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Comparison of Nanoparticles Collected in the MAST Tokamak with Those Produced in Laboratory Plasmas

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Abstract. Among dust particles of various origins collected in the MAST vessel, large quantities of carbon nanoparticles are observed. They are produced in the coldest plasma regions from the nucleation of carbonaceous species originating from physical and chemical erosion of the graphitic plasma facing components. On the other hand, laboratory plasmas studies show that in an environment of reactive carbonaceous species, complex chemical pathways lead to various molecular precursors which depend strongly on plasma conditions. The latter vary very often in a tokamak. Nevertheless, the final nanoparticles produced in laboratory plasmas and in MAST present similarities, giving indications on common growth processes in the plasma.

Keywords: nanoparticles, nucleation, dusty plasmas, carbon, tokamaks
PACS: 52.27.lw, 52.55.Fa, 52.40.Hf

INTRODUCTION

Erosion of plasma-facing components (PFCs) by plasma-surface interaction is one of the processes leading to the production of dust in fusion devices. Large quantities are expected to be produced in ITER and the consequent impact on safety and operational performance is the subject of on-going study. For example, due to a large surface area and chemical reactivity, dust particles can retain deuterium/tritium and affect the fuel inventory during plasma operations. They are potentially radioactive, toxic and explosive when reacting with steam and air. Because of their bad adherence on wall surfaces, dust particles can lead to early termination of plasmas[1]. Consequently, analyses of dust in present day tokamaks are necessary as well as the study of dust formation in laboratory plasmas where controlled conditions are possible in order to improve understanding of dust formation mechanisms in tokamaks.

In this paper, we present analyses of various dust families, collected in MAST, a tokamak of graphitic PFCs. Similar dust particles were already identified in other tokamaks[2-5] with the caveat that the presence of nanoparticles was not mentioned in all tokamaks. Their generation in MAST shows that a part of the carbon species coming from the physical erosion (sputtering) and chemical erosion (mainly, methane release)

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of the PFCs may nucleate in the coldest plasma regions[2]. Carbon nanoparticles generation in laboratory plasmas, i) from sputtered carbon atoms and ii) from methane-containing plasmas is also discussed. These laboratory studies show that the molecular precursors are the result of complex chemical pathways which depend strongly on plasma conditions. In tokamaks, conditions can change from a plasma to the next one and from a tokamak to another one because of different magnetic configurations, designs and modes of operation. Nevertheless, the final nanoparticles produced in laboratory plasmas as well as in MAST present similarities which give information on their mode of growth.

DUST IN MAST

Dust was collected by the filtered vacuum technique in the MAST vessel. **FIGURE 1 (a)** shows a typical example of dust particles on a filter surface. Grains of irregular shape and roughness are located on the left and right sides. Their real origin is established by micro-Raman spectroscopy. Grains which have the same Raman spectrum as the graphitic material of PFCs are directly pulled out from the PFCs during plasma instabilities and off normal events. Grains coming from the flaking of deposited layers have more complex spectra, showing transformations of carbon and hydrocarbon species[6]. Metallic particles are also observed (top of **FIGURE 1 (a)**). They are produced from metallic melting by arcing on the vessel. The irregular layer located below the left grain is an agglomerate of nanoparticles whose magnification is given in **FIGURE 1 (b)** and the corresponding size histogram in **FIGURE 1 (c)**. The size dispersion is narrow and the most probable size is ~ 20 nm. Transmission electron microscopy (TEM) shows that nanoparticles can have a graphitic structure where small graphitic domains have a concentric orientation as shown in **FIGURE 2 (a)**.

NANOPARTICLE FORMATION IN COLD PLASMAS

Studies on the carbon nanoparticle formation in laboratory plasmas have pointed out that chemistry reactions leading to the growth of molecular precursors are complex. Even for a simple hydrocarbon molecule such as methane which is released

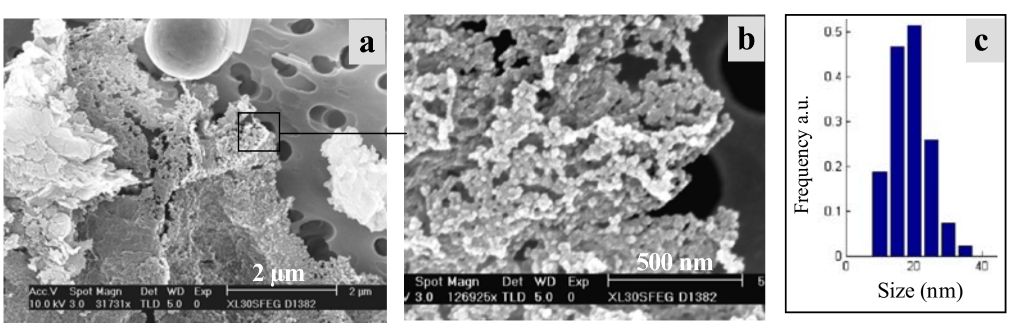

FIGURE 1. (a) Scanning electron microscopy (SEM) image of dust particles on the surface of a filter, (b) magnification of an agglomerate of nanoparticles, (c) nanoparticle size histogram

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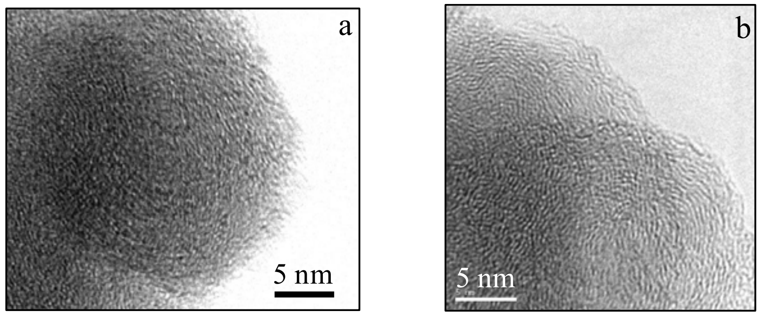

FIGURE 2. TEM images of dust particles made of graphite domains concentrically oriented. (a) They were produced in MAST, (b) in laboratory plasmas from sputtered carbon atoms

by the PFCs, the nucleation process can be the result of several sequences of chemical reactions which vary strongly with plasma conditions[7-9]. At low pressure and power, experiments have shown that positive and negative hydrocarbon ions may develop but with a larger extent for the negative ions because of their trapping in the plasma[7]. In addition, saturated hydrocarbon molecular ions must be considered at low gas temperature while at high temperature and high gas density, successive reactions of hydrogen abstraction and carbon addition lead to the growth of neutral poly-cyclic aromatic hydrocarbon (PAHs) molecules and to a reduced density of positive PAHs while negative species are not stable[10]. In the case of nanoparticles produced from sputtered carbon, studies at low pressure and low input power for instance, show that the nucleation process is the result of a simpler chemistry. The precursors are negative clusters characterized by magic numbers[11]. Of course, all these results are far from being complete and developed models only describe specific experimental conditions.

There is no information on the molecular precursors in tokamaks. Difficulties come from the fact that tokamaks have different magnetic configurations, designs, operation modes and instabilities can also develop. Moreover, dust samples are collected after plasma campaigns of several months. However, the precursor formation may occur in the coldest regions of the plasma situated towards edges where the plasma temperature and density decrease exponentially. In particular in MAST, the e-folding lengths are long and allow having plasma parameters similar to those of laboratory dusty plasmas.

It is worth noting that whatever the nature of the molecular precursors, the final spherical particles produced in MAST, in Tore supra[12] (as shown previously) and in our sputtering discharges and methane-containing plasmas[9], present the same structure of concentric graphitic domains. This structure provides an evidence of growth by accretion in the plasma. It also shows that these particles are synthesized in a hot medium since the graphitic ordering is enhanced by rising temperature. In MAST, they also could be heated on the wall surface because of their bad adherence[13]. Heating mechanisms have for consequence, a partial or a total de-hydrogenation and accordingly, a loss of information on the origin precursors. In MAST, nanoparticles also appear under the shape of dense agglomerates. They are not embedded in deposited layers and they have a narrow size dispersion as do nanoparticles observed in dusty plasmas after their deposition on substrates when the plasma is stopped.

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These observations could also show that there are regions in the MAST plasma edge where nanoparticles are trapped and produced at high density.

CONCLUSION

Nanoparticles produced in gas phase were collected in the MAST tokamak. There is still no information on their molecular precursors as for other tokamaks where they were previously observed because of frequent change of operation modes and consequently, of plasma parameters. However in MAST, they appear under the shape of dense agglomerates and are characterized by a narrow size dispersion like those produced in dusty plasmas. These results indicate that nanoparticles can be produced at high density in the coldest plasma regions of MAST. Their structure of concentric graphitic domains, also observed in laboratory dusty plasmas reveals that they grew in the plasma by accretion and that they were also heated during their transport in the plasma or on the wall surface because of their bad adherence after deposition.

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