Innovative trends in development of plasma technologies

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Abstract. Experimental data on the novel materials generated in fusion devices under conditions of high-temperature plasma loads is reviewed. In fusion devices, due to the interaction of turbulent plasma with the surface, the stochastic clustering occurs and the fractal structure forms on the plasma-facing surfaces. Such surfaces are characterized by an extremely high specific area and statistical self-similarity of the surface roughness. The generated fractal structures are nano-sized and the surface consists from pores and craters ranging in size from tens of nanometers to tens of micrometers. The occurrence of such structures can result in the appearance of additional properties of such a multiscale surface, in particular, the specific catalytic properties. Statistical characteristics of such material surface characterized by the hierarchical granularity and scale invariance qualitatively differ from those of the ordinary rough Brownian surface. This gives basis for development of innovative plasma technologies for the synthesis of new nanostructured materials with the required roughness and porosity for nuclear, chemical, hypersonic technologies, as well for biotechnologies and biomedical applications.

1. Introduction
Stochastic clustering of the material surfaces exposed to the extreme thermal plasma load in nuclear fusion devices has been recently detected [1–5]. In fusion facilities, the plasma-surface interaction is accompanied by numerous effects of strong surface erosion, namely, melting and resolidification of surface layers, melted material motion and surface sputtering, sublimation, evaporation, redeposition of eroded materials over the surface, and variation of the surface layers thickness from tens of nanometers to hundreds of microns. As a result, a structure of such surface obeys the inhomogeneous hierarchical granularity (fractality), i.e., it is characterized by statistical self-similarity and scale invariance and its shape is unusual; e.g., recently, carbon and tungsten materials with cauliflower-like surface were observed in fusion devices [2–5]. Hypotheses on the existence of universal scalings for the stochastic objects that are scale invariant (statistically self-similar) due to “hidden” statistical symmetries are discussed in publications (see, e.g., [2–6]). These objects can be characterized by such statistical properties as statistical inhomogeneity and multiscale invariance, which can be described by power laws (scalings). The scale invariance of such material structures is responsible for the formation of a percolation cluster of defects and dissipative structures in a wide range of scales from submicron up to hundreds of microns scales. The nano- and mesoscale types of structure invariance and self-organization of dissipative structures can control the universal properties of these solid materials.

Development of the stochastic structures on the material surfaces in the course of material deposition from the plasma volume to the surface or during the time evolution of the plasma-metal boundary is widely described in publications (see, for example, [6]). Various theories are treating the
subject of the inhomogeneous clustering of materials (see [6]), including the kinetic models based on
the Smoluchowski equation [2, 3] which were developed for describing irregular structures observed
in solids and agglomerates of various scales. The standard theoretical model which is the most often
considered in publications is based on the Smoluchowski kinetic equation describing the stochastic
aggregation process (see [2, 3]). In publications (see, e.g., [2, 3]), a formal analogy is discussed
between the equation describing the nonlinear fragmentation-aggregation process and the kinetic
equation describing the three-wave turbulence with a power-law spectrum (in the Kolmogorov-
Zakharov approach). Redistribution of mass between clusters in the course of the agglomeration
process (coalescence/decomposition of clusters with different sizes) is similar to the energy transport
in the turbulence cascade. Such an analysis makes it possible to use the results of the turbulence theory
to describe the distributions of clusters over sizes and hierarchical granularity of the surface observed
in experiments.

This review summarizes in brief the recent experimental observations of novel materials with the
stochastic and fractal surfaces formed in fusion devices after the exposure of materials to the high-
temperature plasma loads. Prospects for application of such materials and novel technologies are
discussed.

2. Stochastic clustering of materials under the effect of thermal plasma load
Various materials with different chemical composition and initial crystal structure (tungsten, carbon
materials, beryllium, stainless steel etc.) have been studied after they were exposed to high-power hot
plasma fluxes in fusion facilities [1–5]. High-temperature plasma in fusion facilities produces
extremely high thermal load on the plasma facing materials leading to the occurrence of the specific
conditions for clusters formation on the plasma facing surfaces which are considerably different from
the conditions of solidification and clustering for any other materials being previously under study. In
particular, the hierarchical granularity and self-similarity of carbon, tungsten and beryllium (Figure 1)
surfaces with the cauliflower-like shapes have been revealed for the first time. The clustering of
material surface exposed to the high-temperature plasma qualitatively differs from the rough structure
formation on the ordinary Brownian surface and from clustering occurring under other conditions. The
specifics of materials solidification and clustering in fusion devices which appears under the plasma
effect is associated with the motion of materials (ions, clusters, melt being on the surface etc.) which
occurs under the effect of the stochastic electromagnetic field created by the turbulent edge plasma [7].
This field is responsible for the memory effects, long-term correlations and ensures conditions for the
growth of agglomerates with a self-similar structure [2–4]. In addition to this process, irregular motion
and relaxation of the material (melt) on the surface facilitate the process of clustering under conditions
of the extreme heat load on the material surface. These multiple effects trigger the mechanism of the
fractal structure growth on the surface areas with dimensions from several tens of nanometers to
hundreds of microns (see [4, 5]). Such stochastic clustering occurs mainly due to the collective
(synergistic) effects, rather than due to the specific physical and chemical properties of the initial
materials. Typically, the probability distribution functions (PDFs) for the heights of the surface relief
(Figures 2a and 2b) formed on the material surfaces exposed to the high-temperature plasma have
“heavy” tails and are not described by the Gaussian law (the normal law describing trivial stochastic
surfaces like the Brownian one). These PDFs significantly deviate from that for heights of the
reference surface relief. For example, Figure 2c shows PDF for the heights of the surface relief for the
industrial steel casting sample (Figure 2c) the roughness of which was formed under normal
conditions of solidification (after melting). To describe the experimental fractal landscapes formed in
fusion facilities, it is necessary to involve experimental data on the self-similarity properties of
surfaces with stochastic relief, i.e. the self-similarity scalings (power laws). The revealed power laws
simplify the description and systematization of the dilatation symmetries (symmetries of scale
invariance) of solids and agglomerates.
Figure 2. (a) Height profiles of tungsten sample (W) (obtained using AFM) from the QSPA-T facility and the carbon film (C) from the T-10 tokamak. Probability distribution functions for the surface height increments $\delta y = y(x + l) - y(x)$ are also shown for (b) tungsten sample profile (W) shown in Figure 1a ($l = 19.5$ nm) and (c) industrial steel casting surface profile ($l = 0.5$ $\mu$m); the Gaussian (dotted line) and the Cauchy-Lorentz (line) distributions are shown for comparison.

Generation of the fuzz structures consisting of nanofibers with dimensions of up to 50 nm on the tungsten surface (Figure 3) was observed in fusion facilities [1, 8]. The fuzz structure is usually generated under conditions of high plasma load formed by $\text{He}^+$ ions with energies of more than 20–30 eV; the temperature of tungsten surface should be approximately 1000–2000 K. The thickness of the fuzz layer increases with time as $t^{1/2}$ and, at an ion current density of $10^{18}$–$10^{19}$ $\text{He}/(\text{cm}^2 \text{s})$, the fuzz layer with thickness of ~5 $\mu$m is formed during time of $t \sim 10^4$ s [9]. To date, tungsten fuzz can be produced only in experiments at several plasma facilities in the world, such as the NAGDIS-II, PISCES-B, AIPD facilities (see review [1]) and the plasma facility at the NRU “MPEI” [10]. The fuzz surface has a large specific area, which is of great importance for its application to the adsorption of gases and catalysis. On such a surface, arcs can be easily ignited and this will have a strong effect on the plasma-wall interaction.
Figure 3. SEM micrograph of tungsten fuzz generated in the PISCES-B facility after the exposure of the underlayer to helium plasma: the temperature of underlayer was 1200 K, the exposure time was 4290 s, the He$^+$ ion flux was $2 \times 10^{26}$ particles/m$^2$, and energy of helium ions was 45 eV (see References in [1]).

3. Application of materials with fractal surface structure

Porous tungsten can be used to control the plasma sheath layer and edge plasma turbulence in tokamaks. The edge plasma turbulence near the last closed magnetic surface (LCMS) in tokamaks drives the cross-field particle flux which loads a narrow area on the divertor plates (it has dimensions of several ion gyro-radii). In the ITER, the width of such area is only a few millimetres; and extremely high loads are expected in this region and this can result in melting and destruction of the divertor plates. To achieve a steady-state operation of a fusion reactor, it is required to develop effective techniques to control plasma in the sheath layer and the edge plasma turbulence and to mitigate the thermal load on the surface of divertor plates. It is proposed to control turbulence near the LCMS using a system of electrodes made from porous tungsten [11]. The supply of potential onto the electrodes forces the modulation of plasma instabilities by the longitudinal electric field. In such a scheme, excitation of the ion-acoustic instability occurs under the effect of the longitudinal electric field as it was theoretically considered by V.P. Silin [12] who had predicted the growth of the plasma temperature $T$ with increasing electric field $E$ due to excitation of the ion-acoustic turbulence which occurs in accordance with the formula $T \sim E^2$. The schematic of the experiment proposed for a tokamak is shown in Figure 4: the radial and poloidal widths of the electrodes are 15 mm and 10 cm, respectively; DC biasing voltage $U_{dc}$ between the electrodes is in the range from $-200$ to $+200$ V; RF modulation of the $U_{RF}$ voltage amplitude at a frequency of the ion-cyclotron resonance is used to control fluctuations near the LCMS. In such a scheme, it is expected that the SOL turbulence and the related cross-field transport of turbulent plasma will be affected locally near the LCMS and that will give a positive effect. In contrast to the previous biasing schemes, it is proposed here that the biasing voltage is applied between the electrodes along the magnetic field in the absence of the radial current. The porous tungsten plates used for biasing electrodes have an advantage due to the increased emissivity of the porous surface and reduced surface erosion. A self-sustaining process of maintaining tungsten porosity is expected during a long-term operation of a tokamak fusion reactor.

Control of the turbulent boundary layer of aerodynamic flows. To reduce the aerodynamic drag and thermal load on the streamlined surfaces at supersonic and hypersonic speeds, it is required to cover airplanes with materials with high porosity. In the first experiments [13] in a wind tunnel, the stainless steel model having fractal surfaces obeying the non-Gaussian height statistics in the range from $\sim 500$ n to $\sim 200$ µm was blown round (Figure 5). The fractal surfaces were obtained by means of processing the model by plasma in the QSPA-T facility. The advantage of such surfaces is the coincidence of the spectral and statistical characteristics of the stochastic topography of the surface with the corresponding characteristics of the flow turbulence. The significant attenuation of low frequencies and a change in the aerodynamic drag force were observed in experiments in which the plate with fractal surface was used as a boundary of a turbulent flow [13]. In a wide range of the Reynolds numbers $Re$, a decrease in aerodynamic drag above the plate with fractal surface was recorded as compared to that above the plate with abrasive surface of the same roughness (with the Gaussian height statistics). For the plate with fractal surface, the scaling index $\nu$ for the drag
coefficient $c_s \sim Re^{-\nu}$ is close to that for the smooth plate (made of glass) [13]. This demonstrates the characteristic feature of a fractal surface to reduce aerodynamic drag at supersonic and hypersonic flow speeds.

Figure 4. (a) RF modulation of the plasma potential in the SOL performed using the biasing electrodes made of tungsten with the stochastic surface structure. (b) Schematic of the biasing electrodes used for plasma control near the LCMS in a tokamak with a circular cross section.

Figure 5. (a) Heights profile of a fractal surface obtained by the high-temperature plasma processing of a smooth industrial stainless steel sample. (b) PDF of the profile heights. The Gaussian (dotted line) and the Cauchy-Lorentz (solid line) distributions are shown for comparison.

Figure 6. (a) Aerodynamic drag coefficients as functions of the Reynolds numbers Re for the plates blown round in a wind tunnel: circles, crosses, stars and triangles correspond to a smooth glass surface, rough virgin surface, fractal surface, and abrasive surface PS 280, respectively; (b) Scaling index $\nu$ for the aerodynamic drag coefficient $C_f \sim Re^{-\nu}$. 
Nanostructured metals and their oxides are important materials which can be used as active layers in gas micro-sensors. Tungsten and its oxides are the promising candidates to be used for selective capture of hydrogen. This is important for secure operation of energy systems for hydrogen power engineering. Composite porous materials produced from tungsten and molybdenum are considered to be very promising effective catalytic agents in the production of hydrogen. The technology for manufacturing titanium medical prostheses requires titanium components with highly porous surfaces. Materials with different types of porosity are in demand in biomedical technologies to be used as matrices for creation of complex organometallic compounds (see, e.g., [14, 15]). Electric cardiac pacemakers implanted into human heart to treat heart arrhythmia [17].

Conclusions
In fusion facilities, high-power plasma load applied to the material surfaces and the collective effects occurring during the high-temperature plasma-surface interaction lead to the occurrence of the stochastic clustering and formation of fractal structures on the plasma facing surfaces with typical sizes from tens of nanometers to hundreds of micrometers. Such surfaces are characterized by an extremely high specific area and statistical self-similarity of the surface roughness. Highly porous and fuzz-like structures are formed on the surfaces of carbon, steel and refractory metals (such as tungsten and molybdenum). The occurrence of such structures can result in the appearance of additional properties of such a multiscale surface, in particular, specific catalytic properties. Statistical characteristics of such material surfaces characterized by the hierarchical granularity and scale invariance qualitatively differ from those of the ordinary rough Brownian surface. This gives basis for development of innovative plasma technologies for the synthesis of new nanostructured materials with the required roughness and porosity for nuclear, chemical, hypersonic technologies, as well for biotechnologies and biomedical applications [14–17].

Acknowledgements
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