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Evidence of radiation damage impact on material erosion in plasma environment

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ABSTRACT

Plasma facing materials in a fusion reactor will suffer from both plasma fluxes and DT-neutron irradiations. Experimental investigations have been initiated aiming at assessment of the combined effect of high-level radiation damage and plasma induced erosion on these materials. Complex modeling studies were performed on the ion cyclotron and LENTA plasma simulator at Kurchatov Institute. Carbon materials and tungsten have been irradiated with 3–5 MeV ions to reach 1–10 dpa of radiation damage. The features of irradiated materials are described. Irradiated materials response to deuterium plasma (100–250 eV D^+ ions) at fluence 10^{25} ion/m^2 was studied. Deformation effect and surface microstructure modification have been observed. Evaluation of erosion rate indicated erosion enhancement for radiation-damaged materials.

1. Introduction

Intense flux of high-energy fusion neutrons (14 MeV from DT reaction) is an inherent factor of a fusion reactor. Neutron irradiation of the reactor materials will result in degradation of their physical and mechanical properties and that is an important concern for the development of power reactor components. Energetic neutrons produce atomic displacement cascades and nuclear reactions in the materials giving rise to evolution of their microstructure, accumulation of structure defects and impurities. The divertor and the first wall materials facing plasma will work in the most adverse conditions because of the combined effect of the neutrons and the plasma. Erosion of the plasma facing materials has been investigated for decades, details of erosion processes are believed well established and well understood. However, an extensive experimental data on plasma erosion does not relate to radiation-damaged materials. This paper presents an experimental initiative to assess the influence of radiation damage on erosion under plasma impact at the fusion reactor relevant level.

Defect production by fusion neutrons may be estimated at 2–4 dpa (displacements per atom) for ITER while future reactors as DEMO and POWER may be ranged at 30–80 dpa and 100–150 dpa correspondingly. Preparation of material samples with high level of accumulated radiation damage is a difficult experimental task [1,2]. It may be solved in three different ways. The first one is concerned with fusion reaction neutron source of a high enough intensity, which is not presently available. The other two ways are experimental simulations of fusion neutron effects using neutrons from fast fission reactors or ion beams from accelerators. The latter simulation method has been realized in the present study. The following two features of ion beams as of an irradiation tool were taken into account: wide energy range enabling simulations of the 14 MeV neutron effects and high doses available in relatively short experimental campaigns.

2. Experiment

2.1. Production of radiation damage in materials

Radiation damage in materials was produced with high-energy ions from cyclotron at Kurchatov Institute. The cyclotron provides particle beams (protons and other different kinds of ions) in the energy interval 1–60 MeV, and high ion doses attractive for the fusion research are available on this accelerator in a reasonable operation time [3]. So, the radiation effect equivalent to accumulation of radiation damage produced by fast neutron irradiation to $\sim 10^{26}$ neutron/m^2 (10 dpa) may be reached in a few days period. We have performed irradiations of materials to produce radiation damage relevant to this level, and the samples were prepared for plasma experiments.

Material choice for this stage of the work was based on the following considerations. Though carbon materials are not believed to show promise for application in the next step reactors (DEMO and beyond) because of tritium concerns, they are still considered for ITER. The ITER divertor target candidate CFC SEP NB-31 was

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included in the study. For comparison purposes two other carbon materials as fine grain graphite MPG-8 widely used in Russian fusion devices and pyrolytic quasi-single crystal were included as well. Tungsten was also chosen, and the grade taken for this study had a composition close to that proposed for the ITER application containing 99.95 wt.% of tungsten.

The irradiation methods corresponded to the materials choice and were different for the carbon materials and for tungsten.

2.2. Carbon materials

All three grades of carbon materials were irradiated by $^{12}C^{+}$ ions with the energy of 5 MeV to get the high level of damage. Three levels of radiation damage 1, 5 and 10 dpa in average were obtained in the samples of each carbon material. This was made by irradiation to the total $^{12}C^{+}$ ion doses 10^{17} ion/cm^2, $5 \cdot 10^{17}$ ion/cm^2 and 10^{18} ion/cm^2 performed during several days. The specific of radiation damage by fast ions is that it is produced in the surface layer of the material, the penetration depth being determined by the impinging ion energy. The damage distribution in depth is highly non-uniform corresponding to the ion energy loss along the path within the material.

All three carbon materials under study exhibited notable radiation-induced deformation (swelling). The effect was measured by profilometer, and the maximal linear deformation ΔH was detected on pyrolytic graphite (about 40 μm on 5 dpa sample and in excess of 160 μm profilometer limits on 10 dpa sample). The CFC SEP has shown moderate values of deformation among the three materials (20 μm on 10 dpa sample). Note that swelling occurred in the surface layer corresponding to the range of 5 MeV $^{12}C^{+}$ ions in carbon which was here about 5 μm. 2–4 fold deformation has been measured on CFC. The results of the surface profile measurements were reported in [3] where linear deformation ΔH was presented as a function of the accumulated irradiation dose.

The surface microstructure evolution on the irradiated side of the samples was also registered with SEM technique. Fig. 1 shows the surface of SEP NB-31 having 10 dpa around the border of irradiated zone. The left side of the photo corresponds to the irradiated area; the non-irradiated area lies to the right. The two zones are distinctly different in the picture. The more developed structure is well seen on the irradiated side (left).

2.2.1. Tungsten

Irradiation of tungsten samples was fulfilled with α-particles ($^4He^{+2}$ ions) at energy of 3.0–4.0 MeV. Two irradiations have been done up to now with the ion fluence reached on the samples of $5 \cdot 10^{17}$ ion/cm^2 and 10^{18} ion/cm^2. Calculation of α-particles penetration and of the produced radiation defects has been made (Fig. 2); the maximum of the damage distribution was shown to be at ~6 μm for 4 MeV helium ions. The presented curve is the result of the defect profile calculation by the SRIM program [4,5]. The calculations by this program account for the bombarding ions type and energy and irradiation dose.

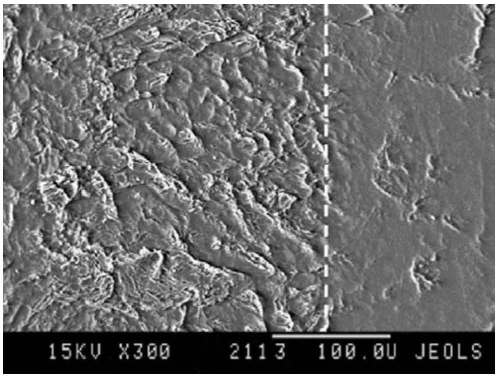

Fig. 1. The SEP NB-31 composite surface: the area irradiated to the dose 10 dpa is to the left, the non-irradiated surface is to the right (scale bar 100 μm).

Here again we found out linear deformation though much lower for tungsten than for carbon materials and only on the sample, which had the higher dose of 10^{18} ion/cm^2. This deformation was at the level 0.1–0.3 μm (2–5% as compared with 6 μm range of 4 MeV α-particles in tungsten). We could not detect deformation with our profilometer on the first sample irradiated to $5 \cdot 10^{17}$ ion/cm^2.

Notable surface changes were observed on the irradiated tungsten. The surface of the tungsten after irradiation is presented in Fig. 3. The left side of the picture shows the non-irradiated area while the right hand side has accumulated the α-particle fluence 10^{18} ion/cm^2. The border separating the two zones is also well visible on the picture. Transition between those two zones attaching the dashed line from the right has probably taken smaller dose.

2.3. Plasma experiments with irradiated materials

Plasma erosion of the materials was studied on the linear plasma simulator LENTA [6] providing steady-state plasmas ($N_e = 10^{12}$–10^{13} cm^{-3}, T_e = 1–20 eV, $j_{ion} = 10^{17}$–10^{18} ion/cm^2 s). The materials after irradiation on the cyclotron to the fast ion doses mentioned above were exposed to deuterium plasma during the time period needed to reach plasma ions fluence on the surface about 10^{21} ion/cm^2. Energy of the bombarding plasma ions was controlled by bias potential at the levels relevant to divertor conditions and taking into account general erosion features of the materials: −100 V for carbon materials and −250 V for tungsten.

Thus, carbon materials have been exposed at ion energy 100 eV. Deuterium ion current density on the surface was about 10 mA/cm^2, sample temperature during plasma operation was maintained below 40 °C. Accounting for the highly non-uniform distribution of radiation damage in the surface layer, the plasma exposure of carbon samples was performed in two steps. Plasma operated for about 1 h at each step. The layer of about a half a penetration depth about 2–3 μm was sputtered during the first step, and the zone of the damage maximum ~3–7 μm was eroded during the second plasma exposure (distribution of primary defects in carbon materi-

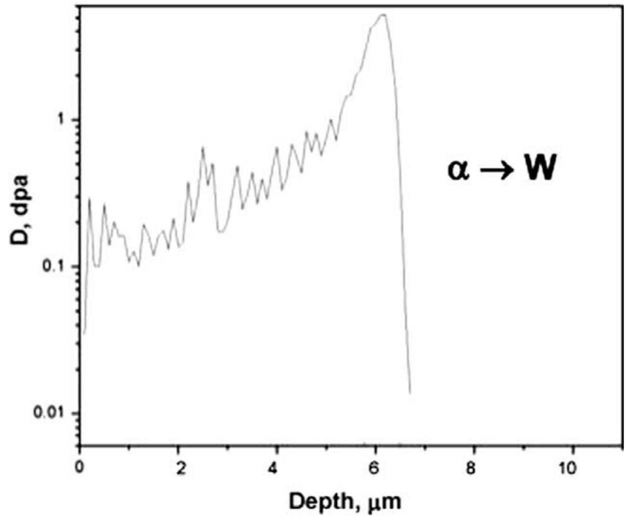

Fig. 2. Calculated profile of radiation defects produced in tungsten (ρ = 19.35 g/cm^3, 183.8 amu) irradiated by 4 MeV α-particles (He^{+2}) to dose $\Phi = 10^{17}$ α/cm^2.

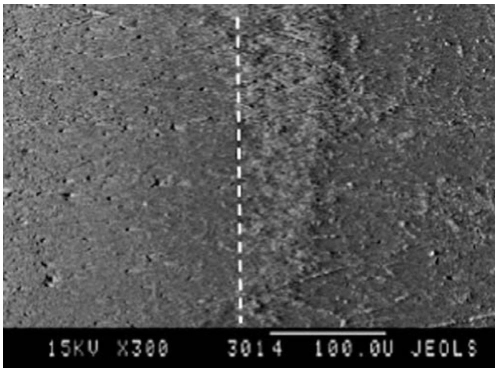

Fig. 3. Irradiation border on the tungsten sample surface: the right part has accumulated the α-particle fluence 10^{18} ion/cm^2; the non-irradiated surface is to the left (scale bar 100 μm).

als had maximum at about 5 μm (see [3,7]) similar to the curve shown in Fig. 2).

Surface microstructure was analyzed at all stages of the study with SEM. The holes, cones, pyramids and whiskers appeared on MPG-8 and CFC surface after the plasma. The signs of erosion along cracks (MPG-8) that took place after irradiation also occurred. The effect of the plasma on the MPG-8 and CFC surface structure is similar on irradiated materials and on the non-irradiated materials but the relief after plasma on the irradiated samples becomes more developed compared with those non-irradiated. Example of the SEP NB-31 surface structure irradiated to 10 dpa and processed by the plasma is shown in Fig. 4.

Tungsten exhibited considerably lower development of the relief after plasma exposure.

Erosion rate was evaluated by weight loss measurements. Fig. 5 shows the pyrographite erosion rate as a function of the impinging ion current from the plasma. The same measurement on the SEP NB-31 is shown in Fig. 6. The slope of the curves presented on the picture gives the erosion yield *Y*. The yields ratios of the irradiated materials to those having no damage deduced from these data were the following: $Y_{\text{SEP-irrad}}/Y_{\text{SEP}} = 2.6 \pm 0.6$ at/ion, $Y_{\text{pyro irrad}}/Y_{\text{pyro}} = 4.8 \pm 0.4$ at/ion. The result shows the increase of the erosion yield for the radiation-damaged material as compared with the non-irradiated material.

Comparison of erosion rates *G* and the eroded depth *Δ* for the two successive plasma exposures is presented in Table 1 giving the results for the three carbon materials irradiated to 1 and 5 dpa. In all cases, the second plasma operation gave higher erosion rates and this is supposed to relate to the maximal radiation damage layer when it was reached. No rise of erosion rate with dose was found and saturation of irradiation effect on erosion yield may be supposed.

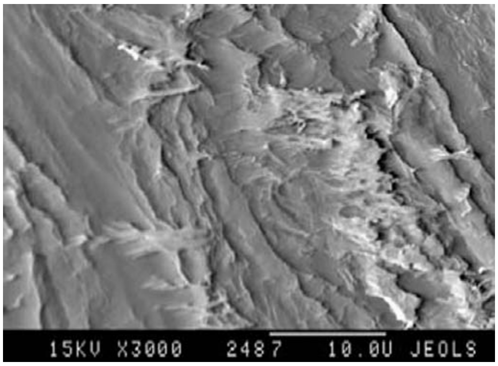

Fig. 4. The irradiated surface of SEP NB-31 (10 dpa) after plasma exposure (scale bar 10 μm).

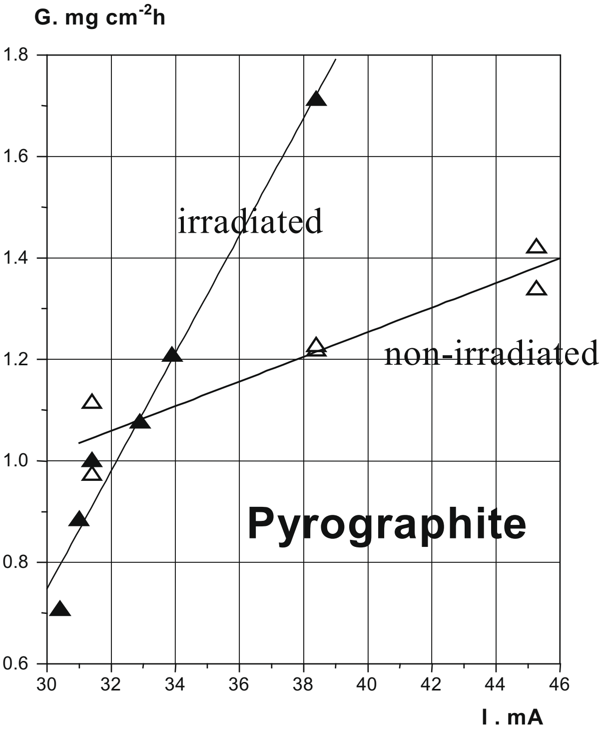

Fig. 5. Erosion rate of pyrolytic graphite vs. plasma ion flux.

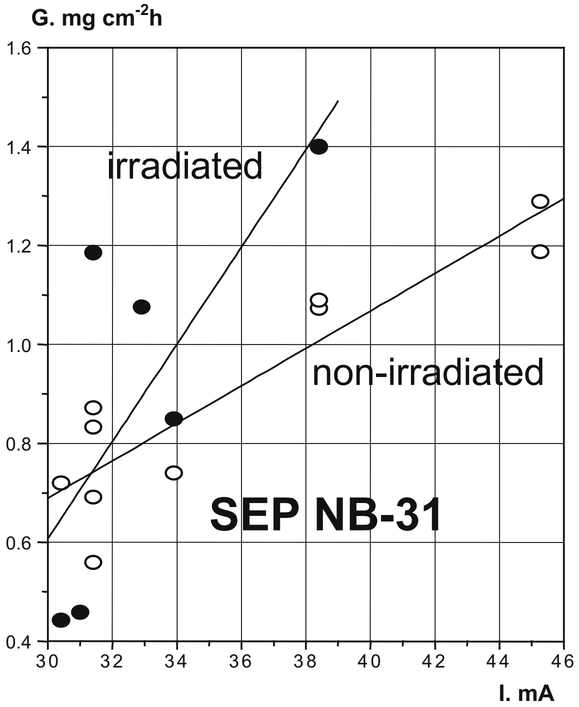

Fig. 6. Erosion rate of SEP NB-31 composite vs. plasma ion flux.

Accumulation of radiation damage in matrix resulting in changes in material microstructure from dense to more friable accounts for the erosion enhancement of irradiated materials in plasma. The phenomenon of erosion rise under ion bombardment, namely, in presence of ionization process is not a new effect (e.g.

Table 1
Eroded depth Δ and erosion rates G for two successive plasma runs.

	Pyrographite		MPG-8		SEP NB-31	
	Δ (μm)	G (mg/cm^2 h)	Δ (μm)	G (mg/cm^2 h)	Δ (μm)	G (mg/cm^2 h)
1 dpa						
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
5 dpa						
First plasma	3.1	0.7	2.8	0.5	2.5	0.4
Second plasma	4.9	1.0	7.4	0.9	7.4	1.2

Erosion depth Δ is given for appropriate initial material density (2.1 or 1.7 g/cm^3).

[8]). Mechanism of the process should be investigated in more details in future experimental research that is in progress now.

3. Summary

New experimental approach has been developed aiming at the investigation of the combined effect of neutron irradiation and plasma bombardment on fusion reactor materials facing plasma. High energy accelerated ion beam was used to produce radiation damage in materials to simulate neutron irradiation. $^{12}C^{+}$ ions were taken to irradiate carbon materials (CFC SEP NB-31, MPG-8, pyrographite) and α-particles to produce damage in tungsten. Efficiency of the method has been demonstrated to obtain high-level radiation damage; the values relevant to a fusion reactor were reached on the materials (1–10 dpa).

Erosion under plasma bombardment was studied on the irradiated materials. Exposure of material to steady-state deuterium plasma in conditions relevant to tokamak SOL has shown that radiation damage had an effect on erosion characteristics. The evidences of radiation damage influence on the erosion process have been found by analysis of deformation, surface modification and erosion data. Differences of surface microstructure evolution in the plasma were detected on irradiated and non-irradiated materials. The tendency to erosion enhancement has been observed on the radiation-damaged carbon materials.

The results of the work substantiate the encouragement for the further development of the proposed method that appears promising for the research of plasma facing materials stability to destructive factors of fusion reactor including neutron irradiation.

Acknowledgements

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