SPECTROSCOPIC STUDIES OF TUNGSTEN SAMPLES EXPOSED TO INTENSE DEUTERIUM AND ARGON PLASMA STREAMS

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The use of tungsten (W) as the main plasma facing component (PFC) was proposed for fusion reactors many years ago. Our recent experiments have been focused on spectroscopic studies of tungsten properties under its irradiation by intense plasma streams. Several samples made of pure W or (90 %W + 10 %Cu) alloy have been exposed to deuterium and argon plasma streams generated by the RPI-IBIS multi-rod plasma injector at different experimental conditions. The optical emission spectroscopy (OES) measurements have been carried out as a function of a plasma-stream energy density. The plasma electron density was estimated on the basis of the Stark broadening of the D_β and D_α spectral lines in a deuterium-plasma stream propagating freely, i.e. without any target, as well as near the irradiated tungsten surface. In this paper the results of a surface analysis of the tungsten samples after their irradiation by pulsed plasma-ion streams, and the influence of those streams on physical and mechanical properties of the irradiated samples, are discussed. A relationship of the structure and properties of the modified surfaces with parameters of the incident plasma-streams is also analyzed.

PACS: 52.25, 52.40.-Hf, 52.50.Dg, 52.70.Kz, 81.40.Wz

INTRODUCTION

The use of tungsten (W) is considered as the main plasma facing component (PFC) for fusion reactors few years ago [1, 2]. Tungsten has shown unique physical properties as the PFC. It is a refractory metal with a high melting point and it has an adequate thermal conductivity at a room temperature, although it is a relatively brittle material [3, 4]. In a comparison with other PFC (e.g., beryllium and carbon) tungsten can be significantly activated by the neutron irradiation. These features have motivated intense research on tungsten properties and behavior, but many questions have still remained unsolved. Hence, our recent experiments have been focused on spectroscopic studies of plasma created near the tungsten surface under its irradiation by intense plasma streams.

1. EXPERIMENTAL SETUP AND DIAGNOSTICS

The recent studies have been performed within the RPI-IBIS device [5, 6]. In general, facilities of the RPI-type are often used for material engineering. During the described experiments the RPI-IBIS device was equipped with two coaxial electrodes, each consisted of 24 thin molybdenum (Mo) rods. The working gas, injected with a fast acting electro-dynamic valve, was deuterium or argon. A condenser bank was charged up to U = 28 kV, and the total energy delivered to the device was equal to 33 kJ. The operational mode of the RPI-IBIS facility was varied by changes of a time delay (τ) between the initiation of the gas puffing and the application of a high-voltage pulse. The investigated targets, made of pure tungsten (W) or W+Cu(10 %) alloy, were placed at a distance of 20 cm from the electrodes outlets, as shown in Fig. 1,a.

The time-resolved spectroscopic measurements were carried out by means of a Mechelle-900 optical spectrometer. All these observations were performed perpendicular to the z-axis.

Time correlations of the discharge current intensity I(t) and voltage U(t) traces with a marker pulse, which was used to trigger the Mechelle-900 spectrometer, are presented in Fig. 1,b.

a

b

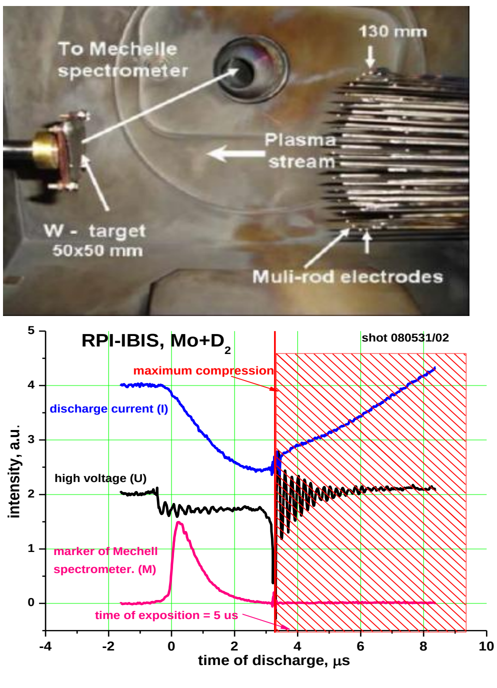

Fig. 1. General view of an electrode system of RPI-IBIS facility with the W - target fixed inside the chamber (a) and an example of the typical waveforms (b)

2. EXPERIMENTAL RESULTS AND DISCUSSIONS

The optical emission spectroscopy (OES) measurements have been carried out as a function of a plasma-stream energy density. A significant influence of that energy on the erosion of the irradiated samples surfaces has been observed for deuterium-discharges. It was experimentally proved that many W I and W II tungsten spectral lines were emitted from a region near the W-target surface, when the plasma stream energy amounted to 8 or 10 J/cm^2, as shown in Fig. 2.

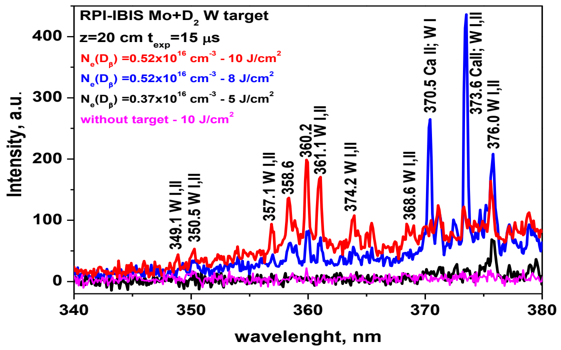

Fig. 2. Optical spectra recorded within the RPI-IBIS device at different plasma stream energies, as measured near the W target and in a free plasma stream

On the basis of the recorded optical spectra it was possible to study a temporal evolution of the plasma emission near the target surface. Analyzing the spectra measured near the W-target surface irradiated by deuterium plasma streams of energy equal to 10 J/cm^2, it was found that many W I and W II spectral lines appeared about 5 µs after the current particularity (so called current-dip). The intense emission of these spectral lines was very short and it lasted about 5 µs only, as shown in Fig. 3,a.

Measurements for another W+Cu(10 %) target were performed at the same experimental conditions, and it turned out that the visible radiation near the irradiated surface appeared immediately after the plasma impact (during the first 5-µs period after the dip). The total intensity of the recorded spectral lines was almost two times higher due to the radiation from evaporated copper ions (Fig. 3,b).

Due to the lack of atomic data of highly-ionized tungsten lines and a wide instrumental broadening of the applied spectrometer (which was larger than the half-width of the recorded tungsten lines), it was difficult to estimate the electron density on the basis of these W-lines. Therefore, to investigate the electron density (N_e) values and their changes near the pure W and W+Cu(10%) targets, the use was made of the observed linear Stark broadening of the recorded D_β spectral line [7, 8].

In the experiments with the pure W-target and that made of the W+Cu(10 %) there were found considerable differences in the dynamics of N_e changes (Fig. 4).

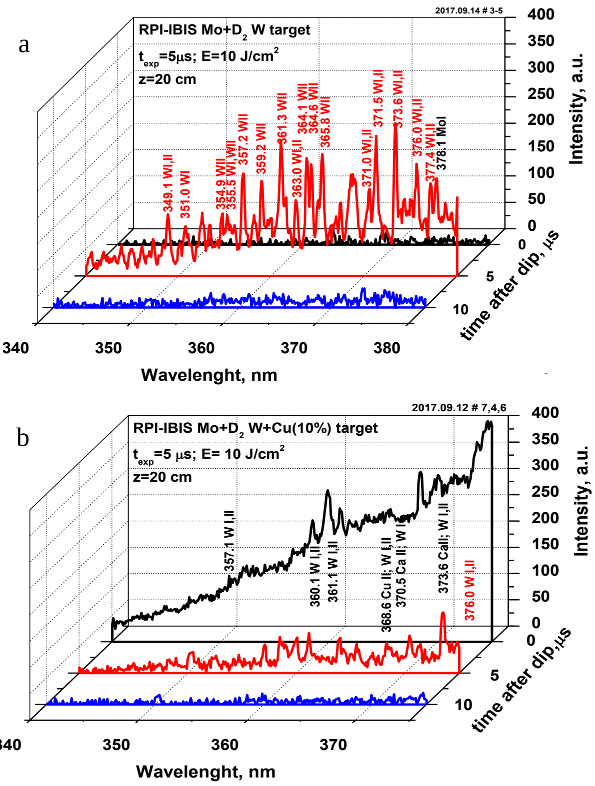

Fig. 3. Optical spectra recorded in the RPI-IBIS device, at the exposition time of 5 µs, during pure deuterium discharges which irradiated the pure W target (a) or the W+Cu(10 %) target (b)

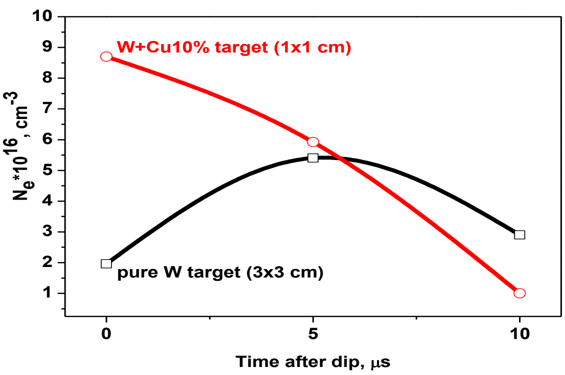

Fig. 4. Electron density (N_e) dynamics near irradiated surface of the pure W and W+Cu(10%) targets exposed to deuterium discharges in the RPI-IBIS facility

The electron density value near the irradiated W+Cu(10 %) target during the current dip amounted to $8.5 \cdot 10^{16}$ cm^{-3} and was about 4 times higher than that observed for the pure W-target at the same period. The pure W-target was characterized by a lower erosion during 5 µs after the discharge current dip, but after this time the N_e dynamics for both targets was very similar.

The next step of the reported experimental series concerned the irradiation of the investigated targets by argon-plasma streams. The targets were located at the same distance of 20 cm from the IBIS electrodes outlets.

The studies of the W spectral lines emitted from the evaporated target material during the argon discharges were performed at the plasma stream energy density equal to 10 J/cm^2, as in the case of the pure deuterium discharges, in order to compare erosion effects caused by different working gases.

It was observed that the main difference between the experiments with deuterium- and argon-discharges was a period of the W I and W II lines emission. For the argon-plasma streams the majority of the W I and W II lines from the irradiated pure W-target was recorded about 15 μs after the current dip (Fig. 5,a), while that from the W+C(10 %) target was observed about 10 μs after the dip (Fig. 5,b).

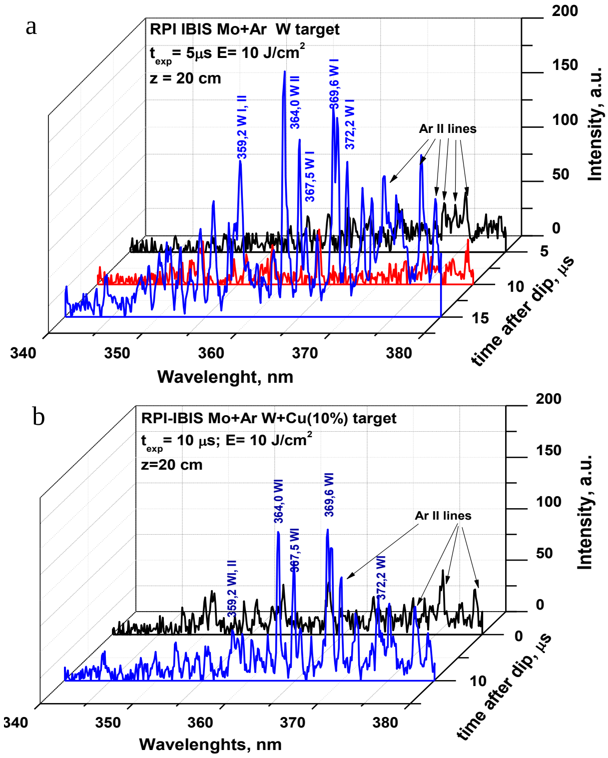

Fig. 5. Optical spectra recorded in the RPI-IBIS device, at the exposition time of 5 μs, during pure argon discharges which irradiated the pure W target (a) or the W+Cu(10 %) target (b)

The reported observation can be explained under an assumption that, in spite of a lower atomic mass of the deuterons, they could have a higher speed and energy than the argon ions. Therefore, the next experimental studies should concern measurements of velocity (and energy) distributions of the emitted deuterons and argon ions in the RPI-IBIS discharges.

During the described experimental campaign with the RPI-IBIS facility the surfaces of the pure W and W+Cu(10 %) targets after their irradiation by pulsed plasma-ion streams were investigated by means of the SEM technique. An influence of the applied plasma streams on the physical- and mechanical-properties of the irradiated samples is presented in Table.

	W+D_2	WCu+D_2	W+Ar	WCu+Ar
Blistering	+	+	+	+
Melting	–	+	–	+
Cracks	–	–	+	–

In the case of the pure W-targets upon the surfaces irradiated by deuterium or argon plasma streams there were visible blistering effects only. Upon the W+Cu(10 %) targets in addition to some blistering there were observed also other damages, like melting spots and cracks, caused by the deuterium plasma as well as by the argon one. These effects can be observed upon the SEM images shown in Fig. 6.

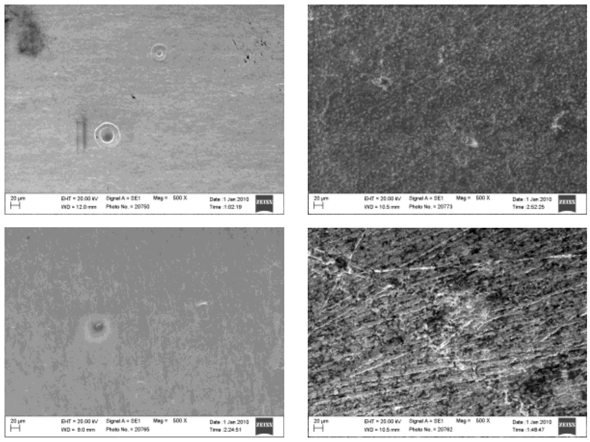

Fig. 6. SEM images of the W and W+Cu(10 %) targets irradiated within the RPI-IBIS device by the deuterium plasma streams (upper pictures) and argon plasma streams (lower pictures)

A dependence of the structure and properties of the plasma-modified surfaces on parameters of the incident plasma streams is analyzed and described in details in another paper published in the same issue [9].

CONCLUSIONS

Optical emission spectroscopy studies of the behaviour of different tungsten samples, during their irradiation by intense plasma streams generated within the RPI-IBIS device, were performed. Characteristic features of the deuterium- or argon-plasma impact upon the pure W and W+Cu(10 %) targets were revealed. A temporal behaviour of the electron density was estimated from the linear Stark broadening of the D_β lines, and a detailed analysis of the recorded optical spectra showed that WI and W II spectral lines from the irradiated pure W target appeared later than those from the W+Cu(10 %) target. Hence, one can deduce that a Cu-admixture to the pure W did not improve the erosion resistance of the target to the intense plasma streams.

An influence of the working gas (D_2 and Ar) on the irradiated samples was also studied. The main damages by deuterium plasma streams appeared during the first 5-μs period after the current dip (during the 1st half-period). Plasma-target interactions caused by argon discharges were characterized by the intense radiation emission about 15 μs after the current dip (during the

2nd half-period). This observation is of importance for understanding of different plasma-tungsten interactions.

The results obtained within the RPI-IBIS plasma facility, i.e. data on the plasma-ion streams and recorded optical spectra, confirmed that this device may be successfully applied for research on interactions of plasma streams with W-targets at power fluxes amounting to 5 MW/cm^2.

The surface analysis of the W samples after their irradiation by pulsed plasma-ion streams, and the studies of an influence of such streams on physical and mechanical properties of the irradiated samples, confirmed the results of the earlier spectroscopic measurements.

ACKNOWLEDGEMENTS

This work was realized in a frame of the bilateral Polish-Ukrainian scientific collaboration programme.

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Article received 15.01.2018

СПЕКТРАЛЬНЫЕ ИССЛЕДОВАНИЯ ВОЛЬФРАМОВЫХ ОБРАЗЦОВ, ОБЛУЧЕННЫХ ИНТЕНСИВНЫМИ ДЕЙТЕРИЕВЫМИ И АРГОНОВЫМИ ПЛАЗМЕННЫМИ ПОТОКАМИ

А. Марченко, В. Махлай, E. Skladnik-Sadowska, K. Nowakowska-Langier, D. Zaloga, M.J. Sadowski

Проведенные эксперименты были направлены на спектральные исследования свойств вольфрама при его облучении интенсивными плазменными потоками. Использование вольфрама (W) в качестве основного компонента дивертора для термоядерных реакторов было предложено много лет назад [1, 2]. Несколько образцов из чистого вольфрама и 90%W+10%Cu облучались потоками дейтериевой и аргоновой плазмы, которая генерируется стержневым плазменным инжектором IBIS, при разных экспериментальных условиях. Спектральные измерения излучения плазмы приповерхностного слоя проводились в зависимости от плотности энергии плазменного потока. Электронная плотность плазмы оценивалась на основе штарковского уширения спектральных линий $D_β$ и $D_α$ как в свободном потоке, так и вблизи поверхности вольфрама. Обсуждаются также результаты поверхностного анализа облученных образцов вольфрама и влияние плазменных потоков на физико-механические свойства вольфрама. Выявлена взаимосвязь параметров налетающего плазменного потока и свойств модифицированных поверхностей.

СПЕКТРАЛЬНІ ДОСЛІДЖЕННЯ ВОЛЬФРАМОВИХ ЗРАЗКІВ, ЩО ОПРОМІНЮВАЛИСЬ ІНТЕНСИВНИМИ ДЕЙТЕРІЄВИМИ ТА АРГОНОВИМИ ПЛАЗМОВИМИ ПОТОКАМИ

А. Марченко, В. Махлай, E. Skladnik-Sadowska, K. Nowakowska-Langier, D. Zaloga, M.J. Sadowski

Експерименти були націлені на спектральні дослідження властивостей вольфраму при його опроміненні інтенсивними плазмовими потоками. Використання вольфраму (W) в якості основного компоненту дивертора для термоядерних реакторів було запропоновано багато років тому [1, 2]. Декілька зразків чистого вольфраму та 90%W+10%Cu опромінювались потоками дейтерієвої та аргонової плазм, що генерується стрижневим плазмовим інжектором IBIS, при різних експериментальних умовах. Спектральні вимірювання випромінювання плазми приповерхневого шару проводилися в залежності від густини енергії плазмового потоку. Електронна густина плазми оцінювалась за штарківським розширенням спектральних ліній $D_β$ та $D_α$ як у вільному потоці, так і поблизу поверхні вольфраму. Представлені також результати поверхневого аналізу опромінених зразків вольфраму та впливу плазмових потоків на фізико-механічні властивості вольфраму. Виявлено взаємозв’язок параметрів налітаючого плазмового потоку та властивостей модифікованих поверхонь.