Innovative potential of plasma technology

V P Budaev\textsuperscript{1,2}

\textsuperscript{1}National Research University “Moscow Power Engineering Institute”, Moscow, Russia
\textsuperscript{2}National Research Center “Kurchatov Institute”, Moscow, Russia
Corresponding author e-mail: budaev@mail.ru

Abstract. The review summarizes recent experimental observations of materials exposed to extreme hot plasma loads in fusion devices and plasma facilities with high-temperature plasma. Plasma load on the material in such devices lead to the stochastic clustering and fractal growth of the surface on scales from tens of nanometers to hundreds of micrometers forming statistical self-similarity of the surface roughness with extremely high specific area. Statistical characteristics of hierarchical granularity and scale invariance of such materials surface qualitatively differ from the properties of the roughness of the ordinary Brownian surface which provides a potential of innovative plasma technologies for synthesis of new nanostructured materials with programmed roughness properties, for hypersonic technologies, for biotechnology and biomedical applications.

1. Introduction

Plasma-surface interaction in a fusion device leads to the change of the surface morphology influenced by several mechanisms including erosion, melting and melt motion over the surface, redeposition of eroded materials, solidification and recrystallization (see [1,2]). Plasma is an object where collective phenomena dominate. Fundamental studies of collective effects in plasma, starting with pioneering works of A.A. Vlasov and L.D. Landau, and in subsequent works by B.B. Kadomtsev, V.P. Silin and other researchers led to the development of kinetic theories of plasma as a multi-particle system, as well as proposals to use plasma for controlled thermonuclear fusion and plasma technologies in materials science. Many books (see e.g. [3]) and reviews are summarized advances in plasma technologies for material processing. Problems of plasma interaction with a material wall, such as plasma sheath problem over a roughen wall, and methods for controlling a plasma sheath are still the subject of active research (see, e.g., reviews [4,5]).

Recently, stochastic surface clustering with hierarchical granularity and statistical self-similarity (fractality) were detected on materials under plasma high heat load. Such a structure of the solid surface is observed [1,2] after the plasma exposure to materials in laboratory plasma fusion devices, in electron beam and laser devices with powerful plasma radiation generated multiple simultaneous effects of erosion and redeposition of eroded material which lead to the surface structure change on the scale of tens of nanometers to hundreds of micrometers. The scale invariance properties of these unique highly porous materials define the coherence of the structure and the formation of percolation cluster of defects and dissipative structures in a wide range of scales starting from sub-micron scale, providing the unique physical and chemical properties. E.g., in experiments with helium plasma in high-temperature plasma facilities, a surface with a pore size and nanofibers up to 50 nanometers and high roughness level is formed on refractory metal. Such nanostructured metals are needed to use in plasma/beam devices [1] including fusion reactors, as well to create high-current cathodes, for coating streamlined surfaces of aircrafts to reduce the aerodynamic drag at supersonic and hypersonic speeds, for synthesis of new nanostructured materials with programmed properties and organometallic composite materials in biotechnology and biomedical applications; as a matrix for the growth of the
organometallic complex compounds. Nanostructured metals and their oxides are materials for use as active layers in gas microsensors, as catalysts in hydrogen technologies.

In this review, we focus on the use of extremely high heat plasma in fusion devices and plasma facilities for material processing to produce self-similarity (fractality) of surface structure and highly porous and roughened surface. A generalized analysis of such data will make it possible to advance in the innovative development of plasma technologies.

2. Plasma-facing materials in fusion devices and plasma facilities

Stainless steel, graphite, tungsten, molybdenum, beryllium are typically used as plasma-facing materials in fusion devices and plasma facilities to provide heat resistance and / or high thermal conductivity of first wall components. Such materials are used in tokamaks, stellarators, and other plasma facilities where powerful loads can lead to overheating and even to the melting of the surface. There are effects of severe erosion, cracking and modification of the surface of materials contacted with the plasma. In the case of cyclic or long-term high-power thermal loads under the action of plasma in such devices, the surface temperature of the materials may exceed the recrystallization temperature leading to a change of the microstructure, grain growth, deterioration of mechanical properties and embrittlement, formation of heterogeneous and porous layers on the surface. General approaches in the literature to the classification of the processes of erosion, modification and destruction of materials under conditions of a powerful high-temperature plasma load are usually based on the experiments of the past decades on non-fusion plasmas and theoretical concepts of the metal behaviour at elevated thermal loads. In view of the complexity of the issue, several effects are separately considered (see [1]) such as sputtering, the action of unipolar arcs and sparks, cracking; melting of the surface layer, molten metal motion over the surface, drop erosion, vaporization and boiling, recrystallization and solidification of the molten layer leading to embrittlement and change in the relief. The listed effects can be supplemented on the basis of new experimental data obtained in recent years, including combining of these effects. An overview of the effects of cracking and erosion in fusion devices, most frequently discussed in the literature in recent years, is given in [1].

For new technological applications, the most interesting effects are the growth of nanoscale layers of tungsten and molybdenum such as "fuzz" (see [1]) and stochastic clustering of the surface with hierarchical granularity observed in recent years in tokamaks, plasma facilities with pulsed and stationary high-power plasma.

Porous (rough) layers with a unique surface structure are observed after irradiation in fusion devices, including so-called materials with a fractal structure that have a chaotic structure with granularity hierarchy (for example, the "cauliflower" type) [6,7], Fig. 1. Such structures have an increased specific area in comparison with the smooth or ordinary structure (e.g., even a cracked surface significantly destroyed). The peculiarity of such fractal structures is the presence of various scales of surface structure (pores, craters, etc.) from tens of nanometers to tens of micrometers, which can provide, for example, additional qualities and catalytic properties of such a multiscale surface. Self-similar (fractal) surface stochastic structure with different scales of granularity ranging from nanometers (Fig. 1) was observed [1,2,6] on various materials, such as carbon, tungsten, beryllium, Fig. 1, irradiated by high-temperature plasma in pulsed facilities (QSPA-T, QSPA-Be) and tokamak T-10 Fig. 1a,2b. It may indicate universal mechanisms of stochastic clustering of materials under the influence of high-temperature plasma (see discussion in [2,6]). Such a clustering qualitatively differs from the trivial roughness of the Brownian surface.

In the experiments on linear plasma facilities NAGDIS-II, PISCES, AIT-PID, porous layers (so-called “fuzz”) on tungsten surface is observed after irradiated by helium plasma, see [1,15], Fig. 2b. The porosity and the depth of such layer depend on the intensity of the helium ions flux on the surface and the total fluence. The grows is observed at a substrate temperature higher than 530° C. A strong decrease in the thermal conductivity of such tungsten surface was observed [15].
3. Plasma technologies to produce highly porous materials with a fractal nano- and microstructure

The problem of fractal growth of interface is considered in condensed matter physics [9]. Synergetic effects should be taken into account. In devices with hot plasma the powerful plasma load on the material surface leads to intense erosion of plasma facing materials such as the evaporation of material, melting, melt moving, cracking and a significant change in the surface structure. It is assuming an influence of plasma parameters on a stochastic clustering of material surface exposed in fusion devices. In fusion devices with magnetically confined plasma, such as tokamaks and others plasma facilities, the near-wall plasma is in a strong turbulent state (see reviews [10,11]). In near-wall (edge) plasma, drift-wave instabilities drive strong fluctuations of plasma density and electric fields. Charged particles (electrons, ions of working gas and impurities, molecular radicals and charged clusters) move over the material surface in turbulent electric fields generated by plasma turbulence. Edge turbulence properties like an intermittency, non-Gaussian statistics, multifractality, anomalous bursty transport and superdiffusion are typically observed in the fusion devices and facilities with high-temperature plasma (see reviews [10,11]). The intermittency and the self-similarity properties are responsible for the memory effect and large-scale correlation in space and time leading to substantial particle, heat and momentum intermittent transport to the surface. The plasma particles over the surface can be involved in stochastic large-scale dynamics known as superdiffusion or Levy-type process with predominant “flights”. It means that the dynamics (driven by fluctuating plasma electric field) of ions and clusters over the surface deviates from normal diffusion (ordinary Brownian motion) influencing the agglomeration process on the surface. Such agglomeration drives a fractal growth of the surface dominated by statistics of dynamics affected by
near-wall plasma turbulence [6,7]. A describing such a complex process requires consideration of the kinetic equations of the general form (e.g., the Smoluchowski kinetic equation). The solution of this equation is a complex theoretical problem, it depends on the symmetry of the problem including functional dependence of the kernel term in the kinetic equation and its property of self-similarity. Experimental data on the self-similarity property of stochastic surface (such as scalings of self-similarity - power laws of scale invariance) should be used to simplify the problem. In this way, it is important to find the most common power laws describing the surface clustering, which will be used for the data systematization and for the description of the material properties after irradiation by plasma. In the literature, it is discussed the formal analogy (see [2]) between the non-linear equation for the fragmentation - aggregation process and kinetic equation describing 3-wave turbulence, for which the power spectrum is proposed in the Kolmogorov-Zakharov approach. Distribution of clusters by mass in the fragmentation - aggregation process (aggregation / disintegration of clusters of different sizes) is similar to the cascade process of energy transfer in turbulence: the number \( N \) of particles with mass \( m \) is described by the power law \( N(m)\sim m^{(3+\eta)\frac{2}{d}} \), \( C \) is a constant; the index \( \eta \) is determined by self-similarity. Agglomeration processes of different self-similarity have different spectra of surface relief that can be used for a classification and a systematization of experimental data. Above view on the problem can be used to develop a novel plasma technology to produce highly porous materials with fractal (self-similar) nano- and microstructure.

Quantitative characteristics of stochastic relief by spectral and statistical analysis allow to characterize the qualitative difference between the stochastic clustering of a material surface after the treatment with high-temperature plasma from rough surfaces formed under other conditions. Fourier spectra of the relief profile characterize the heights (size of structures on the surface). Such spectra (Fig. 3) are broadened without any resonances, indicating no dominant periodic structures in the relief with the power functional dependence on the wave number \( k \) as \( S(k)\sim k^{-\eta} \), the power exponents \( p \) are in the range from -2.4 to -2.8 or more indicating non-trivial stochastic clustering [2]. The statistical properties of stochastic relief self-similarity is described by the probability distribution function (PDF) of the sample relief heights. For the samples irradiated by high-temperature plasma the PDF typically has a "heavy" tails, and can not be described by the Gaussian (normal) law (Fig. 4). It corresponds self-similarity (fractality) with non-Gaussian property. Such statistics differs from the trivial roughness of the Brownian surface (of the Gaussian statistics) as was shown by analysis of reference samples [2]. Revealed power laws of spectral and statistical scalings can be used to describe the symmetry of scale invariance of solids and agglomerates with irregular stochastic structure and can be used for technology developing.

**Figure 3.** The Fourier spectrum of the stochastic relief of tungsten sample from QSPA-T [3] (line) laws are shown for comparison.

**Figure 4.** Probability distribution function for the surface height increments \( \delta y = y(x+l) - y(x) \), tungsten samples, \( l = 19.5 \) nm; Gaussian (dotted line) and the Cauchy-Lorentz.  

The scale invariance of such material structure relates with a percolation cluster of defects and dissipative structures over a wide range of scales, starting from submicron scales. In the literature, hypotheses on universal scaling of stochastic objects with the scale invariance (statistical self-
similarity) are discussed (see [1,2,7-9]) for which "hidden" statistical symmetries are responsible. Typical properties of such objects are statistical heterogeneity and multiscale invariance. Scale invariance and self-organization of dissipative structures at the nano- and meso-scales affect the universal properties of a solid body at a macro scale which is a potential of development of innovative plasma technologies.

4. Application of new materials with fractal and a highly porous nano- and microstructure

In recent years, various strategies for obtaining nanostructured porous metals (including tungsten, molybdenum etc.) formed by nanoparticles, nanocrystals, etc., have been actively discussed and proposed in the literature. Such nanostructured porous and roughen materials possess qualitatively new properties that are in demand in electrochemical catalysis, in the production of sensors, in biomedical technologies, etc. In the context of nanometre-sized structured materials and the perspectives of their technological applications, plasma spray technology is developing to master the coating microstructure at a nanometre scale level [14]. In such spray technology the agglomeration of the injected nanoparticles on the surface can dominantly lead to a Brownian-like surface growth. Novel plasma technology based on high-temperature plasma facilities has a potential to propose approach for new unique surface structure production (see above).

![Figure 5. Fractal surface profile formed in fusion device and used in the wind tunnel experiments](image1)

![Figure 6. Drag reduction c_x vs. Reynolds numbers Re: smooth plate (glass). – O, virgin surface - +, fractal surface - ★, abrasive surface PS 280 – V](image2)

High-porosity coating of aircrafts by refractory materials are required to reduce drag and heat load at supersonic and hypersonic speeds. Properties of the turbulent boundary layer (TBL) over the fractal surfaces of the specific granularity are studied in the wind tunnel [12,13]. The fractal surfaces obeying the non-Gaussian statistics of heights from ~500 nanometers to ~200 micrometers is formed during the process of the plasma-surface interaction in fusion device QSPA-T [12], Fig.5. Such level of roughness satisfies criteria for a damping of turbulent vortexes. In the TBL it was observed significant damping of the low-frequency spectral range and the change of the drag force in experiments with the fractal surface plate [12] as the boundary of the turbulent flow. Within broad range of Reynolds numbers Re it was observed the drag reduction $c_x$ over the fractal plate as compared with the $c_x$ for the abrasive surface (with the Gaussian statistics of heights) of the same roughness, Fig.6. For the fractal surface the scaling index $\nu$ of the drag coefficient $c_x \sim Re^{-\nu}$ is close to the $\nu$ for the smooth plate (glass). It demonstrates a potential of fractal surface to reduce the aerodynamic drag at supersonic and hypersonic speeds.

Nanostructured metals and their oxides are an important material for applications as active layers in gas microsensors. Tungsten and its oxides are promising candidates for selective capture of hydrogen, which is important for hydrogen energy systems and ensuring the safety of such systems. Composite porous materials based on tungsten and molybdenum are considered as a very promising effective catalyst for the production of hydrogen (see, e.g., [16]). An obtaining a highly porous surface of titanium components is of great importance for the technology of manufacturing titanium medical
prostheses. Materials with different types of porosity are in demand as a matrix for the growth of complex organometallic compounds (see, e.g., [17,18]) in biomedical technologies. Electric cardiac pacemakers ([20] implanted into human heart to treat heart arrhythmia.

5. Conclusions
The effects of surface stochastic clustering with hierarchical granularity (statistical self-similarity - fractality) have been recently discovered when the material is exposed to extreme thermal plasma loads in fusion devices and plasma facilities with high-temperature plasma. In such devices the process simultaneously involves multiple mechanisms of erosion and redeposition of eroded material, material melting and movement over surface layers. Such processes lead to the fractal growth of the surface on scales from tens of nanometers to hundreds of micrometers forming statistical self-similarity of the surface roughness with extremely high specific surface. This provides a potential of innovative plasma technologies for synthesis of new nanostructured materials with programmed properties, for coating streamlined surfaces of aircrafts to reduce the aerodynamic drag at supersonic and hypersonic speeds, for biotechnology and biomedical applications. Various materials including refractory metals [1, 2, 21] are the candidates for such technology applications.

References
[1] Budaev V P 2016 Physics of Atomic Nuclei 79(7) 1137-1162
[2] Budaev V P 2017 JETP Letters 105, 5
[3] Lieberman MA and Lichtenberg AJ, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley and Sons, Inc., Publication, 2005)
[4] Robertson S. 2013 Plasma Physics and Controlled Fusion 55 9
[5] Treil J. P. 2016 Journal of Physics D: Applied Physics 49 39
[6] Budaev V P, et. al. 2007 Physica A: Statistical Mechanics and its Applications 382 359-377
[7] Budaev V. P. and Khimchenko L. N., 2007 J. Exp. Theor. Phys. 104 629
[8] Mandelbrot B. B., *The Fractal Geometry of Nature* (W. H. Freeman, New York, 1982).
[9] Barabasi A. L. and Stanley H. E., *Fractal Concepts in Surface Growth* (Cambridge Univ. Press, Cambridge, 1995).
[10] Budaev V. P., Savin S. P., and Zelenyi L. M. 2011 Phys. Usp. 54 875
[11] Budaev V. P., Zelenyi L.M., Savin S.P. 2015 Journal of Plasma Physics 81 6 10
[12] Budaev V P, et. al. 2013 Plasma Physics Reports 39(11) 910-924
[13] Brutyan M. A., Budaev V. P., Volkov A. V., et al , 2013 Uch. Zap. TsAGI 44 (4) 15
[14] Fauchais P and Vardelle A 2011 Journal of Physics D: Applied Physics 44 19
[15] Takamura S. 2015 Journal of Nuclear Materials 463 325–328
[16] Xu-Dong Wang, e.a. 2016 Energy Environ. Sci. 9 1468-1475
[17] Barth J. V. e a a. 2005 Nature 437 671
[18] Wu H. B. 2015 Nature Communications 6 6512
[19] Golestanirad L., e.a. 2013 Front Neuroeng. 6 3.
[20] Xu L. e.a. 2015 Advanced Materials 27(10)
[21] Budaev V P, et. al. 2012 JETP Letters 95(2) 78-84

Acknowledgments
The work has been supported by the Grant RSF № 17-19-01469.