Stochastic clustering of material surface under high-heat plasma load in fusion devices

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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 and the 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 and tungsten materials with cauliflower-like surface recently found in fusion devices [1-3]. 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. 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. In the literature, it is discussed the formal analogy (see, e.g., [4]) 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 $N(m)=Cm^{-(3+\eta)/2}$, C is a constant, η is the self-similarity exponent of the kernel in the kinetic equation; different η exponents can be observed for agglomeration processes. This property can be used to classify stochastic clustering processes.

2. Experimental results

We investigated graphite samples from the T-10 tokamak [5], tungsten samples [1,3], 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 [1,3] and different scales of granularity ranging from nanometers (Fig. 1) similar to previously detected on graphite samples from the T-10 tokamak [5] (Fig. 2).

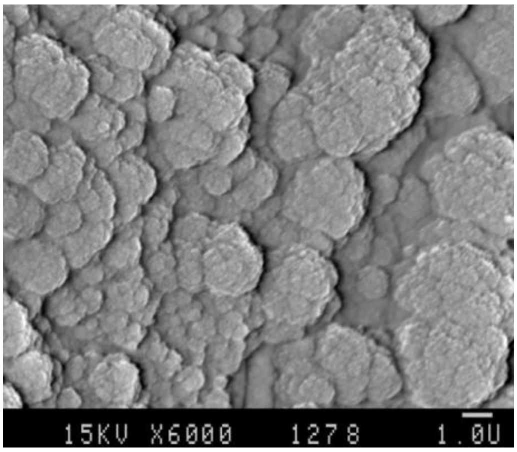

Figure 1. SEM micrograph of tungsten sample after the high heat plasma test in the QSPA-T [1,3].

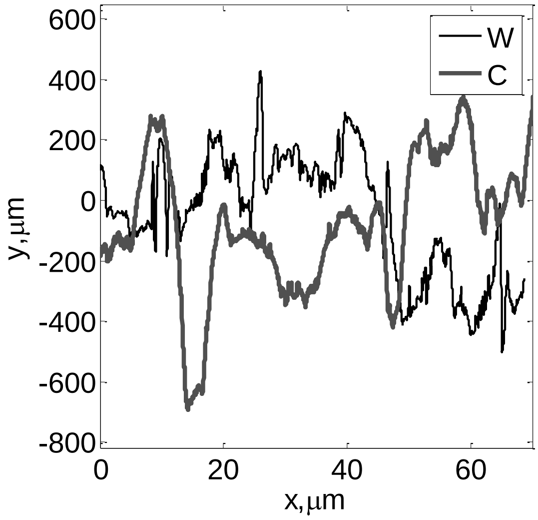

Figure 2. AFM height profiles of tungsten sample (W) from the QSPA-T [1,3] and the carbon film (C) from the T-10 tokamak [5].

Quantitative characteristics of stochastic relief were found by spectral and statistical analysis of the experimental profiles. It allowed to characterize 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 (Fig. 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 [6], stainless steel [7] and graphite [8] 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" tails, and can not be described by the Gaussian (normal) law (Fig. 5). For comparison, sample of industrial steel casting, which rough surface was formed during solidification after melting, has the PDF of heights close to the Gaussian law (Fig. 6) indicating the trivial statistical properties of clustering. Self-similarity of the stochastic relief is characterized by the Hurst exponent H [5,8] (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) [5,8].

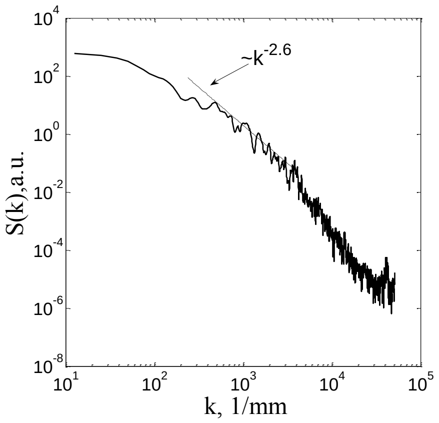

Figure 3. The Fourier spectrum of the stochastic relief of tungsten sample from QSPA-T [1,6] in Fig. 2

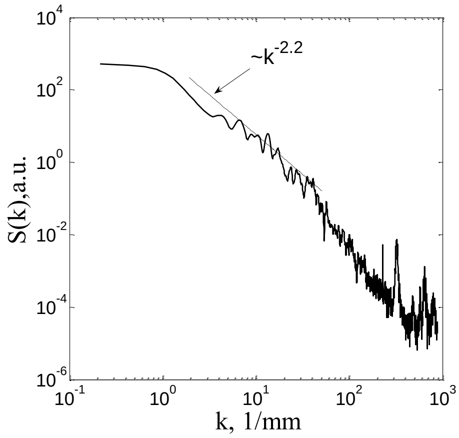

Figure 4. The Fourier spectrum of the stochastic relief of molybdenum surface after irradiation by plasma in the magnetron discharge

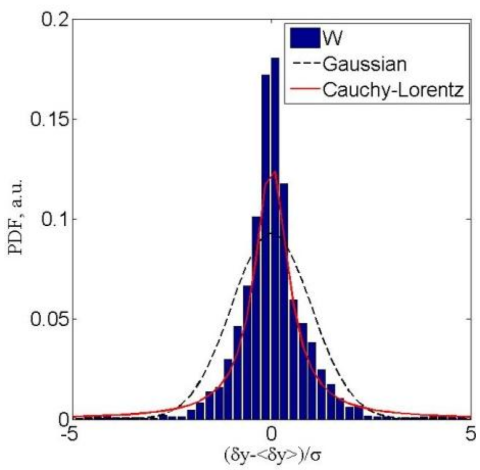

Figure 5. Probability distribution function for the surface height increments $\delta y = y(x+l) - y(x)$, tungsten samples in Fig.2 , l = 19.5 nm; Gaussian (dotted line) and the Cauchy-Lorentz (line) laws are shown for comparison.

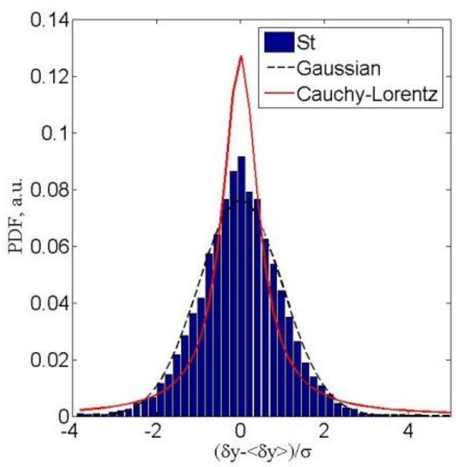

Figure 6. Probability distribution function for the surface height increments $\delta y = y(x+l) - y(x)$, industrial steel casting, l = 0.5 μm; Gaussian (dotted line) and the Cauchy-Lorentz (line) laws are shown for comparison.

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} [6]	-2.62	0.86
2	Tungsten after high heat plasma test in QSPA-T, 50 pulses of 2 MJm^{-2} [6]	-3.18	0.81
3	Carbon film from the T-10 tokamak [5]	-2.49	0.78
4	Carbon film from the T-10 tokamak [5]	-2.59	0.77
5	Graphite limiter from NAGDIS-II [8]	-2.29	0.68
6	Stainless steel after high heat plasma test in QSPA-T [7]	-2.85	0.72
7	Stainless steel after high heat plasma test in QSPA-T [7]	-2.87	0.68
8	Molybdenum after irradiation by plasma in the magnetron discharge	-2.2	0.6
9	Industrial steel casting after solidification	-2.41	0.58

3. Conclusions

High-temperature plasma in fusion devices produces exceptional extreme load on the plasma facing material leading to specific surface clustering conditions which are strictly different from any other conditions of solidification and clustering of materials previously analysed. This study has demonstrated inhomogeneous stochastic clustering of the surface with properties of the self-similarity of granularity from nano- to macroscale. In particular, the hierarchical granularity and self-similarity with cauliflower-like shape of tungsten surface have been revealed. The clustering of materials irradiated by high-temperature plasma qualitatively differs from the ordinary Brownian surface roughness and from clustering under other conditions revealed by comparing the results with those for the molybdenum sample after exposure in the magnetron plasma discharge and for the industrial steel casting with the ordinary roughness formed typically at solidification after melting. The experimental results reported possibly indicate universal mechanisms of stochastic clustering of materials exposed to the high-temperature plasma.

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