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Stochastic clustering of material surface under high-heat plasma load

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ABSTRACT

The results of a study of a surface formed by high-temperature plasma loads on various materials such as tungsten, carbon and stainless steel are presented. High-temperature plasma irradiation leads to an inhomogeneous stochastic clustering of the surface with self-similar granularity – fractality on the scale from nanoscale to macroscales. Cauliflower-like structure of tungsten and carbon materials are formed under high heat plasma load in fusion devices. The statistical characteristics of hierarchical granularity and scale invariance are estimated. They differ qualitatively from the roughness of the ordinary Brownian surface, which is possibly due to the universal mechanisms of stochastic clustering of material surface under the influence of high-temperature plasma.

1. Introduction

Effects of stochastic clustering of a surface have been recently detected in materials under extreme thermal plasma loads in laboratory nuclear fusion devices [1,2]. The process of plasma–surface interaction in these devices involves numerous mechanisms of intensive surface erosion including melting and resolidification of surface layers, melted material motion and sputtering over surface, sublimation, evaporation, redeposition of the eroded material on the surface, recrystallization, reformation of surface layers from tens of nanometers to hundreds of microns. In results, a structure of such surface obeys inhomogeneous hierarchical granularity (fractality) – statistical self-similarity and scale invariance of the surface structure with unusual shape; e.g., carbon materials with cauliflower-like surface recently found in fusion devices [3].

Hypotheses of universal scalings of stochastic objects with scale invariance (statistical self-similarity), which is due to "hidden" statistical symmetries, are discussed in the literature (see, e.g., [4–6]). The statistical properties of such objects are statistical inhomogeneity and multiscale invariance, which is described by power laws (scalings). The scale invariance of such materials structure 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 micron scales. Scale invariance in a structure and self-organization of dissipative structures at nano- and mesoscales can regulate the universal properties of such solid materials. Restructuring and stochastic clustering of surface cause significant changes in the physical and chemical properties of solid surface leading to an influence on the plasma–surface interaction and feedback effects.

The growth of the stochastic structure of materials in the process of deposition from the volume to the surface or during the evolution of the interface boundary is widely described in the literature (see, for example, [5]). Inhomogeneous clustering of materials is the subject of various theories (see [5]), including kinetic models based on the Smoluchowski equation [7,9], for describing irregular structures observed in solids and agglomerates of various scales, e.g., of cosmic objects [8].

The standard theoretical model, most often considered in the literature, is based on Smoluchowski kinetic equation described stochastic aggregation process (see Refs. [7,9]): two particles (or clusters) with masses m_1 and m_2 interact and adhere forming a new particle (cluster) with mass $m = m_1 + m_2$. In such a model it is assumed that aggregation is irreversible in the sense that large particles (clusters) do not decay. The equation for the concentration $N(m,t)$ (see, e.g., [10]):

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$$\frac{\partial N(m,t)}{\partial t} = \frac{\Lambda}{2}\int_0^\infty dm_1 dm_2 K(m_1,m_2) N(m_1,t) N(m_2,t) \times \left[\delta(m-m_1-m_2) - \delta(m-m_1) - \delta(m-m_2)\right] + \frac{J_0}{m_0}\delta(m-m_0) - \frac{J}{M}\delta(m-M) \quad (1)$$

The kernel $K(m_1, m_2)$ and the factor Λ control the rate of interaction of clusters (particles). The last two terms in (1) are the source (incoming particles of mass m_0 with the flux J_0) and the sink (removal of particles of mass M with a flux J).

In the standard agglomeration model, the evolution and distribution of clusters in scales (mass and size of clusters) are governed by the kernel $K(m_1, m_2)$ in the kinetic equation (1), the kernels with self-similarity properties are considered in the literature (see, for example, [9]):

$$K(hm_1, hm_2, hm) = h^\eta K(m_1, m_2, m), \quad K(m_1, m_2) \sim m_1^\mu m_2^\nu,\ \mu + \nu = \eta. \quad (2)$$

In the literature, it is discussed a formal analogy (see, e.g., [10]) between the equation for the nonlinear fragmentation–aggregation process and the kinetic equation describing 3-wave turbulence, for which the power-law spectrum is considered in the Kolmogorov–Zakharov approach [11–14]. The redistribution of mass between clusters in the process of agglomeration (the sticking/decay of clusters of different sizes) is analogous to the energy transfer in turbulence cascade. Such an analysis makes it possible to use the achievements of the turbulence theory to describe the distribution of clusters in scales and the hierarchical granularity of the surface observed in experiments (see, for example, [3,15]).

The kinetic equation with kernel (2) can be treated by using the theory of A.N. Kolmogorov [11] and the methods developed by V.E. Zakharov [12–14]. A self-similar solution and universal spectra of kinetic equations in the framework of the theory of weak turbulence were obtained for the number N of particles with mass m:

$$N(m) = Cm^{-(3+\eta)/2}, \quad (3)$$

where η is the self-similarity exponent of the kernel (2) and C is a constant.

It follows from (2) and (3) that different spectra (2) with different η exponents can be observed for agglomeration processes with different self-similarity indices μ and ν. This property can be used to classify stochastic clustering processes.

In the standard agglomeration model, it is assumed that there is no spatial correlation between aggregates. In real experimental conditions of plasma–surface interaction in fusion device, this assumption is not fulfilled: there are spatio-temporal correlations of the processes [2,16]. Also, processes of decay of clusters are possible (in analogy with turbulence where the reverse cascade regulates process). These processes lead to a deviation from the spectrum (3) considered in the Kolmogorov–Zakharov approach. Theoretically, such a problem is discussed, for example, in [10], where multifractal scaling of the correlation function is considered.

To simplify the problem, it is necessary to involve experimental data on the self-similarity properties – self-similar scalings of a stochastic surface relief. On this way it is important to find the most general power laws realized in real clustering processes. Revealed power laws will facilitate the description and systematization of the dilatation symmetries (symmetries of scale invariance) of solids and agglomerates.

The effect of fractal surface growth is observed in various deposition experiments (for example, molecular beam epitaxy, vapor deposition etc. [5]) where the dynamics of agglomerated particles and clusters is affected by several driven and damping growth mechanisms (elementary processes) on large spatio-temporal scales. The problem of fractal growth can be described by the theoretical models treated nonlinear equations like Kardar–Parisi–Zhang equation (see [5]) considered effects from competing elementary processes. As was shown by theoretical treatment (based on Smoluchowski kinetic equation etc.), scale invariance properties will inherit the statistics of forces regulated the dynamics of agglomerating particles.

The critical issue of the problem is how the surface morphology would be influenced by elementary processes. In case of plasma–surface interaction (PSI), 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 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 [5] 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 effect 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 [27]. 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 inhered 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), 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.

In this work, the spectral and statistical properties of the stochastic clustering of material's surfaces formed under the high-temperature plasma load in nuclear fusion devices are analyzed in comparison with clustering of reference samples of the ordinary Brownian-like roughness formed at solidification after melting or low-temperature plasma impact.

Materials of various chemical composition (such as tungsten, stainless steel and graphite) with crystalline virgin structure and smooth surface, were irradiated by high heat plasma in fusion devices in exceptional extreme conditions which are strictly different from any other conditions of solidification and clustering of materials previously analyzed. The characteristics of self-similarity of the surface structure from nanoscale to macroscale are found from the data of high-resolution profilometry, scanning electron microscopy and atomic force microscopy.