Observations of Skeletal Microstructures in Various Types of Dust Deposit in Tokamak T-10

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Abstract. An analysis of electron transmission and scanning micrographs of various types of dust deposit in tokamak T-10 was carried out for (a) analyzing the origin of non-trivial (e.g. cauliflower-like) structures in dust deposits in tokamaks, and (b) verifying the former hypothesis for the possibility of self-assembling, during electric breakdown, of skeletal macrostructures from wildly formed carbon nanotubes. The results show (i) the presence of tubular structures in the range of diameters D ~ 5 nm - 10 μm; (ii) the trend of assembling bigger tubules from smaller ones (i.e., the self-similarity); (iii) the ability of nanotubular structures to build up the skeletons of various topology, including the tubules, cartwheels, dendrites; (iv) the presence of an amorphous (mostly, hydrocarbon) component which may hide the internal skeleton either fully (to give a solitary dust particle, e.g. of submicron size) or partly (to give an agglomerate of visually separate particles); (v) the similarity of tubules and cartwheels in the dust deposits, in the range D < 10 μm, and in the (high temporal resolution) images of plasma in tokamaks, Z-pinches and plasma focus, D ~ 100 μm - 10 cm.

1. Introduction

During routine fusion reactor operation and at plasma disruptions plenty of plasma facing material erosion products (dust and films) will be formed. Dust is dangerous radioactive and toxic material. Its hazard degree, mobilization capability and catalytic efficiency depend on dust particle size and structure. Therefore, a series of dust structure characterization studies were performed during past years in tokamaks, and the experiments simulating working conditions in tokamaks were carried out. Experimental evidences for and characterization of dusty particles cover a range from ~ 100 μm down to ~ 100 nm; see [1] for tokamak TEXTOR and the survey [2] (Sec. III.A.2) for tokamaks DIII-D, ALCATOR C-MOD, and TFTR. The strongest evidence for a self-organized structuring of the tokamak dust deposit was probably the fractal structures of a cauliflower-like form [3] observed in [1]. The enhancement of spatial resolution up to ~10 nm, via using the transmission electron micrography, allowed to produce a database which covered various types of dust deposit in tokamak T-10 and enabled to find, besides cauliflower-like structures, new types of structuring (such a database has been produced within the frame of the safety and environmental program of the ITER project, see the survey [4]).

One way in interpreting the non-trivial structuring (e.g., of a cauliflower-like form) is to extend the approaches formerly developed for low-temperature plasmas in the plasma processing devices to the case of plasmas in the scrape-off-layer and divertor in tokamaks (see, e.g., the survey [5] and references therein). Such an approach known as the concept of dusty plasmas is based on the particle kinetics in strongly coupled Coulomb systems in which plasma's non-ideality comes from the high electric charge of dust particles. In this frame, the aggregation of cauliflower-like structures takes place in the peripheral plasma interior and results from the action of the ambient plasma on the highly-charged dust microparticles. Another approach may be based on the physics of interaction of an ion beam with a solid target (this approach is a base for the widespread experimental modeling of the plasma-surface interaction in fusion plasmas). In this frame, one could explain the structuring with the processes which take place essentially on the surface of fusion facility's wall [6].

The present paper reports on the studies aimed at (i) analyzing the probable mechanisms of the origin of non-trivial structures in the dust deposits and (ii) verifying some points of a novel approach which is based on the hypothesis [7(a-c)] for the possibility of self-assembling, during electric breakdown, of skeletal macrostructures from wildly formed carbon nanotubes (or similar nanostructures of other chemical elements) and for the probable role of such a dust in the electric breakdown phenomena in gaseous discharges.

2. Skeletal structures in dust deposits

The database [4] includes micrographs of various types of dust deposits. The first class includes **dust particles** of various type, namely: (A) deposited on a filter mounted on a stock located in the tokamak vacuum chamber well outside the plasma column (Fig. 1); (B) extracted from the oil, which has been used in the tokamak vacuum pumping system (Figs. 2,3); (C) redeposited on a filter during vacuum suction of the dust from the crimp in the tokamak vacuum chamber (Figs. 4-6). The second class includes 1-30 μm thick **films** deposited on the internal surface of the tokamak vacuum chamber (Fig. 7). Below we present a gallery of the images of typical samples of all the above-mentioned types.

It is not surprising that we found the tubules of diameters D~ 5-30 nm which are typical for individual carbon multiwall nanotubes. The novel results are the observations [8] of various **skeletal** structures assembled from nanotubular blocks. In particular, these include (i) tubules (D ~ 70 nm - 10 μm) (see Figs. 2,5,7), (ii) cartwheels (D ~ 70 nm - 10 μm) located either on their own axle-tree (Fig. 3) or in the edge cross-section of a tubule (Figs. 2,7), (iii) dendrites of submicron size (Fig. 1,5,6). Sometimes, all three kinds of skeletons are represented by a single sample (Fig. 2) that is partly not surprising because the cartwheel on the axle-tree may be considered as a simple type of a dendrite (Fig. 3).

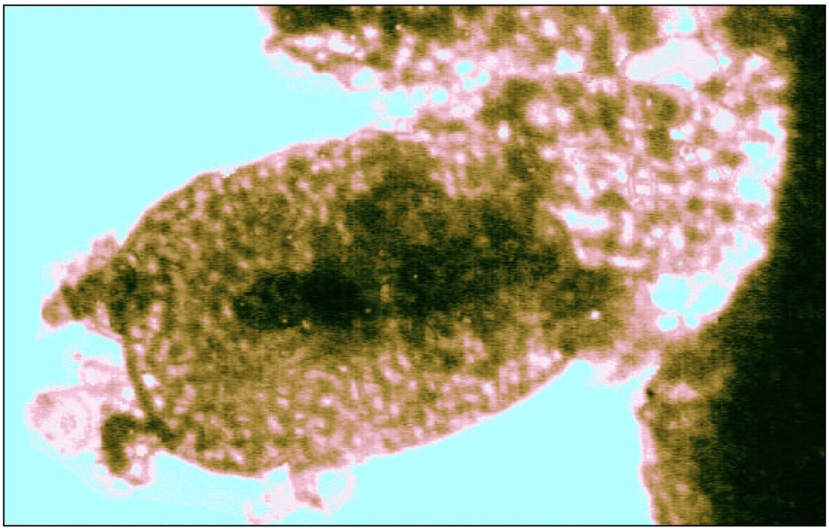

FIG. 1. The transmission electron microscope (TEM) image (magnification 9,000) of an egg-shaped carbon particle of the deposit of type (A). Image width is ~750 nm. The internal opaque rod (as a trunk) and the surrounding complicated network of fibers (as a crown) compose a dendrite. The phenomenon of tubularity of structuring is seen in the coaxial tubule, of outer diameter ~60 nm, located on the left edge of the particle.

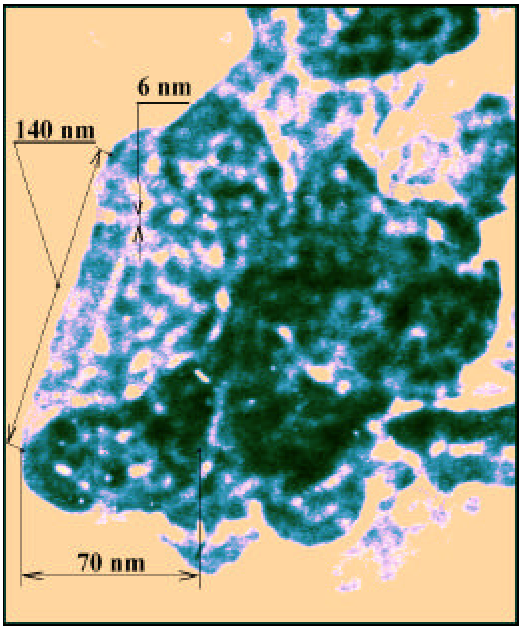

FIG. 2. The TEM image (magnification 34,000) of the fragment of a dust particle ~1.2 mm in size (deposit of type B). The tubule whose edge with the distinct central rod is seen in the lower left part of the figure, is of diameter D ~70 nm and ~140 nm long. The cylindrical formation (D ~15 nm), which is seen on the left side of the tubule, is its constituent part. The radial bonds between the side-on cylinder and the central rod are of D ~5 nm.

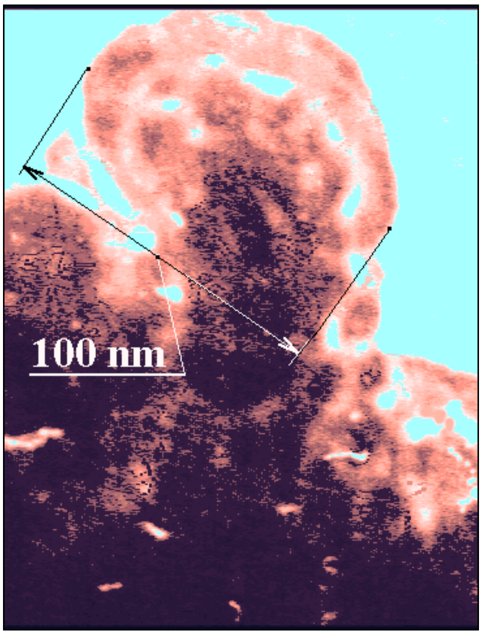

FIG. 3. The image of the cartwheel (all conditions are similar to those of Fig. 2), which is seen on the top of the figure as a wheel (D ~100 nm) declined with respect to figure's plane and connected by radial bonds with a thick vertical formation which is a sort of the axle-tree for this wheel.

The skeletons as a rule are embedded into **amorphous** component (AC), mostly hydrocarbonic one. The AC may hide the skeleton either fully or partly. In the first case, this may give a solitary dust particle, e.g. of submicron size (Fig. 1). In the second case, the AC is concentrated around basic blocks of the skeleton, thus producing visual effect of separated or weakly bound blocks. For dendritic skeletons, this looks like an agglomerate of visually separate particles (AVSP) [8(c)] (Figs. 4-6).

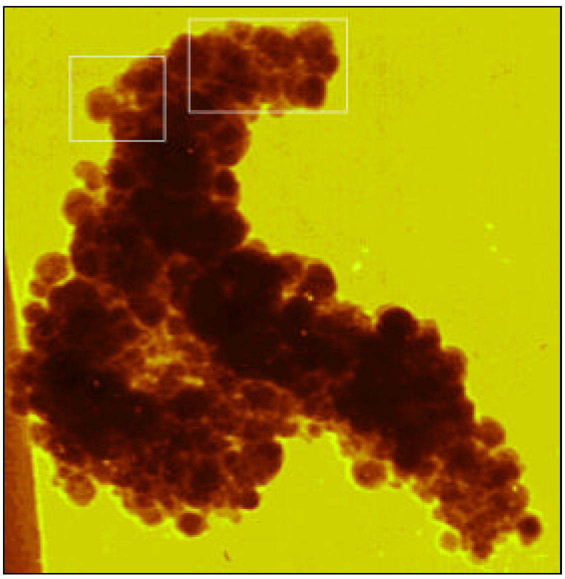

FIG. 4. The TEM image (magnification 26,000) of an agglomerate of visually separate dust particles (deposit of type C; the filter's fiber is partly seen as a dark band on the left hand side of the image). Image width is 590 nm. The magnified images of the windows are given in Figs. 5,6.

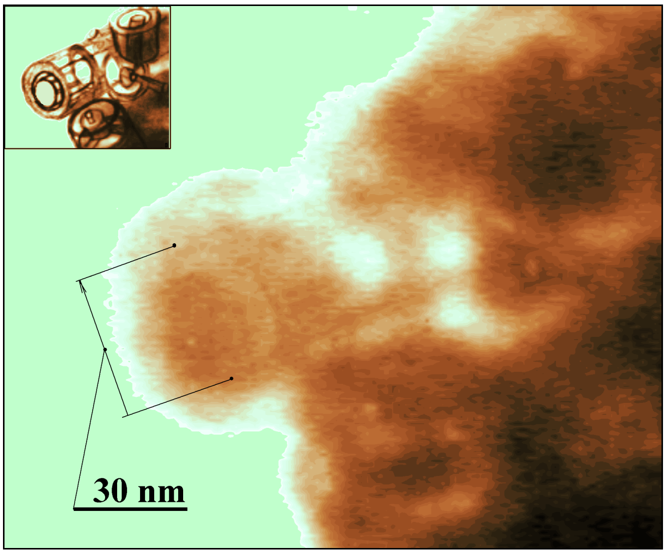

FIG. 5. Magnified image of the window in Fig. 4. The visually separate, quasi-spherical particle appears to be a projection of the edge of a tubular structure (D ~ 30 nm) which is a part of skeletal structure. For the comments on obtaining a schematic drawing, shown in the left upper corner, see [8(c)].

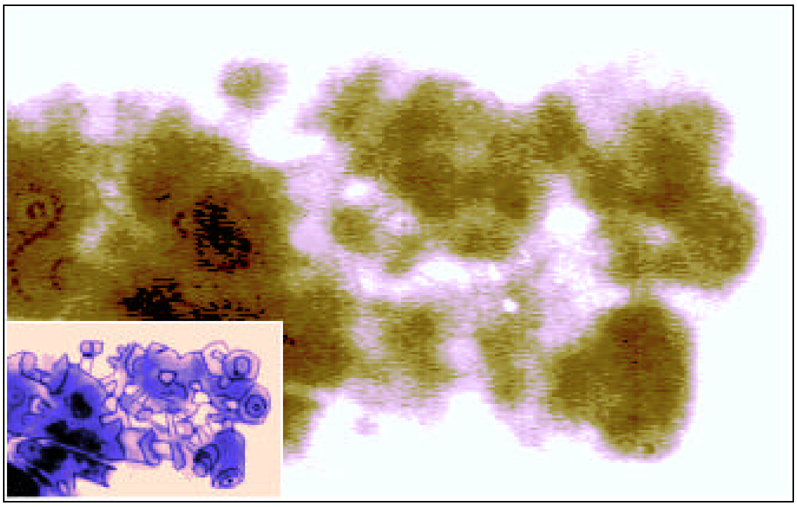

FIG. 6. The right upper edge of the agglomerate shown in Fig. 4. There is a bunch of dendritic structures (presumably, cartwheels on their own axle-trees). Figure width is ~180 nm. A schematic drawing shown in the left lower corner is obtained similarly to that in Fig. 5.

And finally, the ~1-30 μm thick films contain skeletal structures which are seen in the surface layer (Fig. 7) and the fractures of the film.

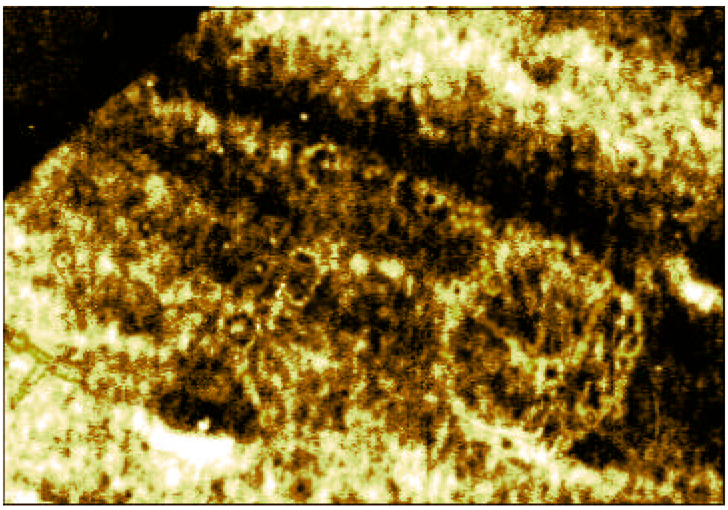

FIG. 7. The scanning electron microscope (SEM) image (magnification 2,000) of the surface layer of the film deposited at the internal surface of the T-10 tokamak chamber. Figure height is ~15 mm. Diameter of the tubular structure, whose edge is seen in the right lower part of the Figure, is ~5 mm.

The distinguishable topology of the structures (namely, tubules and especially cartwheels) allows to identify the ***similarity*** of the structures found (i) in the range D ~ 10 nm - 10 μm in the dust deposits [8(a)] and (ii) in the range 100 μm- 10 cm in the high-time-resolution images taken in the visible light during ***electric breakdown*** in various types of electric discharge (specifically, 300 μs before appearance of discharge electric current measured by the Rogovsky coil in tokamak T-6 and, respectively, 100 ns -- in plasma focus LV-2, see survey [7(d)] and [7(e,f)]). This similarity allows to draw a bridge between unusual forms of the dust and their probable role [7(a-c)] in the electric breakdown in fusion facilities.

3. Conclusions

The above results allow us to draw the following conclusions:

- tubular structures seem to be the major building blocks in the observed skeletons in the entire range D ~ 100 nm - 10 μm;
- within this range, the trend toward self-similarity (i.e. assembling of bigger structures from the similar smaller ones) is seen;
- dendricity of many skeletons (including that of an essentially tubular structure, see Fig. 2) favours the possibility of a streamer-like mechanism of self-assembling of macroscopic skeletons from nanotubular blocks during electric breakdown;
- the structures of non-trivial topology (e.g., agglomerate of visually separate particles), observed in the dust deposits, may possess an internal skeleton hidden by an amorphous component.

Acknowledgments

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