EROSION MECHANISMS AND EROSION PRODUCTS IN TUNGSTEN TARGETS EXPOSED TO PLASMA HEAT LOADS RELEVANT TO ELMS AND MITIGATED DISRUPTIONS IN ITER

V.M. Safronov[1,3], N.I. Arkhipov[1], N.S. Klimov[1], I.S. Landman[2], D.S. Petrov[1,4], V.L. Podkovyrov[1], I.M. Poznyak[1,3], D.A. Toporkov[1], A.M. Zhitlukhin[1]

[1] State Research Center of Russian Federation Troitsk Institute; for Innovation and Fusion Research, 142190 Troitsk, Moscow reg., Russia;
[2] Karlsruhe Institute for Technology, IHM, P.O. Box 3640, 76021, Karlsruhe, Germany;
[3] Moscow Institute of Physics and Technology, 141700 Dolgoprudny, Moscow Region, Russia;
[4] Moscow Engineering Physics Institute 115409 Kashirskoe shosse 31, Moscow, Russia

Tungsten targets 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. Material erosion caused by melt motion and by emission of droplets has been studied.

PACS: 52.75.–d, 52.70.–m, 52.40.Hf, 28.52

1. INTRODUCTION

Carbon-fibre composite (CFC) and tungsten are considered presently as armour materials for the divertor targets in ITER. During the transient processes, such as ELMs and disruptions, the divertor armour will be exposed to the high plasma loads [1] which can cause a severe erosion of the armour materials. Erosion reduces lifetime of the divertor components and produces the material dust, which being tritiated, radioactive and chemically reactive presents a serious problem for a safety. In addition the material erosion leads to production of impurities, which can penetrate into the hot fusion plasma causing its radiative cooling. The exact amount and properties of the eroded materials are critically important to analysis of tokamak-reactor.

The plasma heat loads expected in the ITER transient events are not achieved in the existing tokamak machines. Therefore, behavior of candidate armour materials is studied 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. The present work refers to experimental study of tungsten armour. The 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 caused by splashing and motion of the molten metal.

2. EXPERIMENTAL TECHNIQUE

2.1. MK-200UG EXPERIMENT

At MK-200UG facility, the targets are tested by magnetized hydrogen plasma streams with heat load $Q = 0.05\ldots1\ \mathrm{MJ/m^2}$ and pulse duration $\tau = 0.05$ ms. The plasma heat load Q varies by changing the plasma density in the range $n = (0.1\ldots2)\times10^{20}\ \mathrm{m^{-3}}$ while the impact ion energy remains practically unaltered $E_i = 2\ldots3$ keV. Plasma pressure varies in the range $P = 0.03\ldots0.5$ bar. Diameter of the plasma stream – $d = 0.06\ldots0.1$ m. Plasma/target interaction occurs in the magnetic field $B = 0.5\ldots2$ 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 the transient processes. The disadvantage of MK-200UG facility is small duration τ of the plasma pulse. Because of the small pulse duration the facility is not suited for longevity test of the divertor materials. Nevertheless it is quite suitable to simulate the initial stage of the ITER transient events under rather realistic plasma parameters. These experimental data need for development and validation of appropriate numerical models [7-9].

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 $0.1\ldots2.5\ \mathrm{MJ/m^2}$. As the plasma load condition is very relevant to the ITER transient events, the facility is applied mainly for longevity testing of candidate armour materials including investigation of the erosion mechanisms, erosion products, and resultant surface damage. Taking into account that the facility is not equipped by the magnetic field and that the plasma stream density $n \geq 10^{22}\ \mathrm{m^{-3}}$ and pressure $P = 1\ldots7$ bar is larger than it is expected in ITER, the QSPA-T experiment seems to give the upper limit of erosion.

3. EXPERIMENTAL RESULTS

3.1. EJECTION OF DROPLETS

Under action of intense plasma stream a melt layer forms at the surface of any metallic target. A thickness of the melt layer depends on the loading conditions but as a rule it is much greater than a thickness of the evaporated layer. As the melt layer is subjected to the action of various forces there are many erosion mechanisms, which can cause a loss of the liquid metal. Particularly the melt erosion results from the melt motion along the target surface under the action of the plasma stream and from ejection of metal droplets due to the hydrodynamic instabilities developed in the liquid metal. An important task of the simulation experiment is to investigate the existing erosion mechanisms and to quantify their contributions to the net erosion.

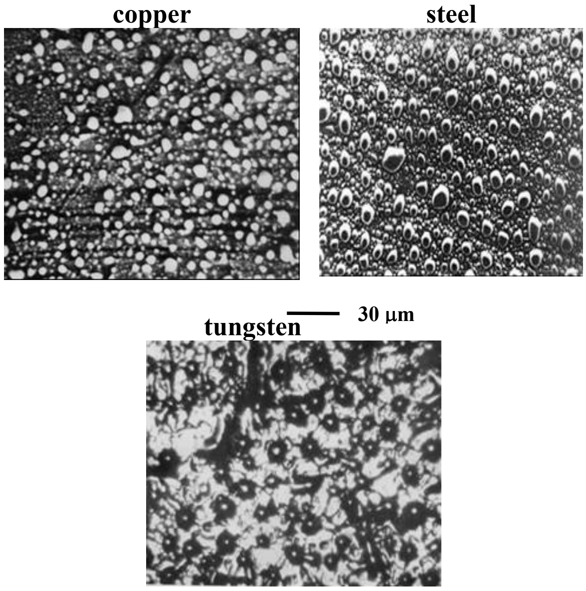

Fig.1. Droplets in MK-200UG experiment (copper, steel - graphite collector, tungsten - copper collector)

Ejection of metal droplets has been studied at varying loading conditions as at MK-200UG so at QSPA-facility. It was found that the droplet emission happens practically simultaneously with the beginning of the target melting and that amount of droplets increases with the plasma load.

The droplets have been detected in experiments with all metallic targets. In MK-200UG experiment the droplets were collected at the polished graphite, copper or silicon plates placed near the exposed target surface (Fig.1) and afterwards the collected droplets were analyzed with a microscope. In QSPA-T experiment the droplets emitted from the tungsten target were recorded by use of CCD camera (Fig.2).

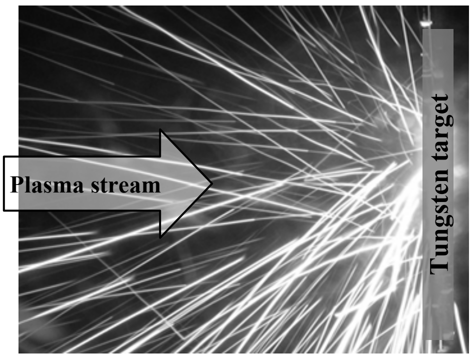

Fig.2. Traces of hot tungsten droplets at QSPA-T

Typical size of droplets obtained at the collectors and recorded by CCD camera was measured to be of the order of 10 μm. Because of the rather large size of the particles the obtained material dust is not very dangerous from the viewpoint of ITER safety. Meanwhile some issues remained in respect to existence of smaller droplets which could not be detected by the applied diagnostics but which could present a real problem for tokamak safety.

New diagnostics was developed for online registration of the erosion products including small particles and droplets. The diagnostics is based on the laser techniques. It is capable to measure a summarized cross-section of all the particles and droplets through attenuation of the laser beam $I(z)/I_0$.

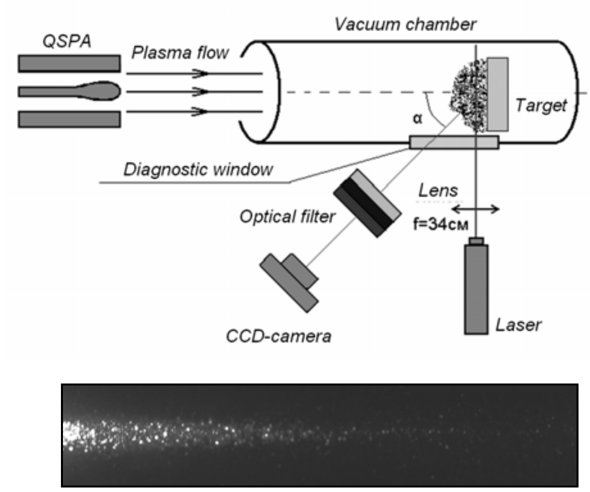

Fig.3. Scheme of laser diagnostics for on-line measurement of erosion products (upper); trial figure obtained on graphite dust (lower)

The above diagnostics was applied for investigation of droplets in experiment with tungsten, copper, steel and niobium. Fraction of small droplets (d ≤ 1 μm) was measured to be negligible in all cases. Thus the assumption concerning existence of sub-micron droplets seems to be invalid.

3.2. SURFACE EROSION

Melt layer erosion occurs mainly because of two erosion mechanisms: due to ejection of the metal droplets from the target surface and due to melt motion along the target surface. A contribution of these erosion mechanisms to the net erosion was studied in the present experiment.

Droplet ejection results in a partial loss of the molten material therefore a contribution of this mechanism to the net erosion might be determined by weighting the target before and after the plasma exposure. Melt motion leads to displacement of the material along the surface and this mechanism might be evaluated through the measurement of the surface profile.

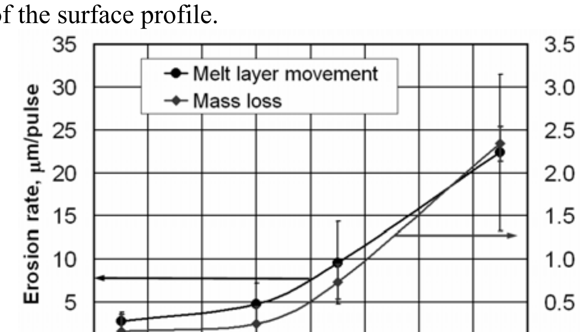

Fig.4. Erosion rates of steel targets caused by melt motion and droplet ejection at QSPA-T facility

Because of severe surface cracking the tungsten targets are not suitable for a precise measurement of the melt displacement. Therefore another metallic targets such as copper, steel, aluminum and niobium were applied in the present experiment. Fig.4 shows experimental result obtained at QSPA-T facility with the steel targets. One can see that the surface erosion caused by the melt motion is 10 times larger than the erosion due to the droplet ejection. Identical result was obtained in the experiments with other metals. It means that formation and ejection of droplets seem to present some problem for ITER safety but not for erosion of the divertor armour materials.

Under the plasma stream action, melt moves along the exposed surface in a radial direction from the stream axis to periphery that results in formation of the erosion crater and of the melt mountains at the crater edge. Depth of the crater and height of the mountains rises linearly with a number of plasma impacts.

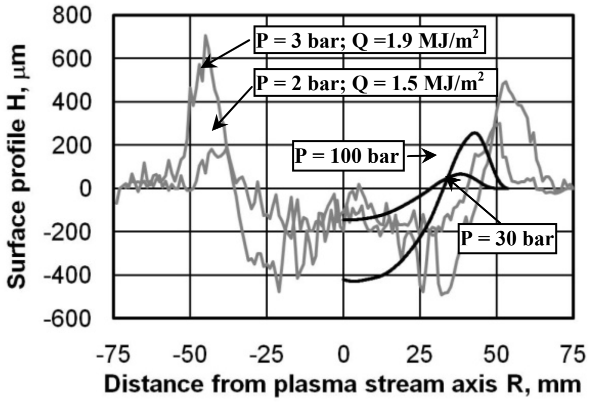

Fig.5. Erosion profiles measured on steel targets (QSPA-T, 25 shots) and results of numerical analysis

The most probable cause of the observed melt motion is a pressure gradient formed by the plasma stream at the target surface. However this assumption does not agree with the numerical analysis (Fig. 5). The erosion crater and the melt displacement obtained in the numerical modeling based on the melt motion due to the pressure gradient are much smaller than the measured ones. It means that a real driving force differs from the pressure gradient.

SUMMARY

Tungsten targets were tested by intense plasma streams at plasma gun facilities MK-200UG and QSPA-T under the plasma heat fluxes relevant to ELMs and mitigated disruptions in ITER. The targets made of steel, copper, aluminum, and niobium were examined also.

Ejection of the metallic droplets and their properties have been studied. It's shown that the erosion products consist mainly of 'large' droplets (d $\geq$ 5 mm). The metallic dust consisting of a huge amount of sub-micron droplets was not found.

Melt layer erosion occurs mostly due to the melt motion. A contribution of droplet ejection is negligible. The measured melt displacement can not be explained by pressure gradient. There is another, more effective driving force.

ACKNOWLEDGEMENTS

The work is supported partly by RFBR grant No 09-02-13562.

REFERENCES

1. G. Federici, et al.// *Plasma Phys. Control. Fusion*. 2003, v. 41, p.1523.
2. N.I. Arkhipov, et al.// *J. Nucl Mater*. 1996, v. 233-237, p.686.
3. V.I. Tereshin, et al.// *J. Nucl. Mater*. 2003, v. 313-316, p.767.
4. V. Belan, et al.// *J. Nucl. Mater*. 1996, v. 233-237, p.763.
5. V.T. Astrelin, et al.// *Nucl. Fusion*. 1997, v. 37, p.1541.
6. J.Linke, et al.// *J. Nucl. Mater*. 1994, v. 212-215, p.1195.
7. I.S. Landman, et al.// *J. Nucl. Mater*. 2005, v. 337-339, p.761.
8. S. Pestchanyi and I. Landman // *Fusion Eng. Design*. 2006, v. 81, p. 275.
9. B. Bazylev, et al.// *Physica Scripta*. 2004, v. T111, p. 213.

Article received 15.09.10

МЕХАНИЗМЫ И ПРОДУКТЫ ЭРОЗИИ ВОЛЬФРАМОВЫХ МИШЕНЕЙ ПРИ ТЕПЛОВЫХ ПЛАЗМЕННЫХ НАГРУЗКАХ, ХАРАКТЕРНЫХ ДЛЯ ELM И ОСЛАБЛЕННЫХ СРЫВОВ В ITERe

В.М. Сафронов, Н.И. Архипов, Н.С. Климов, И.С. Ландман, Д.С. Петров, В.Л. Подковыров, И.М. Позняк, Д.А. Топорков, А.М. Житлухин

Мишени из вольфрама были подвергнуты воздействию интенсивных потоков плазмы на плазменных ускорителях МК-200UG и КСПУ-Т. Испытания проводились при плазменных нагрузках, характерных для ELMов и ослабленных срывов в ITERe. Исследована эрозия материала, обусловленная движением расплава и капельным разбрызгиванием.

МЕХАНІЗМИ І ПРОДУКТИ ЕРОЗІЇ ВОЛЬФРАМОВИХ МІШЕНЕЙ ПРИ ТЕПЛОВИХ ПЛАЗМОВИХ НАВАНТАЖЕННЯХ, ХАРАКТЕРНИХ ДЛЯ ELM І ОСЛАБЛЕНИХ ЗРИВІВ В ITERі

В.М. Сафронов, М.І. Архипов, М.С. Клімов, І.С. Ландман, Д.С. Петров, В.Л. Подковиров, І.М. Позняк, Д.А. Топорков, О.М. Житлухін

Мішені з вольфраму були піддані впливу інтенсивних потоків плазми на плазмових прискорювачах МК-200UG і КСПУ-Т. Іспити проводилися при плазмових навантаженнях, характерних для ELMів і ослаблених зривів в ITERі. Досліджено ерозію матеріалу, що обумовлена рухом розплаву і краплинним розбризкуванням.