Study of erosion products in experiments simulating ELMs and disruptions in ITER on plasma gun QSPA-facility

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Abstract

The experimental date on structure of deposited material from eroded CFC and W macrobrush targets under simulated ITER type I ELMs and disruptions heat loads are presented. Experiments were realized in QSPA plasma gun facility (TRINITI, Troitsk). Macrobrush targets were exposed to a large number of repetitive plasma pulses (up to 100) with heat loads 0.5 ÷ 1.6 MJ/m^2 and time duration 0.5 msec.

The main result of experiments was effect of fractal (“cauliflower”) dust formation for both W and CFC erosion. The typical dimension of dust particles was 0.1-3.0 μm, up to 20 nm, detected by scanning tunneling microscope. Particles size distribution (“scaling”) has power-law dependence, i.e. $N \sim r^{-\alpha}$, indicate a significant numbers of nanoparticles. For carbon particles $\alpha \approx 2.2$, for tungsten - $\alpha \approx 2.3$. With decreasing a plasma energy load (0.5 MJ/m^2) impact on a CFC target only flakes have been found in the deposits but the amount of dust particles was negligible small. Increasing on a W macrobrush target plasma pulse energy up to 1.6 MJ/m^2 reduced to appearance metal droplet.

Introduction

ELMs (Edge Localised Modes) and disruptions are a concern for the thermonuclear reactor ITER because they have the potential to produce considerable erosion damage of plasma facing components and reduce significantly the lifetime of divertor target materials [1]. The basic mechanisms of surface erosion during ELMs and disruptions are evaporation, melt layer losses with splashed droplets for metals and brittle destruction (formation of surface cracking with spallation of detached grains). In addition, thermally induced cracks can easily develop and grow under high cycle thermal fatigue conditions, preparing “self-castellated” and roughened surface [2]. The largest power loads on the divertor target in ITER are expected during the thermal quench of plasma disruptions and Type I ELMs. Because of their larger number compared to disruptions during ITER operation Type I ELMs are likely to dominate the erosion of PFCs under transients. The expected type I ELM energy fluxes to the ITER divertor plate are of 0.5 – 4 MJ/m^2 in timescale of 0.3 – 0.6 ms. Thermal quench energy fluxes of 2 – 13 MJ/m^2 in timescale of 1 – 3 ms with a maximum 30 MJ/m^2 in timescale 10 ms. Accordingly the temperature rise in divertor may reach more then 1000 ^{0}K. The erosion of ITER PFCs under ELMs and disruptions is presently modeled by plasma-material damage codes, which can evaluate the expected erosion of CFC, W and Be PFCs in ITER under transient loads. For different single disruptions and ELMs, the heat loads at the divertor surface and parameters of plasma shield being formed from evaporated material in front of the target are calculated using the two-dimensional MHD code FOREV-2D [3]. In case of metallic target melt motion erosion is calculated by the fluid dynamics code MEMOS-1.5D in the "shallow water" approximation, with the surface tension and viscosity of molten metal taking into account plasma pressure gradient along the divertor plate, as well as the gradient of surface tension and tangentional force of the dumping plasma [4]. The 3D code PHEMOBRID is applied for simulations of lateral side melting of W brushes. For CFC armour erosion heat conductivity properties with account of degradation of the matrix due the crack formation as well as phenomenological model of brittle destruction are implemented [5]. The code PEGASUS [6] is the powerful tool for simulation of fine details of brittle destruction and heat conductivity properties of carbon based materials. These codes are being validated by experiments in which ITER relevant targets are exposed to large energy loads by laser, electron beams and by energetic plasma impact [7]. Although the quantitative agreement between experiments and modeling is improving, the integral understanding of the erosion, migration and deposition of materials during transient energy loads in ITER is poor at present. The formation of metallic and hydrocarbon dust particles and the growth of porous hydrocarbon films [8] can impose very restrictive limits on the operation of ITER because of their safety implications. Furthermore, small dust particles can be transported injected by SOL plasma flows into the bulk plasma and may contribute significantly to the core plasma impurity concentration [9]. Deposits with high porosity that may be produced during transient loads in ITER can have significant amounts of absorbed tritium leading to a considerable retention. Because of this reasons, the ITER project has setup a rigorous safety limit based on the chemical reactivity and radiological hazard of the dust.

Experiment

A collaborative research activity on the investigation of erosion of PFC for ITER divertor and deposited films and dust under ELMs like plasma heat load was undertaken in frames of joint EU-RF experiment. CFC and tungsten macrobrush divertor plates were manufactured in EU (Plansee AG, Austria) according to the ITER divertor target specifications (carbon fibre composite NB31 and pure and La$_2$O$_3$-doped deformed tungsten with a grain orientation perpendicular to the target surface). These targets have been exposed to Type I ELM and disruption-like loads (GW/m^2 range) at the plasma gun facility QSPA at the TRINITI institute (fig.1) [10]. The energy of the plasma pulses loads covered a range of 0.5-1.6 MJ/m^2. For all plasma pulses the duration was 0.5 ms. The diameter of QSPA plasma cloud ~ 5 cm, ion energy ≤ 100 eV, electron temperature ≤

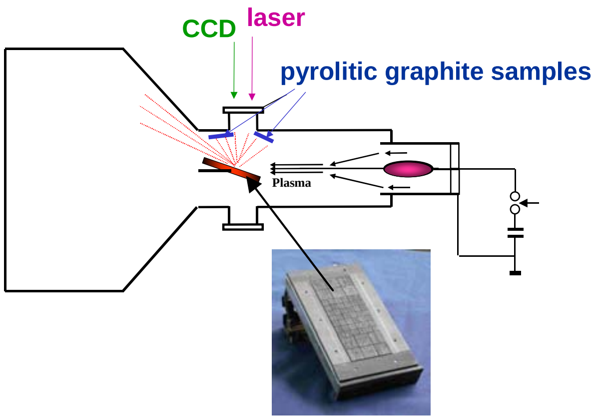

Fig.1. The QSPA plasma gun facility and W macrobrush target

10 eV, density $\leq 10^{22}$ cm^{-3}. Melting temperature (3680 ^{0}K) of W macrobrush run up with 0.38 MJ/m^2, but boiling point (5900 ^{0}K) - with 0.67 MJ/m^2. During the experiments, the macrobrushes were preheated to a temperature of 500 ^{0}C and was tilted at the 30^0 incidence angle to the plasma stream. Collectors for re-sputtering deposits were installed at a distance of ~ 20 cm from the CFC and W targets. The analysis of erosion products was made after series of, typically, ~ 100 shots. Scanning electron and tunnelling microscopes were used as basic diagnostics for films and dust analysis.

Material deposition

The principal and unexpected result of impact type I ELMs-like plasma on W and CFC macrobrush was in formation the films, consisted of the dust particles, spilling by amorphous paste. In the case of experiments with W macrobrush target and power load 1.0 MJ/m^2 and CFC macrobrush target with power load 1.0 – 1.6 MJ/m^2 a large number of dust particles with spherical shapes have been measured (fig.2).

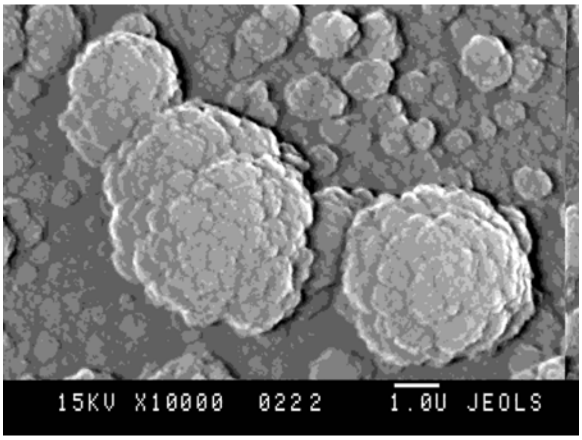

Fig.2 Dust particles after W macrobrush target erosion with 1 MJ/m^2 energy load.

The dust particles observed by scanning electron microscopy had typical dimensions of 0.1-3.0 μm in both cases. All particles had fractal surface structures ("cauliflower"). In other words they were formed by accumulation of small clusters, which in turn consisted of clusters with even smaller size, etc. Further surface measurements of 100 nm clusters by scanning tunneling microscopy show that they consist for ones turn of 20 nm particles cone-like type (fig 3). The analysis of fractal surface of individual dust by "counting–box" method [11] gives power law clusters distribution i.e. $n_i \sim x^D$, where n_i are the number of clusters with characteristic dimension x on the individual dust surface. Fractal dimension D ~ 2.2 - 2.4 for both tungsten and carbon particles.

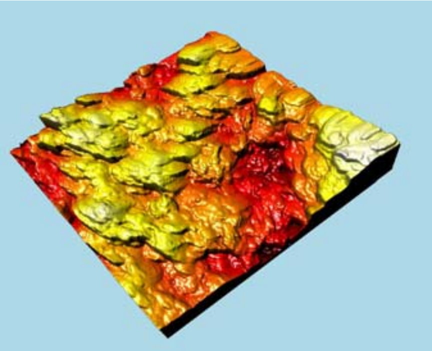

Fig.3. 50 nm particles detected by STM

Since collectors cover by dust particles then somebody may calculate all individual dust as a unit. Both tungsten and carbon particles size distribution has power-law dependence, i.e. $N \sim r^{-\alpha}$. (fig.4), where N are the number of dust with characteristic dimension r. For carbon particles $\alpha \approx 2.2$, and for tungsten particles $\alpha \approx 2.3$. Even if take account of the particles with the average size 20 - 100 nm, measured by scanning tunneling microscope, then the α for both material practically don't change.

In addition to the spherical dust particles on the collectors surfaces there were found out agglomerated clusters with elongated shape and average dimension near 3×10 μm, which also agglomerated in spread coral- type structure (fig.5). Surface structure of such clusters and corals are similar to dust surface structure.

One peculiarity of the films, consisted from the fractal dust particles is the island structure of deposits on the collectors surfaces. That is material density distribution is nonuniform. There are areas with coral – like surfaces, where fractal dust pressed hardly, and which edged by barrier region without any dust particles (fig 5). One can suppose that there are forces on the dust particles, which make it move into the island.

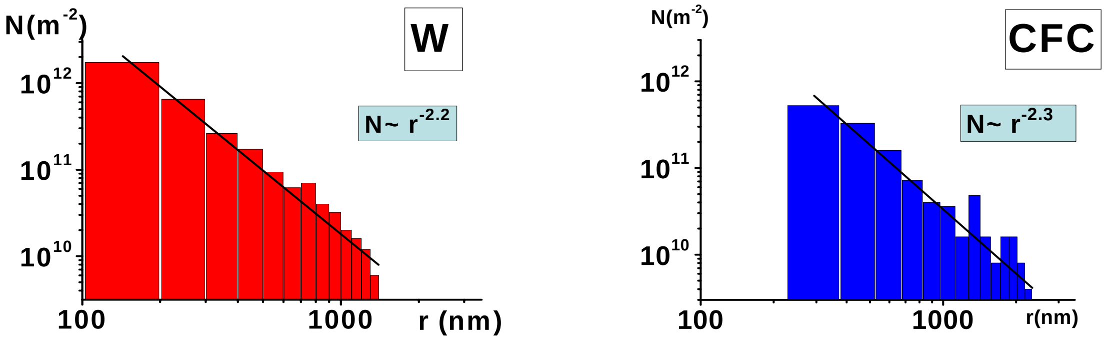

Fig.4. The dust particles size distribution - $N \sim r^{-\alpha}$, after erosion CFC and W macrobrush target by simulated ITER type I ELMs heat loads.

But in the case of plasma energy load of 0.5 MJ/m^2 impact on a CFC target only flakes have been found in the measured deposits but the amount of dust particles was negligible small (Fig.6). The deposited films have a complex structure with a large number of porous with diameters of 100 nm. Typical dimensions of flakes were 30 μm in plane and less 1μm in thickness. The flakes surface cover by nanocone, which form up in lattice structure. The pair correlation function (PCF) has crystal–like type of structure and gives average distance between the cones near 20 nm. In other words the nanocone structure have long correlation length and the flakes shows self-organisation of their surfaces up to sub-micron scales.

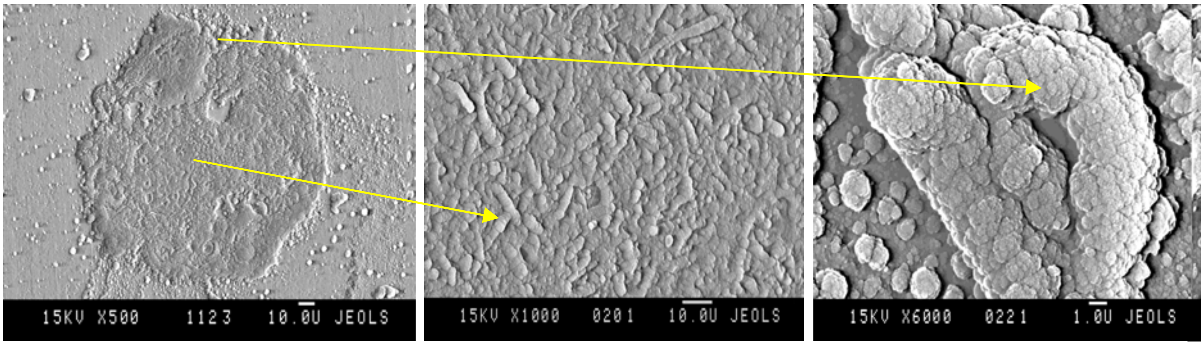

Fig.5. Agglomerated coral-like structure after W macrobrush target erosion

At increase in plasma pulse energy up to 1.6 MJ/m^2 on a W macrobrush gives greatly increasing the number of metal droplet, with higher dimension and smooth surface. As a rule individual droplets has spherical shape or there are tracks, consist from the elongated droplets, be situated on one line.

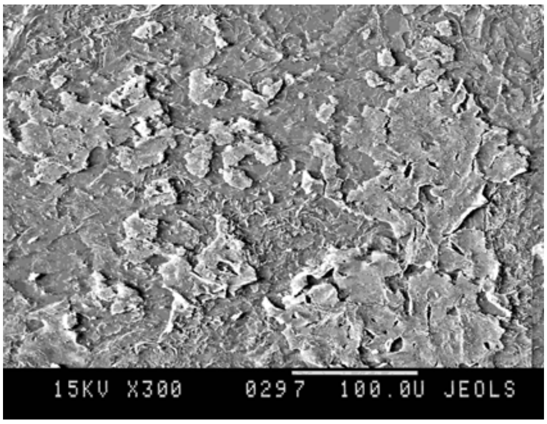

Fig.6. Flaking deposits structure at energy load - 0.5 MJ/m^2 on CFC macrobrush target erosion.

Discussion

In accordance with predictions [12] in the realize experiments evaporation and splashing may estimate as the major mechanisms for W macrobrush erosion and sublimation - for CFC macrobrush during Type I ELM and disruption loads. But the effect of fractal dust formation was unexpected in current experiments. At a plasma pulse energy near 1.0 - 1.6 MJ/m^2 in both cases the possible mechanism of fractal dust particles and coral-type structures formation are, apparently, primary coagulation from supersaturated vapor with the subsequent agglomeration in larger clusters. An experiments show that even CFC macrobrush erosion at 1.6 MJ/m^2 energy load produce vapor carbon droplets (Fig.7). The presences of cracks on the thin film surfaces in both cases indicate either the high temperature gradient during material cooling or low heat conductivity of material and show the possibility of films destroying (flaking). The main question is where "cauliflower" dust particles form – during the vapor droplet flight or on the wall (or collector) surface before resolidefication the vapor. CCD camera, installed for diagnostic the heated droplet tracks, didn't detect it in condition, when fractal dust particles are forms. The estimation of possible vapor droplet (or particle) transit time to the wall (or collector surface) gives value ~ 10 μs. This time low enough for particles coagulation into clusters in vacuum chamber volume. The most likely process is the fractal particles formation from supersaturated vapor on the wall surface, before the vapor cooling. An island structure of sprayed material and big fractal elongated clusters denotes of this process.

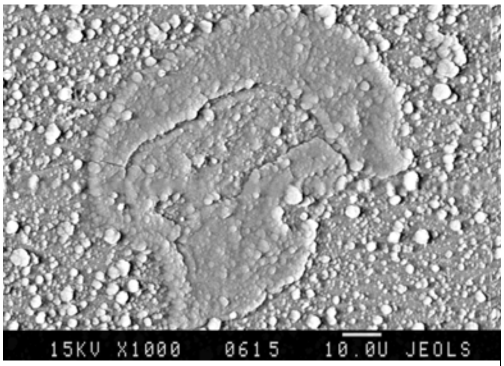

Fig.7.Vapor carbon droplet during CFC macrobrush erosion at 1.6 MJ/m^2 energy load.

A sharply changes of deposits structure there are at smaller energy - 0.5 MJ/m^2 for CFC, leading to formation "pancake" films structures with a combination of nanovoid and nanocone on the surfaces. The founded out minimum particles size is 20 nanometers. Such condensation from the gas phase or vapor droplet and growth through hydrocarbon molecules are the likely mechanisms of flakes formation and surface self-organization for CFC case. The deposits has a developed surface that may lead to high absorption of deuterium and tritium in a thermonuclear reactor. Just as the fractal dimension D = 2.2-2.4 of "cauliflower" dust particles pointed out the high porosity of it and consequently high probability to gas sorption.

There are the same sharply changes of deposits structure with high energy load on W macrobrush. In accordance with modeling [13] at 1.6 MJ/m^2 energy load major macrobrush erosion mechanisms is melting with droplet splashing. Against to 1.0 MJ/m^2 it confirms by another shape of dust particles on the samples surface and appearance the shaft of light tracks from heated droplets, indicated by CCD.

The dust particles size distribution – $N \sim r^{-(2.2\div2.3)}$, indicate a significant numbers of nanoparticles during erosion CFC and W macrobrush. Some fusion facilities detected nanodust in the vacuum chamber and even the same size distribution [14]. Such distribution gives high total sorption surface even if to exclude the dust fractality, and may give at least ten time higher sorption surface for ITER dust. Heated nanosize clasters may increased considerably the electron emission.

The similarity of the above-named structures and structures of a dust and films, received in T-10 tokamak draw attention [14]. The feature of "H-mode" T-10 regime was in significant power flow on to a small surface of graphite tiles in HFS of a circular limiter with power load nearby 50 MW/m^2 (ITER-like power load). These tiles were heated up to 2000 ^{0}C, and the basic mechanism of erosion was intensive sublimation of graphite under intensive arcing. Near to this place grew a films, consisting of spherical particles with fractal structures [15] (Fig.8). The same situation was with self-organizing of a films surface. The surfaces of T-10 hydrocarbon films in nanoscale are covered by nanocones, marshaled in structures of lattice type. The surfaces of these films in micro scale range consist of fractal structure with fractal dimension D = 2.15 ÷ 2.32.

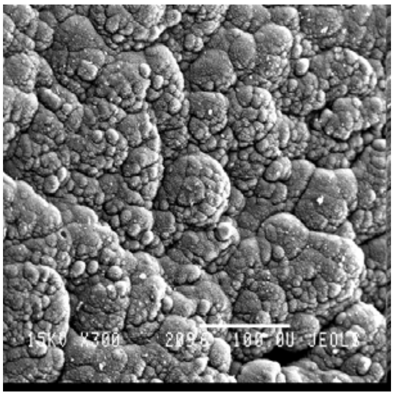

Fig.8 The surface of T-10 flake.

Conclusion

Detected mechanism of possible formation of carbon and tungsten fractal dust up to nanoscale size from evaporated materials and films formations from them may change conception of energy and particles balance in ITER divertor chamber. For example, constant reproduction of a dust and films with strongly developed surface may lead to a constant deuterium and tritium sorption. Erosion of such structures can essentially differ from standard. The dusts and films developed surface (or nanoscale cone on it) can lead to increase in secondary electron emission, and, accordingly, to cooling divertor plasma. Safety requirements at presence of nanoparticles in divertor may lead to change of reactor economy. A clearing of such sponge-structured metal films from deuterium and tritium may become the serious problem.

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