INVESTIGATION OF EROSION MECHANISMS AND EROSION PRODUCTS IN DIVERTOR ARMOUR MATERIALS UNDER CONDITIONS RELEVANT TO ELMS AND MITIGATED DISRUPTIONS IN ITER

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Carbon fibre composite (CFC) and tungsten were irradiated by intense plasma streams at plasma gun facilities MK-200UG and QSPA-T. The targets were tested by plasma loads relevant to Edge Localised Modes (ELM) and mitigated disruptions in ITER. Onset condition of material erosion and properties of erosion products have been studied.
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1. INTRODUCTION

Carbon-fibre composite (CFC) and tungsten are foreseen presently as armour materials for the divertor targets in ITER. During the transient processes, such as ELMs and mitigated disruptions, the targets are exposed to the plasma heat loads up to 10 MJ/m^2 on the time scale of order of 1 ms that can cause a severe erosion of the armour materials [1]. Plasma-induced erosion is a major concern for safe, successful and reliable reactor operation. Erosion restricts lifetime of the divertor components, leads to contamination of hot plasma by heavy impurities and can produce a substantial amount of the material dust, which being tritiated, radioactive and chemically reactive presents a serious problem for a safety. The exact amount and properties of the eroded materials are critically important to analysis of tokamak-reactor.

The ITER transient loads are not achieved in the existing tokamak machines. Therefore, erosion of candidate armour materials is investigated by use of powerful plasma guns [2-4] and e-beam facilities [5,6], which are capable to simulate, at least in part, the loading condition of interest. In the present work, the CFC and tungsten targets have been tested by intense plasma streams at the pulsed plasma gun MK-200UG and quasi-stationary plasma gun QSPA-T. The targets were examined by plasma heat fluxes relevant to ITER ELMs and mitigated disruptions. Primary attention has been focused at investigation of erosion onset conditions and properties of erosion products.

2. EXPERIMENTAL TECHNIQUE

2.1. MK-200UG EXPERIMENT

At MK-200UG facility, the targets are tested by magnetized hydrogen plasma streams with heat load $q = 0.05…1$ MJ/m^2 and pulse duration τ=0.05 ms. The plasma heat load q varies by changing the plasma density in the range $n = (0.1…2)\times10^{20}$ m^{-3} while the impact ion energy remains practically unaltered $E_i = 2…3$ keV. Plasma pressure varies in the range $P = 0.03…0.5$ bar. Diameter of the plasma stream $d = 0.06…0.1$ m. Plasma/target interaction occurs in the magnetic field $B = 0.5…2$ T.

Plasma stream parameters such as heat flux $w = q/\tau$, impact ion energy E_i, density n, pressure P, and negligible percentage of impurities (<1%) are close to the expected in ITER during transient processes. The disadvantage of MK-200UG facility is small duration τ of the plasma pulse and it is not suited for longevity test of the divertor materials. Nevertheless the facility is quite suitable to simulate the initial stage of the ITER transient events and to study the plasma/material interaction under rather realistic plasma parameters.

The present experiment at MK-200UG was aimed at

- measurement of melting and boiling points for tungsten i.e. quantification of minimum heat load causing tungsten surface melting and boiling;
- determination of evaporation point for CFC and investigation of carbon vapor properties.

These experimental data need for development and validation of appropriate numerical models [7-9].

Calorimeters, photo cameras, infrared pyrometer, and spectrometers have been used as diagnostics.

2.2. QSPA-T EXPERIMENT

At QSPA-T facility, the targets are irradiated by hydrogen plasma steams with the pulse duration 0.5 ms and heat load 0.1…2.5 MJ/m^2. The plasma load condition is relevant to the ITER transients; therefore the facility is applied for longevity testing of candidate armour materials and investigation of the erosion mechanisms, erosion products, and the resultant surface damage. Taking into account that the facility is not equipped by the magnetic field and the plasma stream density $n \geq 10^{22}$ m^{-3} and pressure $P = 1…7$ bar is larger than in tokamak plasma, the QSPA-T experiment seems to give the upper limit of erosion, which might be expected in ITER.

Onset conditions of CFC and tungsten erosion have been studied in the present QSPA-T experiment. The erosion was quantified by means of mass loss measurements and analysis of the exposed surface damage with profilometer and microscope. Droplets and particles emitted from the target surface due to macroscopic erosion mechanisms have been studied by use of diagnostics based on CCD camera.

3. EXPERIMENTAL RESULTS

3.1. EROSION OF CFC TARGET

Under action of intense plasma stream the CFC target is eroded mainly due to the thermal evaporation and brittle destruction [8]. Both of these erosion mechanisms are realized when the surface heats up to the temperature T ≈ 4000 K. Evaporation of the target surface and evaporation of small carbon particles, which are formed due to CFC brittle destruction, results in formation of carbon vapor in front of the target surface.

Onset condition of CFC evaporation has been experimentally studied at MK-200UG. The target was irradiated by increasing heat load and visible spectroscopy was applied for detection of carbon vapor appearance. Infrared pyrometer was used for online measurement of the target surface temperature $T_s(t)$. It's found that the evaporation is absent at the plasma load q ≤ 0.1 MJ/m^2 (T_s ≤ 2200 K); weak evaporation takes place at q ≈ 0.15 MJ/m^2 (T_s ≈ 3000 K); intense evaporation starts at q = 0.2 MJ/m^2 (T_s ≈ 4000 K). The surface temperature grows with the plasma load, it runs up to a peak value of T_s ≈ 4000 K at q = 0.2 MJ/m^2 and remains unaltered with further increase of the plasma load. The plasma load q = 0.2 MJ/m^2, which heats the surface to the sublimation point, corresponds to a threshold of intense CFC evaporation.

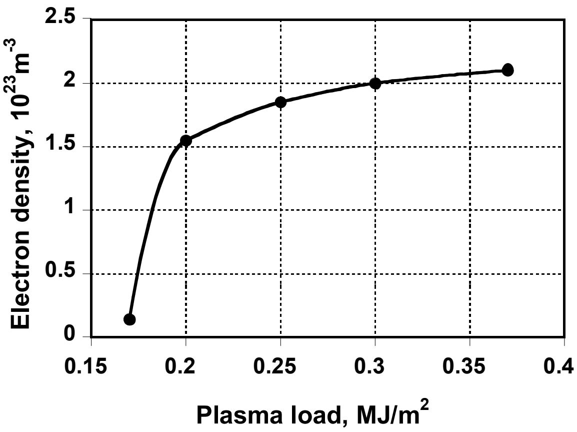

Fig.1. Electron density of carbon vapor plasma (MK-200UG, 0.5-cm distance from target surface)

The evaporated carbon is ionized quickly and carbon plasma arises. Spectrum of carbon plasma consists of spectral lines of C^{+1}–C^{+5} ions, continuous spectrum is observed near the surface at distances ≤ 1 mm. Electron density n_e of carbon plasma evaluated from Stark broadening of spectral line CIV(4658.3A°) is shown in Fig.1. At low heat loads the density rises steeply: variation of q from 0.17 to 0.20 MJ/m^2 results in increase of n_e by a factor of 10. At q > 0.20 MJ/m^2 the density grows slightly keeping at a level of $n_e=2\times10^{23}$ m^{-3}. This experimental fact confirms also that a threshold of intense CFC evaporation is about q = 0.2 MJ/m^2.

At q = 0.1…0.15 MJ/m^2 the density of carbon plasma was too small to be measured by the applied diagnostics. But after the target was exposed to 200 plasma shots the density increases to the measurable magnitude n_e=(3…4)× 10^{21} m^{-3} at the same plasma load. Properties of CFC seem to be degraded during multiple plasma exposures that lead to intensification of vaporization.

Numerical simulation for CFC surface temperature evolution under the plasma exposure has been done using PEGASUS-3D code [8]. Temperature dependence for CFC thermal conductivity at T=2500…4000 K was taken from analytical extrapolation of the thermoconductivity measured at T≤ 2500K [10]. The performed simulation reveals that the reference thermal conductivity λ_{ref} is incompatible with the measured temperature. According to numerical modeling an intense evaporation with λ_{ref} should start at q=0.3 MJ/m^2 while in the experiment it happens at q=0.2 MJ/m^2. It was assumed that a real thermal conductivity differs from the reference one because of degradation of CFC properties due to plasma irradiation. Most probable reason for this degradation is brittle CFC destruction caused by multiple thermal shocks [8]. The best fit for the experimental results corresponds to the reduction of λ_{ref} by a factor about 3.

Similar results have been obtained at QSPA-T facility [11]. The obtained experimental data (Fig.2) demonstrate clearly that the CFC erosion starts at essentially lower plasma loads than it follows from calculation data obtained for the reference thermal conductivity λ_{ref} .

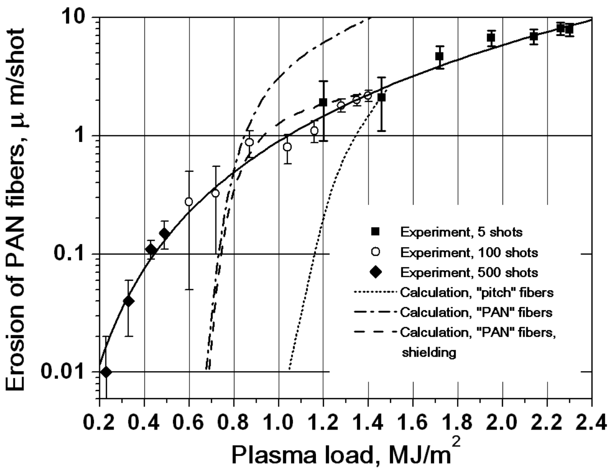

Fig.2. CFC erosion at QSPA-T

The performed experimental studies have shown that the CFC resistance against action of intense plasma streams is worth than it was expected before. It should be noted also that carbon plasma formed due to CFC erosion expands from the target along the magnetic field lines with a velocity V=(1…2)×10^4 m/s. Density of carbon ions measured at MK-200UG facility at 15-cm distance is n_c ≥ 10^{21}m^{-3} that is larger than a density of tokamak plasma. It means that during ELMs large amount of carbon impurities might move from the divertor to the main chamber causing a contamination of hot plasma.

3.1. EROSION OF TUNGSTEN TARGET

At MK-200UG and QSPA-T facilities there were measured the minimal plasma loads q_m and q_b, which cause tungsten surface heating to melting and boiling temperatures (T_m = 3650 K, T_b ≈ 6000 K):
MK-200UG - q_m = 0.30 MJ/m^2; q_b = 0.65 MJ/m^2;
QSPA-T - q_m = 1 MJ/m^2; q_b = 2.2 MJ/m^2.

At the time-constant heat flux the integral plasma load q, which is required for surface heating to a certain temperature T_s, is proportional to $\tau^{1/2}$. Taking into account that the plasma pulse duration at QSPA-T (τ = 0.5 ms) is 10 times larger than at MK-200UG (τ = 0.05 ms) the data obtained at both facilities are in a good agreement. The experimental data agree also with the result of numerical modeling.

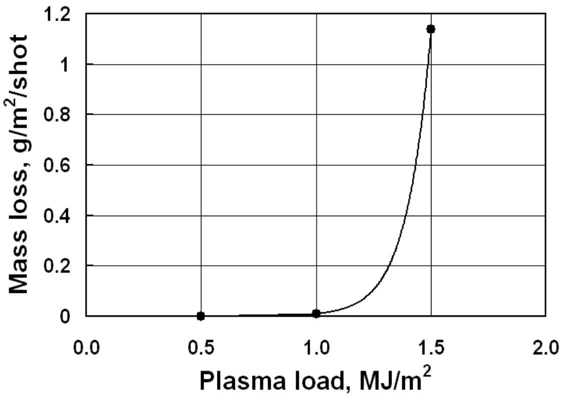

Fig3. Mass loss of tungsten

Onset condition of tungsten erosion has been studied at QSPA-T facility. The tungsten target was tested at varying plasma load and a mass loss was measured. At the plasma load below the melting point $q < 1$ MJ/m^2 the mass loss is negligible but it rises steeply at $q > q_m$ (Fig.3).

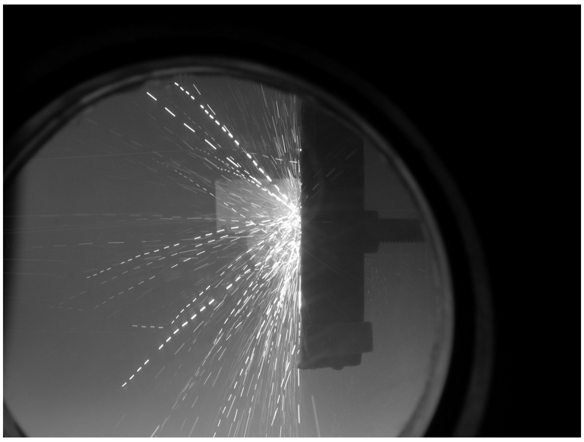

Fig.4. Emission of droplets from tungsten target

The mass loss results from melt layer splashing and emission of droplets under the stream action (Fig.4).

SUMMARY

CFC and tungsten targets were tested by intense plasma streams at heat fluxes relevant to ELMs and mitigated disruptions in ITER.

Intense evaporation of CFC happens at lower plasma load than it results from the numerical modeling based on the reference thermal conductivity. Degradation of the thermal conductivity could be caused by brittle CFC destruction under multiple plasma exposures.

Erosion of tungsten begins with the surface melting. The erosion is caused mainly by melt splashing.

Erosion of tungsten target starts at larger plasma load than CFC erosion.

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ИССЛЕДОВАНИЕ МЕХАНИЗМОВ И ПРОДУКТОВ ЭРОЗИИ ОБЛИЦОВОЧНЫХ МАТЕРИАЛОВ ДИВЕРТОРА В УСЛОВИЯХ, ХАРАКТЕРНЫХ ДЛЯ ЭЛМов И ОСЛАБЛЕННЫХ СРЫВОВ В ИТЭРе

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С-С композит и вольфрам были подвергнуты воздействию интенсивных потоков плазмы на плазменных ускорителях МК-200UG и КСПУ-Т. Мишени испытывались при плазменных нагрузках, характерных для ЭЛМов и ослабленных срывов в ИТЭРе. Были проведены исследования начальных условий эрозии материалов и свойств продуктов эрозии.

ДОСЛІДЖЕННЯ МЕХАНІЗМІВ І ПРОДУКТІВ ЕРОЗІЇ ОБЛИЦЮВАЛЬНИХ МАТЕРІАЛІВ ДИВЕРТОРА В УМОВАХ, ХАРАКТЕРНИХ ДЛЯ ЭЛМів І ОСЛАБЛЕНИХ ЗРИВІВ В ІТЕРі

В.М. Сафронов, М.І. Архипов, М.С. Клімов, Д.В. Коваленко, І.С. Ландман, А.А. Москачова, С.Є. Песчаний, В.Л. Подковиров, І.М. Позняк, Д.А. Топорков, О.М. Житлухін

С-С композит і вольфрам були піддані впливові інтенсивних потоків плазми на плазмових прискорювачах МК-200UG і КСПП-Т. Мішені випробувалися при плазмових навантаженнях, характерних для ЭЛМів й ослаблених зривів в ІТЕРі. Були проведені дослідження початкових умов ерозії матеріалів і властивостей продуктів ерозії.