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DUST PARTICLES IN CONTROLLED FUSION DEVICES: GENERATION MECHANISM AND ANALYSIS

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1. Introduction

Generation and in-vessel accumulation of carbon and metal dust are perceived to be serious safety and economy issues for a steady-state operation of a fusion reactor, e.g. ITER [1,2]. The major concerns are related to the risk of pressure rise and explosion under massive air or water leak on hot dust and, to fuel retention in particles loosely bound to surfaces. There is also an operational risk arising from the degraded performance of diagnostic components (e.g. first mirrors [3] and windows) or pumping components such as cryo-panels. The impact of levitation of charged tritiated dust on plasma performance has also been addressed [4]. As a consequence, there are administrative and safety limits of dust content in the ITER vessel [5]. When talking about safety, another important issue is the dust formation during the process of fuel and co-deposit removal from plasma-facing components (PFC). It has been shown that photonic [6], thermal and oxidative [7] methods for fuel removal may lead to dust release from the treated surfaces. The access to in-vessel components of a D-T reactor will be extremely limited. Therefore, in present-day machines one has to determine the amount, location and properties of dust, recognize the generation mechanism and the impact of dust on plasma operation. The importance of such studies was recognized at TEXTOR already in mid nineties. Over the years several comprehensive dust surveys have been carried out on the occasion of major shut-downs which gave access to all in-vessel components [1,8,9].

The intension of this contribution is to provide an account on: (a) properties of carbon and metal dust formed in the TEXTOR tokamak during campaigns comprising 4 - 24 h of plasma operation; (b) dust generation associated with removal of fuel and co-deposit from carbon plasma-facing components (PFC); (c) morphology of PFC surfaces after different cleaning treatments.

2. Experimental

The collection of dust in TEXTOR was preceded by an experiment aiming at the mobilization of fine dust during the vent. Several camera systems were engaged during a controlled gas blow into the vessel. It did not cause observable dust mobilization and levitation thus showing that fine dust adheres very well to PFC surfaces probably due to Van der Waals forces as suggested in [10]. During the first hours after opening of TEXTOR dust and debris were collected by vacuum cleaning using cascade series of meshes and filtering paper connected to a vacuum pump. Sampling of deposits from the liner and limiters was done using adhesive carbon stickers and ultra-fine copper nets for microscopy and, by direct scraping-off deposits with a plastic knife. The material (loose particles) was separately taken from the bottom and the low-field side of the Inconel® liner, from the main graphite limiters pump toroidal belt ALT-II, poloidal and inner bumper and from the bottom shield of the dynamic ergodig divertor (DED). Magnetic and non-magnetic fractions were separated prior to further studies.

Observations of dust during the plasma operation was accomplished by fast cameras and spectroscopy. No serious impact on the plasma performance has been noted, thus confirming previous findings [1].

The material retrieved from the vessel was examined scanning and transmission electron microscopy (SEM and TEM), energy dispersive X-ray spectroscopy (EDX), nuclear reaction analysis (NRA) using a $^{3}He^{+}$ beam of energy of 1.4 MeV in order to assess surface distribution of deuterium. The total fuel content was determined by means of temperature-programmed desorption spectrometry (TDS). Specific surface area of some dust samples was performed by means of the Brunauer-Emmett-Teller (BET) method.

3. Results

3.1. Morphology

The amount of loose material found on the floor of the TEXTOR liner was about 2 g; the size varied from 0.1 μm to 1 mm. This material contained mainly debris originating from damaged PFC tiles and diagnostics, whereas the amount of fine carbon dust did not exceed 0.2 g. Images in Fig. 1 (a-c) show dust-forming flaking layers from the deposition zone on ALT-II limiter, liner and the main poloidal limiter, respectively.

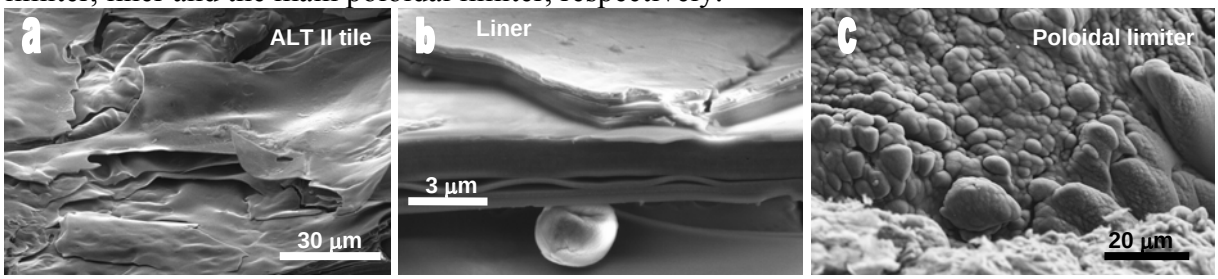

Fig. 1. Structure of flaking, dust-forming co-deposits formed on: deposition zone of toroidal limiter ALT-II (a), liner (b) and main poloidal limiter (c).

The layers on Fig.1 (a,b) are fairly flat and stratified, whereas co-deposits shown in Fig. 1 c have granular and columnar structure. It is related to the difference in temperature in various places in TEXTOR: 300-350 ^{o}C in the deposition zone of ALT-II, 200-250 ^{o}C on the liner and even over 2000 ^{o}C on the surface of the poloidal limiter. As a result, the porosity and specific surface area of deposits differs. For instance, the specific surface area of columnar deposits formed on the neutraliser plates of ALT-II (maximum temperature over 2000 ^{o}C) was 24,2 m^2g^{-1} as determined with the BET method. The temperature of PFC surface is decisive for the fuel content in co-deposits and then, in the dust formed by flaking.

Fig. 2 a shows a debris collected from the bottom of the liner, whereas TEM image (Fig. 2 b) presents an amorphous deposit with embedded tiny particles (50-80 nm) of crystalline matter, as confirmed by electron diffraction; see pattern in Fig. 2 c. In all cases the elemental composition determined by EDX revealed that the material was composed only of carbon.

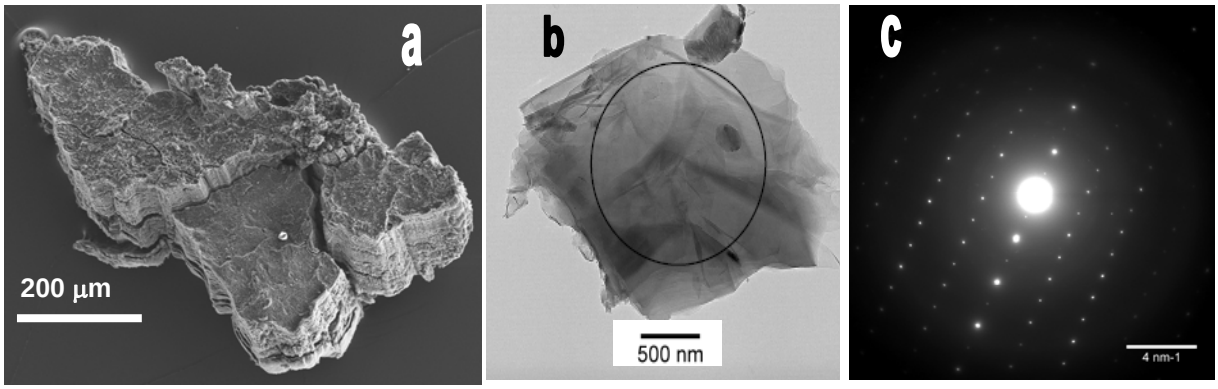

Fig. 2. (a) Graphite debris collected from the bottom of the liner (a); amorphous carbon co-deposit with embedded nano-size particles of crystalline carbon (b) and corresponding diffraction pattern (c).

One may tentatively suggest that the presence of such crystalline graphite objects in the loose material could be associated with brittle destruction [12,13] of carbon PFC caused by highly

localised power loads due to disruptions. The final confirmation of that phenomena taking place in TEXTOR is still needed by systematic combined studies using cameras and spectroscopy methods for dust tracing in the plasma and, by detailed dust survey during the next opening of the TEXTOR vacuum vessel. It should be stressed, until now no direct evidence of brittle destruction has been found in present day tokamaks, but it was detected in a reversed field pinch as a result of highly localized wall-locked modes [1]. Therefore, the effect cannot be excluded in future devices in the case of giant edge localized modes (ELM), vertical displacement events (VDE) or disruptions.

3.2. Fuel content

Fuel inventory in a reactor must be carefully controlled. This applies predominantly to the assessment of fuel reteined in co-deposits and dust. The total amount of deuterium in co-deposits and dust collected from various locations was with TDS by monitoring masses 2 (H_2), 3 (HD), 4 (D_2), 18-20, i.e. water group and various hydrocarbons $C_xH_yD_z$. The desorption was done at temperatures of up to 1000 ^oC. The data are normalized for the mass of flakes taken for TDS (1 mg). Graphs in Fig. 3 (a-b) show spectra recorded during outgassing flaking co-deposits formed in the deposition zone of the toroidal belt limiter ALT-II (a) and on a grill of the antenna for ion cyclotrone resonance frequency (ICRF) heating. As inferred from intensity of H_2 and HD traces, the amount of hydrogen in both types of flakes is substantial. It may be related to the porosity of materials and absorption of water when flakes are in contact with ambient air. There are two major differences: (i) the amount of fuel which is distinctly greater in the ALT-II flakes and (ii) the release characteristics of D_2. While the desorption characteristic from ALT II has a standard shape with a peak around 520 ^oC, the release from the other sample is characterized by several sharp peaks (like "bursts") thus indicating features characteristic for desorption from metals. It agrees with previous morphology studies showing that flakes from ALT contain carbon (80 % at) and only ~1 % of metals, while in flakes from the antenna the amounts is 25 % and 30 % at, respectively [11]. This is due to effective carbon removal by energetic species produced during ICRF pulses.

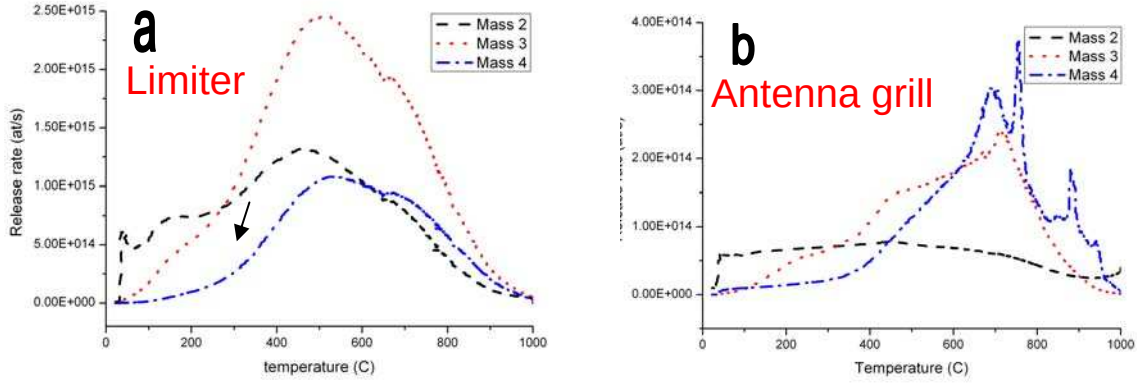

Fig. 3. Thermal desorption spectra of H_2, HD and D_2 from flaking co-deposits on the ALT-II toroidal limiter tiles (a) and ICRF antenna grill (b).

3.3. Dust generation in connection with fuel removal methods

The safety limit for tritium inventory in ITER is currently set at the level of 700 g. In the case of carbon PFC this level can reached during less than 100 shots because of chemical erosion and fuel co-deposition [5]. The development of co-deposit and fuel removal methods is essential but equally important is to assess the impact of different techniques on the surface state of treated materials and dust generation. It has already been shown that high power laser pulses may efficiently remove the layer but the ablated material is only partly converted to

gaseous products. Major part of the layer is converted into dust thus distributing fuel and flakes to the surrounding areas [6].

Another approach to fuel removal is based on heating or oxidation. Even a long-term heating in vacuum at 350 ^{o}C (maximum foreseen baking temperature of the ITER divertor) does not reduce the fuel content [14]. It can be achieved at 800-1000 ^{o}C which is not conceivable from the engineering point of view. Such high-temperature annealing leads to cracking and flaking of co-deposits as dust. Similar effect is observed when oxidizing PFC tiles with co-deposits in air at 300 ^{o}C [7]. Microscopy images in Fig. 4 (a-c) show the original surface of the RF antenna protection limiter with a deposit and flaking layers following annealing and oxidation, respectively.

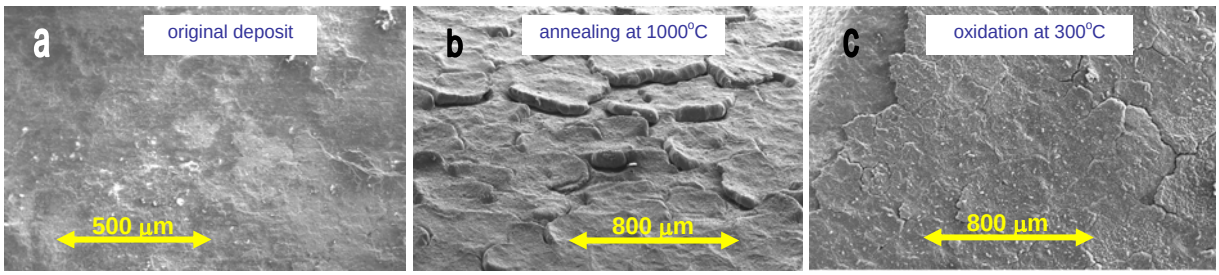

Fig. 4. SEM images of the: original co-deposit on a tile surface (a); craking and flaking of co-deposits after annealing in vacuum (b) oxidation in air (c).

4. Concluding Remarks

In a carbon wall machine the disintegration of flaking co-deposits on PFC is the main source of dust. The study has shown that also brittle destruction is to be taken into account when assessing dust production in future devices. The generation of dust by photonic and oxidative methods for fuel and co-deposit removal may also create some problems if applied in the carbon surrounding. The issue of metal dust (beryllium and tungsten) formation is still be properly addressed. It will be done in connection with ITER-Like Wall [15] operation of JET.

Acknowledgements

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