Stochastic nanostructure and fuzz-like structure formation on the material surface under powerful plasma load in the plasma linear multicusp device

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Abstract. The plasma linear multicusp (PLM) device was constructed to test materials by powerful plasma loads. The facility is a linear magnetic trap with an 8-pole multicusp magnetic plasma confinement. In the PLM, the electron temperature of the hot and cold fraction is of 50 and 10 eV, the electron density—$2 \times 10^{18} \text{ m}^{-3}$, the stationary plasma confinement is up to 200 min and more, which is an advantage for testing materials of the divertor and first wall of a fusion reactor. Tungsten, molybdenum, graphite, iron were tested in stationary helium discharges in the PLM with the thermal load more than 1 MW/m$^2$. The temperature of the tested plates reached 1000 °C and more. A stochastic nanostructured surface and fuzz-like structure with fibers of less than 50 nm in a diameter were observed on the surfaces irradiated by hot plasma.

1. Introduction

Strong erosion with stochastic clustering of a surface has been recently observed in materials under extreme thermal plasma loads in nuclear fusion devices [1–3]. The process of plasma interaction with the surface in magnetic synthesis devices includes several mechanisms of intense surface erosion, including melting and dissolution of surface layers, movement of molten material over the surface, sputtering, evaporation, re-deposition of the destroyed material on the surface, recrystallization, and reformation of surface layers with thicknesses from tens of nanometers to hundred microns [1]. As a result, the structure of such a surface obeys inhomogeneous hierarchical granularity (fractality), statistical self-similarity and scale invariance of the surface structure with an unusual shape; e.g., materials with cauliflower-like and fuzz-like surface recently found in fusion devices [1–5].

In plasma–surface interaction (PSI), physical and chemical sputtering, thermal annealing due to plasma heat flux, material erosion and re-deposition, melting, cracking should be considered in the problem depending on their intensity and coupling. The uniqueness of the PSI under high heat load in fusion devices is that many elementary processes can affect simultaneously.
As a result, the surface morphology evolution is influenced by not a single of the above listed elementary processes, but by a cumulative integral effect of many processes. This leads to synergistic effects considered by the theory (see, e.g., [3]) taking into account surface growth instability driven by stochastic motion of agglomerated particles and clusters. This distinguishes the PSI in fusion devices from the PSI in other plasma facilities, where surface morphology evolution can be influenced dominantly by only one elementary process. Experimental data are needed to clarify such issues. In fusion devices, the fluctuating electric field driven by turbulence regulates the orbit of deposited ions leading to the random walking of the deposited particles; the fluctuation of plasma density and pressure can affect the dynamics of agglomerated atoms and clusters on the surface. So, at high heat load on the surface in fusion devices the surface morphology evolution can be influenced by the fluctuations of forces driven by turbulent plasma. The main exceptional statistical property of near-wall plasma turbulence in fusion devices is intermittency with non-Gaussian statistics [6, 7]. This statistics is responsible for long-range correlation and specific dynamics of particles, e.g., Levy-flights of deposited particles. Theoretical treatment of such process predicts the fractal surface growth of scale-invariance (self-similarity) topography with statistics of roughness inherited from statistics of driven forces, e.g., non-Gaussian statistics of near-wall plasma turbulence. Such statistics can lead to a qualitatively particular shape of the surface (e.g., cauliflower-like [2, 3]), which has the property of scale invariance inherited from turbulence statistics. To clarify all issues of such problem there are needed the study of the surface roughness over large scales (from nanoscales up to hundreds of macroscales) which are larger than typical scales interested in detail earlier, when only effects of elementary processes were mainly paid attention.

The plasma linear multicusp (PLM) device at the National Research University “MPEI” has been constructed [5] for material treatment with high-heat plasma. The device is used as well to test materials of the international thermonuclear experimental reactor (ITER) and future fusion reactors like the fusion neutron source (FNS) and the demonstration reactor (DEMO). The PLM device is a plasma trap with a linear multicusp configuration of a magnetic field and a stationary plasma discharge with plasma parameters that provides a powerful plasma-thermal load up to 5 MW/m$^2$ on materials. At the facility with a stationary plasma discharge, investigations of a nanostructured surface formation on refractory metals (tungsten, molybdenum, titanium and others) will be carried out. In the experiments, it is planned to develop a new technology for creating a highly corrugated and highly porous surface structure of refractory metals, including the so-called “fuzz” with pore size and nanofibers 50 nm, which is of considerable interest for material science, nuclear, power engineering and biomedical technologies.

2. Plasma linear multicusp device—PLM

The plasma device PLM [8,9] is a linear magnetic trap with an 8-pole multicusp magnetic field. Parameters of the device are as follows: longitudinal (axial) magnetic field on the axis of the coil—up to 0.01 T; magnetic radial field of cusps produced by permanent Nd magnets at the edge—0.2 T; the internal diameter of the discharge vacuum chamber—0.16 m; the length of the discharge chamber—0.72 m; the chamber is cooled by water which ensures a steady state plasma discharge.

Plasma parameters are as follows: duration of plasma discharge—up to 200 min or more; plasma discharge current—up to 30 A; plasma density—up to $3 \times 10^{18}$ m$^{-3}$; the electron temperature—up to 4 eV, with a fraction of hot electrons—up to 30 eV. The ion plasma flow onto the metal test sample—up to $3 \times 10^{21}$ m$^{-2}$s$^{-1}$.

Plasma heat load on test target samples is more than 1 MW/m$^2$, experiments with a load of up to 5 MW/m$^2$ are planned. The working gases are helium, argon and deuterium. The cathode is made from tantalum wire heated up to 2680 K. The tantalum screen is used to increase the efficiency of cathode heating made from tantalum. The helium plasma discharge in
The micrograph from scanning electron microscope (SEM) MIRA3 TESCAN of metallographic sections of W sample after irradiation with the high heat plasma in the PLM device. SEM high voltage (HV) mode at 112-thousand-fold (kx) magnification (MAG), working distance (WD) 14.72 mm and the detector module at the back scattering electron mode (Det: BSE) are used.

The PLM has been investigated, discharge duration was up to 200 min in experiments. Plasma discharge current with tantalum cathode reached the value of more than 15 A, it has the parabolic dependence on longitudinal magnetic field. Anode was heated by plasma up to 500 °C during stationary plasma discharge. An experimental database on the parameters of helium plasma in the PLM was obtained—plasma density, plasma electron temperature, plasma fluxes to the surface, and surface temperatures of the samples irradiated by plasma. Spectrum of the helium plasma radiation demonstrates dominant intensity of helium lines. Additional study of impurities lines needed to reveal impurity concentration taking into account possible effect on the plasma properties from even low impurity concentration (see, e.g., [10]).

The optical emission spectra of helium plasma in the PLM were recorded with a resolution of 0.12 nm in the wavelength range of from 290 to 1010 nm. It is mainly due to the lines of helium
atoms at wavelengths of 318.7, 389.0, 396.4, 471.3, 492.2, 501.6, 504.7, 587.8, 667.8, 706.5 and 728.1 nm. Spectrum interpretation was performed using lines data from the Atomic Spectra Database of the National Institute of Standards and Technology (USA). In the experimental spectrum, spectral lines of ionized helium (He II 468.7 nm and He II 656.2 nm), as well as the spectral lines of hydrogen H 486.1 nm and H 656.3 nm were identified. To determine the temperature (average electron energy), we used the method of the relative intensity of the atomic and ionic helium lines, which has the smallest error due to the large (more than 50 eV) energy gap between the excited states of the atom and the ion. The HeI 468.7 nm and HeI 471.3 nm lines were used. The observed intensity of the spectral line of atomic helium is 100 times higher than the intensity of the ionic one, which corresponds to the electron temperature $T = 2.5 \text{ eV}$ in plasma with the electron density of $6 \times 10^{11} \text{ cm}^{-3}$, which was measured by the Langmuir probe method. Using the Langmuir electric probe method, plasma parameters were measured in the PLM for various discharge parameters. A tungsten probe immersed in the end part of the
plasma column behind the anode was used. The probe was supplied with a voltage from $-110$ to $+50$ V (relative to the wall of the discharge chamber) from a stabilized power supplier. In the experiments with different plasma discharge currents, the current-voltage characteristics of the probe was analyzed and plasma density (by ion saturation current), electron temperature (by transition characteristic), floating potential (allowed to determine the plasma potential) were determined. Analysis of the IV characteristics (in the voltage range from $-44$ to $0$ V) in a semi-log graph has showed two zones with different slopes, which indicate two components (fractions) of electrons with “hot” and “cold” temperatures. The temperature of the “hot” and “cold” electrons was determined from the slopes of such a graph. The estimates of the temperature of the hot fraction of electrons obtained by this method were 50 eV, the cold fraction of electrons was from 1 to 10 eV. The electron temperature estimate, carried out using spectrometric data in analyzing the emission lines of helium ions, was about 2.5 eV, which is also in the range from 1 to 10 eV and is consistent with probe measurements.

**Figure 3.** The SEM micrograph of fuzz structure on W sample after irradiation with the high heat plasma in the PLM device obtained using the detector module of in-beam second emission (Det: In-Beam SE).
3. Stochastic and fuzz-like nanostructure formation under plasma irradiation
The PLM device is used for materials treatment with stationary hot plasma. Such studies will make it possible to advance the understanding of powerful hot plasma interaction with materials such as tungsten, molybdenum, steel, including materials of the first wall and the divertor of the ITER. The relevance of the work at this facility is related to the observation of increased erosion of tungsten in modern fusion devices that it is necessary to investigate in full-scale experiments to establish the physical mechanisms of erosion.

Series of experiments are carried out aimed at developing a technology for obtaining a highly porous surface of refractory metals (tungsten, molybdenum and others), including the “fuzz”—type structure with a unique structure consisted from nanofibers of size of up to 20 nm. The fuzz surface has a large specific area, which is of great importance for the adsorption of gases and catalysis. On such a surface, arcs can be easily ignited leading to a strong effect on plasma-wall interaction including turbulence control and anomalous diffusion [6,7]. Tungsten, molybdenum, graphite, iron were tested in stationary helium discharges in the PLM with the thermal load
more than 1 MW/m². The temperature of the tested plates reached 1000 °C and more. Current on the tungsten test sample of 2×2 cm² reached 10 A and more. A stochastic nanostructured surface and fuzz-like structure with fibers of less than 50 nm in a diameter were observed on the tungsten plates (figures 1–4). The thickness of the fuzz layer is of more than 1.5 µm as seen on metallographic sections, see figure 1. Nanofibers of 20 nm in a diameter are formed on the surface, see figure 4. Similar fuzz-like structure with nanofibers of less than 50 nm in a diameter was observed on the molybdenum and iron samples irradiated by hot plasma in the PLM.

At present, the following is known about the formation of tungsten fuzz on the surface of tungsten [11]: to generate fuzz, it is necessary to irradiate a tungsten surface in the plasma with the energy of He⁺ ions of more than 30 eV; the temperature of tungsten surface should be from 1000 to 2000 K. The other temperature intervals: below 1000 K, the adatoms concentration is so high and the distance between them is so short that clusters are formed rather quickly, and their transfer to the top of the nanofibers is impossible; above 2000 K, the formation of clusters from adatoms is impossible because of their thermal decomposition. The thickness of the fuzz layer increases with time as t¹/² and at an ion current density from 10¹⁸ to 10¹⁹ He/(cm² s), a fuzz layer of 5 µm is formed during the time of 10⁴ s (see [11]). Since the structure of the fuzz is formed under the plasma irradiation at a high temperature, the test target should be pre-heated. According to the theoretical estimates [12], the temperature of tungsten from 1385 to 1680 K under the irradiation with helium plasma is recommended for the PLM plasma device.

4. Conclusions
The PLM device at the NRU MPEI has been constructed to treat materials including testing materials of fusion reactors—ITER, FNS, DEMO. The device is a plasma trap with a linear multicusp configuration of a magnetic field and a stationary plasma discharge with plasma parameters that provides a plasma-thermal load up to 5 MW/m² on materials. The experiments with helium plasma have been carried out. Plasma load on test samples up to 1 MW/m² has been reached in these experiments. A stochastic nanostructured surface and fuzz-like structure with fibers of less than 50 nm in a diameter were observed on the tungsten, molybdenum and iron plates irradiated with hot plasma in the PLM. It is planned to develop a new technology for creating a highly corrugated and highly porous surface structure of refractory metals, including the “fuzz”-like nanostructure with pore size and nanofibers 50 nm, which is of considerable interest for material science, nuclear, power engineering and biomedical technologies. Refractory metals with a high-porosity nanostructured and fuzz-like surface are in demand for operation under extreme thermal and plasma-beam loads, in a fusion reactor, to cover the streamlined surfaces of aircraft in order to reduce aerodynamic drag at supersonic and hypersonic speeds, in biomedical applications.

Acknowledgments
The work was supported by the grant of the Russian Science Foundation No. 17-19-01469, the automatic system instrument construction was supported by the Russian Federation Megagrant No. 14.Z50.31.0042.

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