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Effect of radiation damage on material erosion in plasma

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Selection of plasma-facing materials (PFM) is one of the key issues in a fusion reactor development. Materials operating in contact with plasma are subjected to destruction (erosion) under high particle and heat fluxes. Mainly the erosion in plasma limits the service life of such reactor components as divertor and the first wall. At the same time, plasma-facing materials (PFM) will be subjected not only to the plasma exposure but to the neutron irradiation as well. Radiation damage produced in materials by fast neutrons (14 MeV for D-T reaction) is an important factor of a fusion reactor causing material degradation. While important data on the erosion effects have been collected up to now for non-irradiated materials, it is difficult to qualify the materials with respect to plasma erosion taking into account radiation damage. The PFM choice for the ITER actually made presents only an intermediate step towards the fusion reactor and it does not seem to be the final solution of the problem. Therefore the investigation of radiation damage effect on PFMs is now of primary importance though a fusion neutron source has not yet been developed. We present here the first experimental results on evaluation of high-level radiation-damage effect on erosion of materials under plasma impact.

Experimental task, facilities and methods. The work is aimed on obtaining experimental characteristics of PFMs erosion in plasma accounting for radiation damage production at high level. A combined two-stage study was performed on the basis of high-energy ion accelerator and plasma facility at RRC KI. The experimental procedure includes the simulation of neutron radiation damage in material samples using cyclotron and their subsequent exposure to high flux plasma. Radiation damage in materials can be induced by fast ions of different types on Kurchatov cyclotron at 1-30 MeV [1]. The real damage profile can be calculated by the SRIM program [2] in the dependence on irradiation dose, type of ions and energy. It is possible to reach the radiation damage level in materials on the cyclotron equivalent to irradiation by fast neutron at dose ~10^{26} neutron/m^2 (10 displacements per atom (dpa)) in a few days run. One needs much more time (from months to a year) and material resources to get the same level in a fast fission reactor, the task becoming though possible but practically very difficult. The damaged materials were exposed to steady-state deuterium plasma on the linear plasma simulator LENTA [3]. The performance data of the facility are the following: $N_e=10^{18}$-10^{19} m^{-3}, T_e=1-20 eV, $j_{ion}=10^{21}$-10^{22} ion/m^2s. Energy of the bombarding plasma ions was controlled by bias potential at 100 eV (the level relevant to divertor conditions).

Carbon materials were taken at this initial stage of the study: pyrolytic graphite (quasi single crystal) as a reference grade, MPG-8 graphite (used in tokamaks, ex. T-10 limiter) and CFC SEP NB-31 suggested for the ITER divertor target.

The modification of surface microstructure was analyzed with SEM. Profilometry was used to evaluate radiation induced deformation. Plasma erosion was measured by weight loss method. Comparative analysis was made of radiation-damaged materials and of those having no damage.

Production of radiation damage in carbon materials on the cyclotron in RRC KI. The samples of pyrographite, MPG-8 and SEP NB-31 have been irradiated by $^{12}C^+$ ions with the energy of 5 MeV to get the high level of damage. Three experimental runs were performed realizing total carbon ion doses 10^{17} ion/cm^2, $5\cdot10^{17}$ ion/cm^2 and 10^{18} ion/cm^2. These regimes produced three levels of radiation damage in average 1 dpa, 5 dpa and 10 dpa correspondingly.

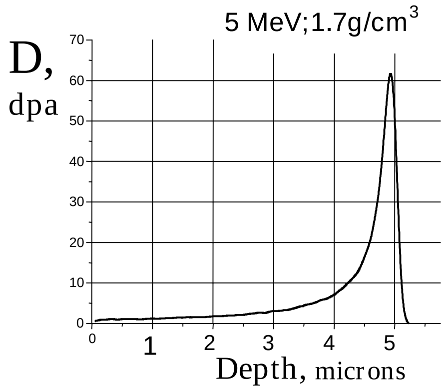


Fig. 1.

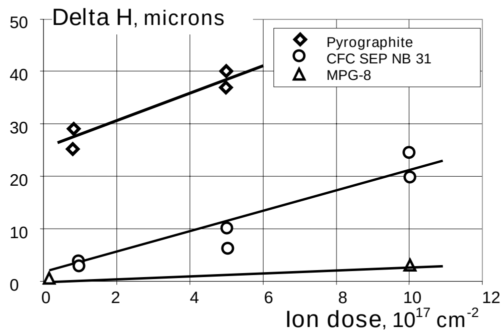
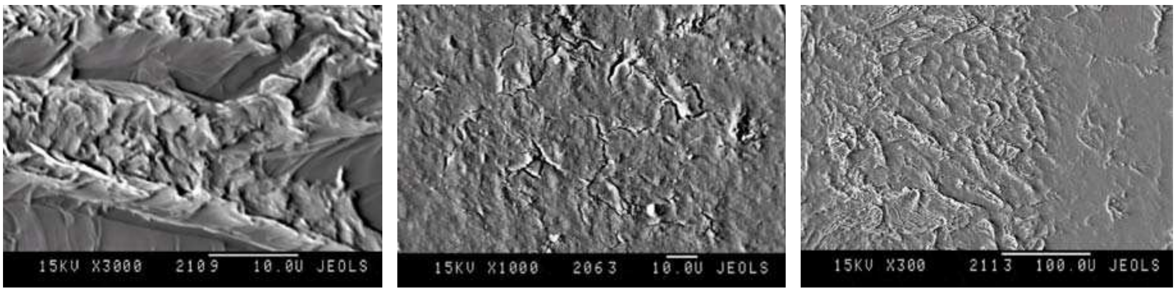


Fig.2.

The radiation damage depth distribution after ion irradiation is highly non-uniform having a maximum near the projective penetration depth of $^{12}C^+$ ions. Fig. 1 shows the result of numerical calculation for 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 after irradiation with 5 MeV carbon ions to the dose 10^{18} ion/cm^2. Maximal value in this distribution D_{max}= 65 dpa lies at a depth of ~ 5 μm while the average value is $\langle D \rangle$=9,7 dpa.

Materials experience radiation-induced erosion and deformation under fast ion impact. The measured values of linear deformation ΔH (swelling) are given in Fig.2 for the materials under study as a function of the ion irradiation dose. Maximal deformation corresponded to pyrographite. The CFC showed also an important deformation under irradiation. Surface microstructure modifications were observed after ion irradiation, the most pronounced changes corresponded to pyrographite and CFC. Splitting, cracking and surface deformation after fast ion irradiation are shown in Fig. 3 (a- pyrograhite 10 dpa; b- MPG-8, 5 dpa; c – CFC, 10 dpa, right on the photo is the non-irradiated area).



a b c

Fig. 3.

Plasma erosion of damaged materials. Taking into account a highly non-uniform radiation damage distribution in the surface layer and the maximum supposed position at 4-5 μm in our samples we have made exposure of them to the plasma in two steps. At the first run only low depth layer was eroded not achieving the depth of the maximum, the latter covered by the erosion at the second run. The plasma exposure parameters were the following: plasma ion current density about 10 mA/cm^2, deuterium ion energy 100 eV, and exposure time was 1 hour. The sample temperature during plasma operation was not higher than 40 C (active cooling of the sample holder).

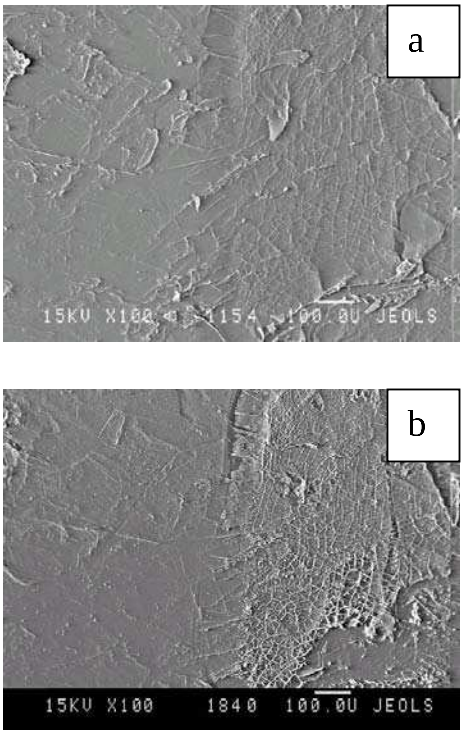


Fig. 4.

Surface modification after plasma bombardment is illustrated in Fig. 4 (pyrographite 1 dpa; a – before plasma; b – after plasma). Erosion of the damaged area (right on the photo) is well seen.

Fig. 5 shows: a – MPG-8, 5 dpa; b – SEP, 10 dpa after plasma exposure. Formation of the holes and pyramids is characteristic for the erosion process. Erosion along the crack is seen on the SEP photo. Average erosion rate G was deduced from the weight losses for all plasma runs for each material. It was found to rise when the erosion reached the layer with the maximal radiation damage level. All three materials showed tendency to enhancement of G in the second run where 4-5 μm layer was reached by erosion. The maximal enhancement factor corresponded to the CFC and it was ~2.6.

Summary.

Combined method of experimental modeling of neutron irradiation and plasma erosion is developed to investigate plasma facing materials for fusion application. It is based on employing high-energy ion accelerator to produce radiation damage and plasma facility to obtain erosion.

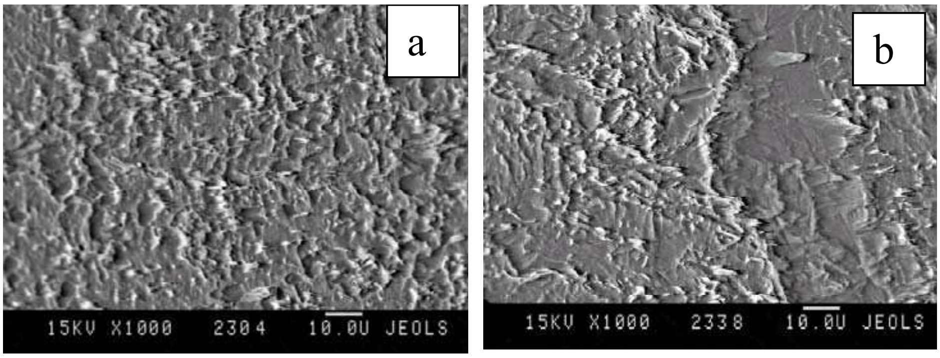


Fig 5.

High-level radiation damage was achieved by irradiations with fast ions on the Kurchatov cyclotron. The samples of carbon materials (pyrographite, MPG-8 and CFC SEP NB-31) at radiation damage levels 1-10 dpa have been produced.

The study of the damaged materials under deuterium plasma revealed the radiation damage influence on the erosion process. The microstructure change difference was observed for damaged and non-irradiated materials, the erosion effect being more pronounced for the pyrolytic graphite and the CFC. The tendency to erosion rate enhancement in the plasma by the factor of 2-3 is also suggested for the studied radiation damaged materials.

The results of the present work seem to be an important basis for the further development of the investigations on material radiation resistance to aggressive factors of fusion reactor including neutron radiation effects.

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