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Powerful steady-state plasma interaction with fusion materials

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Materials working in contact with plasma in fusion devices are subjected to particle and radiation fluxes that result in degradation of their properties thus limiting the lifetime of plasma-facing components. Together with investigations in large tokamaks, linear plasma simulator machines are widely used for experimental exploration of multitude of complex near-wall processes and plasma effects on these materials. Steady-state operation and plasma parameters relevant to tokamak SOL and divertor offer favorable experimental conditions for fusion related research and development of plasma-facing materials. This paper gives a short review and some recent results obtained on the LENTA and SPRUT-4 linear plasma divertor simulators at Kurchatov institute.

Fusion materials have been intensively studied in these facilities for more than the last ten years. The basic operation principle of the machines is generation of plasma with an electron beam – the so-called beam-plasma discharge (BPD). Two main BPD modifications employed in these works are the discharge in magnetic field and the discharge in crossed E×B fields. Axial magnetic field is typically 0.1- 0.4 T, injector power 1 - 25 kW, plasma density 10^{11}- $5\cdot10^{13}$ cm^{-3}, electron temperature 0.5 - 30 eV.

Experiments are focused mainly on the following research tasks: interaction of a plasma stream with gas target (gas divertor simulation); tests of materials (carbon-based, high Z) in divertor related conditions – erosion, redeposition, hydrogen species retention, material mixing; search for new materials (lithium).

Actually recognized divertor problem concerns very high power deposit both in steady state (~10 MW/m^2), and during transitions - ELMs and disruptions (~65 $MJ/m^2s^{1/2}$). Here we focus our work on materials subjected to the combined action of high power load at low ion bombardment energy that is expected at the target in the ITER divertor in steady state. The ions would have energy of few eV - tens eV, and high power load would appear as elevation of surface temperature (e.g. during intervals between ELMs). To study material response to these conditions, we dispose a salient feature of our BPD devices, namely, while using the energy of the plasma we also use the excess energy of the electron beam to elevate even more the total power load on the exposed surface. The power flux in our experiments may reach 25 MW/m^2 and more that highly exceeds the level of usual steady-state plasma experiments.

Gas divertor was simulated in a plasma stream propagating through a neutral gas target. Plasma detachment effect was experimentally observed at pressures ~100 mTorr in the gas target region. Material samples were exposed to plasma in conditions close to the detachment in deuterium plasma. Photo in the Fig. 1 illustrates plasma irradiation of a graphite sample. Surface temperature of the target in the hot spot ranges at 1000 – 1600K.

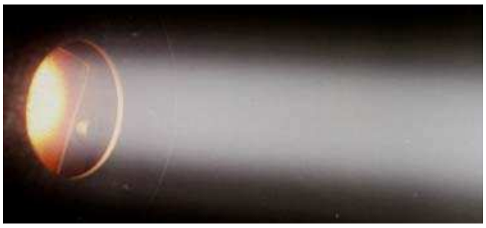

Fig 1.

We present here below some findings on erosion of tungsten, carbon materials, W+C and lithium.

Tungsten. Tungsten is a candidate ITER armour material. Having a high-energy threshold of the physical sputtering it is only expected to suffer erosion losses during plasma disruptions. To protect the tungsten liner from carbon deposition, its working temperature is proposed to be in the range of 773–1473 K. However, we observed sputtering of a W–0.04Mo specimen in steady-state deuterium plasma at subthreshold ion energy of 5 eV at 1473 K [1]. Then we took four different grades of tungsten W-1La_2O_3, W-13I, W-10Re and W⟨111⟩ and exposed them to the plasma flux 1.1×10^{22} $m^{-2}s^{-1}$ in the range of 1300–1600 K at the sample surface. Two irradiation runs were carried out to ion doses $F_1 = 1.5 \times 10^{26}$ m^{-2} and $F_2 = 2.8 \times 10^{26}$ m^{-2}. That is, the total dose was 4.3×10^{26} m^{-2}. The sputtering yield was measured, and the erosion effect of all tungsten grades was shown to occur. Thus, the sub-threshold sputtering of tungsten by 5-7 eV ions in dense deuterium plasma took place for all the W grades under study. The minimal yield (1.7×10^{-5} at./ion) was observed in the case of single crystal W⟨111⟩ and the maximal one (4.2×10^{-5} at./ion) – in the case of a La_2O_3-doped sintered W grade. The two-step experiment showed also the dependence of the sputtering effect on the ion irradiation dose - the yield was lower for the higher dose. Moreover, the surfaces microstructure change was detected, and a submicrocrystalline cellular structure appeared on all the samples. This is seen in Fig. 2, which shows the surface microstructure of the plasma exposed W-10Re specimen. Most of the cells are about 2 orders of magnitude smaller than the W grains (150-300 nm vs. 10÷40 μm). Following the exposure to 5-eV deuterons with a dose of $4.3 \cdot 10^{26}$ m^{-2} at 1520 K, the W specimens contained less than 0.05 at.% D in a 20 nm thick

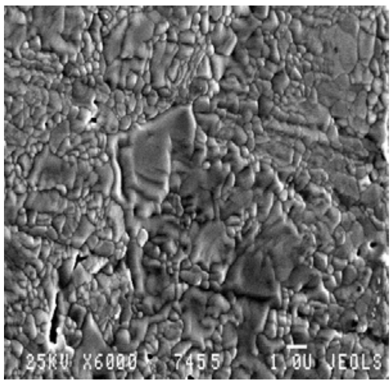

Fig. 2

surface layer. Adatom activation theory has been developed to explain the phenomenon of subthreshold sputtering at elevated temperature [1].

C-based materials. Chemical erosion as a way of tritium retention is of the most concern in fusion reactor since carbon-based materials are applied. We took MPG-8 Russian graphite and the ITER candidate CFC grade SEP NB 31 and we also found chemical erosion under deuterium plasma bombardment with low energy ions (5-20 eV). The measured erosion yield was $1.7 \cdot 10^{-2}$ at/ion for MPG-8 and $0.9 \cdot 10^{-2}$ at/ion for SEP at temperatures 1000-1200C. The similar measurements were made on the same materials with cold surface (RT). The MPG-8 yield fell down by an order to $1.1 \cdot 10^{-3}$ at/ion, but still was rather important. Generation of deuterocarbons followed the erosion in all cases. These were CD_4 and its products (M/e = 18, 16 и 14) as well as higher deuterocarbons C_2D_2 and others (M/e = 30, 34, 36).

High Z materials and material mixing. High Z material mixing with carbon was observed in the above plasma condition. An example of mixing of eroded carbon on a molybdenum collector installed beside the plasma column during irradiation of a carbon specimen in deuterium plasma is illustrated in Fig 3. It shows distributions of materials including the retained deuterium in the surface layer. Simultaneous sputtering of W+C specimens gave evidence, on the other hand, of material mixing in our conditions and of chemical processes. For instance, collecting of erosion products on a cold surface beside the plasma has shown formation of chemical products such as WC. Fig. 4 gives the TEM view of the deposit that was identified by electron diffraction as nanostructured WC.

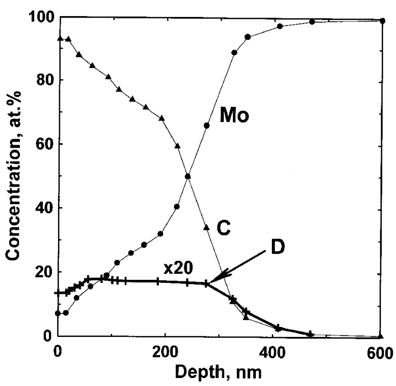

Fig. 3

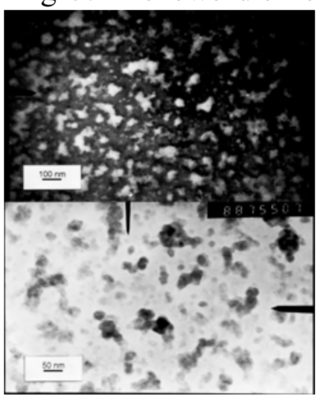

Fig. 4

Lithium. Lithium is now more intensively studied as a plasma-facing material. SPRUT-4 experiments have been conducted on liquid lithium surface at power flux 1-25 MW/m^2. The surface was made with capillary porous structure filled with liquid lithium. Evaluation of erosion effect was made for the conditions of electron beam load on the lithium target and of Li-plasma generated at the surface. We have found out that at surface temperatures 400-900C the main erosion was due to evaporation. However, the process does not go by a conventional way, which is characterized by activation energy of 1.5 eV, but by rather smaller value of 0.5 eV (Fig. 5). Fig. 6 gives the comparison of Li erosion rates obtained in different devices studying lithium surface in contact with plasma. This was characteristic of the plasma experiments and has found interpretation by adatom sublimation activated by radiation [4] similarly to the tungsten erosion approach.

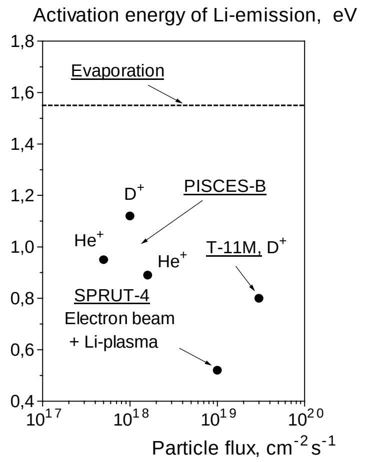

Fig. 5

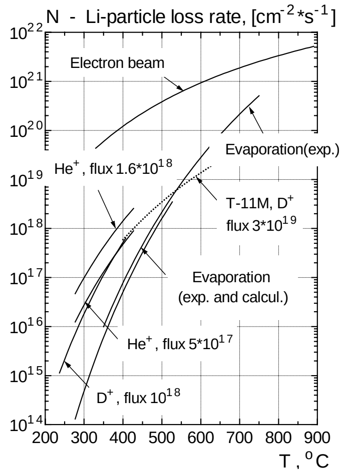

Fig. 6

Summary. Plasma-gas and plasma-surface interaction phenomena relevant to fusion reactor have been investigated in linear plasma facilities. Steady-state plasma streams were generated with a beam-plasma discharge.

Experimental study of plasma facing materials has been conducted in gas divertor simulated conditions. Tungsten, graphites, CFCs and lithium were in the scope of investigation. Low bombarding energy of ions 5-20 eV and high surface temperature (higher than 1000C) were characteristic of these experiments.

Subthreshold tungsten erosion in deuterium plasma has been found at surface temperature higher than 1270K. Adsorbed atom sputtering mechanism has been considered to explain the phenomenon.

Chemical erosion of graphites and CFCs has been demonstrated for cold (< 50C) surface with erosion yield about 10^{-3} at/ ion and its enhancement with temperature to ~10^{-2} at/ ion at 1200 – 1470K.

Mixing of carbon with W and Mo with deuterium accumulation in the mixed layer was found. Also, chemical activity of the species involved resulted in formation of tungsten carbide on the surface.

Reducing of activation energy from 1.5. eV/at to 0.5 eV/at was characteristic of lithium emission under the plasma particle . Radiation activated adatom sublimation model has been referred to as a physical mechanism of lithium emission.

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