Modification of Internal Properties of Vanadium and Structure of its Surface at the Action of Pulsed High-Temperature Dense Deuterium Plasma

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Abstract – This work presents experimental research on the influence of a high-temperature dense plasma pulse on vanadium. Vanadium can be used as a basic element for the creation of low-activated alloys which could serve as construction elements for future thermonuclear power stations. The experiments were made on a 4 kJ Plasma Focus installation. These installations are capable to form a pulse of axial plasma flows moving with velocity of approximately 10^8 cm/s and plasma density of about 10^{18} cm^{-3}. It was found that due to pulse irradiation of vanadium by deuterium plasma, shock waves arise which result in super-deep penetration of deuterium inside of the studied sample. This process is accompanied by changes in the vanadium structure, the occurrence of pores in it, and changes in its mechanical properties. The break-away of vanadium particles from the back-side surface of the sample and the formation of craters were also observed.

1. Introduction

The study of materials under the influence of concentrated fluxes of various natures is very important for the development of thermonuclear devices. For example, such plasma action on materials can take place during the plasma disruption in thermonuclear reactors with magnetic confinement of plasma, and also in systems of inertial thermonuclear fusion. In this paper, we study the influence of super short pulses of powerful dense high-temperature deuterium plasma on the internal and surface properties of vanadium. Vanadium was chosen because it is a low-activated material and therefore can be used as a basic element for the creation of alloy materials for thermonuclear devices. It was shown earlier that due to the action of concentrated pulses of energy flows on metals, shock waves arise. The dissipation of their energy at the propagation through the crystal structure causes the creation of dot defects (vacancies, internodal atoms [1]), which influence their physical and physical-chemical properties [2]. The purpose of the this research was to study the influence of shock waves produced by super-power pulses of deuterium plasma on the intrusion deuterium into the sample of vanadium, which produce structural and mechanical changes in the vanadium sample and on the properties of the free (back side of sample, not exposed to the plasma) surface of the sample.

2. The Experiment and Methods

Samples of vanadium were irradiated by a high-velocity flow of deuterium plasma created in the plasma focus installation "Tulip" of the P.N. Lebedev Physical Institute [3]. The installation has the following parameters: energy of the condenser battery of 3.6–4 kJ and a maximum current of 400 kA. The discharge chamber of the installation was filled with deuterium up to a pressure of 1.5 Torr. The deuterium contained an impurity of hydrogen of no more than 0.2%. The velocity of the plasma flow was approximately 10^8 cm/s and the density of the plasma was 10^{18} cm^{-3}. The duration of a plasma pulse was 100 ns. The energy flux density carried by the plasma into a sample was approximately 10^8 W/cm^2. The time between separate pulses was longer than 3 minutes. The purity of vanadium was 99.8% and the thickness of the sample was 0.22 mm. The vanadium samples were fastened in special revolving container. The distance from the container–cathode to the anode was 10 mm. The observation of the structure of the internal and free surface of the samples was done by atomic-force electron-optical scanning microscopy. We also conducted microstructural 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

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. The cross-section of the structure of the irradiated sample is presented in Fig. 1,a,b. It is characterized by the creation of wavy lines (doubles of deformation), which arise usually in metals due to superfast deformations. The creation of the doubles of deformation is also observed directly on the irradiated surface in the area of action of the plasma [3]. The most important result our observations of the structure is the detection of visible pores with spherical contours on the entire irradiated sample.

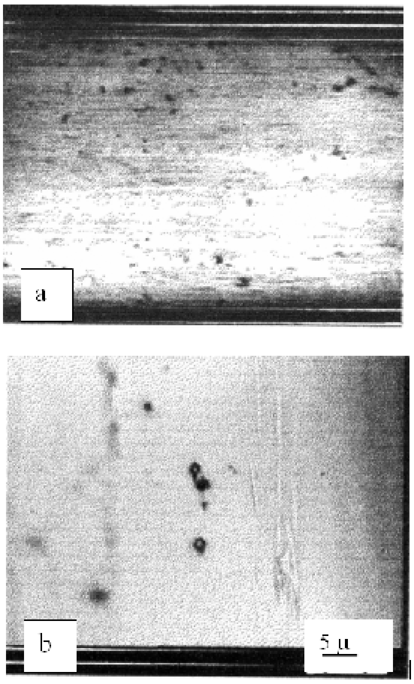

Fig. 1. shows the structure of the cross-section of the flat sample of vanadium after it was irradiated by a plasma pulse (the irradiated side of the sample with pores); a – magnification 440x, b – magnification 1000x

The change in the microhardness of the irradiated annealed vanadium along the cross-section of a sample is presented in Fig. 2,a. The maximum microhardness of 210 kg/cm^2 is observed near the irradiated surface. With increasing depth, the microhardness falls to 130 kg/cm^2, being 1.3 times higher than the microhardness of the non irradiated vanadium (100 kg/cm^2). Thus, under the action of hydrogen-deuterium plasma, there is strong (approximately double) hardening of the surface layers of vanadium. Characteristically, the small drop in the microhardness in a depth of 0.02 mm from the surface of the irradiation is connected, as shown by the structural research, with an area where the concentration of the doubles of deformation is smaller than those near the surface and in deeper layers of the sample. Such decrease in the concentration of the doubles of deformation is possibly connected with the maximum steeping of the front of a shock wave [4] which in dependence on the value of the initial pulse of pressure can be reached on some distance from a surface. A shock wave with maximal steeping of front of pressure propagates from this distance into the depth of the sample. Dissipation of this shock wave primarily results in the creation of dot defects (vacancies, internodal atoms). The creation of non-equilibrium dot defects influences the character of the structural changes in a crystal.

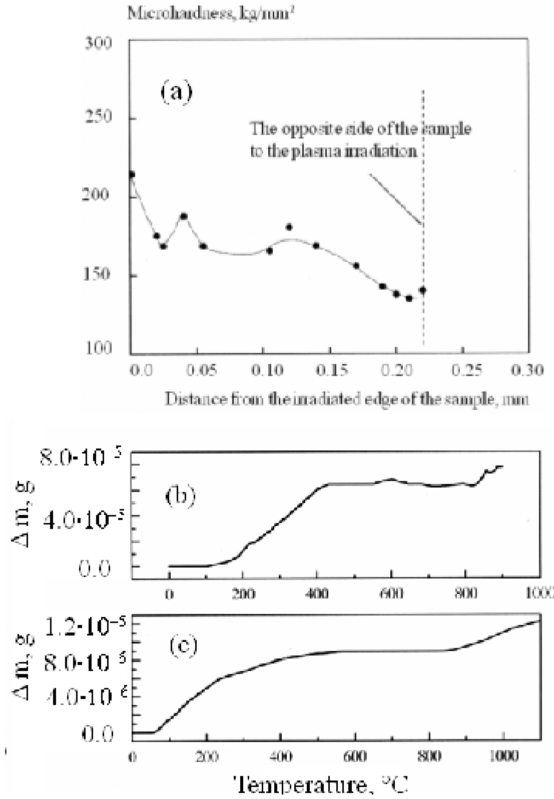

Fig. 2. Change of microhardness on a cross-section of the irradiated sample of vanadium (a); change of weight of the irradiated sample of vanadium at a isochronal annealing up to 900 °C (the first annealing) (b); change of weight at the repeated annealing (c)

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. 2,b), and the repeated annealing of this sample up to same temperature (Fig. 3,a), is shown in Fig. 2,c. The greatest decrease of weight in a sample is observed at temperatures between 200 and 400 °C. At repeated isochronal annealing (with a similar speed of 10 °C/min), the essential decrease of change in weight of a sample (Fig. 2,b) is observed at the preservation of the same character of temperature dependence as at the first annealing. The isochronal annealing of pure, non-irradiated vanadium under the same experimental conditions has not shown a change of its weight. Thus, 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. Thus, it is possible to estimate on the basis of the change in weight of the irradiated plate of vanadium, that the content of deuterium makes up 0.06 weight % (1.5 at. %). This amount is three orders higher than the amount of hydrogen in the initial sample. According to the diagram of a state V–D [5], solubility of deuterium in vanadium at room temperature does not exceed 10^{-4} weight %. As temperature rises, the solubility increases and at a concentration of 4 weight % of D_2, hydride of vanadium VD with an ordered tetragonal structure is formed. Hydride of vanadium is created up to a maximum temperature of 135°C. Above this temperature, the hydride decomposes and a solid solution of V–D implantation is created. Approximately at this temperature, the noticeable decrease in weight of the samples, irradiated by the plasma pulse (see Fig. 2,b,c), is also observed. The detection of spherical extractions of a size less than 100 Å by means of tunnel electron microscopy testifies to the presence of hydrides on the surface of the irradiated plate of vanadium [3]. The concentration of these extractions is higher on the irradiated surface. It is possible to conclude that these hydrides and visible pores are major factors influencing the change in microhardness of the samples. 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. It is impossible to explain this effect by the diffusion mechanism and also by the implantation of fast ions of deuterium (with a maximum energy 200 keV). This implies that one of the basic reasons of the super-deep penetration of deuterium into vanadium is the shock-wave mechanism.

The complete picture of the back side of the irradiated plate of vanadium with thickness of 0.22 mm is shown in Fig. 3,a. 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 10 μ exhibit round shapes bordered by rims (Fig. 3,b). Their depth is approximately 10 times smaller than the visible diameter (flat craters).

The second group – craters with external sizes 10 μ show a clearly expressed internal column structure (Fig. 4,a). Rims around the craters are absent, but they are surrounded with conic creations of various sizes.

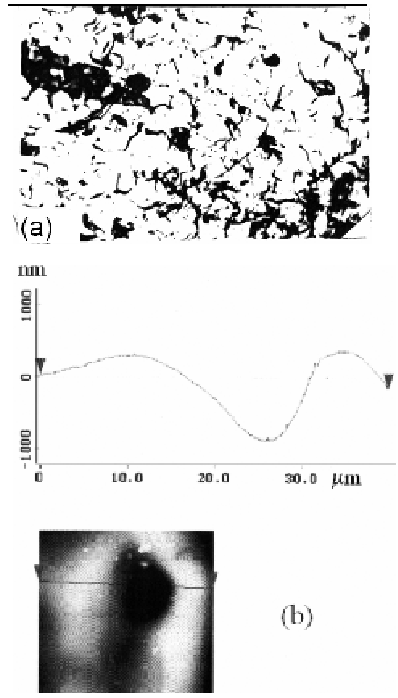

Fig. 3. The surface of a plate of vanadium with thickness of 0.22 mm – the side opposite the irradiation (a); the shock crater with rim (b)

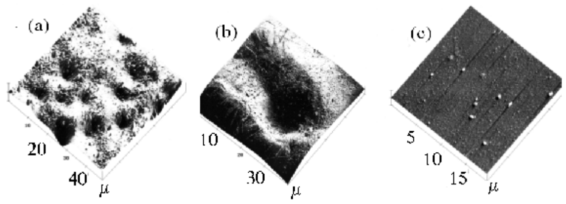

Fig. 4. Craters with internal string structure(a); a large cumulative crater (b); side of a silicon target with cumulative nano-particles of vanadium (c)

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. 4,b).

As shown in [7], the cumulative vanadium dispersion detected on a silicon plate-target (Fig. 4,c) consists of nano-particles of vanadium with size 0.01 microns and separate large particles with 0.5 microns which resemble solidified liquid drops. Their height above the surface of silicon does not exceed 100 nm. Thus, 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) [8] is observed. In [6] 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. 4,b). 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. Conclusion

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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References

[1] Z.I. Mezokh, V.A. Yanushevich, L.I. Ivanov, Physics and chemistry of processing of materials **4,** 163 (1971).

[2] V.A. Yanushevich, L.I. Ivanov, Physics and chemistry of processing of materials **6,** 3 (1977).

[3] L.I. Ivanov, L.I. Dedjurin, I.V. Borovitskaya, O.N. Krokhin, V.Ya. Nikulin, S.N. Polukhin, A.A. Tikhomirov, A.S. Fedotov, Problems of Atomic Science and Technology, Series of Plasma Physics **5**, 83 (2002).

[4] L.I. Ivanov, N.A. Litvinova, V.A. Yanushevich, J. of Quantum electronics **1**, 204 (1977).

[5] *Handbook under edition of the academician V. Lyakishev,* V. 2, Moscow, Mechanical engineering, 1997, pp. 364–365.

[6] I.V. Borovitskaya, L.I. Ivanov, A.I. Dedjurin, O.N. Krokhin, V.Ya. Nikulin, A.A. Tikhomirov, Perspective materials **2**, 24 (2002).

[7] L.I. Ivanov, A.I. Dedjurin, I.V. Borovitskaya, O.N. Krokhin, V.Ya. Nikulin, S.N. Polukhin, A.A. Tikhomirov, A.S. Fedotov. Pramana – Journal of physics **6,** 1179 (2003).

[8] A.I. Akishin, L.S. Novikov, *Methods of imitation of influence of an environment on materials of space vehicles*. Moscow, Publishing house of the Moscow University, 1986, pp. 56–59.