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Journal of Nuclear Materials 337–339 (2005) 862–866

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Influence of beryllium plasma seeding on the erosion of carbon

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Abstract

This paper is concerned with the influence of beryllium (Be) impurities in a deuterium (D) plasma on the erosion of graphite (C). C targets biased at −50 V were exposed to a Be seeded D plasma in the temperature range from 500 K to 1280 K and Be plasma concentrations in the range from 0.01% to 0.3% in the PISCES-B divertor simulator. It was found that even at these low Be concentrations, the C samples are covered with a shielding Be layer which almost eliminates chemical and physical erosion of the C sample in the observed target temperature range. A combinatorial approach was used to model these experimental results by using the well established Monte Carlo code TRIDYN together with an analytical model. The paper gives an overview of the experimental data, how the modelling results compare with the experiments and how these results can be extrapolated to ITER.

PACS: 79.20.A; 81.05.T; 61.80.Jh
Keywords: Beryllium; Chemical erosion; Carbon impurities; Erosion and deposition

1. Introduction

The major problem with respect to using CFC and carbon based components is, that eroded C retains large amounts of D and T when re-deposited from the plasma in the form of amorphous carbo hydrides (a-CH) layers. These layers are difficult to remove because they usually form in remote areas [1] due to the low sticking coefficients of their precursor molecules. The radiation inventory resulting from T in these layers accumulation severely limits the operation time of ITER in the D–T phase.

Be is subject to strong physical sputtering resulting in a predicted Be plasma concentration in the ITER divertor region in the range from 1% to 10%. Therefore the divertor will be exposed to a high flux of Be from the plasma. The incident Be impurities may interact with the C surface to inhibit its erosion and hence alleviate some of the difficulties associated with the use of C in the ITER divertor.

In order to simulate these conditions, C targets were exposed to a Be seeded, steady state D plasma in the PISCES-B facility. In addition to the erosion studies presented here also re-deposition experiments have been performed which are described in [2]. The targets were exposed at temperatures ranging from 500 K to 1280 K and Be plasma concentrations ranging from 0.02% to 0.3%. The possible formation of Be layers will be governed by deposition and erosion/re-deposition of Be and at temperatures above ≈1000 K also radiation enhanced erosion [3] and diffusion of Be come into play. To model the measured equilibrium Be surface concentration the

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doi:10.1016/j.jnucmat.2004.08.018

well known Monte Carlo code TRIDYN [4] and an analytical model were used. The model was benchmarked using the experimental results, to allow extrapolation to ITER conditions.

2. Experimental

The PISCES-B device simulates the plasma conditions present in the divertor of today's fusion devices and is described in more detail in [5]. The target is completely engulfed by the D plasma and was biased at -50 V. The target is heated by the plasma and the temperature is measured by a thermocouple from rear side of the exposed target. Be is introduced into the D plasma through an effusion cell which is mounted ≈ 120 mm up stream from the target. The typical Be plasma concentrations were kept well below 1% in order not to change the plasma parameters.

The primary plasma diagnostic is a double head reciprocating Langmuir probe situated ≈ 100 mm up stream from the target. The typical plasma parameters for the experiments presented here were: $T_e = 6$ eV, $n_e = 3 \times 10^{18}\ \mathrm{m}^{-3}$ and ion flux $\Gamma = 3 \times 10^{22}\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$.

To measure changes in the target surface composition due to exposure to the Be seeded D plasma, the target holder can be moved in-situ into an AES/XPS surface analysis chamber.

The Be plasma concentration and the C chemical erosion were measured spectroscopically using the Be II line at 467 nm and integrating the CD-Band [5] from 426 nm to 431 nm. The spectrometer views the plasma through a large window that allows axially resolved spectrometry of the plasma column. The excitation rate coefficients required to calculate the Be plasma concentrations as a function of electron density n_e and temperature T_e were taken from the ADAS database [6].

The targets used in the experiments were made from Grade ATJ isomolded graphite manufactured by GrafTech International Ltd. with a density of $1760\ \mathrm{kg\ m}^{-3}$ and an average particle size of 25 μm. The targets were unpolished, cleaned with ethanol in an ultra sonic bath and then degassed under vacuum (10^{-6} Pa) at 1273 K for 20 min prior to installing them in PISCES-B.

3. Modeling

The goal in modelling this system is to be able to calculate the equilibrium surface composition of Be and C for a given set of experimental conditions, namely sample temperature, T_{Sample}, and the composition and energy of the particle spectrum (C, Be, D, D_2, D_3) incident on the C target.

The energy of the incident species is determined by their charge state and the potential difference, ΔV, between the plasma and the biased target. Since the ion temperature, $T_i \ll \Delta V$, e_0 the thermal energy distribution has only a negligible influence on the particle energies. ΔV is given by the difference between the plasma potential (-10 eV for these experimental conditions in PISCES-B) and the bias voltage (-50 V for all experiments presented here) resulting in $\Delta V = -40\mathrm{V}$.

Due to the Be plasma seeding the chamber walls of PISCES-B are coated with Be, resulting in very low plasma impurity concentrations. The only notable impurity is C with a concentration $\xi_C < 0.1\%$ resulting from chemical erosion of a-CH deposits from the vacuum vessel wall. These erosion products enter the plasma at thermal energies and are fragmented and ionized before they hit the C target. Simulations at low temperatures, where ξ_C is the only unknown parameter (see Section 3.3), showed that a value of $\xi_C = 0.05\%$ gives the best fit to the data. Therefore all the simulations assume an intrinsic C^{1+} concentration in the plasma of $\xi_C \equiv 0.05\%$. The Be concentration in the plasma is taken from the experiments. As was found experimentally all Be hitting the C target was singly ionized provided that the electron temperature was $\geqslant 6$ eV. The partial concentrations of D^+, D_2^+ and D_3^+ as a functions of T_e, n_e and P_N are determined based on the measurements and simulations in [7]. For our typical set of experimental parameters: $T_e = 6$ eV, $n_e = 3 \times 10^{18}\ \mathrm{m}^{-3}$ and $P_N = 10^{-2}$ a the partial concentrations are: 53% D^+, 25% D_2^+, 22% D_3^+.

Summarizing the above the processes that in principle have to be included the simulation are: physical sputtering of Be and C, chemical erosion of C by D, deposition of C, Be on the C target, diffusion of Be, re-deposition of eroded species. The most important processes with respect to the Be surface coverage are the deposition of Be and C, the physical erosion of Be and C, the chemical erosion of C and the re-deposition of eroded Be. Due to the low diffusivity of Be in C [8] diffusion of Be into the C target bulk is compensated by the high incident Be flux and can thus be neglected in the temperature range treated here. Also reflection of Be and C is $\ll 0.1\%$ and can be neglected.

3.1. Analytical approach

An analytical formulae for the equilibrium surface concentration of Be C_{Be} on the target surface is developed for the two (Be and C) component system. This model neglects D accumulation and treats D only as an incident eroding species. This is also what is measured by the Auger Electron Spectroscopy that was used in the experiments and can not detect D. Assuming that implantation and erosion occur uniformly in a layer of thickness Δx with number density N [m^{-3}] and areal densities [m^{-2}] of Be $\sigma_{\mathrm{Be}} = C_{\mathrm{Be}} N \mathrm{d}x$ and C

$\sigma_C = (1 - C_{Be})N\mathrm{d}x$ it can be shown that in equilibrium $\frac{\mathrm{d}C_{Be}}{\mathrm{d}t} \equiv 0$ the changes in areal density $\frac{\mathrm{d}\sigma_{Be}}{\mathrm{d}t}$ and $\frac{\mathrm{d}\sigma_C}{\mathrm{d}t}$ have to obey

$$\frac{\mathrm{d}\sigma_{Be}}{\mathrm{d}t} = \left(\frac{\mathrm{d}\sigma_{Be}}{\mathrm{d}t} + \frac{\mathrm{d}\sigma_C}{\mathrm{d}t}\right) C_{Be}. \quad (1)$$

The changes in the areal densities of Be, $\frac{\mathrm{d}\sigma_{Be}}{\mathrm{d}t}$, and C, $\frac{\mathrm{d}\sigma_C}{\mathrm{d}t}$, due to erosion and deposition can be written as

$$\begin{aligned} \frac{\mathrm{d}\sigma_{Be}}{\mathrm{d}t} &= \Gamma(\xi_{Be} + (R_{Be} - 1)C_{Be}Y_{Be}), \\ \frac{\mathrm{d}\sigma_C}{\mathrm{d}t} &= \Gamma(\xi_C + (R_C - 1)(1 - C_{Be})Y_C), \end{aligned} \quad (2)$$

ξ_{Be}, ξ_C = fraction of Be and C in incident flux, Γ = incident flux [$\mathrm{m^{-2}\,s^{-1}}$], Y_{Be}, Y_C = total sputter yields of Be and C including chem. erosion by D, R_{Be}, R_C = re-deposition fraction for Be and C.

Using (2) in (1) and solving for the equilibrium Be surface concentration C_{Be} one obtains

$$\begin{aligned} C_{Be} = {} & \frac{1}{2(Y_{Be} - R_{Be}Y_{Be} + (-1 + R_C)Y_C)} \\ & \times \Big(\xi_{Be} + \xi_C + Y_{Be} - R_{Be}Y_{Be} - Y_C + R_C Y_C \\ & \pm(-4\xi_{Be}(Y_{Be} - R_{Be}Y_{Be} + (-1 + R_C)Y_C) \\ & + (-\xi_{Be} - \xi_C - Y_{Be} + R_{Be}Y_{Be} + Y_C - R_C Y_C)^2)^{\frac{1}{2}}\Big). \end{aligned} \quad (3)$$

Eq. (3) has two solutions (±) but only the negative solution gives physically reasonable results.

3.2. TRIDYN

The monte carlo code TRIDYN [4] simulates the collisional transport of fast ($v \gg v_{\mathrm{Thermal}}$) atoms in amorphous targets using the binary collision approximation. In addition to physical sputtering, implantation and reflection it also calculates changes in the target composition and layer growth/recession due to the bombardment. TRIDYN does not take diffusion or chemical erosion into account. However TRIDYN can still be used to simulate the high temperature exposures (≈1000 K) where chemical erosion is negligible, thermally enhanced erosion is not yet effective and Be diffusion is still small and compensated by the incident Be flux. These simulations require values for the surface binding energies E_B of C on C, Be on Be and Be on C. For C on C and Be on Be the sublimation energies of Be (3.31 eV) and C (7.41 eV) were used. According to [9] the average (5.36 eV) of the E_B values for the pure components was used for the mix term Be on C.

As explained in Section 3, the incident D flux contains a mixture of molecular ion species. They were introduced into the simulation as three types of D each with an abundance and energy derived from the composition and energy of the incident molecular ion: 37% D at 13.3 eV corresponding to 22% D_3^+ at 40 eV, 31% D at 20 eV corresponding to 25% D_2^+ at 40 eV and 32% D at 40 eV corresponding to 53% D^+ at 40 eV.

3.3. Simulation input parameters

The required input parameters for the analytical model are the fractions of Be and C in the incident flux, the total physical erosion yield of Be and C, the chemical erosion yield of C and the re-deposition probabilities of Be and C. While the fractions of Be and C in the incident flux can directly be taken from the experimental data, the erosion yields have to be determined from a combination of experimental data and computer simulations. The total physical erosion yields $Y_{Be,Phys}$ and $Y_{C,Phys}$ of Be and C were determined through a series of TRIDYN calculations. The input parameters for TRIDYN calculations were already described in Section 3.2. Under these conditions TRIDYN gives a total physical sputter yield of 0.001 for Be and 3×10^{-4} for C. The total erosion yield of C $Y_{C,Tot}$ is given by the sum of the chemical erosion yield Y_{Chem} and physical erosion yield $Y_{C,Phys}$. $Y_{C,Tot}$ was taken from the weight loss of C samples exposed to a pure D plasma in PISCES-B at the same surface temperatures and plasma conditions as in the Be seeding experiments. Y_{Chem} was determined from this value for $Y_{C,Tot}$ by subtracting the calculated $Y_{C,Phys}$. This resulted in $Y_{Chem} \approx 4\%$ at 500 K and $Y_{Chem} \approx 0.1\%$ at 1000 K. At 1200 K and 1280 K chemical erosion was nonexistent and pure physical sputtering was assumed in the simulation.

The re-deposited fraction R_C of C varies depending on the dominant erosion process. At low temperatures where chemical erosion is dominant, the re-deposited fraction R of chemically eroded C in PISCES-B for $n_e = 3 \times 10^{18}\,\mathrm{m^{-3}}$ is ≈25% [5]. At temperatures where physical erosion dominates, R_C is negligible due to the high ejection energy (≈4 eV compared thermal energies for chemically eroded species) and thus R_C = 5% was assumed a temperatures above 1000 K.

Be has an ≈2 eV lower ionization energy leading to a smaller mean ionization distance and hence to a higher re-deposited fraction R_{Be}. Measurements of the mean ionization distance indicate a value of R_{Be} of ≈50%.

Thermally enhanced erosion of Be must be taken into account at temperatures above 1000 K. Data for the thermally enhanced erosion of Be can be found in [3]. However these measurements were done for a pure Be target so this data can not directly be applied to the thermally enhanced erosion of a Be/C mixed surface. Therefore the enhancement was treated as a free parameter in the simulations. The best fit was obtained for yield enhancements by factors of 4 and 7 at 1200 K and 1280 K respectively.

4. Results and discussion

Fig. 1 shows the change in the CD-Band integral normalized by the D_{gamma} (434 nm) intensity. It decays linearly with increasing Be plasma concentration. The highest plasma concentration in this case was 0.15% which resulted in decay of the CD-Band intensity of 80%. This correlates well with the Be surface concentration of ≈80% measured after the exposure indicating a coverage effect. To conclude that the total C erosion (chemical and physical) decreases, one has to compare the weight loss of the targets at a given temperature with and without Be seeding. Comparing the total weight loss (erosion), normalized to the same total fluence, of two C targets exposed at 500 K with 0% and 0.15% Be respectively, one finds a decrease in the weight loss (erosion) from −43 mg to −4 mg corresponding to a reduction of ≈90%. This again correlates well with the measured Be surface concentration of ≈80% after exposure. The influence of the deposited Be on the weight change is negligible. Even if all the Be incident on the C target would be deposited this would only lead to a weight increase of ≈1mg which is still outweighed by the amount of eroded C.

In Fig. 2, the Be surface concentration after exposure to a Be seeded D plasma is shown as a function of the Be^{1+} plasma concentration for two different target temperatures. The Be surface concentration quickly increases with the Be plasma concentration. Given the small Be plasma concentrations this seems surprising at first, but the equilibrium Be surface concentration is determined not only by the influx/erosion ratio of Be but also by the depletion of C from the surface as can be seen in the derivation of the analytical model. Fig. 2 also shows the results of the model calculations. The input parameters used in these calculations are summarized in Table 1. The input parameters used in the TRIDYN calculation are given in Section 3.2. The surface concentration predicted by TRIDYN at 1000 K is generally too low. This is due to the fact that it does not take into account the weak yet persistent chemical erosion at 1000 K, also it does not include re-deposition of the eroded Be. This results in an underestimation of the C depletion and Be enrichment of the surface leading to smaller Be surface concentrations. The high temperature data (1280 K) in Fig. 2 shows the influence of thermally enhanced erosion of Be. It enhances the loss of Be from the surface resulting in a weaker increase of the Be surface coverage with Be plasma concentration. It is important to note that despite the increased Be loss from the surface, almost full Be coverage is still possible at slightly larger Be plasma concentrations still <1%.

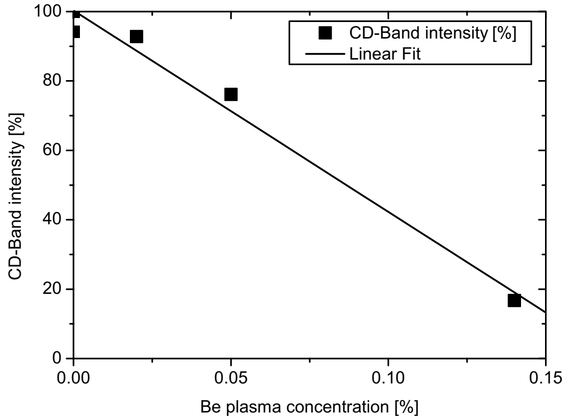

Fig. 1. Decrease of the normalized CD-Band intensity (i.e. chemical erosion) of a C target as function of the Be plasma concentration.

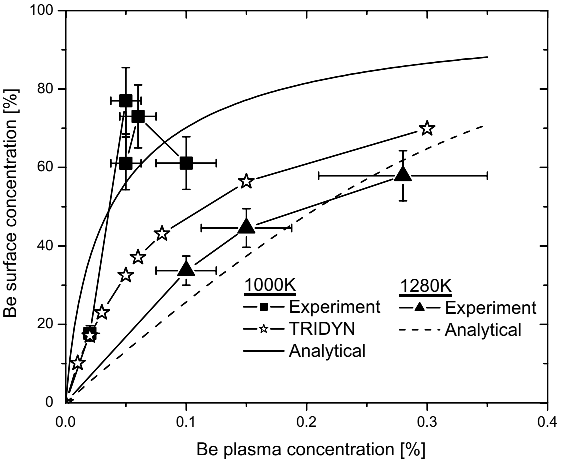

Fig. 2. Be surface concentration after exposure to a Be seeded D plasma for 1000 K and 1280 K target temperature. Also shown are results from analytical and TRIDYN modelling.

The Be equilibrium surface concentrations calculated by the analytical model reproduce the measured data well, especially given the large error bars in the Be plasma and surface concentration. Extrapolating these results to ITER is difficult since the plasma concentrations of Be and C in the ITER divertor are not known. Also particle energies and thus erosion yields of Be and C vary strongly across the divertor. Therefore, a parameter scan was conducted varying the Be and C plasma concentrations and

Table 1
Parameters used in analytical calculations

Parameter	500 K	1000 K	1200 K	1280 K
R_C	0.25	0.25	0.05	0.05
R_{Be}	0.5	0.5	0.5	0.5
$Y_{C,Tot}$	0.04	0.001	0.0003	0.0003
$Y_{Be,Tot}$	0.001	0.001	0.004	0.007

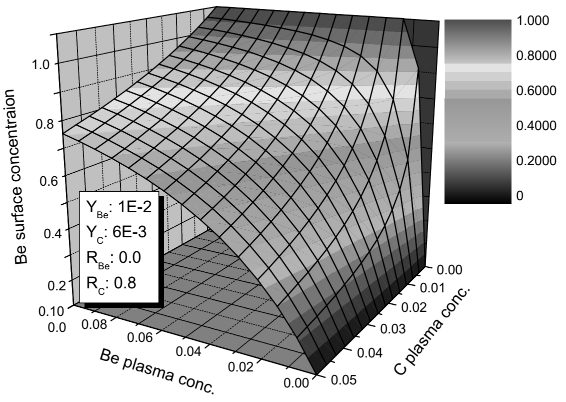

Fig. 3. Calculated equilibrium Be surface concentrations for a worst case extrapolation to ITER divertor conditions.

calculating the equilibrium surface concentration from Eq. (3) in a worst case scenario with respect to layer formation (i.e. low C and high Be erosion). The erosion yield of Be deposited in the divertor was assumed to be equal to the erosion yield of 10^{-2} [10] expected in the main chamber of ITER. No information is available for the Be re-deposited fraction so as a worst case 0% re-deposition was assumed. The C erosion yield of 6×10^{-3} and the C re-deposited fraction of 80% were taken from [10]. Fig. 3 shows the resulting dependence of the Be surface concentration on the C and Be plasma concentration. Once can see that even for these worst case conditions a Be surface coverage of 60–80% arise depending on the C to Be ratio in the plasma.

5. Conclusions

It has been shown both experimentally and explained in modelling calculations that small amounts ($\ll$1) of Be in the incident flux lead to the formation of protective Be coatings that basically stop the erosion of the exposed C target in PISCES-B. The two component model developed to simulate the formation of Be layers on C from a Be seeded D plasma have successfully reproduced the PISCES-B data as function of temperature and Be plasma concentration.

Extrapolating these results to ITER is difficult partly because the conditions in the divertor are not well known, but also due to processes like ELM's, in–out divertor asymmetries, toroidal flows etc. However once the incident particle spectrum is known, the formation of protective Be layers can be simulated using the developed models. The Be covering the C strike points will probably be removed by ELM's, but the coverage may reform very quickly depending on the incident Be flux. Based on TRIDYN calculations one can assume that these layers will from within ms in ITER resulting in Be coverage in between ELMs. In conclusion these are encouraging results with respect to the use of C together with Be in ITER.

Acknowledgement

This work was partly funded by the task TW2-TPP-ERDEP of the EFDA technology programme.

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