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Skeletal dendritic structure of dust microparticles and of their agglomerates in tokamak T-10

B.N. Kolbasov, A.B. Kukushkin *, V.A. Rantsev-Kartinov, P.V. Romanov

Institute for Nuclear Fusion of Russian Research Centre "Kurchatov Institute", Moscow, 123182, Russia

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Abstract

The dendritic skeletons are found in submicron dust particles contained in various types of dust deposit in tokamak T-10. These skeletons are composed of few-several nanometers thick fibers and are partly/fully embedded in an amorphous component. The agglomerates of visually separate particles (VSPs) are shown to possess a common dendritic skeleton with the distribution of amorphous component being peaked around basic blocks of the dendrite to form the VSPs. The dendricity of above skeletons is compatible with a hypothetical streamer-like mechanism of assembling a skeleton from nanotubular blocks.

1. Introduction

Recently an analysis of the database on the transmission and scanning electron micrography of various types of dust deposit in tokamak T-10 was carried out, being aimed at verification of the hypothesis [1,2] which suggested the presence of a microsolid skeleton in the observed long-lived filaments in plasmas (such skeletons might be assembled during electric breakdown from the wildly formed carbon nanotubes or similar nanostructures of other chemical elements). The results showed [3] the presence of (i) tubules of the size typical for individual carbon multilayer nanotubes (from few nanometers to few tens of nanometers); (ii) tubular structures 50–100 nm in diameter, which are built from smaller tubules; (iii) signs, on the surface of the films, of tubular structures of diameter in the micrometer range, which are sometimes built from tubules of smaller diameter. These results appeared to be compatible with hypothesis [1,2] in the sense that (1) the trend of assembling larger tubules from smaller ones (i.e., the self-similarity) is seen in the dust deposits in the range from ~ 10 nm to ~ 10 µm; (2) this trend becomes more distinct in comparing the obviously microsolid tubular structures, which contain distinguishable structures (namely tubules and, especially, those with a cartwheel in its edge cross-section) in the range ~ 10 nm to ~ 10 µm, with similar structures found earlier in the few centimeters range in the visible light images of plasma in tokamaks TM-2, T-4, T-6 and T-10 [4], and in the millimeter range, in a gaseous Z-pinch and plasma focus [4].

The present Letter is aimed at further verification of hypothesis [1,2]. This assumes analyses of such individual microparticles in the dust deposit in tokamak T-10, which are partly/fully *transparent* to a transmission electron micrography (TEM) and possess a resolvable *skeletal* structure. It is the fine structure

* Corresponding author.
E-mail address: kuka@nfi.kiae.ru (A.B. Kukushkin).

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of the skeletons that will enable us to suggest an answer to the following questions: (i) are there the features common for *various* types of skeletons (including tubular skeletons of various size observed in [3]); (ii) may the visually separate dust particles in the micron-sized agglomerates of such particles be linked together by skeletal bonds; and even (iii) may such an agglomerate possess a *unified* skeleton?

This study may shed a light on the probable mechanism of skeleton's formation and on the origin of non-trivial structures which were observed in various dust deposits and may be explained by the quite different mechanisms of their formation. This pertains, in particular, to the cauliflower structures [5] observed in the dust deposits in tokamaks TEXTOR [6,7] and T-10 [8].

One way in interpreting such a structuring 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 [9] 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 plasma environment 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 [10].

The hypothesis [1,2] suggested one more approach which is based on the action of a hypothetical universal mechanism of the buildup of skeletal structures. Such structures have been observed in the plasma interior [4] (as a non-chaotic long-lived network of long, and often straight, filaments) and various dust deposits [3], and compared with each other in [3]. The hypothesis [1,2] for forming/sustaining the skeletons exploited the predicted and experimentally observed trend [11], in the electric current-carrying media, toward the so-called force free magnetic configuration which is characterized by a self-consistent local shear of electric current and magnetic field. The success of principles [11] in spheromaks and reversed field pinches is widely known (see also [12], for the case of systems with a strong external magnetic field—tokamaks; and [13], for an extension of principles [11] to tokamak plasma steady-state profiles with internal transport barriers). The global trend [11] predetermines the presence of azimuthal currents, along with longitudinal ones, in a straight/curved plasma column—in particular, in the interior of an individual filament of the current. In the media containing a microdust component, this general trend should work at microscales as well and may, in a plasma environment, "dress" the nanotubular blocks with the dipole magnetic field (here, the plasma environment originates from "instant" electrons, easily ejected from the nanotubules by the external electric field, and eventually involves the plasma of the working gas and/or erupting electrodes). Magnetic dipole attraction of such nanoblocks may be a "glue" essential for the buildup—already at the electric breakdown stage—of various *long-lived* skeletons of macroscopic size. The hypotheses of trapping, and low-dissipation confinement, of magnetic field by the nanotubular blocks and their assemblies have been assumed in the hypothetical qualitative scenario [1,2] of electric breakdown. These hypotheses are supported by the following recent experiments: first, observations [14] of unexpectedly low dissipation (even at room temperatures) of magnetic field trapped by the non-processed fragments of cathode deposits which contain various assemblies of multiwall carbon nanotubes, and, second, observations [15] of quite unexpected ferromagnetic properties of a *pure* carbon (specifically, rhombohedral C_{60}) with a Curie temperature near 500 K. Besides, the presence of skeletons (specifically, tubular and cartwheel-like structures in the range of diameters ~ 100 µm to ~ 10 cm) at initial stage of electric discharge (e.g., yet before appearance of the discharge electric current detected using Rogovsky coil) was shown [16] in the high-resolution visible light images of plasma in tokamak, plasma focus and vacuum spark.

The Letter is organized as follows. First, we analyze the structure of skeletons which are found in individual dust particles (Section 2) and, further, the structure of the agglomerates of visually separate dust particles (Section 3).

2. Skeletal structure of dust particles

The skeletal structuring of dust particles is analyzed with the help of the transmission electron microscope TEM JEM-100CX (for magnification $M = 10\,000$, its space resolution is 5 nm). The original TEM images have been processed with the method of multilevel dynamic contrasting (MDC) [17,18] (this method may increase spatial resolution by the order of magnitude). Basically, the structuring under search is practically resolvable, however, without any MDC processing: it is merely suffice to magnify the original image to a proper size. The MDC processing resolves the fine structure and makes it more distinct.

The pictures of Figs. 1–6 are obtained from the original images using a "homogeneous" map of contrasting, i.e., a single for the entire image (in general, the map of contrasting is a dependence I_1 vs. I_0 which prescribes that the given value I_0 of image's blackening is to be replaced at all points where this value is encountered in the original image, by the certain value I_1). The reliable identification of structuring requires [17,18], however, variable (i.e., "breathing", "dynamic") map to avoid artifacts and select an optimal final image. The best would be having an optimal map for each patch of the image (we would call this a mosaic MDC). This, however, makes the image either unreasonably complicated, because of boundary effects, or requesting additional, non-contrasting procedures. Therefore we present here the images obtained with a homogeneous map of contrasting and additionally, in the windows in Figs. 3, 5, 6, we give a schematic drawing of the structuring that has been revealed through mosaic MDC processing, to help a reader in recognizing the structuring in the presented image.

We analyzed dust particles (i) deposited at a quartz filter mounted on a stock located in the tokamak vacuum chamber well outside the plasma column (Figs. 1, 2); (ii) extracted from the oil, which has been used in the tokamak vacuum pumping system, and redeposited on a highly homogeneous, ~ 30 micrometer thick carbon film (Fig. 3); (iii) deposited

Fig. 1. The transmission electron microscope (TEM) image (magnification 9 000) of an egg-shaped carbon particle deposited at a quartz fiber of the filter mounted on a stock residing inside tokamak T-10 chamber, well outside the plasma column (the filter's fiber is seen as a black region in the right-hand side of the picture). Image's 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.

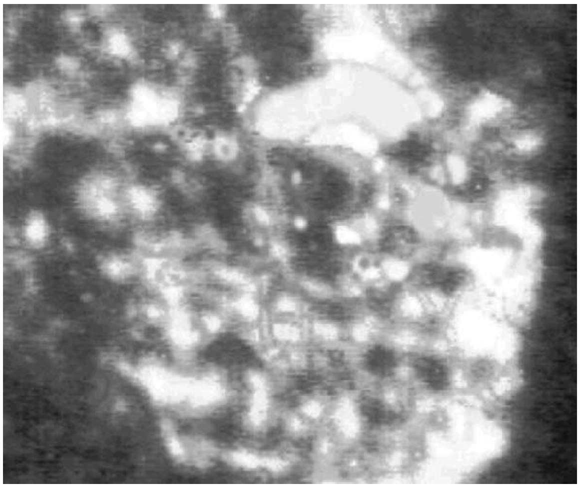

Fig. 2. A fragment, namely the upper right part, of Fig. 1. The network of nanofibers of diameter ~ 5 nm forms, in particular, a grid with inter-fiber space of ~ 10–20 nm. The coaxial structure (presumably, a torus of outer diameter ~ 130 nm) residing on a thick axle-tree, is a sort of dendrite.

at a glass fiber filter during pump out of the dust in the crimp in the tokamak vacuum chamber (Figs. 4–6).

The data show that submicron particles of various form may possess a skeleton which is partly/fully em-

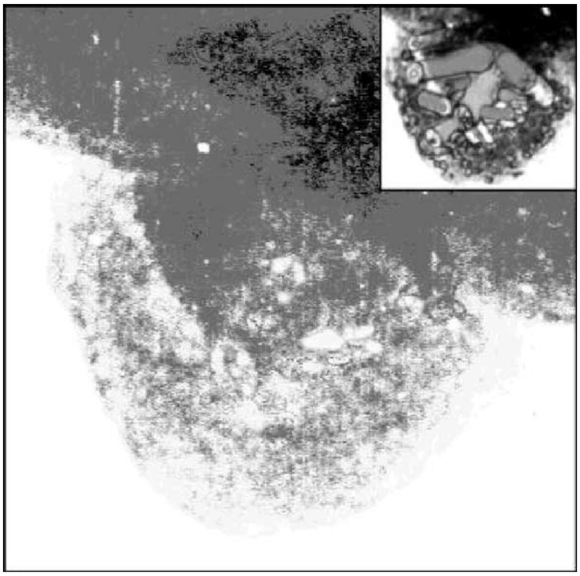

Fig. 3. The TEM image (magnification 50 000) of a part of the ∼ 400 nm sized particle extracted from the oil, which has been used in the tokamak T-10 vacuum pumping system, and redeposited on a highly homogeneous, ∼ 30 micrometer thick carbon film. Image's width is ∼ 120 nm. The ∼ 3 nm thick branches, which are seen in the center of a crown-like formation, "grew" at a tubular trunk (seen in the center and declined with respect to image's plane) which, in turn, has grown from the main body of the particle. A schematic drawing of the structuring revealed from mosaic MDC processing (see Section 2) of the image is shown in the frame in the right upper corner.

bedded in an amorphous component. The role of such a component has been studied in the much more treatable case of apparently homogeneous dust films, of thickness of few tens of microns, deposited on the internal surface of the tokamak vacuum chamber. It appears that thermal processing of these films leads to a partial disappearance of the amorphous component (formed, mostly, by hydrocarbons). Specifically, this manifests as a decrease of relative concentration of hydrogen in the sample [19]. The above transformation of the sample results in a visual stripping of skeletal structures whose presence in the sample before processing was substantially less clear.

On the whole, the available database shows the diversity of skeletal structures of dust particles. The skeletons of dust particles seem to determine the topology and spatial dimensionality of these particles. An example of the individual particle which appears to possess a dendritic skeleton is shown in Fig. 1.

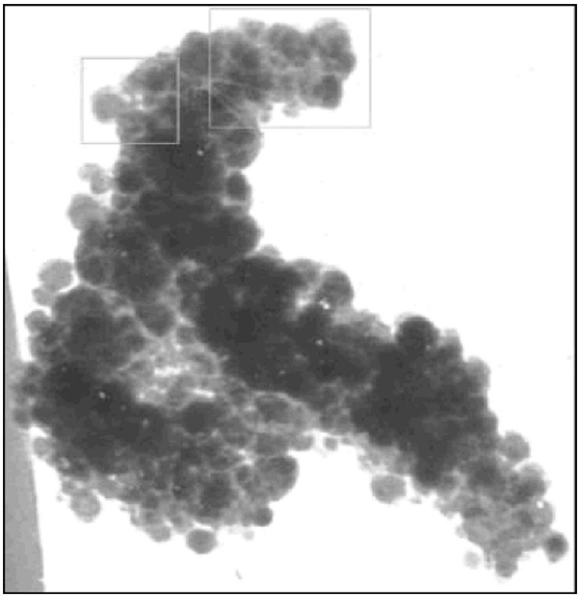

Fig. 4. The TEM image (magnification 26 000) of an agglomerate of visually separate dust particles redeposited at a glass fiber of the filter during pump out of the dust in the crimp in the tokamak T-10 vacuum chamber (the fiber is partly seen as a black band on the left-hand side of the image). Figure width is 590 nm. The magnified images of the windows are given in Figs. 5 and 6.

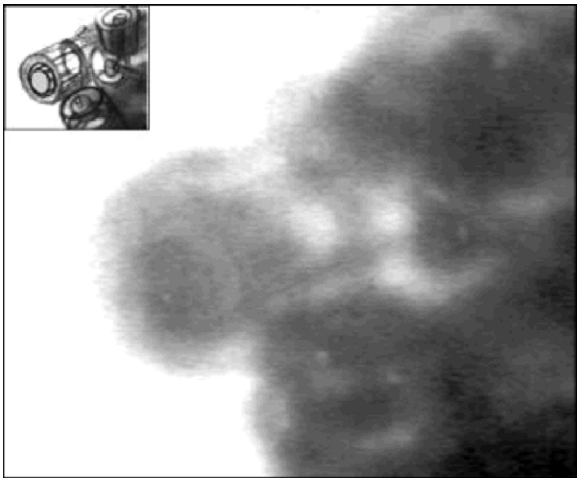

Fig. 5. The image of the left upper edge of the agglomerate (see left window in Fig. 4). The visually separate, quasi-spherical particle appears to be a projection of the edge of a tubular structure which is a part of the skeletal structure of the agglomerate. Figure width is ∼ 120 nm. A schematic drawing, similar to that of Fig. 3, is shown in the frame in the left upper corner.

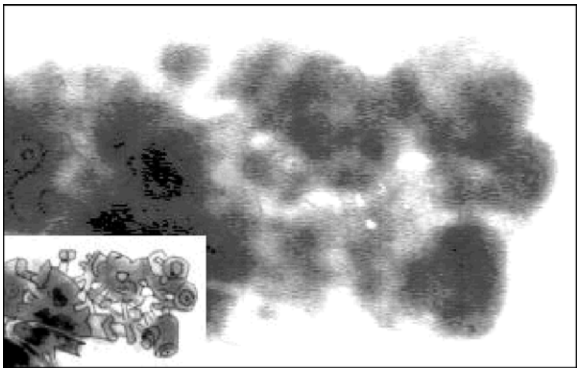

Fig. 6. The image of the right upper edge of the agglomerate (see right window in Fig. 4), which shows a bunch of dendritic structures (presumably, cartwheels on their own axle-trees). Figure width is $\sim$ 180 nm. A schematic drawing, similar to that of Fig. 3, is shown in the frame in the left lower corner.

The fine structure of skeletons is determined, in turn, by the "networking" of nanofibers (see Fig. 2). Fig. 3 shows a transparent part of the dust particle which contains a dendritic skeletal structure.

Regarding the structure of the nanofibers themselves, the previous TEM data showed that their typical diameter lies in the range few-several nanometers and their internal structure is presumably a tubular one. The tubularity is suggested by the distinct walls of these fibers when a single fiber may be resolved (i.e., when there is no superposition of fibers in the TEM image), see, e.g., Fig. 1 in [3]. Besides, the tubularity is more distinct for tubular structures of a larger size (see, e.g., a coaxial tubule of the outer diameter $\sim$ 60 nm on the left edge of the dust particle in Fig. 1).

3. Skeletal structure of agglomerates of visually separate dust particles

Let us proceed with analyzing the agglomerates of visually separate dust particles. Fig. 4 shows typical example of such an agglomerate. It appears that not only the visually quasi-spherical particles possess an internal skeletal structure (Fig. 5) but the neighboring particles often belong to a common skeletal structure (Fig. 6). The skeletal structure seems to be a base of the entire agglomerate. Significantly, the ball shaped or similar structures located near the transparent edge of the agglomerates as a rule appear to be a cartwheel-like structure located at the axle-tree connected with the skeletal structure of the entire agglomerate (see schematic drawing in the frame in Fig. 6).

It follows from Figs. 4–6 that the agglomerates of visually separate dust particles appear to be such a particle which contains (i) skeletal blocks arranged in a more or less ordered unified skeleton, and (ii) an amorphous component whose distribution is peaked around basic blocks of the dendrite to form the visually separate quasi-spherical blocks. Roughly speaking, the quantity of amorphous component in these dust particles seems to be not sufficient to fill in the gaps between neighboring blocks of the skeleton.

4. Discussion and conclusions

Now we have to draw a bridge between two trends in the observed structuring: namely, the formerly observed tubularity [3] and the dendricity of Figs. 1, 3, 5, 6. First of all, the cartwheel-like structure located at a bare axle-tree seems to be the simplest dendrite (see Fig. 3 in [3] and Figs. 2, 6). Further, the above structure is such a block which often appears in the edge cross-section of a tubule (see Figs. 2, 5 in [3]). However, stronger arguments in favor of the relationship between tubularity and dendricity are still desired. In general, identification of dendricity requires—because of relatively higher geometrical complexity as compared to a bare tubule—a bigger piece of luck for a researcher. This is the case, e.g., with Fig. 2 in [3], which is a TEM image of a microparticle. This microparticle possesses a tubular structure and is absolutely free of amorphous component (thanks to rectification of the dust deposit originally extracted from the oil used in the vacuum pumping system of tokamak T-10). It is seen that the central internal rod plays the role of a trunk because the radial links exist not only in the edge cross-section of the cartwheel but also between the trunk and the side-on tubules in the intermediate cross-sections. Thus, the available data suggest that the tubular building block seems to be such a particular product of a general dendritic mechanism, which gives the *optimal* building block for the buildup of skeletal objects of macroscopic size (note that just tubular blocks were suggested [1,2] to be responsible for the self-similarity of macroscopic skeletons).

The phenomenon of skeletons of a *dendritic* structure, which is found here both in individual particles of various form and agglomerates of visually separate particles, allows us to suggest that a wide class of skeletal structures may be formed—at least at submicron length scales—by the hypothetical mechanism [1,2] of streamer-like (i.e., dendritic) assembling of skeletons from nanotubular blocks.

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