower κ.

Fig. 2 shows the time evolution of the surface temperature for various values of κ_{film}. The figure shows that T_S is getting higher as κ_{film} is reduced, as expected. Also, the maximum T_S occurs at $t = 0.5$ ms for all the cases. The inset in Fig. 2 plots the maximum T_S vs. κ_{film}, further demonstrating increased T_S as a result of lower κ_{film}. For instance, if κ_{film} was somehow reduced to 10% of that of bulk W, T_S would be as high as ~4000 K, which would exceed the melting point of W (the model did not take phase change phenomenon into account).

The modeling result shown above highlights the importance of the near-surface thermophysical properties of PFCs on the surface temperature, especially in the case with large transient heat loads. The higher surface temperature may pose severe challenges for the operation of fusion reactors. It may exceed the melting point of W and directly cause the failure of the material. It could also lead to very large thermal stress in the near-surface regime and consequently lead to failure via delamination or cracking. Therefore, understanding the thermal properties of the thin damaged regime is vital in assessing the thermomechanical behaviors of PFCs.

As the damaged regime is only nanometers (implantation depth) to microns (diffusion distance) thick, conventional steady state thermal conductivity measurement techniques are not applicable. In this work, we describe the application of an advanced thermal characterization technique referred to as the '3ω method' to measure the thermal conductivity of the micro-sized near-surface damaged regime of PFCs. Using W as a model PFC material, we measured the thermal conductivity of the thin (~1 µm thick) ion beam displacement-damaged regime on W samples. Our measurements demonstrated more than a 50% reduction in thermal conductivity of the damaged near-surface regime compared to pristine W (from ~179 W m^{-1} K^{-1} to 73.5 ± 23.2 W m^{-1} K^{-1}). Therefore, our measurement provides not only a quantitative thermal conductivity value for future PFC designs, but also offers insights into thermo-mechanical properties of such materials.

2. Background of the 3ω method

To measure the thermal conductivity of the near-surface irradiated regime, a temperature gradient has to be established across the thickness of this regime. Because of the thin film-like nature of the ion-damaged surface (a few µm), a conventional steady-state method is not suitable as an enormously large heat flux would be needed to establish a measurable temperature differential. In this work, we use the 3ω method that has been employed previously to measure the thermal conductivity of bulk and thin film materials. This frequency domain method was first proposed and developed by Cahill [10] with the initial objective of greatly reducing possible errors from blackbody radiation for high temperature measurements, and was later extended to thin film thermal characterization [11–13].

In a typical 3ω measurement, a metal strip is used both as a micro-sized heater for applying a periodic heat flux and a sensitive thermometer for measuring the surface temperature, as shown in Fig. 3(a). The thermal conductivity determination in the 3ω method relies on thermal penetration depth, which hinges on the frequency of the applied periodic thermal wave. Similar to Eq. (2), the penetration depth (δ_p) of a periodic heat fluxes with frequency ω_q is defined as,

$$\delta_P = \sqrt{\frac{2\alpha}{\omega_q}} = \sqrt{\frac{2\kappa}{\rho C \omega_q}} \qquad (3)$$