Tests of tungsten divertor mock-ups of tokamak-reactor with powerful plasma and e-beam loads

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Abstract. Plasma-facing materials of divertor and the first wall of a hybrid thermonuclear reactor are studied in plasma and beam facilities with extreme high thermal and beam load. Tests of tungsten divertor mock-ups of tokamak reactor are tested with high-heat flux in the plasma device and in the e-beam facility. Water-cooled mock-ups are tested with the combination of plasma and e-beam loads: (1) thermocyclic tests with electron beam powerful load from 5 to 10 MW/m² and then (2) plasma tests in the PLM device with stationary plasma loads up to 1 MW/m². These two tests are carried out for the first time and simulate the variable load on divertor plates in tokamak-reactor during stationary discharges with transient ELM events. The e-beam facility provides a complete simulation of the conditions of heating and cooling of the tested components. The advantages of the tests are stationary plasma discharges in the PLM plasma device modeling reactor conditions in the divertor and SOL.

1. Introduction

Tests of tungsten targets, limiters, and devertor plates in modern tokamaks have shown the significant change in the surface structure under the powerful plasma loads [1]. For the tokamak-reactor, including hybrid reactor, fusion neutron source FNS and DEMO, full-scale tests of the divertor and the first wall materials are required. The process of plasma-surface interaction (PSI) in magnetic fusion
devices involves several mechanisms of surface erosion including melting and resolidification of surface layers, melted material motion over surface, sputtering, evaporation, redeposition of the eroded material on the surface, recrystallization, reformation of surface layers from tens of nanometers to hundreds of microns [1,2]. The uniqueness of the PSI under high heat load in fusion devices is that many elementary processes can affect simultaneously. As a result, the surface morphology evolution is influenced by not a single of the above listed elementary processes, but by a cumulative integral effect of many processes. This leads to synergistic effects considered by the theory (see, e.g. [1]) taking into account surface growth instability driven by stochastic motion of agglomerated particles and clusters. In results, a structure of such surface obeys inhomogeneous hierarchical granularity, statistical self-similarity and scale invariance of the surface structure with unusual shape; e.g., materials with cauliflower-like and fuzz-like surface recently found in fusion devices [1]. In plasma-surface interaction, physical and chemical sputtering, thermal annealing due to plasma heat flux, material erosion and redeposition, melting, cracking should be considered in the problem depending on their intensity and coupling. For testing fusion materials, it is extremely important to ensure adequate conditions for the plasma load on materials [1], in which the processes of changing the structure of the plasma facing surface should be investigated. For such purposes, the PLM device was constructed [6,7]. The facility is a linear magnetic trap with a multicusp magnetic plasma confinement scheme - an 8-pole multicusp. A feature of this device is the stationary plasma confinement, which is an advantage for testing materials of the divertor and first wall of a fusion reactor. Thermal loads on tungsten plates of the lining of the divertor in tokamak-reactor at the stationary discharge stage can reach values of more than 10 MW / m² (up to 20 MW / m²) and during disruptions and ELMS, pulse loads will increase significantly (see [1]), which can lead to significant overheating and even to tungsten melting. Relevant tests of the divertor mock-up and prototypes are required [3,4]. It is extremely important to ensure adequate conditions for the beam and plasma heat load on tungsten [1] and to develop methods for the effective cooling of divertor plates.

![Fig.1. The tungsten divertor mock-up made of ITER-grade materials, ITER-grade tungsten plates of 20x20x8 mm are soldered onto a CuCrZr bronze substrate, a tube for water cooling with a diameter of 14 mm.](image1)

![Fig.2. The target with tungsten divertor mock-up constructed with cooling tubes for high-heat flux test in the e-beam heating facility.](image2)

2. The e-beam test

For plasma-beam tests, water-cooled mock-ups of the divertor plate was designed and manufactured in Efremov Institute (NIIEFA), Fig. 1,2. It was used ITER-grade tungstenVM-P (see [1]). Such water-cooled mock-ups are tested at with the combination of plasma and e-beam loads: (1) thermocyclic tests with powerful electron beam load from 5 to 40 MW/m²; in these tests, water cooling is provided; and then (2) testing in the PLM plasma device [5,6] with stationary plasma loads up to 5 MW/m². Such two tests are carried out for the first time and simulate the variable load on divertor plates in the ITER during stationary discharges with transient ELM events. Plasma tests in the PLM device [5, 6], which is a linear system with a multicusp magnetic plasma confinement, are carried out for the first time. The advantage of the PLM device is the steady-state-stationary hours-long discharge.
The plasma parameters of such tests: the electron density is more than \(3 \times 10^{12} \, \text{cm}^{-3}\), the electron temperature is \(1 - 10 \, \text{eV}\), similar to the parameters of the near-wall plasma in the tokamak, which, combined with the condition of a stationary multi-hour load on the target, creates adequate conditions for plasma testing of fusion materials. The results of such tests are of interest for evaluating the erosion of tungsten in a fusion reactor, including hybrid reactor, fusion neutron source FNS and DEMO. The facility for the e-beam test \([3,4]\) consists of the following components: heating system by e-beam, a hydraulic and vacuum system, and a control system. Figure 3 shows a schematic diagram of the facility. Spray pattern is detected by PIV technique, Fig.3b.

![Schematic diagram of the facility](image)

**Fig. 3.** (a) View of the e-beam facility for HHF tests of mock-ups and schematic of the spray system for cooling: 1 - test section, 2 - sealing unit, 3 - nozzle, 4 - air (gas) supply line, 5 - water supply line. (b) The nozzle spray pattern obtained with PIV \((p_{\text{air}} = 2 \times 10^5 \, \text{Pa}, p_{\text{water}} = 1.5 \times 10^5 \, \text{Pa})\). (c) A corrugated surface of tungsten exposed with e-beam 40 MW/m².

The e-beam facility provides a complete simulation of the conditions of heating and cooling of the tested components. One-sided heating of the target is carried out by e-beam. The main objective of the test is to obtain heat transfer parameters. The horizontal target is heated in a vacuum chamber by the scanning electron beam generated by an electron gun with an accelerating voltage up to 60 kV and a current of up to 250 mA. The electron beam scanning provides uniform heating of the target surface.
The hydraulic system of the facility provides stable parameters of water flow in the following range of parameters: pressure 0.5—2.5 MPa, mass flow rate is up to 1 kg / s, water inlet temperature is from 15° C to 60° C. Gas-liquid spray generator with nozzle is used for cooling of the tube of the tungsten mock-ups, Fig. 3b,c. The following parameters are measured: the temperature of the target wall, the temperature and pressure of water at the inlet and outlet. The power is determined both by calorimetric measurements, and by the product of a fixed accelerating voltage and anode current through the target. To measure the anode current, the target is electrically isolated from the hydraulic circuit. Experimental data will be obtained in the following range of water flow parameters: pressure is 0.7–2.0 MPa, mass flux is 340—25000 kg / (m² s), water temperature at the inlet is below 60 ° C. The studies are performed for cooling tapes in the tube with a swirling coefficient of the flow 0.90 - 0.19, and 0 [3,4]. Typically, corrugated surface of tungsten exposed with e-beam 20-40 MW/m² is formed, Fig. 3c.

Fig. 4. (a) View of the PLM plasma device. SEM micrographs of tungsten after the high heat plasma tests in the PLM device: (b), (c) growth of micro- and nanostructured surface on corrugated tungsten exposed with e-beam 40 MW/m² (see Fig 3c). (d) Nanostructured “fuzz” on tungsten surface after processing with plasma in the PLM plasma facility.
3. High-heat flux plasma load

The plasma linear multicusp (PLM) device \([5,6]\), Fig. 4d, is a linear plasma trap with a multi-cusp configuration of a magnetic field and a stationary plasma discharge that provides a powerful plasma-thermal load up to 1 MW/m\(^2\) on test materials. Investigations of a nanostructured surface formation on refractory metals (tungsten, molybdenum, titanium and others) is carried out at the facility.

The test targets (Fig.1) are irradiated with helium plasma in experiments of discharge duration up to 200 min and more. Plasma parameters are as follows: plasma density is up to \(3 \times 10^{18}\) m\(^{-3}\), the electron temperature is up to 10 eV, with a fraction of hot electrons of temperature up to 50 eV, the ion plasma flow onto the test sample is up to \(3 \times 10^{21}\) m\(^{-2}\) s\(^{-1}\), discharge current reached the value of more than 15 Amps. Magnetic field was of 0.01 Tesla in the center and up to 0.1 Tesla in the cusps. The targets have no active cooling in these experiments. An analysis of the surface of tungsten targets (made of ITER-grade tungsten) is carried out after treatment. Based on the micrographs of the SEM and X-ray analysis, it is concluded that the surface morphology of such samples is significantly changed from virgin structure. A growth of micro- and nanostructured surface on corrugated tungsten exposed with e-beam 20 and 40 MW/m\(^2\) was observed, see Fig 3c. Typically a nanostructured highly porous surface is formed on this corrugated surface after plasma irradiation with loads of more than 1 MW/m\(^2\) \([7-10]\), e.g. the growth of fuzz-type structures on surface is detected, Fig. 4d.

4. Conclusion

High–heat flux tests of mock ups of hybrid reactor are carried out at NRU “MPEI”. Water-cooled mock-ups are tested with the combination of plasma and e-beam loads: (1) thermocyclic tests with powerful electron beam load from 5 to 40 MW/m\(^2\) in the e-beam facility, water cooling is provided in these tests; and then (2) testing in the PLM plasma device with stationary plasma loads up to 5 MW/m\(^2\). Such tests are carried out for the first time and simulate the variable load on divertor plates in the ITER during stationary discharges with transient ELM events. Tungsten samples are irradiated with helium plasma in experiments on the PLM plasma device with discharge duration up to 200 min and heat load of 1 MW/m\(^2\).

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