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Application of plasma focus installations for a study of the influence of deuterium cumulative flows on materials*

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Abstract. In this work, as an example of an application of the plasma focus (PF) device, we study the influence on alloys of vanadium of a cumulative flow producing in the PF device. The experiment was done in a 4-kJ PF device with various gas fillings and various anode shapes. It was found that the velocity of the axial cumulative flow depends on the type of gas and is about $5\cdot 10^7$ cm/s for deuterium and $2\cdot 10^7$ cm/s for argon fillings of plasma focus chamber; the shape of the flow is changed from a broad conical fly for deuterium to a quasi-one-directional stream for argon. The dynamics and structure of such flows are investigated by means of laser diagnostics and an image converter camera.

The experiments show that cumulative flows produce various defects in tested samples. The appearance of a large number of cracks on the surface of vanadium under the impulse influence of deuterium plasma shows that pure vanadium cannot be used for the construction of thermonuclear fusion reactors.

Such PF installations could also be used effectively for the study of other material and construction elements proposed for the use in thermonuclear machines.

Keywords. Plasma focus; z-pinch; science material; alloys of vanadium; material for thermonuclear reactors; plasma-material interactions.

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1. The experimental set-up

In the experiment, high-temperature deuterium plasma streams were created on the experimental plasma focus installation 'Tulip' at the P.N. Lebedev Physical Institute. Maximum energy of plasma focus pulse was 4 kJ with a current of 400 kA (figures 1 and 2).

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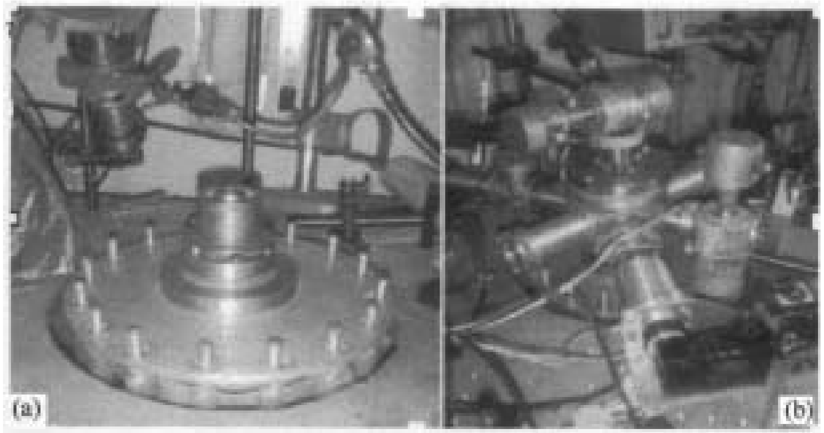

Capacity of condenser bank	20 μF
Operating Voltage	10–20 kV
Maximum current	600 kA
Operating gas pressure (D_2 or gas mixture)	0.3–1.5 Torr
Neutron yield	$2{\cdot}10^8$ n/pulse
Rate of operation	Several hundreds discharges per day

Figure 1. The experimental set-up. (**a**) The electrodes of PF-4 and (**b**) PF-4 with diagnostics.

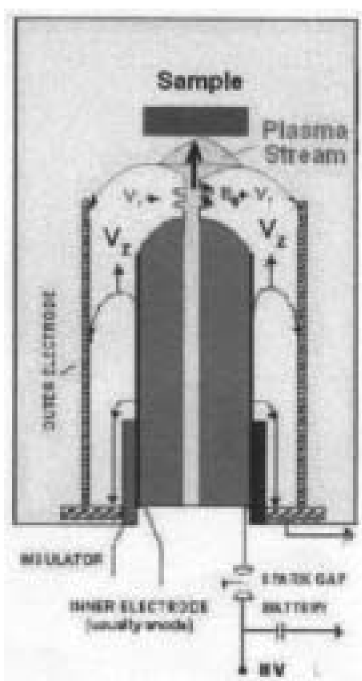

Figure 2. The scheme of the experiment.

Figure 3. MCP pictures of plasma focus in visible light.

Figure 4. The structure of the surface of vanadium sample after it was irradiated by pulse of deuterium plasma. The thickness of the sample is 0.29 mm. The size of the influence area is 11×7 mm.

The speed of the axial deuterium plasma flow was 2–4 $\cdot 10^7$ cm/s and the plasma density was 10^{18} cm^{-3} (figure 3). Time duration of the deuterium plasma pulse did not exceed 100 ns, which corresponds with the experimental values of the time period of plasma disruption in the thermonuclear reactor with the magnetic plasma confinement. Imitation research of changes in physical–mechanical characteristics of vanadium was done with 10 pulses of plasma. Time interval between pulses was 3 min. According to the calculations and direct measurement method, the temperature on the reverse side of the samples did not exceed 300°C.

Electropolished flat samples of pure vanadium were used in the experiment. The thicknesses of the samples were varied from 0.29 to 0.55 mm. The samples were placed at a specified distance away from the anode of the plasma focus installation. Maximum power sent to the sample in single pulse did not exceed 10^8 W/cm^2.

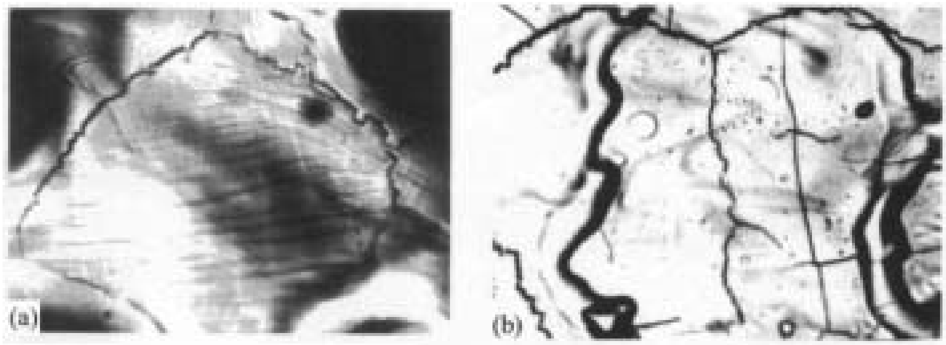

Figure 5. (**a**) The center of the vanadium sample with a thickness of 0.55 mm. The irradiation by plasma at a distance of 10 mm from the anode of plasma focus. (**b**) The center of the vanadium sample with a thickness of 0.55 mm. The irradiation was done by the plasma at a distance of 32 mm from the anode of plasma focus. The cracks appearance is seen.

2. Results and discussions

A central bend of the sample surface with the plasma action to the samples, depending on their thickness, is observed from the experiments. For example, with the thickness of vanadium sample at 0.29 mm and the diameter of the plasma pinch at 11 mm, the bend in the vanadium sample was 0.29 mm. The sample with the thickness of 0.55 mm was bent by 0.18 mm. In both cases, the samples were placed 10 mm away from the anode. Figure 4 shows the surface of the vanadium sample with a width of 0.29 mm after it was irradiated. One can see the formation of stretched crests, which form the so-called periodic running waves of deformation. They are especially clear in the peripheral part of the sample. The crests are chaotic with their shapes changed in the central part of the sample.

Such a distribution in the visible surface disturbances shows that the intensity of plasma streams in the plasma focus installation is irregular. It is greater in the center [1]. Due to the spread of the periodic waves of deformation, the thickening of the edges of the sample has occurred. The vanadium sample with the original thickness of 0.29 mm originated the thickening of 0.09 mm. This shows that, parts of the material in the sample shifted from the center to the periphery under the action of deformation waves.

Physical model of appearance and distribution of periodic running waves of deformation and dissipation of these waves with real crystal-like structure are discussed in [2,3]. Deformation of vanadium by the running deformation waves leads to significant changes in the structure of the outer layers: bands of slips appear in grains of poly-crystallized vanadium and grain-boundaries have a stair-case structure (figure 5). Also, deep extended cracks appear (figure 6), which are not characteristic to the non-deformed materials. Multitude of small-size extractions and large individual circular particles are also seen on the sample surface.

Besides, according to the scanning tunnel microscopy, on the surface of grains the directed wave-like structures are also formed, in which, the extraction of sphere particles, the size of some of these particles does not exceed 200 Å, are observed (figure 7). In accordance with a diagram of the state of vanadium–deuterium [4], deuterium with up to 40 at.%

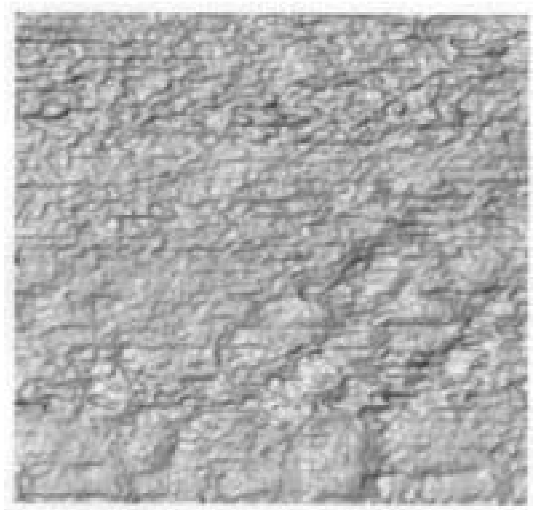

Figure 6. The scanning tunnel microscopy of the center of the vanadium sample with a thickness of 0.29 mm. The irradiation of the sample was done by the pulse of deuterium plasma at a distance of 10 mm from the anode of plasma focus. Size of the area is $1.2\times1.2\ \mu$m.

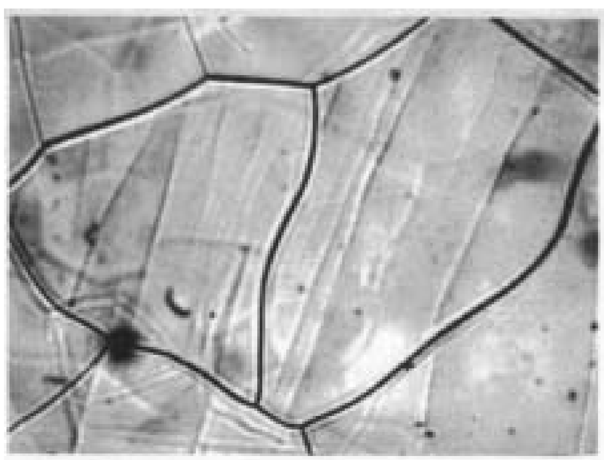

Figure 7. The structure of the opposite side of vanadium sample with a thickness of 0.32 mm after the influence of 10 pulses of deuterium plasma. The sample was placed at 32 mm from the anode. Magnification is 440.

creates interstitial solid solutions with vanadium, in which δ-phase of vanadium deuteride is present. With the increase of deuterium concentration in solid solution the concentration of δ-phase increases. Based on this data, one can conclude that the observed extractions belong to hydride formations of vanadium.

It is interesting to evaluate the depth of diffusive penetration of deuterium into vanadium in typical isothermal conditions with a temperature of 900 K during one pulse of

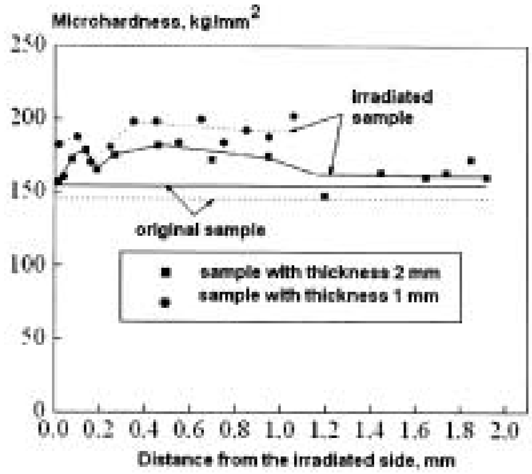

Figure 8. Micro-hardness of the original and irradiated samples of vanadium.

100 ns. Diffusion coefficient of deuterium under the chosen temperature is taken from [5] and equals $1.5{\cdot}10^{-4}$ cm/s^2. Using this value, the depth of deuterium penetration $x = \sqrt{Dt}$ during one pulse will not exceed 0.1 μm. Point defects (vacancies and interstitial atoms) appear and the dislocation structure of the material is changed. This takes effect under the multiple irradiation of the sample (10 impulses with 3 min interval), because of the dissipation of shock waves that pass through poly-crystallized structure. This can considerably affect the value of the depth of deuterium penetration into samples [6,7]. One can make such decisions based on the values of micro-hardness of the irradiated and non-irradiated samples of vanadium (load $P = 50$ g) (figure 8).

Thus, micro-hardness of vanadium samples with a thickness of 0.29 mm under the impulse irradiation at a distance of 10 mm from the anode, on the irradiated and non-irradiated side, equals 219 and 210 kg/mm^2 accordingly; micro-hardness of the original vanadium sample was 150 kg/mm^2.

These changes in micro-hardness, depending on the original thickness of samples correlates with the observed bending of samples. The bend of a 'thick' sample was 1.6 times smaller than that of a 'thin' one. From this, one can conclude that shock waves that appear due to the impulse action of deuterium plasma on the surface on vanadium lead to plastic deformation of the samples and stimulate the extra-deep penetration of deuterium into the samples in comparison with that of the thermal diffusion. As a result of this, vanadium becomes fragile, fractures (cracks) appear on the surface layers, and hardness is significantly increased.

This conclusion is supported by Antonova [8] in which he found that the saturation of vanadium with hydrogen in the isothermal conditions with concentration up to 33 at.% cause an increase of hardness up to 240 kg/mm^2. It is worthwhile to point out that Ivanov *et al* [7] experimentally show that the structural defects created by shock waves have irregular volume distribution. This could lead to a significant concentrated irregularity in the distribution of deuterium in vanadium. As a result, vanadium deuteride will be distributed irregularly in the studied sample.

Finally, we would like to note an interesting fact that was observed during our experiment: exit of shock waves of compression on the non-irradiated surface of vanadium and the occurrence of unloading waves lead to the exposure of structure of non-irradiated surface (figure 7), i.e., the effect of cumulated etching of the surface is observed.

3. Conclusions

The effect of extra-deep penetration of deuterium is observed when the pulse action of deuterium plasma with energy level of up to 4 kJ and the pulse duration of 100 ns. As a result, vanadium becomes considerably more fragile.

Surface morphology of vanadium, with the pulse action of deuterium plasma, is formed by the propagation from the center of the action to the periphery of periodic running deformation waves, which cause the displacement of the material.

The formation of a microwave-oriented structure is observed on the surface of grains of the poly-crystallized vanadium under the pulse action of deuterium plasma.

The experiments show that plasma focus installation could be used also effectively for the study of other material and construction elements proposed for the use in thermonuclear machines.

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