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Material testing with the use of plasma focus device

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Abstract

This work shows that small Plasma Focus Installation (PF) with the energy stored in capacitors less than 4 kJ can be used for to test materials which are to be used in the future thermonuclear devices. As an example of such application of the PF we conducted the experiment on the influence of cumulative plasma streams produced in PF on vanadium.

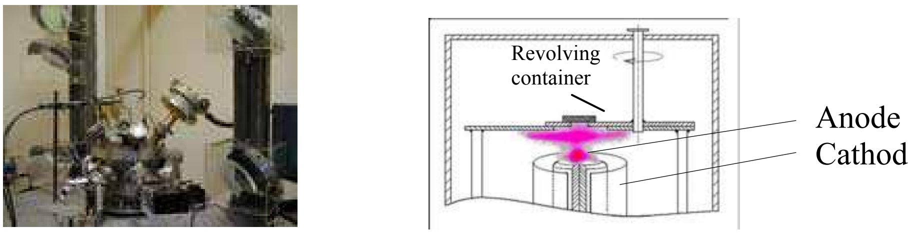
Introduction

In the development of thermonuclear reactors with magnetic or inertial confinement of plasma it is very important to know the stability of construction materials for discharge chamber and its design elements to the impact of pulsed deuterium-tritium thermonuclear plasma. The purpose of the work is to show that the plasma focus device can be used to test materials and construction elements proposed for the use of the future thermonuclear reactors. It is known that in plasma focus installation due to non-cylindrical plasma compression of plasma-current sheath (PCS) the axial cumulative streams are produced. We conducted the experiment with parameters of such streams and studied the effect of plasma streams on vanadium.

2. The experiment and methods.

The research was conducted on a plasma complex "TULIP" of P.N. Lebedev Physical institute [1]. The experiments were done on small plasma focus PF-4M with energy stored in the capacitors of 4 kJ, with operating voltage between 10-20 kV, maximal current of up to 600 kA, pressure of D_2 or mixture of gases in the PF chamber between 0.3-10 Torr, and neutron yield of $2 \cdot 10^8$ n/pulse.

Diagnostics: Laser examinations by shadow and interferometric methods, MCP photography in visible and soft X-ray range of radiations [3,4].



(a) **(b)**

Figure 1. (a) -PF-4M device and (b) - the scheme of the experiment.

The vanadium samples were attached in a special revolving container. The distance from the container-cathode to the anode was 10 mm. The observation of the structure of the internal and non irradiated backside surface of the samples was done by atomic-force electron-optical scanning microscopy. We also conducted the micro-structural analysis of the cross-section of the samples and measured their microhardness. The cumulative spraying of the surface layers was registered on polished silicon plates. The plates were placed at a distance of 1-1.4 mm from the non irradiated surface of the vanadium.

3. Results and discussions

Figures 2a,b show images of the PF obtained with the use of the MCP converter in the visible range of plasma radiation. These images display the propagation of axial plasma streams for two kinds of filling gases: deuterium and argon. From these images, the axial velocity of plasma streams was determined (see Fig. 2c). One can see that in the case of deuterium plasma the velocity of plasma stream at the distance 0.5 cm from the anode is approximately 10^8 cm/s. Taking into account that the value of plasma density (from interferometric measurements [2]) in this place is 10^{18} cm^{-3} it is possible to evaluate the energy flux density, which for our case equals 10^{11} W/cm^2.

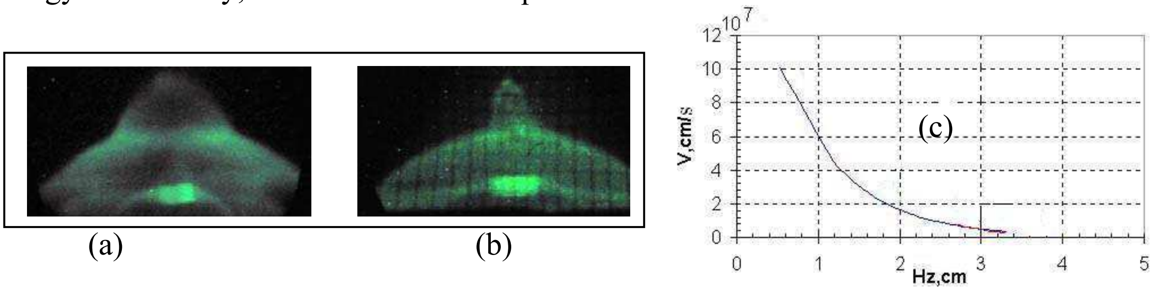


Figure 2. The MCP converter pictures with the 3 ns resolution: (a) – for deuterium plasma, (b) – for argon plasma. (c) - The velocity of the axial stream in dependence on the distance, H_z, from the anode.

Fig. 3a shows the structure of the surface of the vanadium sample exposed to the pulse of deuterium plasma. After exposure to 10 pulses of deuterium plasma onto a plate of vanadium with a thickness of 0.22 mm, and an action area of 0.8 cm^2, we observed a bend of 0.3 mm.

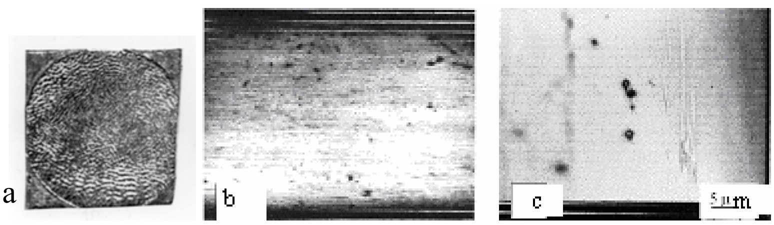


Figure 3. (a) -The structure of the surface of the vanadium sample exposed to the ten pulses of deuterium plasma. The thickness of the sample is 0.29 mm. The size of the exposed area is 11 x 7 mm. (b,c) - The structure of the cross-section of the flat sample of vanadium after it was irradiated by a plasma pulse (the irradiated side of the sample with pores); with magnification 440x, and (c) -magnification 1000x .

The cross-section of the structure of the irradiated sample is presented in figures 3b and 3c. It is characterized by the creation of wavy lines (doubles of deformation), which arise usually in metals due to superfast deformations. The most important result our observations of the structure is the detection of visible pores with spherical contours on the entire irradiated sample.

The change in the microhardness of the irradiated annealed vanadium along the cross-section of a sample is presented in Fig. 4a. The maximum microhardness of 210 kg/cm2 is observed near the irradiated surface. Thus, under the action of hydrogen-deuterium plasma, there is strong (approximately double) hardening of the surface layers of vanadium.

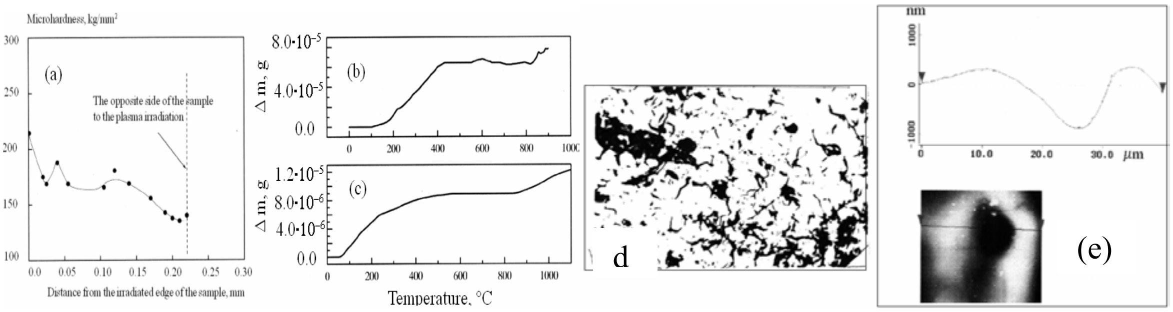


Fig. 4. (a) - Change of microhardness on a cross-section of the irradiated sample of vanadium, (b) - Change of weight of the irradiated sample of vanadium at a isochronal annealing up to 900°C (the first annealing), (c) - Change of weight at the repeated annealing. (d) - The surface of a plate of vanadium with thickness of 0.22 mm - the side opposite the irradiation, (e) - The shock crater with rim.

The change of weight of a flat sample of vanadium with a thickness of 0.22 mm during isochronal annealing in the vacuum chamber for the thermographic analysis up to a temperature of 900°C (fig. 4b), and the repeated annealing of this sample up to same temperature, is shown in figure 4c. The isochronal annealing of pure, non-irradiated vanadium under the same experimental conditions has not shown a change of its weight. It is possible to conclude that the change in weight of the irradiated samples, with temperatures approaching 900° C, is connected only to the release of the deuterium or its light molecular compounds, implanted by the plasma pulse.

Mass - spectrometric analysis has shown that at the isochronal annealing of the irradiated vanadium up to a temperature of 600° C, deuterium is released. From our observations follows that the influence of high-temperature dense deuterium plasma pulses on vanadium result in the super-deep penetration of deuterium into the sample to a depth of exceeding 0.22 mm. One of the basic reasons of the super-deep penetration of deuterium into vanadium is the shock-wave mechanism.

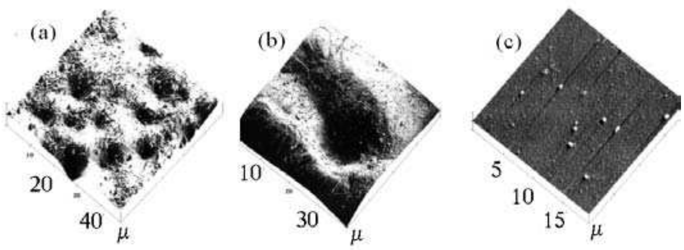


Figure 5. (a) - craters with internal string structure. (b) - a large cumulative crater. (c) - side of a silicon target with cumulative nano-particles of vanadium.

The complete picture of the back side of the irradiated plate of vanadium with thickness of 0.22 mm is shown in fig. 4d. The borders of grains and numerous craters of various sizes and forms are visible. The analysis by atomic-force microscope of the structure of the non-irradiated surface of a vanadium plate 0.22 mm thick after 10 pulses of deuterium plasma revealed three groups of craters each having a different structure and size: the first group - craters of size 10μm exhibit round shapes bordered by rims (fig. 4e). The second group - craters with external sizes 10μm show a clearly expressed internal column structure (fig. 5a). Rims around the craters are absent, but they are surrounded with conic creations of various sizes. The third group - craters of large sizes of any form. Feature of these craters are the presence of the clearly expressed rims with the ejection of thin strings with a diameter of 100 nm. The internal structure of these craters is the same as in the previous group - they have an internal column structure (fig. 5b).

As shown in [6], the cumulative vanadium dispersion detected on a silicon plate-target (fig. 5c) consists of nano-particles of vanadium with size 0.01 microns and separate large particles with 0.5 microns which resemble solidified liquid drops. It was shown experimentally that the dissipation of shock waves formed under the influence of high-temperature deuterium plasma pulses on vanadium results in the destruction of its surface outside the irradiated zone and the creation of a cumulative cloud of vanadium nano-particles containing separate micro-particles. The velocity of micro-particles should be within 2-4 km/s, as shock craters cannot be formed on the target with these velocities, and the adhering of particles to a target with high adhesion (shock alloy) [7] is observed. In [5] it was assumed that escaping cumulative micro-particles of vanadium are in a liquid state. This conclusion is supported by our results about structure of the large craters (fig. 4b). The rims of these craters are lined by filaments, appearance of which is possible to explain only by the occurrence of a liquid phase at the dissipation of the energy of the shock waves on the surface of vanadium.

4. Conclusions

Under the influence of pulsed high-temperature deuterium plasma, the super-deep penetration of deuterium into vanadium is revealed. This causes a change of physical-mechanical properties and structure of vanadium, and also leads to the creation internal pores. This effect is important for the choice of constructional materials of the first wall of reactors of thermonuclear fusion with magnetic or inertial confinement of plasma. Also, pulsed high-temperature dense plasma can be used for the internal hardening of metals.

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