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OVERVIEW OF THE RECENT EXPERIMENTAL STUDIES OF PLASMA-FACING COMPONENTS IRRADIATED WITH DIVERTOR RELEVANT PLASMA

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Abstract

Plasma-surface interaction in fusion devices is characterized not only by high energy content, but also by collective effects under the influence of strong turbulence of the near-wall plasma. The stochastic structures of statistical self-similarity have been observed on the material surface irradiated with high heat flux plasma in fusion devices. The problem of the observed surface structures relates to the growth of stochastic interface boundaries under the influence of several competing agglomeration mechanisms of plasma-surface interaction. In fusion devices, this leads to the growth of unique stochastic relief with a self-similar structure and hierarchical granularity of the material with a long-range order in the structure from tens of nanometers to hundreds of micrometers, resulting in high porous structure which needs to be considered in the problem of in-vessel components of fusion reactor.

1. INTRODUCTION

Plasma tests of materials (tungsten, beryllium, graphite, steels, liquid metal components) in modern fusion devices have revealed a significant change in the surface structure under the influence of powerful plasma loads [1-15]. The plasma-surface interaction (PSI) in magnetic fusion devices involves several mechanisms including erosion and damage of the surface, melting and recrystallization of surface layers, movement of molten material over the surface, sputtering, evaporation, re-deposition of eroded material on the surface, modification of surface layers on the scales from tens of nanometers to hundreds of micrometers (see, for example, the review [1]). The conditions corresponding to the plasma load in a fusion reactor cannot be fully achieved in modern tokamaks. To identify the dominant PSI mechanisms under long-term irradiation, steady-state plasma tests of fusion materials are performed in linear plasma devices - divertor simulators and plasma accelerators such as NAGDIS-II, PLM–M, PISCES, MAGNUM-PSI, QSPA-T, QUSPA-Be and others. Experimental studies of plasma-facing components exposed in fusion plasma devices have revealed not only erosion but also substantial surface modification of plasma-facing materials.

2. REVIEW OF EXPERIMENTAL STUDIES

In tokamaks, an extremely irregular, stochastic shape of the surface with micro- and nanostructure was observed on areas of contact with hot plasma and redeposition of eroded material (graphite, tungsten, byrillium in tokamaks T-10, TEXTOR, JET, JT-60U, D-IIID and others [1, 16- 19]). In experiments with graphite in-vessel components, the formation of re-deposited layers with "cauliflower" type [16, 20], globular [16, 1], ovoid [16], stratified [1], columnar [1] surface shapes were observed.

When replacing graphite in–vessel components with tungsten (in recent decades on JET, AUG, T-10, WEST, EAST [21], and others tokamaks), with the initial goal of eliminating the problem of forming porous carbon films, desirable conditions to preserve the crystalline structure of tungsten surface faced to plasma during long-term plasma exposure were not achieved. Tests of ITER-grade tungsten in tokamaks (T-10, JET, WEST, EAST e.a.) and the QSPA-T plasma gun (see [1,4]) have demonstrated the effects of cracking and erosion, see Fig.1, including arc erosion with the formation of deep craters, Fig.2. In addition to melting and erosion, the growth of heterogeneous porous layers on surfaces near the zones of high-heat plasma load have been observed on tungsten limiters and tungsten divertor plates [1, 22,23]. A typical feature of the surfaces in such zones, as in those previously discovered on graphite components, is the stochastic topography of the relief and its statistical self-similarity on height scales from ~10 nanometers to ~100 micrometers [3], Fig. 3. These observations led to a detailed study in order to identify possible universal mechanisms of such stochastic clustering of the surface [2,3] under high heat plasma load.

Various types of self-similar topographic surfaces on plasma facing materials (PFMs) exposed in fusion devices have been observed [16, 24]. Fig. 3 shows the relief of a material with a surface of the "cauliflower" type on tungsten (of initially smooth polycrystalline surface). Similar irregular surface shapes have been observed earlier on tokamaks with graphite PFMs, such as T-10, TEXTOR and JET, see review [16], the thickness of the layers and films is from ~100 to ~300 micrometers. X-ray analysis of chemical composition of the surface material showed [24] that the structure is very complex, with the inclusion of hydrogen and other chemical elements. Spectroscopic studies (see [24,25]) have shown that its complex structure contains aromatic rings as structural elements, that is, it differs significantly from the virgin structure of graphite. The high porosity and specific area of such a surface leads to the effect of hydrogen isotopes retention in the pores and large area of an non-homogeneous or porous surface. Experimental studies of the specific area of porous surfaces in experiments with graphite in-vessel components have shown that it can be ~100 or more times larger than a smooth surface. In future fusion reactors, tritium retention in such surface seems to be a problematic issue taking into account the limitation of tritium retention (in ITER it is limited to ~ 1 kg [26]). The heterogeneous structure of the irregular plasma-facing surface is a negative factor in tokamak operation. A change in the structure of the plasma-facing materials leads to a change in their physico-chemical properties, the working gas trapped in the pores on the surface can be released uncontrollably and enter the plasma discharge affecting the operational performance.

To reveal the mechanisms of PSI, experiments in linear plasma devices - divertor simulators should be fulfilled and analyzed (see recent results from NAGDIS-II, PLM etc.). Stochastic clustering of tungsten, graphite, molybdenum, titanium, and lithium irradiated with multi-hour plasma has been studied in PLM (Plasma Linear Multicusp) plasma device [27-29]. The PLM plasma parameters: plasma density ~ $(0.5- 5)\times 10^{13}$ cm^{-3} , electron temperature ~1-10 eV with a fraction of hot electrons with a temperature up to 50 eV. The effects of the formation of porous surfaces under the plasma load were also observed during tests of capillary-porous systems (CPS) with liquid metal lithium in the T-10 tokamak and in the linear plasma device PLM (divertor simulator) [9]. Lithium materials deposited in the T-10 tokamak in experiments with lithium CPS were subsequently irradiated with steady-state plasma in PLM to test the evolution of the over-deposited layers under long-term plasma load. The analysis showed that lithium composites have a modified structure with a hierarchical granularity and a high specific surface area, Fig.4. The topology of such a structure, with a "cauliflower" type shape, is similar to the previously observed morphology of carbon composites deposited in tokamaks [10]. Similar observations were on titanium surface with an initial smooth surface irradiated with helium plasma in PLM for 200 min [30]. The thermal load on the titanium samples was 0.5 - 1 MW/m^2. As a result of the plasma load, the stochastic surface with hierarchical granularity was formed, Fig. 5.

Recently, materials with the surface of "fuzz" type with a high specific area [1,5,6] have been found in fusion devices. On tungsten, under steady-state plasma irradiation (see [6,8]), "fuzz"-type surfaces with fibers of 20-50 nanometers in diameter and a layer thickness of ~1.6 microns are formed, Fig.6. The formation of nanostructured porous tungsten should be taken into account when analyzing the erosion and modification of tungsten plates faced to plasma in ITER and large tokamaks. Combined tests of tungsten samples with a "fuzz" type structure using an electron beam and steady-state plasma load revealed the stability of such structure to powerful plasma and beam loads [7].

Generalized analysis of PFM tests resulted in the conclusion that the evolution of surface morphology under high-heat plasma load in fusion devices is dominated by not one elementary process, but by the combined integral effect of many processes. This leads to synergistic effects considered by the theory (see [2,3]), taking into account the instability of surface growth caused by the stochastic movement of agglomerated particles and clusters. As a result, the structure of such a surface, in addition to the previously known effects of cracking and erosion under high-heat load, also acquires the property of heterogeneous hierarchical granularity, statistical self-similarity and scale invariance of the surface structure, with high porosity on scales from tens of nanometers to hundreds of micrometers.

When analyzing the surface structure and topography of the relief formed by plasma irradiation in the tokamak, the question arises about the dominant mechanisms of PSI. It should be noted that the role of arc processes in the problem of plasma-surface interaction in fusion devices has been considered in recent decades in a large number of papers, see [31, 32]. The mechanism of electrical breakdown of the plasma layer over the surface with the formation of unipolar arcs is taken into account. The relationship between such arcs ignition and the formation of irregular surface is discussed [31,33]. Such inhomogeneous surface subsequently generates non-homogeneous electric fields in the plasma layer above the surface and contributes to the generation of unipolar arcs. In particular, such a breakdown is facilitated by the inhomogeneous surface facing the plasma. In experiments on the tokamak T-10 with tungsten limiters, intense arc erosion with the formation of deep craters was observed (Fig. 2) [33]. Arc craters and tracks were observed on tungsten plates analyzed after a series of about 400 experiments on T-10 tokamak. The arc craters in diameter from ~1 microns to ~100 microns were observed on the surface, Fig. 2. An arc current of ~100 A is required to form such large-scale crater with the diameter of up to 100 microns. For craters with a diameter of $r \sim 10$ microns, the thermal diffusion time is estimated as $\tau \sim r^2/\chi \sim 1$ μs, assuming a thermal diffusion coefficient of $\chi \sim 1$ cm^2/s. This time $\tau \sim 1$ μs is significantly less than the typical time scales of 10-100 microseconds of large-scale fluctuations in plasma density and electric field caused by near-wall plasma turbulence [14]. Such conditions are favorable for the generation of arcs [32, 34-37]. The nature of the erosion of the tungsten surface after powerful plasma-thermal load indicates an ecton mechanism of electron emission (explosive electron emission) [36,37]. Arc processes on porous materials, such as tungsten fuzz, were studied in PLM device. The computational and theoretical consideration of arc ignition was carried out under the assumption of simplified models of plasma-wall interaction (for example, a smooth surface, classical consideration of a stationary near-surface plasma layer), see, for example, [37,38]. The results of such work should be supplemented by taking into account the turbulence properties of the near-surface plasma generated electric fields leaded to a breakdown and by considering the rough surface (see discussion in [33]). Thus, the mechanism of ignition of multiple arcs on a rough surface should be considered, which in turn deform the surface, maintaining roughness.

Fig. 1 Tungsten after plasma irradiation in tokamak T-10

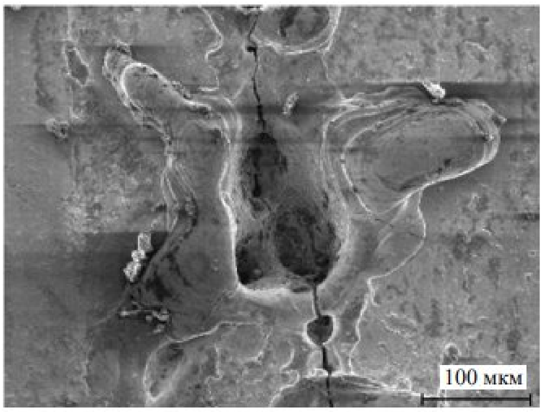

Fig. 2 Arc crater on tungsten irradiated in tokamak T-10

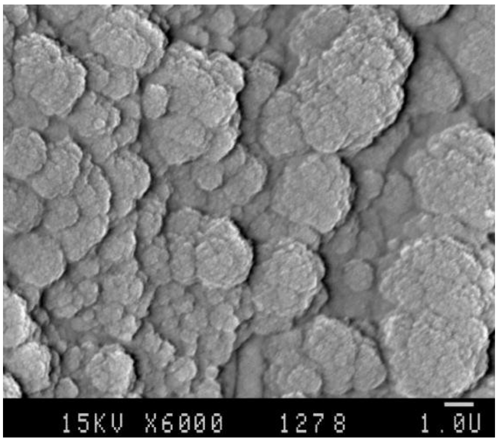

Fig.3 Tungsten surface after plasma irradiation in QSPA plasma accellerator

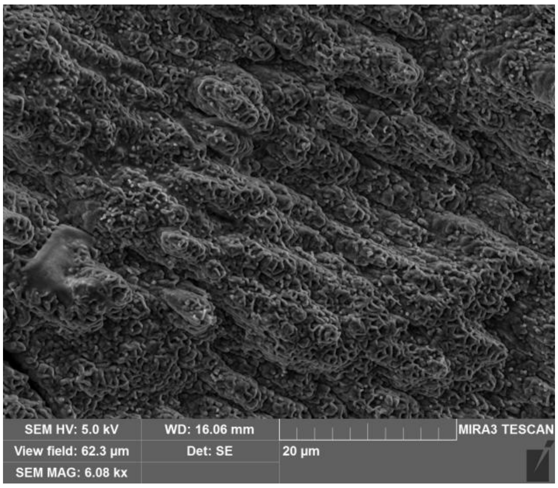

Fig.4 Lithium sample from tokamak T-10 after irradiation with helium plasma in PLM linear plasma device

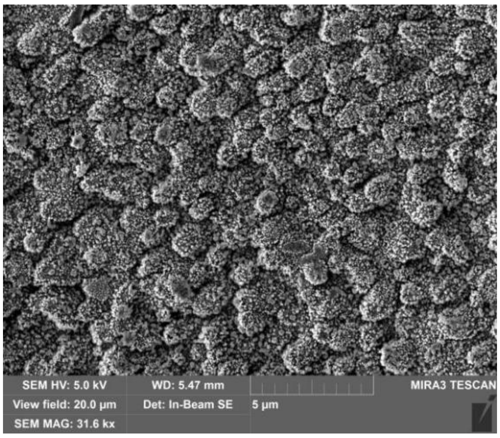

Fig.5 The titanium surface irradiated with plasma in PLM linear device

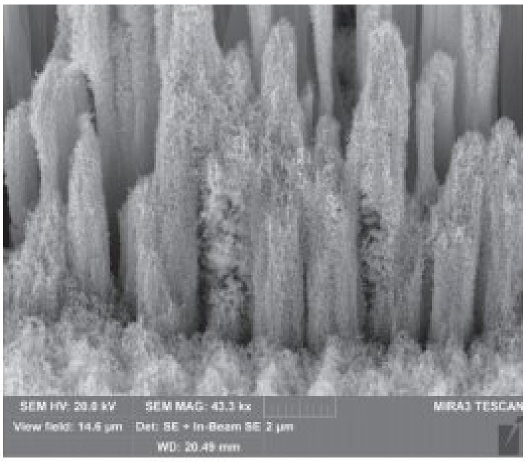

Fig.6 Tungsten surface with a "fuzz" structure after irradiation with helium plasma in PLM linear plasma device

The plasma-surface interaction in fusion devices is characterized not only by the high energy content of the plasma load on the material, but also by collective effects under the influence of strong plasma turbulence affecting the evolution of the plasma-wall system and the restructuring of the material surface. The problem relates to condensed matter physics considered the formation of interface layers when two (or more) phases interact under the regulation of several nonlinear competing mechanisms that form an interface inhomogeneous layer. In the plasma-wall system, the dynamics of turbulent plasma, multiple mechanisms of erosion and redeposition of eroded material, melting, movement and resolidification of surface layers on scales from tens of nanometers to hundreds of micrometers are simultaneously involved in the process. As a result, a stochastic surface with scale invariance of the structure is formed. Such a stochastic structure with hierarchical granularity is not amorphous in the classical sense. In experiments, it is formed on the surface of various materials such as tungsten, carbon materials, titanium, molybdenum, beryllium, steel, composite materials, that are exposed to hot magnetized plasma in fusion devices.

The analysis of experimental observations have revealed the specific features of the surface relief – the statistical and spectral characteristics of the relief heights, it has properties that differ from the simplest stochasticity of the Brownian surface type. Turbulent fluctuations of the near-wall plasma, which affects the surface material in experiments, have the same statistical and spectral characteristics [2]. The specific property of the near-wall plasma in fusion devices is the non-Gaussian statistics of electric field fluctuations with long-range correlations [39,40]. The dynamics of particles of the eroded material during redeposition from plasma and their agglomeration on the surface is governed by stochastic electric fields with long-range correlations generated by turbulent plasma [2]. Electric field affects the stochastic agglomeration leading to the growth of the stochastic relief of a surface with a self–similar structure (hierarchical granularity - fractality) with non-Gaussian statistics, which differs from the simplest roughness observed in other processes of stochastic agglomeration [3,4]. So, the dominant factor in such process in fusion device is the collective effect during stochastic clustering rather than the chemical elemental composition and physical characteristics of the solid material. As a result, materials with initially smooth crystalline or polycrystalline surfaces acquire irregular, stochastic surfaces with micro- and nanostructures, for example, with a cauliflower-like shape, when exposed to long-term plasma fluxes in tokamaks and other fusion devices.

To describe the observations, one should consider theories and hypotheses suggesting universal patterns of stochastic interface growth. Kinetic models offer a description of stochastic clustering with a self-similar structure (fractal structure) and consideration of power-law solutions, for example, by analogy with the description of three-wave turbulence, see [2]. Such power laws describe experimentally observed characteristics of the roughness of materials after plasma exposure in fusion devices. The height statistics of a stochastic relief are usually non-Gaussian and its probability distribution functions have "heavy" tails, with a Hurst self-similarity index from 0.68 to 0.86 [2,3]. This distinguishes them from Brownian surfaces with the trivial stochastic surface. A generalized comparison with clustering under conditions different from the effects in fusion devices have demonstrated a difference in the characteristics of the relief structure [2,3]. Stochastic clustering of materials from fusion devices is characterized by multifractal statistics. The quantitative characteristics of the statistical heterogeneity of the structure of such a material, e.g. the multifractal spectrum with a broadening of 0.5 to 1.2, are in the range observed for typical multifractal objects and processes in nature [2,3].

Materials with a stochastic surface structure are promising for controlling plasma-wall interaction in fusion reactor. It was proposed to use tungsten electrodes with a stochastic self-similar surface relief [23] to control the near-surface turbulence plasma using electric field (biasing).

A comprehensive review of the mechanisms of formation of the stochastic structure of materials exposed to turbulent plasma is necessary to identify universal mechanisms that can be used to develop methods for PSI controlling [41]. To develop theoretical model, experimental data of statistical self-similarity of observed stochastic surfaces in a wide range of spatial scales, starting with nanoscales, should be analyzed.

3. CONCLUSION

Stochastic clustering has been observed on the material surface (W, Mo, Li, Ti) irradiated with high heat plasma fluxes in fusion devices. Experimental results show that multiple processes of erosion and redeposition of the eroded material, surface melting and motion of the surface layers lead to a stochastic surface growth with the self-similar structure and hierarchical granularity on the scales from tens of nanometers to hundreds of micrometers. The moving of eroded material during redeposition from plasma and agglomeration on the surface is governed by stochastic electric fields generated by the near-wall plasma. The specific property of the near-wall plasma in fusion device is strong turbulence with long-range correlations generated electric field fluctuations with the non-Gaussian statistics. It leads to the stochastic agglomerate growth with a self-similar structure (hierarchical granularity - fractality) of non-Gaussian statistics contrary to a trivial roughness observed in ordinary processes of stochastic agglomeration. The dominant factor in such process in fusion device is the collective effect during stochastic clustering rather than the chemical elemental composition and physical characteristics of the solid material. To identify the dominant PSI mechanisms generated the stochastic clustering and porosity, steady-state plasma tests of fusion materials are needed to be continued in divertor simulators in support of fusion reactor technology.

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