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Influence of radiation damage on plasma facing material erosion

V.S. Koidan *, A.N. Brukhanov, O.K. Chugunov, V.M. Gureev, B.I. Khripunov, S.N. Kornienko, B.V. Kuteev, S.T. Latushkin, A.M. Muksunov, V.B. Petrov, A.I. Ryazanov, V.P. Smirnov, V.G. Stolyarova, V.N. Unezhev

Russian Research Centre 'Kurchatov Institute' (RRC KI), Moscow, Russia

A B S T R A C T

New experimental approach is developed to explore plasma facing materials accounting for neutron induced radiation damage on erosion of these materials in plasma. The radiation damage has been produced in carbon materials by 5 MeV $^{12}C^{+}$ ions accelerated on cyclotron of Kurchatov Institute. A high level of radiation damage (1–10 dpa) has been obtained on these materials. The erosion of irradiated materials including CFC under plasma impact was studied on the LENTA linear plasma simulator. Surface modification was analyzed and the erosion rate was evaluated. Enhancement of the erosion process was detected for the radiation-damaged materials.

1. Introduction

Interaction of plasma with the first wall is actually the most important and crucial problem for the development of a fusion reactor. Limitations on the operation lifetime are put by erosion of the plasma facing materials (PFM) under plasma bombardment. Therefore, the selection of PFMs becomes one of the first importances in the nearest future. D-T reaction neutrons (14 MeV) represent an important destructive factor for PFMs. Will neutron irradiation have any effect on the PFM erosion in the plasma presuming a hundred dpa of radiation damage for the fusion reactor? This question remains without any experimental answer though material erosion in plasma has an extensive database from the reactor-level tokamak machines and simulation facilities. This paper describes a new experimental approach to investigation of plasma erosion accounting for radiation damage effect and gives the first experimental results on the erosion at high level of radiation damage in materials.

2. Production and characteristics of radiation damage in carbon materials

There are different principal possibilities to obtain a high level of radiation damage in materials. The first one is related to a fusion neutron source of a sufficiently high intensity, but it is not yet realized today. Second, fission neutrons from a fast reactor may be taken; but a long irradiation time (minimum near one year) is needed to accumulate damage at a high enough level. Finally, fast charged particles from accelerators suit well for the radiation damage modeling in fusion materials. We have chosen the latter possibility and have realized it in the following way. Radiation damage in materials was produced by fast heavy ions accelerated on Kurchatov cyclotron that is similar to the method used for SiC in [1]. The cyclotron of Kurchatov Institute operates with different types of ions (H^{+}, He^{+}, Li^{+}, C^{+}, etc.) in the energy interval 1–60 MeV. Fusion reactor relevant doses of tens dpa equivalent to neutron irradiation of 10^{26} n/m^2 are accumulated on this cyclotron in a few day period of irradiation.

Carbon materials were studied first: pyrolytic graphite quasi single crystal as a reference grade, MPG-8 Russian grade fine grain graphite and CFC SEP NB-31 suggested for the ITER divertor target.

Three levels of 1 dpa, 5 dpa and 10 dpa have been obtained on the above materials by irradiating on the cyclotron with 5 MeV $^{12}C^{+}$ ions to the doses 10^{17} ion/cm^2, 5×10^{17} ion/cm^2 and 10^{18} ion/cm^2 correspondingly [2]. The irradiation temperature was near $T \approx 200$ °C. This method gives accumulation of radiation damage in a surface layer as thick as about penetration depth of the accelerated ions. Sputtering effect and radiation-induced deformation (swelling) take place on the materials along with the damage produced by the ions. The maximal observed linear deformation ΔH more than 160 µm (detected by profilometer) corresponded to pyrographite irradiated to 10 dpa. CFC has also shown an important deformation (about 20 µm at 10 dpa). MPG-8 was the most radiation resistant among the studied materials, only 3 µm of linear deformation detected after irradiation to 10 dpa. An example of the SEP NB-31 surface profile registered in the vicinity of the irradiation border on the sample having 10 dpa is given in Fig. 1: non-irradiated side is to the left, damage zone is to the right. Radiation swelling and sputtering features are observed on the irradiated side.

Analysis was made of the resulting radiation damage profile by calculation (SRIM program [3]) in dependence on irradiation dose

* Corresponding author.
E-mail address: koidan@nfi.kiae.ru (V.S. Koidan).

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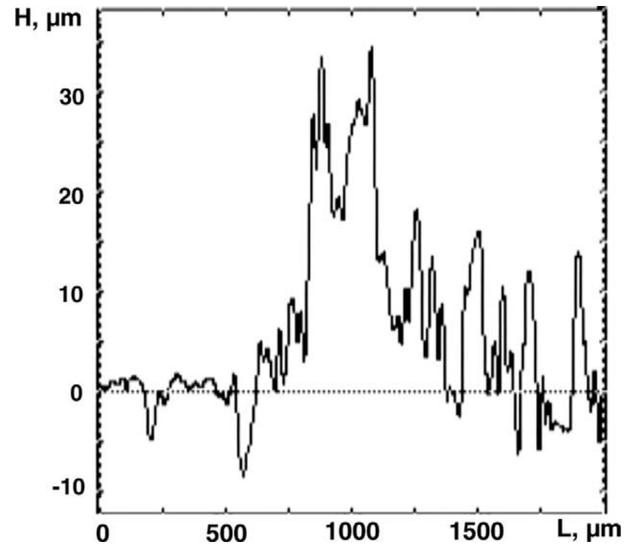

Fig. 1. Surface profile of 10 dpa sample SEP NB-31 around the irradiation border (approx. at 800 µm).

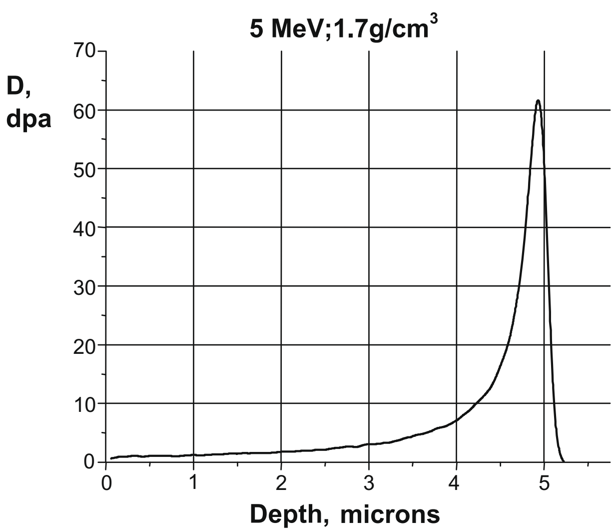

Fig. 2. Calculated profile of primary radiation defects produced in carbon material (ρ = 1.7 g/cm^3) irradiated by 5 MeV carbon ions up to 10^{18} ion/cm^2 dose.

and ion energy. Fig. 2 shows the result of numerical calculation for the profile of the primary radiation defects D (dpa) as a function of depth for a carbon material with density ρ = 1.7 g/cm^3 (MPG-8) after irradiation with 5 MeV carbon ions to the dose 10^{18} ion/cm^2. The average value of this distribution is $\langle D \rangle$ = 9.7 dpa. The maximal value D_{max} = 65 dpa lies at a depth of ~5 µm.

3. Plasma erosion study of irradiated materials

After ion irradiation on the cyclotron the materials under study were exposed to steady-state deuterium plasma on the linear plasma facility LENTA [4] ($N_e = 10^{18}$–10^{19} m^{-3}, T_e = 1–20 eV, $j_{ion} = 10^{21}$–10^{22} ion/m^{2}s) to obtain erosion characteristics. The highly non-uniform radiation damage distribution is the characteristic feature of this irradiation method and it was taken into account during plasma exposure of the irradiated samples. The plasma processing included two steps of durable plasma operation (1 h each). The layer of about a half a penetration depth was eroded during the first step (about 2–3 µm), and the zone of the radiation damage maximum was eroded in the second plasma exposure (~3–7 µm). The plasma exposure parameters were chosen as follows: deuterium ion current density on the surface about 10 mA/cm^2, ion energy 100 eV (bias potential) and sample temperature during plasma operation was maintained at a low level (not higher than 40 C).

Surface microstructure was analyzed at all stages of the study with SEM. The microstructure changes were found both after fast ion irradiation and each plasma exposure. Fig. 3 shows MPG graphite surface: left on this picture is the area irradiated to the dose of 10 dpa, to the right is the non-irradiated area. Deformation and cracking are seen on the damaged area. The SEP NB-31 surface is presented in Fig. 4. The border separating irradiated and non-irradiated areas is well seen here again; the damage zone is to the left in the picture.

The effect of plasma-induced erosion is exhibited by surface modification resulting from sputtering [5]. The modification of the surface becomes more pronounced on irradiated materials: holes, cones, pyramids and whiskers appear on MPG-8 and CFC, erosion along cracks occurs. Example of the SEP NB-31 surface irradiated to 10 dpa and processed by the plasma is shown in Fig. 5.

Erosion rate of the materials was measured by weight losses after plasma exposure. The erosion yield was also evaluated taking into account impinging ion flux on the surface. It was found rising when the erosion process reached the layer of the maximal

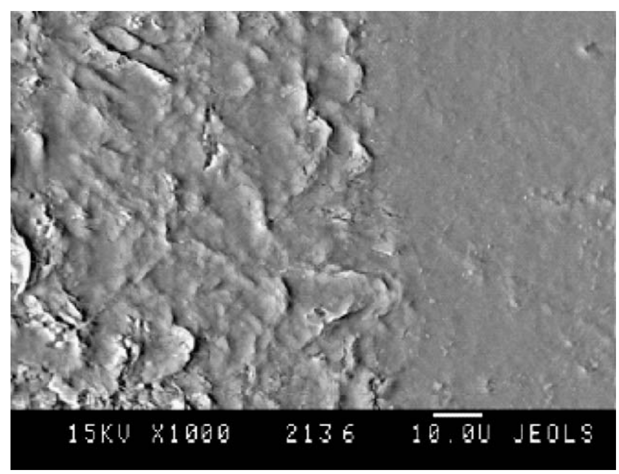

Fig. 3. Irradiation border on MPG-8 graphite: area irradiated to the dose of 10 dpa is to the left, the non-irradiated surface is to the right (scale in µm).

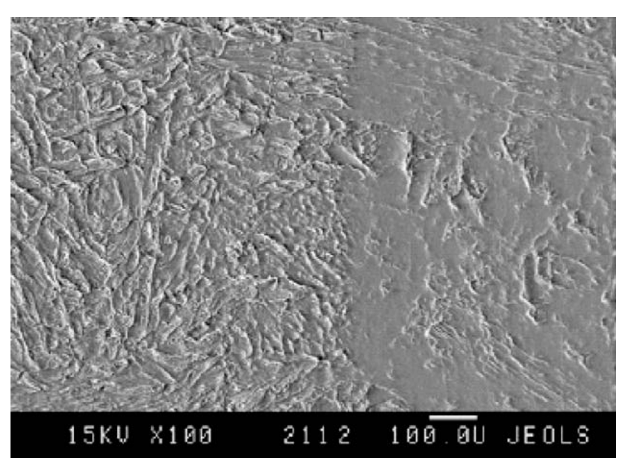

Fig. 4. The border of irradiated area on SEP NB-31 surface (10 dpa): damage zone is to the left (scale in µm).

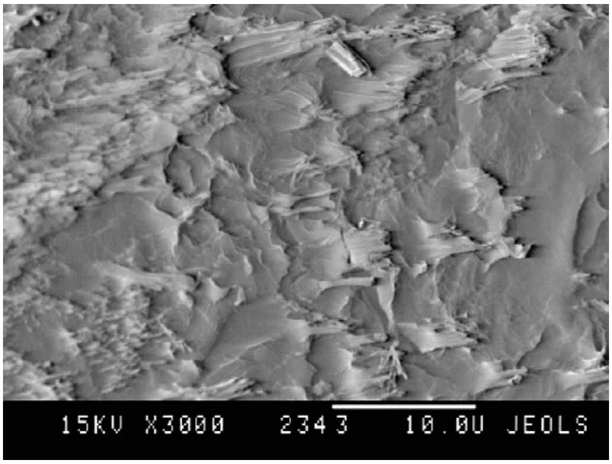

Fig. 5. Plasma exposed (10 dpa) SEP NB-31 surface (scale in μm).

Table 1
Plasma eroded layer Δ and erosion rate *G*.

	Pyrographite		MPG-8		SEP NB-31	
	Δ, μm	*G*, mg/cm^2h	Δ, μm	*G*, mg/cm^2h	Δ, μm	*G*, mg/cm^2h
First plasma	3.8	0.9	3.6	0.6	2.5	0.5
Second plasma	7.2	1.7	5.7	1.0	7.4	1.4

radiation damage. Table 1 illustrates this observation. The erosion rate is given for three materials irradiated to 1 dpa dose for two (see above) successive plasma exposures. Erosion rates for the second one at the depth of maximal radiation damage are higher in all three cases. The maximal enhancement factor corresponds to the CFC (~2.6). Even larger values of plasma erosion rate are supposed for the samples having accumulated the higher radiation damage, which are now studied in details.

All these observations lead us to the conclusion that the radiation damage in materials influence on plasma erosion of PFMs expressed in its enhancement. The erosion increase of irradiated materials in plasma is supposed to be determined by the radiation damage accumulation in matrix that results in the material microstructure change from dense to more friable.

4. Summary

New approach of the investigation of the combined radiation damage effect and plasma attack on plasma facing materials for fusion has been developed. Experimental modeling of radiation damage effect on behavior (erosion) of plasma facing materials has been performed experimentally. Using high-energy ions to produce radiation damage in materials made it possible to achieve high levels of radiation damage in materials relevant to D-T fusion reactor. Carbon materials having accumulated the radiation damage level of 1–10 dpa have been produced and subjected to plasma environment relating to a tokamak SOL. Pyrographite, MPG-8 and CFC SEP NB-31 were taken for these studies. The evidences of radiation damage influence on the erosion process have been found by analysis of deformation, surface modification and erosion data. Erosion enhancement in the plasma is observed for the studied radiation-damaged materials. The results of the work are encouraging for further application of the developed method to investigations of material radiation resistance to aggressive factors of fusion reactor including neutron radiation effects.

Acknowledgement

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