The heat exchange reduction of tungsten “fuzz” surface irradiated with helium plasma in the PLM device

D N Gerasimov, S D Fedorovich, P Budaev, S B Morgunova, A V Karpov and Z A Zakletskii

1 National Research University "MPEI", Moscow, Russia
2 NRC Kurchatov Institute, Moscow, Russia
E-mail: budaev@mail.ru

Abstract. In this work, we measured thermal conductivity of tungsten surface layers grown under helium plasma irradiation in the PLM device at NRU “MPEI”. A stochastic nanostructured fuzz-type surface with fibers of less than 50 nm has grown on the irradiated samples. The duration of discharges in the PLM reached 200 minutes, the thermal load on the surface of the test plates during plasma irradiation was more than 1 MW / m² and more. Scanning electron microscopy (SEM) analysis revealed the nanostructured fuzz layer of the depth of approximately 1.6 µm on the tungsten exposed to plasma at 950 °C. The density of fuzz layer was observed to depend on the plasma load. We adopted the well-established laser flashing method in order to measure the heat transfer characteristics of tungsten nanostructured surface. Results from measurements show that heat exchange was reduced in the fuzz layers compared to that of pristine tungsten. This reduction can be attributed to the fuzz fibers on the surface.

1. Introduction

Tungsten surface structure under a powerful plasma load in modern fusion devices was observed to change significantly [1]. The process of plasma-surface interaction (PSI) in magnetic fusion devices involves several mechanisms of surface erosion including melting and resolidification of surface layers, melted material motion over surface, sputtering, evaporation, redeposition of the eroded material on the surface, recrystallization, reformation of surface layers from tens of nanometers to hundreds of microns [1,2]. In results, a structure of such surface obeys inhomogeneous hierarchical granularity, statistical self-similarity and scale invariance of the surface structure with unusual shape; e.g., materials with cauliflower-like [1,3,4] and fuzz-like fiberform nanostructured surface recently found in fusion devices [1-5]. In plasma-surface interaction [4-22], physical and chemical sputtering, thermal annealing due to plasma heat flux, material erosion and redeposition, melting, cracking should be considered in the problem depending on their intensity and coupling. The particle bombardment could in turn modify thermo-mechanical properties of the material such as the thermal conductivity and mechanical strength. The reduced thermal conductivity of the near surface region could lead to a
larger surface temperature rise on the plasma-facing materials under heat loads, especially the transient loads to be expected in fusion tokamak-reactor, such as edge localized modes (ELMs) [18,19]. For such purposes, the PLM device at NRU “MPEI” was constructed [6,7]. A feature of this device is the stationary plasma confinement, which is an advantage for testing materials of the divertor and first wall of a fusion reactor. In this work we present results of the experimental investigation of the heat exchange at the surface modified under helium plasma irradiation. We show that variations of the heat exchange properties are significantly changed.

2. Tungsten samples irradiated with He-plasma

Tungsten foil was exposed to helium plasma in the PLM linear divertor- plasma simulator at NRU “MPEI”. During the plasma exposure, sample temperature was monitored. Plasma conditions were measured using a reciprocating Langmuir probe. The duration of the plasma exposure was 200 minutes. The plasma conditions were as following: electron temperature was of $\sim 4$ eV, plasma density was of $\sim 3 \cdot 10^{18}$ m$^{-3}$. The incident ion energy of 60 eV was achieved by applying a negative bias to the sample manipulator. The sample temperature of about 1200 K was maintained. The surface morphology of tungsten sample was examined using a scanning electron microscope (SEM) before and after He plasma exposure. The surface has changed after exposure. The metallographic sections of tungsten sample after irradiation with the high heat plasma in the PLM device have revealed nanostructured “fuzz”-type structure grown on the surface with fibers of 20-50 nanometers, Fig.1. Scanning electron microscopy (SEM) analysis revealed the nanostructured fuzz layer of the depth of approximately 1.6 µm on the tungsten exposed to plasma at 950 °C. The density of fuzz layer was observed to depend on the plasma load.

3. Experimental method

We use LFA-457 setup, which is the experimental standard equipment by NETZSCH for investigation of thermal diffusivity $\alpha$ of a solid sample. Laser flash (pulse) method is the well-known method [12] proposed in early 1960s to measure thermal diffusivity of the sample heated by the intense light emission, for example, by laser pulse. In the simplest case, 1) for the infinitively thin
of the depth of the pulse absorption, 2) for the adiabatic conditions on sample, the temperature dependence on the reverse side of the sample of thickness $\delta$ obeys correlation

$$
\Delta T(t) = \frac{Q}{\rho C \delta} \left[ 1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp \left( -\frac{\pi^2 n^2}{\delta^2} at \right) \right],
$$

where $Q$ is the radiant energy of the laser pulse, $\rho$ is the density of the sample, $C$ is the heat capacity, $\Delta T(t) = T(t) - T(0)$. Thus, measuring the dependence $T(t)$ (so-called the thermogram) in experiment, one may calculate the thermal diffusivity with

$$
a = \frac{1.385^2}{\pi^2 t_{1/2}},
$$

where $t_{1/2}$ is the time when the temperature reaches its maximum.

This formula does not consider the heat exchange of the sample. To take into account this factor we must use another correlation [13]

$$
\Delta T(t) = \frac{Q}{\rho C \delta} \left[ \exp \left( -\frac{\beta at}{\delta^2} \right) + 2 \sum_{n=1}^{\infty} (-1)^n \exp \left( -\frac{\pi^2 n^2}{\delta^2} at \right) \right],
$$

where factor $\beta$ takes into account the heat losses on both sides:

$$
\beta = \frac{\delta}{\lambda} \left[ \left( \frac{\partial q}{\partial T} \right)_{x=0} + \left( \frac{\partial q}{\partial T} \right)_{x=\delta} \right],
$$

$\beta$ has a meaning of the mean HTC on the sample surfaces. Thus, heat exchange influences the measurement of the thermal diffusivity. We see clearly on the thermogram the presence of the heat losses from the sample and, moreover, may calculate the rate of these losses.

Thus, in experiments we investigate the laser heating of tungsten samples to check out two effects: 1) a possible variation in the thermal diffusivity as it is (explored during the heating phase), and 2) a variation in the HTC that can be observed on the thermogram at the cooling phase.

We investigate different samples which had different structures. The first samples with thickness 0.015 mm. The second set of samples were of the thickness 0.021 mm both for the flat and for the tungsten irradiated with plasma. To compare the results for different samples, it should be noted that the error in the determination of the thickness was about 0.002 mm. All measurements were done in the air atmosphere at the pressure of $10^5$ Pa and temperature of 25 $^\circ$C.
Results and discussion

For different samples of the modified tungsten with “fuzz”-type structure, we see that any variation of thermal diffusivity cannot be detected in LFA-experiments (see Fig. 2). We discuss the reasons above: our samples with thickness of ~10 μm are ‘too fat’ to discover any changes in their bulk properties caused by the change in the surface layer of depth ~10 nm. Thus, the heating phase does not disclose any useful information.

However, we see other results for the cooling phase. On Fig. 2 we see the same thermograms for the pure samples of tungsten and for the samples with modified surface as on Fig. 2, but for the longer time. The rate of the cooling is clearly different: modified surface cools down more slowly than the polished sample.

Moreover, it should be noted that for the cooling phase

\[ \frac{\rho CV}{V} \frac{\Delta T}{dt} = -\alpha \Delta TS \]  

(5)

where \( V \) and \( S \) is the sample volume and its surface area correspondingly (where \( \Delta T(t) = T(t) - T_m \) is the temperature difference between the sample temperature \( T(t) \) and the temperature of the surrounding medium \( T_m \)). Consequently, for \( \alpha = const \) we have the dependence

\[ \Delta T(t) = \Delta T(0) \exp\left(\frac{-\alpha St}{\rho CV}\right) \]

(6)

The total heat capacity of the sample \( \rho CV \) does not depend on the surface modification. Factors depended on the surface state are the heat transfer coefficient \( \alpha \) and the surface area \( S \); the surface modification acts on these factors reversely, as it was discussed above. For surface areas we have condition for the modified surface and the polished one in a form \( S_{\text{mod}} > S_{\text{pol}} \), while we can expect \( \alpha_{\text{mod}} < \alpha_{\text{pol}} \). From Fig. 2 it follows that the total cooling rate for modified surface is much slower.

Fig. 2. The thermograms: cooling rate is different for the modified irradiated with plasma and pristine polished surface of tungsten samples.
therefore, the decrease in the heat transfer coefficient dominates increase of the effective surface area due to the surface modification.

According to all the consideration, determining the complex $\gamma = \alpha S/(\rho CV)$ from the experimental data, we can estimate the role of the surface modification qualitatively.

For the first set of samples (Fig. 2) we have for the polished tungsten (taken from the clear part of the tungsten tape) $\gamma_{\text{pol}} = 0.0095 \pm 0.0007 \text{ s}^{-1}$, while for the modified sample $\gamma_{\text{mod}} = 0.0050 \pm 0.0004 \text{ s}^{-1}$ (the uncertainty was calculated as the standard deviation for different measurements).

However, for the second set of samples – with different kind of the irregular structure on the surface – we have almost the same results: $\gamma_{\text{pol}} = 0.0177 \pm 0.005 \text{ s}^{-1}$ and $\gamma_{\text{mod}} = 0.0170 \pm 0.002 \text{ s}^{-1}$. We may note that even in this case we have $S_{\text{mod}} > S_{\text{pol}}$, and $\alpha_{\text{mod}}$ differs from $\alpha_{\text{pol}}$ slightly stronger than values $\gamma_{\text{mod}}$ and $\gamma_{\text{pol}}$ from each other; nevertheless, in this case we do not see such impressive results as for the first set.

Thus, we see that the effect of the surface modification on the heat exchange properties of the tungsten strictly depends on its structure. The difference between the heat transfer characteristics of the surfaces before and after plasma influence may be strong.

5. Conclusion

In this work, we measured thermal conductivity of tungsten surface layers grown under helium plasma irradiation in the PLM device at NRU “MPEI”. A stochastic nanostructured fuzz-type surface with fibers of less than 50 nm has grown on the irradiated samples. The duration of discharges in the PLM reached 200 minutes, the thermal load on the surface of the test plates during plasma irradiation was more than 1 MW / m$^2$ and more. Scanning electron microscopy (SEM) analysis revealed the nanostructured fuzz layer of the depth of approximately 1.6 µm on the tungsten exposed to plasma at 950 ºC. The density of fuzz layer was observed to depend on the plasma load. We adopted the well-established laser flashing method in order to measure the heat transfer characteristics of tungsten nanostructured surface. Results from measurements show that heat exchange was reduced in the fuzz layers compared to that of pristine tungsten. This reduction can be attributed to the fuzz fibers on the surface. The change of the heat transfer coefficient is different for different samples and strongly depends on the porous structure that appears on the surface under the plasma influence. The largest observed variation in HTC is not less than 50%.

This work suggests that reduced thermal conductivity of plasma facing materials needs to be considered in the in-vessel components of a future fusion reactor.

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