Stochastic clustering of material surface under powerful load of high-temperature plasma

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Abstract. The results of a study of a surface formed by high-temperature plasma loads on refractory metals such as tungsten and stainless steel are presented. There is an inhomogeneous stochastic clustering of the surface with self-similarity properties of the granularity structure from nanoscale to macro scale, similar to the previously described fractal structure of carbon materials from fusion device. The statistical characteristics of hierarchical granularity and scale invariance are estimated that qualitatively differ from the properties of the roughness of the Brownian surface, which is possibly due to the universal mechanisms of stochastic clustering of materials under the influence of high-temperature plasma.

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]). 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 fusion device.

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 \( N(m) = Cm^{(3+\eta)/2} \), where \( C \) is a constant; the index \( \eta \) is determined by the property of 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.

2. Experiment and results
We investigated tungsten samples [3], manufactured from polycrystalline tungsten plates of originally smooth surface, after the high heat flux test in the QSPA-T facility by high-temperature plasma with
loads expected in the ITER. After the tests the tungsten samples have a rough surface with stochastic structure [3] and different scales of granularity ranging from nanometers (Figure 1) similar to the previously detected on graphite samples from the T-10 tokamak [4] (Figure 2).

Figure 1. SEM micrograph of tungsten sample after the high heat plasma test in the QSPA-T [3].

Figure 2. AFM height profiles of tungsten sample (W) from the QSPA-T [3] and the carbon film (C) from the T-10 tokamak [4].

Quantitative characteristics of the stochastic relief were found by spectral and statistical analysis of the experimental profiles. It allowed characterizing the qualitative difference between the stochastic clustering of samples after the treatment with high-temperature plasma from rough surfaces formed under other conditions. Fourier spectra of the relief profile (Figures 3, 4) characterize the heights (size of structures on the surface). The spectra are broadened without any resonances, indicating no dominant periodic structures in the relief. The spectra have the typical decaying shape observed usually in objects that have scale invariance and statistical self-similarity. The functional dependence of the Fourier spectrum on the wave number $k$ can be described by a power law $S(k)\sim k^p$, the power exponents $p$ are presented in Table 1. Note that for the tungsten samples [3], stainless steel [5] and graphite [4, 6] after exposure to high-temperature plasma in the T-10 tokamak, in the QSPA-T and in the NAGDIS-II plasma facilities the index $p$ has the value in the range of -2.4 to -2.8 or more. In contrast, for reference samples not treated by the high-temperature plasma (such as molybdenum after irradiation by low-temperature plasma in the magnetron discharge and industrial steel casting after solidification), the index $p$ ranges from -1.97 to -2.2. 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" tail, and cannot be described by the Gaussian (normal) law (Figure 5). For comparison, a sample of the industrial steel casting, the rough surface of which was formed during solidification after melting, has the PDF of heights close to the Gaussian law (Figure 6) indicating the trivial statistical properties of clustering. Self-similarity of the stochastic relief is characterized by the Hurst exponent $H$ [4, 6] (Table 1); tungsten, graphite and stainless steel samples after exposure to high-temperature plasma have the rough surface relief characterized by the Hurst exponent in the range from 0.68 to 0.86, which corresponds to an irregular stochastic clustering with hierarchical granularity (fractality) [4, 6].
3. Conclusions
The paper presents the results of a study of the irregular surface structure formed after high-temperature plasma loads on samples of tungsten and stainless steel, the materials used for the manufacturing of the first wall components in fusion plasma devices. An inhomogeneous stochastic clustering of a surface with self-similarity properties of the granularity structure from nanoscale to macroscale is found, similar to that found earlier for carbon materials [1, 2]. It may indicate universal mechanisms of stochastic clustering of materials under the influence of high-temperature plasma. Such a clustering qualitatively differs from the trivial roughness of the Brownian surface; it was shown by analysis of reference samples - molybdenum after irradiation by plasma in the magnetron discharge and a casting sample of industrial steel with the typical trivial roughness formed...
by solidification after melting. Revealed power laws of spectral and statistical scalings can be used to describe the symmetry of scale invariance of solids and agglomerates with irregular structure.

Table 1. Scaling index of the Fourier spectrum $p$, Hurst exponent $H$.

| N | The sample                                                                 | $p$  | $H$  |
|---|---------------------------------------------------------------------------|------|------|
| 1 | Tungsten after high heat plasma test in QSPA-T, 2 pulses of 2 MJm$^{-2}$ [3] | -2.62| 0.86 |
| 2 | Tungsten after high heat plasma test in QSPA-T, 50 pulses of 2 MJm$^{-2}$ [3] | -3.18| 0.81 |
| 3 | Carbon film from the T-10 tokamak [4]                                     | -2.49| 0.78 |
| 4 | Carbon film from the T-10 tokamak [4]                                     | -2.59| 0.77 |
| 5 | Graphite limiter from NAGDIS-II [6]                                       | -2.29| 0.68 |
| 6 | Stainless steel after high heat plasma test in QSPA-T [5]                 | -2.85| 0.72 |
| 7 | Stainless steel after high heat plasma test in QSPA-T [5]                 | -2.87| 0.68 |
| 8 | Molybdenum after irradiation by plasma in the magnetron discharge          | -2.20| 0.60 |
| 9 | Industrial steel casting after solidification                             | -2.41| 0.58 |

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