Parametric dependencies in the formation and structure of co-deposited beryllium layers on the wall structures of fusion reactors

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Introduction

Formation and characteristics of co-deposited layers on plasma-facing components (PFCs) is a key research area for the safety of future fusion reactors, especially to reliably estimate retention of tritium (T) in the PFCs. Due to the potentially complicated structure of the expected co-deposits, reference layers are needed for elucidating the role of different plasma and material parameters in the retention process [1]. Here, we have put the focus on beryllium (Be)-based reference layers: Be is used as the main wall material at JET in its ITER-Like Wall (ILW) configuration [2] and until recently has also been the baseline material for the first wall of ITER [3].

We have produced the reference layers with varying (i) *compositions* – consisting of Be, deuterium (D) as a proxy for T, as well as various light impurities such as H, He, C, N, O, and Ne; (ii) *surface temperatures* during the layer production and during their annealing after the deposition phase and (iii) *surface roughness* with the goal of simulating the impact of (gaseous) impurities, thermal treatment, and surface morphology in fuel accumulation during extended plasma operations The properties of the produced layers, in particular their D concentrations, were determined using different surface-analysis techniques.

Experimental

All the reference layers were produced on tungsten (W) substrates to mimic the situation observed at the JET-ILW divertor. The selected deposition method was High-Power Impulse Magnetron Sputtering (HiPIMS) [4]. The applied surface-analysis techniques, included Elastic Backscattering Spectrometry (EBS) for the elemental composition of the layers; Nuclear Reaction Analysis (NRA), Time-of-Flight Elastic Recoil Detection Analysis (TOF-ERDA), and Thermal Desorption Spectroscopy (TDS) for their D content (in at.% and in at/cm^2); Secondary Ion Mass Spectrometry (SIMS) and X-ray Photoelectron Spectroscopy (XPS) for extracting detailed elemental depth profiles at the surface and deeper in the layer; and Raman spectroscopy and Grazing Incidence X-ray diffraction (GIXRD) for collecting structural information of the produced samples. The specifications of the studied layers are summarized in Table 1.

Table 1. Studied reference layers with their labelling scheme, nominal composition, gas content, thickness, roughness, as well as deposition and annealing temperatures. Here, 25°C corresponds to nominal room temperature (i.e., no thermal treatment performed) and arithmetic mean value (R_a) is used to characterize the surface roughness. The thickness of the layers was typically 5 μm, while values up to 30 μm were used for A1/A2 samples.

Sample code and type	Gas	Roughness (R_a, nm)	Deposition temperature (°C)	Annealing temperature (°C)
A1/A2: Be95D5/Be90D10	D	Smooth – 2000	25 – 400	25 – 100 (~20 min)
B1/B2: Be80D20/Be80H20	D/H	Smooth	25	25 – 500 (15 min)
C1: Be90D5O5	D + O	Smooth	25	
C2/C3: Be75D20O5/Be76D10C7O7	D + O	Smooth	25 – 200	
D1/D2: Be92.5D5He2.5/Be90D5He5	D + He	Smooth	25 – 400	
D3/D4: Be87.5D10He2.5/Be85D10He5	D + He	Smooth	25	
E: Be90D5H5	H + D	Smooth	25 – 400	
F1/F2: Be92.5D5N2.5/Be90D5N5	D + N	Smooth	25 – 400	
G1/G2: Be92.5D5Ne2.5/Be90D5Ne5	D + Ne	Smooth	25 – 400	
G3/G4: Be87.5D10Ne2.5/Be85D10Ne5	D + Ne	Smooth	25	

Results

Reference layers produced with different gas contents (Table 1) indicate that especially inclusion of He or Ne (at sufficiently high concentrations of >2 at.%) will increase D retention. This can be noticed in Figure 1 where the data from comparable batches (D5 or D10, corresponding to low or high D flux during the deposition) are collected. We attribute the reason to lattice modifications and creation of defects with the increasing impurity flux during layer production. Other gases have a smaller effect and may even decrease retention. Inclusion of carbon, for its part, increases retention, with a strong contribution from C-D bonds [1].

Even stronger effect on retention is caused by the temperature of the co-deposited layers. According to Figure 2 (left), an increasing deposition temperature T_{depo} reduces retention, similarly to results in [1]. In some layers (mainly containing H or He), retention slightly increases until 100°C before rapidly decreasing towards zero at higher temperatures. It is worth pointing out that retention remains at a smaller level when the deposition temperature is kept constant (T_{depo} = 100-200°C) compared to applying JET-like heating-cooling cycles (T_{base} ~60°C, ΔT ~150°C for 40 s, cycle ~2000 s). Annealing of the reference layers (during 15 minutes at a pre-determined T_{anneal}) also leads to reduced retention with increasing T_{anneal} as Figure 2 (right) shows, both in the case of H and D as the plasma gas. In addition, the Raman analyses showed for the first time clear signs for the formation of hydrides (BeH_x or BeD_x) in reference layers when the temperature was 100-150°C. Fuel retention thus largely depends on the balance between implantation (due to incoming particle flux), bonding (chemically or due to defects), and desorption (due to heating) at a given temperature.

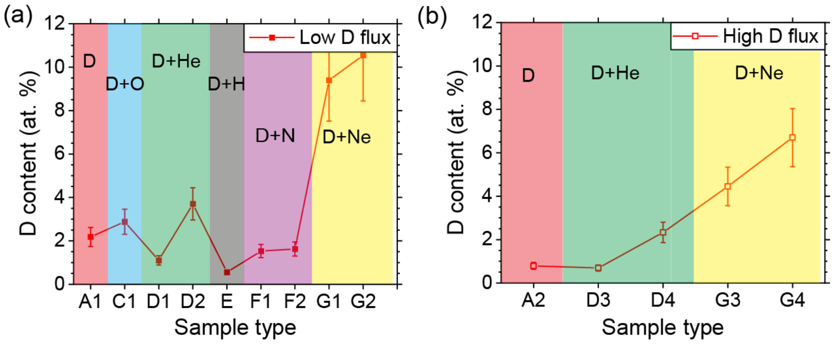

Figure 1. Average D retention (at.%, based on NRA and TOF-ERDA data) for reference layers produced under a (a) low and (b) high D flux during the deposition and in the presence of varying impurity gases. The estimated error is ~20% for the D contents – similarly to all the other ion-beam data shown in this article.

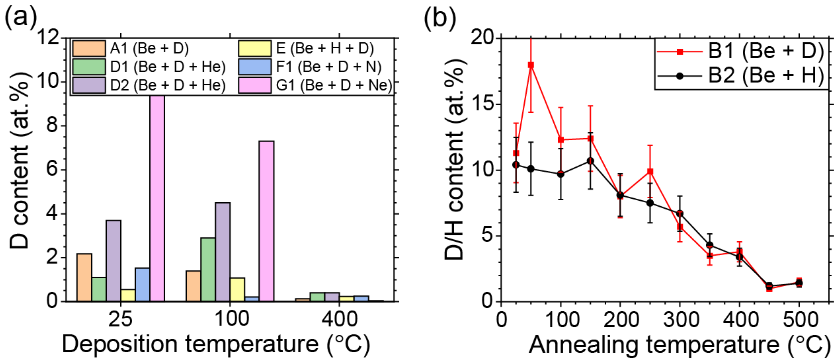

Figure 2. Average D (or H) retention (at.%, based on NRA and TOF-ERDA data) for different reference layers as a function of (a) the deposition temperature and (b) the annealing temperature.

Besides fuel retention, the size of crystallites evolves with the surface temperature. From the GIXRD results in Figure 3 (left), one can see that the crystallites become consistently larger as the surface temperature increases and that the phenomenon is much more prominent during the deposition than the annealing phase. Simultaneously, the lattice constant d decreases. Such results suggest efficient relaxation of tensile stresses induced at low temperatures.

Surface roughness, on the other hand, does not show a systematic effect on D retention as we notice from Figure 3 (right). There are some indications that layers on rough surfaces contain more D, however, no strong conclusions on the role of roughness can be made based on the present data set. Earlier results from tokamaks [5] indicate that more light impurities (including D) will accumulate on rough surfaces, which we attribute to successive erosion-deposition cycles on rough terrains.

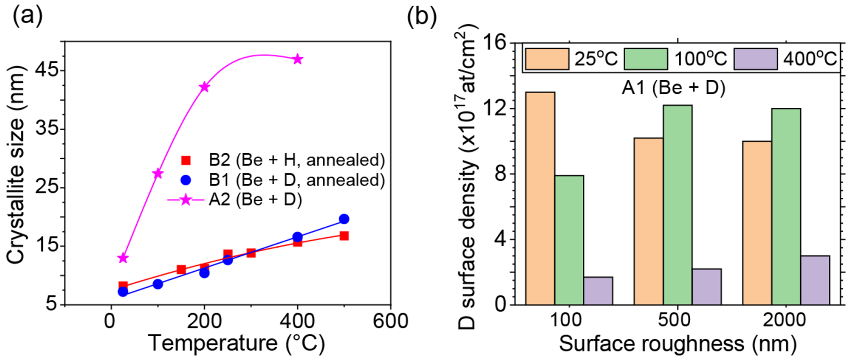

Figure 3. (a) Size of the crystallites in deposited or annealed reference samples as a function of temperature (GIXRD). (b) Surface density of D in selected reference layers as a function of surface roughness (TDS).

Discussion and conclusions

We have investigated fuel retention on Be-containing co-deposits with the help of reference layers to elucidate the role of different physical parameters in the retention process. Increasing surface temperature will drastically reduce retention while inclusion of sufficiently large amount of He and/or Ne in the deposit will enhance retention. These can be attributed to strong lattice modifications and alteration of defect concentrations in the layers, while increasing temperature will also efficiently release stresses formed during the deposition stage. The composition of the reference layers is similar to those measured for JET-ILW co-deposits and annealing of the layers at constant temperatures will even make their structure closer to the experimental observations (see, e.g., [6]). In the future, the results will be generalized to the selected first-wall structures of ITER.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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