Erosion of W and CFC in ITER ELMs I Type simulation experiment: fractal nanodust - structure and properties.

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Introduction

ELMs (Edge Localised Modes) and disruptions are likely to dominate the erosion of PFCs under transients [1] because of their larger number compared to disruptions during ITER operation Type I ELMs. 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. Accordingly the temperature rise in divertor can reach more than 1000 ^{0}K. Although the quantitative agreement between experiments and modelling is improving, the understanding of the erosion, migration and deposition of materials during transient energy loads in ITER is poor at present. Deposits with high porosity, which can be produced during transient loads in ITER, may 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 .

Collaborative research activity on the investigation of dust was undertaken in frames of joint EU-RF experiment. CFC and tungsten macrobrush divertor plates were manufactured in Plansee AG (Austria) according to the ITER divertor target specifications. These plates have been exposed to ITER type I ELM loads at the plasma gun facility QSPA at the TRINITI [2]. The energy of the ELM-like loads consists of 1-1.5 MJ/m^2, the duration was 0.5 ms. For such energy loads the evaporation is estimated as the major mechanism for W macrobrush erosion and sublimation - for CFC macrobrush [3]. During the experiments, the macrobrushes were preheated to the temperature of 500 ^{0}C. The estimated collector temperature was ≈ 300 ^{0}C. In many cases a polished SS collector has been used. The analysis of erosion products was made after series of, typically, ~ 100 shots. Scanning electron, tunnelling (STM) and atomic-force (AFM) microscopes were used as basic diagnostics for dust analysis.

Nanodust. Surface tension

The principal and unexpected result of impact type I ELMs-like plasma on W and CFC macrobrush was in formation of the films, consisted of a large number of dust particles with spherical shapes (fig.1.b) spilling by amorphous paste on collector [4]. Further analysis by STM/AFM found out that the amorphous pasta structure in reality consists of nanoparticles with dimensions of 20-50 nm and less. Spherical dust particles had fractal structures (“cauliflower”). In other words they were formed by accumulation of small clusters, which in turn consisted of clusters with even smaller size, etc. The maximum size of the spherical dust particles is 2 μm, but W dust agglomerates only into elongated clusters ~ 2×10 μm, which exhibit a tendency to roll up into tore.

The studies of many collectors showed that they were coated non-uniformly by material. Usually there are material tighten to the central collector area forming the dense, coral-like structure from the dust particles after big number of shots (~ 100). There are “tongues of flame” structures on the collector edges. But small quantity of material on the collector surface leads to dust tighten into circular flat “islands / pancakes”, scattered between separate dust clusters. Studying the problem of where the agglomeration start there are no any evidence of cluster agglomeration from supersaturated vapor only in volume, during the movement to a collector. Therefore surface agglomeration of dust clusters and shrinkage into circular structures pointed out the big surface tension (big surface energy) of clusters.

The experiments on simultaneous sputtering of W fractal dusty film and polycrystalline W film by Ar^+ beam (3 keV, 3 mA/cm^2) also indicate on the big surface

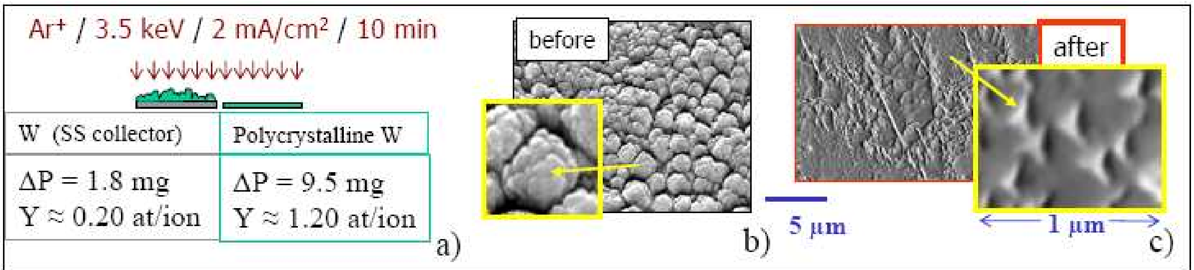

Fig.1. Ar^+ sputtering: experimental dates (a), before (b) and after (c) surface modification

energy of fractal film. The weight loss (or sputtering yield) of such film is 6 times less that of polycrystalline W film (Fig.1a). For all that the surface structure of polycrystalline W film didn’t changed much, but the surface structure of W fractal dusty film changed dramatically. There are appeared big uniform areas with ample evidence of “liquid melt” and circular, smooth particles equal diameters and high density surface whiskers. Also the third order symmetry axis typical for monocrystalline tungsten appeared on the surface of "melt" (Fig.1c). It is strange that evident transition of material from fractal phase to crystalline phase takes place with specific Ar^+ beam power 5 W/cm^2 only, although well known W fusion heat equals ≈ 200 J/g. But if suppose that surface energy of fractal clusters convert into fusion heat than such transition can supply with junction of clusters of some nanometer dimensions only. Such estimation is in good agreement with experimental dates.

Dust particles distribution. Fractality

As it was shown earlier [4] the sputtering of W and CFC by ITER ELM I type plasma energy load with 1.0 ÷ 1.5 MJ/m^2 result in power-law dependence of particle size distribution i.e. $N \sim r^{-\alpha}$ with $\alpha = 2.2 - 2.3$ in the characteristic particles size range 0.1 ÷ 2 µm. Additional studies of particle size distribution by STM/AFM in the range of 20-100 nm found out the power-law dependence can be extended up to 20 nm range (Fig.2).

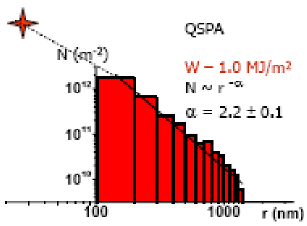

Fig.2. QSPA-facility dust size distribution

The same results were obtained in tokamak T-10 with high power load to the graphite limiter. In this regime the half of the tokamak heating power came into the small inner part of circular limiter providing the specific power load ~ 50 MW/m^2 during 0.5 sec. [5]. This results in increasing surface temperature up to 2000 ^{0}C, strong sublimation of graphite under intensive arcing, dust appearances with initial dimension near 25 nm and further agglomeration . But the same power-law dependence of particle size distribution i.e. $N \sim r^{-\alpha}$ with $\alpha = 2.3$ was obtained in the range 50 – 200 nm. (Fig.3). The results from some facilities [6][7] reveals the similar dependence.

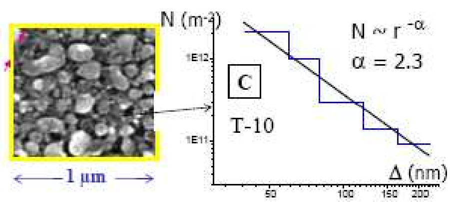

Fig.3. T-10 tokamak dust size distribution

It is significantly that the power-law dependence with the fractional power describes the fractal structures.

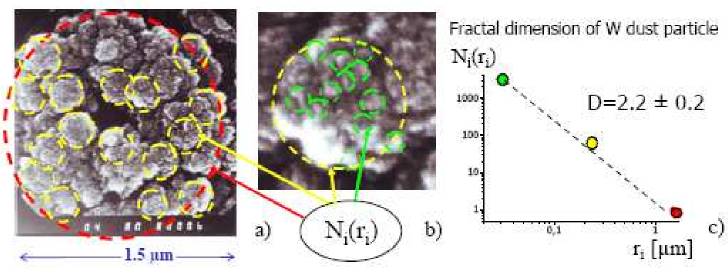

Fig.4. QSPA dust structure (a,b) and fractal dimension (c).

The analysis of individual dust particles or agglomerates found out their fractal structure. I.e. the connection number of particles N_i with radius r_i have power-law dependence – $N_i \sim r_i^{-D}$. The fractal dimension $D = -\partial \log N_i / \partial \log r_i$ determined by *box* *counting method* equal 2.2 for many dust particles (Fig.4). It is essential to pay attention to the fact of proximity the values of α - which describe distribution of total number of dust particles and fractal dimension – D of single particles. Thus, if fractal cluster with the size r_0 consist of the particles with size a_0, then the numbers of particles inside the r_0: $N_{r0} = (r_0 / a_0)^D$.

Extrapolation to ITER

One of the main dangers in ITER is films/dust/deposits growth with highly developed surface that can lead to high absorption of deuterium and tritium. To suppose that the mechanism of divertor plate material redeposition in ITER has the same nature as the QSPA macrobrush material redeposition, the Specific Surface Area (SSA) can be estimated.

For the solid-state particles no difference between SSA estimated from existent ITER log-normal dust distribution and power-law dust distribution, where SSA depends on highest possible cluster dimension r_0. But on the contrary, if dust clusters have power-law distribution and **fractal** structure, then SSA depends on minimum dust size a_0.

$$\mathrm{SSA} = S_0/\rho V = \int_{a_0}^{r_{\max}} A r^{-\alpha} 4\pi a_0^2 (\frac{r}{a_0})^D dr \Big/ \rho \int_{a_0}^{r_{\max}} A r^{-\alpha} \frac{4}{3}\pi a_0^3 (\frac{r}{a_0})^D dr = \frac{3}{\rho a_0}$$

Assuming in accordance with the experiments $a_0 \approx 10$ nm it results in SSA ≈ 250 m^2/g for carbon and 30 m^2/g for tungsten, that is **≈ 60 times higher** of existent calculations of ITER SSA (≈ 4 m^2/g for carbon).

The discussed mechanism of surface particles agglomeration into the fractal clusters can create serious problems for ITER.

Acknowledgement

This work was supported by the scientific school 1880.2006.2 “Physics and technologies of nuclear fusion”, and in part by INTAS grant 1000008-8046.

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