EFFECT OF PULSE FLOWS OF CHARGED PARTICLES ON THE STRUCTURE AND MECHANICAL PROPERTIES OF METALS

I. M. Neklyudov, V. N. Voevodin, V. F. Rybalko,
N. V. Kamyshanchenko, and V. A. Belenko

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We investigate the effect of pulse flows of hydrogen, helium, and hydrogen–helium plasma of a specific power of $20-30\ \mathrm{GW/m^2}$ on the surface structure and mechanical properties of vanadium, niobium, and Kh16N15M3B and Kh18N10T austenitic stainless steels. Plasma bunches acted for $2\ \mu\mathrm{sec}$ with an average energy of particles of ≈ 2 keV. Tests of samples made of austenitic steels for tension showed that irradiation up to doses of $\approx 10^{18}\ \mathrm{cm}^{-2}$ strengthens them by a factor of 1.8 and decreases the relative elongation by a factor of 2.3–2.7. A layer-by-layer electron-microscopic analysis revealed that a cellular structure is formed in the surface layer $\approx 25\ \mu$m in thickness as a result of irradiation, which explains the change in mechanical characteristics of the steels.

One of the factors that causes radiative damage of materials in thermonuclear fusion installations is the impact of flows of fast charged particles or neutral atoms (helium and the isotopes of hydrogen) arriving from plasma to the inner surface of a discharge chamber, the first wall.

In choosing materials for the first wall of large-scale experimental installations of thermonuclear fusion or thermonuclear reactors, it is necessary to predict the behavior of materials in the reactor during the planned period of service, taking into account all factors of radiative impact as well as thermomechanical loads. For this purpose, the data on the behavior of materials under conditions of their irradiation by stationary monoenergetic beams of ions of hydrogen and helium were used for a long time. In such an approach, the effect of the pulse character of irradiation and the dispersion of the energy spectrum of bombarding particles were not considered.

In the beginning of the 1980s, it was shown in [1, 2] that the dispersion of the energy spectrum of charged particles results in a suppression of one of the most intensive factors of erosion of metal surfaces, namely, the radiative helium blistering. In this connection, it appears necessary to revise the conclusions concerning the possibility of using a number of materials in thermonuclear reactors.

The interest in the effect of the pulse character of irradiation arose when it became clear that, on the one hand, plasma instabilities, including the complete disruption of a pinch, cannot be completely eliminated in thermonuclear reactors, and, on the other hand, it is necessary to take into account the periodic impact of powerful shocks of plasma flows (with a specific energy release of $100-1000\ \mathrm{GW/m^2}$) on the material of the first wall. The first experimental data [3, 4] indicate that such plasma shocks can substantially change the mechanical properties of metals, in particular, those of structural steels.

In what follows, we present a brief review of the results of investigations of the effect of irradiation by powerful pulse flows of plasma on the surface structure and mechanical properties of commercially pure niobium and vanadium as well as stainless steels as promising materials for the discharge chamber of a thermonuclear reactor or its interior elements [5–7].

Experimental Equipment and Procedures

Samples were irradiated at the “Prosvet” coaxial plasma accelerator of the National Scientific Center “Kharkov Physicotechnical Institute,” which was described earlier [8] (see Fig. 1).

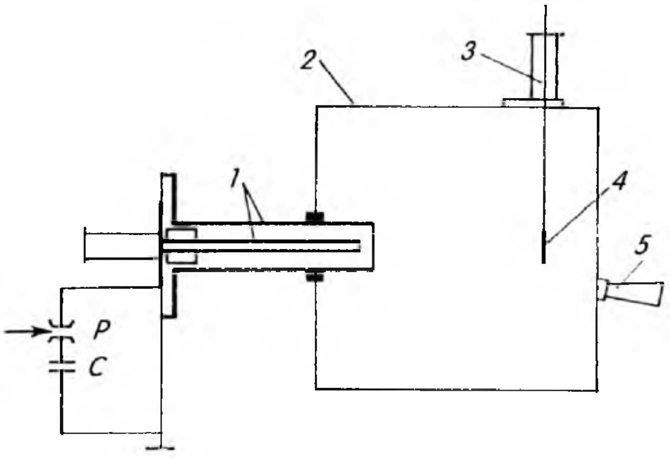


Fig. 1. Basic diagram of the plasma accelerator: (1) coaxial electrodes, (2) vacuum chamber, (3) lock device, (4) cartridge with targets, (5) Thompson mass-spectrometer, (P) discharger, (C) battery of capacitors.

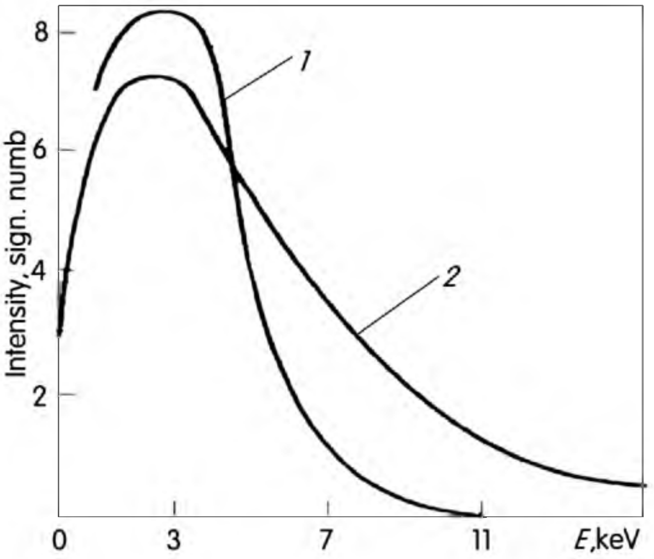
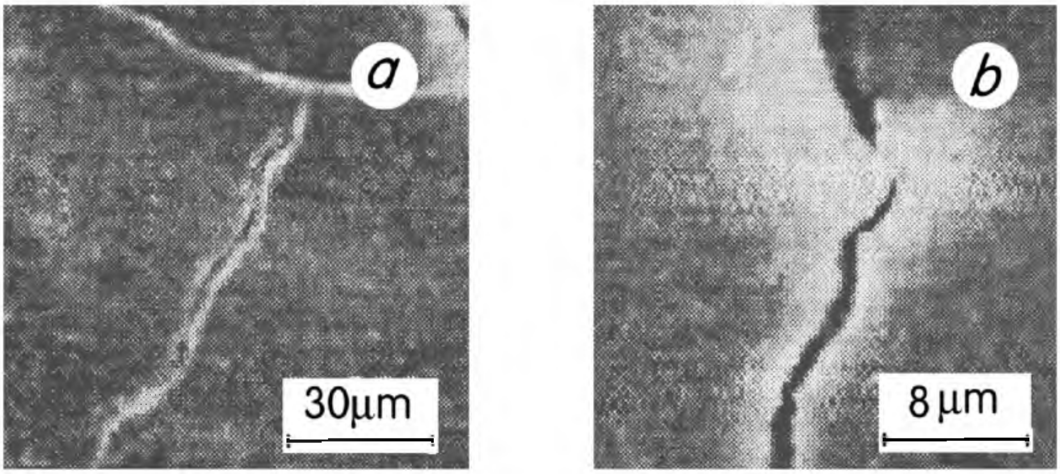


Fig. 2. Energy spectra of particles in a plasma bunch of the accelerator "Prosvet" (1) and the rated energy spectrum in the flow of atoms of deuterium and tritium to the first wall of a UWMAK II thermonuclear reactor [10] (2).

The accelerator operates in the mode of single pulses, by "shooting" one plasma bunch at the target approximately every 5 min. The temporal duration of a bunch is 2 μsec, its particle density is $\sim 5 \cdot 10^{20}\ \mathrm{m}^{-3}$, and the mean particle energy is 2 keV. The plasma density in a bunch was measured by an interferometer, and the energy and specific density were measured by a calorimeter. The mass fraction of the ion component in the bunches and its energy in the process of irradiation were determined with the use of a Thompson mass-spectrometer, the axis of which was positioned at an angle of 15° to the accelerator axis. With such a geometry, the measured mass spectrum of particles does not differ from the mass spectrum at the accelerator axis [9]. The accelerator makes it possible to obtain plasma bunches of any gases, including hydrogen, helium, or their mixture in various proportions. The spectra of the flows of ions of hydrogen and atoms of deuterium and tritium to the wall of the discharge chamber of a UWMAK II power reactor are qualitatively similar [10] (see Fig. 2). This means that the plasma accelerator allows one to model sufficiently well the conditions of irradiation in thermonuclear reactors with respect to energy distribution.



(a) (b)

Fig. 3. Microstructure of the surface of niobium irradiated by hydrogen plasma up to a dose of $\approx 1.8 \times 10^{22}$ H^+ ions per m^2: (a) general view; (b) details.

Samples of vanadium and niobium foils of commercial purity and also of Kh16N15M3B and Kh18N10T austenitic stainless steels $\sim 200\,\mu m$ in thickness were under investigation. They were cut by a stamp in the form of strips 50×8 mm in size, the size of the central working section being 10×3.5 mm. After stamping, vanadium and niobium samples were annealed in vacuum at $P = 13$ mPa for 30 min at a temperature of ~1000°C and then chemically polished, and samples of stainless steels were annealed in vacuum at a temperature of 1050°C for 0.5 h and then electrically polished. After this treatment, the mechanical characteristics of the steel samples met the technological requirements.

Samples were irradiated in a special metal cassette, the construction of which ensured good thermal contact with a massive metal base. The temperature of the base was monitored by a thermocouple. During irradiation, the temperature increased at most by 5–10°C. The temperature of the sample surfaces was not under control, although, as was demonstrated by estimates in [11], it can exceed 1000°C at the moment of impact of a plasma pulse, especially for stainless steels with low thermal conductivity. The volume of the cassette allows us to simultaneously place up to six samples in it.

We studied the morphology of the surface of irradiated and nonirradiated samples of vanadium and niobium, investigated the change in microhardness of the surface as a result of irradiation, and also carried out tests for breakage. For this purpose, we used a metallograph of the type MMR-4 and an electron-scan microscope in a “Camebax” device, a PMT-3 microhardness meter, and a tensile-testing machine of type 1246. Samples of stainless steels (original and irradiated) were broken at a laboratory-type machine at room temperature and a rate of deformation of $2 \cdot 10^{-3}\,\text{sec}^{-1}$ [12]. Moreover, we investigated the microstructures of steel samples with the use of a JEM-1000X electron microscope with an operating voltage of 100 kV.

Results and Discussion

Vanadium and Niobium

Half of the samples made of each material were irradiated by bunches of hydrogen plasma up to $2.4 \cdot 10^{22}\,\text{ions/m}^2$ (400 shots per sample), and the other half remained in the vacuum chamber outside the irradiation zone.

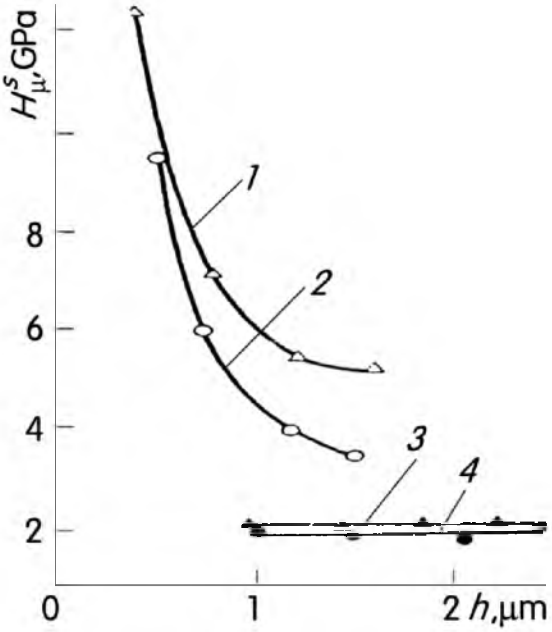


Fig. 4. Cross-sectional dependence of the microhardness of irradiated (1, 2) and nonirradiated (3, 4) samples of niobium (1, 3) and vanadium (2, 4).

Table 1. Properties of Nonirradiated (Numerator) and Irradiated (Denominator) Samples of V and Nb

	σ_u, MPa	$\sigma_{0.2}$, MPa	δ, %
V	432/422	428/411	7.3/6.0
Nb	283/284	223/223	15.2/12.3

The study of the surface of the irradiated samples with the use of the electron-scan microscope revealed the appearance of deep cracks on the grain boundaries of both metals (see Fig. 3). Such a strong intergranular cracking can affect the mechanical properties of the sample as a whole [3], the more so, as the microhardness of the surface layer 1–3 µm in thickness increases 3–6 times as a result of irradiation (see Fig. 4). However, no noticeable changes in the mechanical properties of vanadium and niobium were detected after the breakage (see Table 1).

Changes in the Mechanical Properties of Kh16N15M3B and Kh18N10T Austenitic Stainless Steels [14, 15]

Preliminary experiments indicate that samples bend in the form of an arc toward the plasma flow during irradiation. To avoid this bending, samples were alternately irradiated from the front and rear sides until the total number of pulses reached 50 for each side, which corresponds to doses of $(6–7) \cdot 10^{21}$ ions/m^2. We also studied the effect of helium and mixed hydrogen–helium plasma on the mechanical characteristics (see Table 2). It was established that irradiation by pulse flows of plasma causes changes in the mechanical properties of the steels, the degree of which is independent of the chemical composition of plasma within the experimental error. In this case, the yield strength increases 1.7–1.8 times, the tensile strength increases at most by 10%, and the relative elongation decreases approximately 2–3 times for Kh16N15M3B steel and 2–7 times for Kh18N10T steel. As a result, the plasticity of both steels turns out to be below that required by specifications.

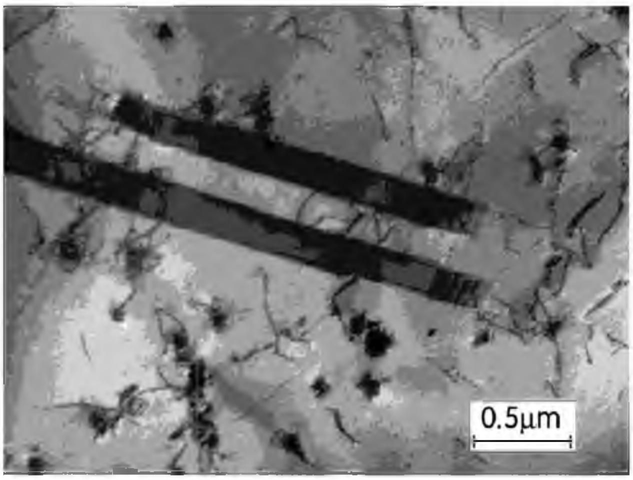


Fig. 5. Microstructure of a nonirradiated sample of Kh16N15M3B steel.

Table 2. Characteristics of Kh16N15M3B (Numerator) and Kh18N10T (Denominator) Steels

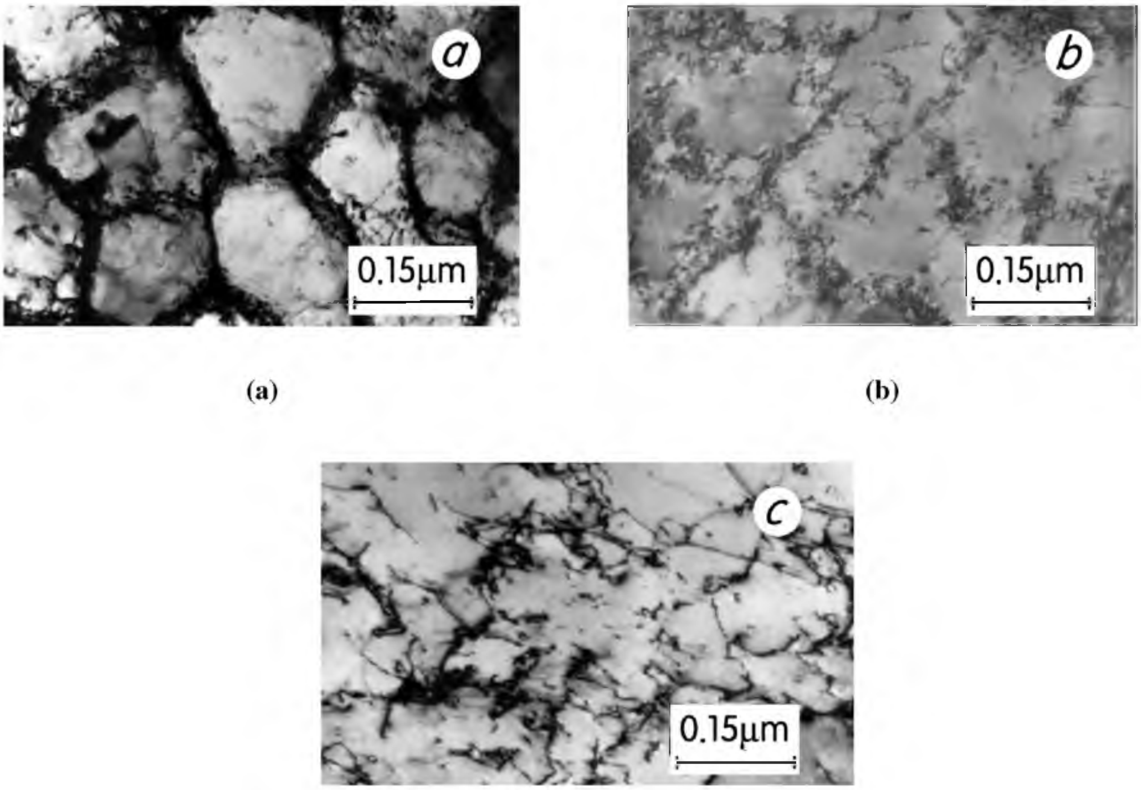
Sample condition	σ_u, MPa	$\sigma_{0.2}$, MPa	δ, %
Nonirradiated	5160/5925	2011/2031	42/63
Hydrogen plasma	5297/6199	3453/3502	17/27
Helium plasma	5503/5533	3620/3865	18/23
50% H + 50% He plasma	5680/6053	3423/3296	18/23

Additional experiments showed that short-term annealing (10 min at 1050°C) does not completely restore the mechanical properties of the steels. Etch removal of a layer up to 20 μm in thickness from the surface of both sides of irradiated samples practically does not affect the mechanical characteristics. Consequently, the changes are caused by processes in the bulk of the material. Since, under irradiation by hydrogen plasma, hydrogen can diffuse at large depths to the metal volume by causing its embrittlement, while diffusion of helium to the volume is excluded under irradiation by helium plasma, we drew a conclusion about the thermomechanical origin of the observed effects [16].

Thus, pulse plasma flows of large specific power, which impact the surface of austenitic steels even at rather moderate integral flows of particles $(1 \cdot 10^{22}\ \mathrm{m}^{-2})$, can substantially change the mechanical characteristics of steels, in particular, can abruptly reduce their plasticity.

Electron-Microscopic Investigations of Sample Surfaces

It was established that the results for both steels are qualitatively similar. Therefore, we present the data only for Kh16N15M3B steel, which has a single-phase, face-centered cubic structure, equiaxed grains (of an average size of ~25 μm) with large-angle boundaries, and a small number of annealing twins (see Fig. 5). Precipitations of the second phases are represented by niobium carbonitrides 0.1 to 1 μm in size with a density of $\sim 10^{16}\ \mathrm{m}^{-2}$. The density of dislocations is $\sim 5 \cdot 10^{12}\ \mathrm{m}^{-2}$.



(a)

(b)

(c)

Fig. 6. Changes in the cellular structure arising in Kh16N15M3B steel as a result of irradiation by flows of helium plasma, at various depths from the irradiated surface: (a) 5 μm, (b) 10 μm, (c) 25 μm.

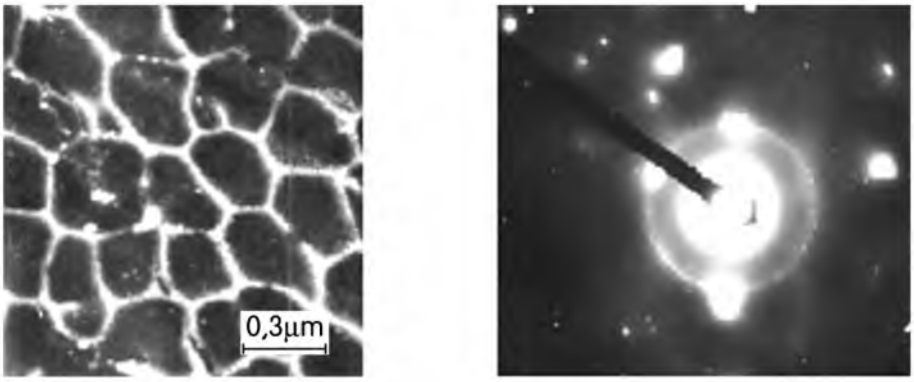


Fig. 7. Dark-field image of a section of a sample of Kh16N15M3B steel in the light of a reflex of the quasi-amorphous phase.

Irradiation substantially changes the microstructure of the surface layer. It leads to grain fragmentation into blocks, as a result of which there arises an unusual cellular structure with cells 0.15–0.25 μm in size (see Fig. 6). Grain boundaries are broken and repeat the boundaries of the cells. Along the block boundaries, one observes the interlayer of the second phase, which differs in contrast from the matrix. Carbonization of niobium was not detected, and the density of dislocations turned out to be low. With the use of electron diffraction analysis and dark-field electron microscopy, we established that the interlayer of the second phase between cells represents a quasi-amorphous phase (see Fig. 7). But we did not succeed in determining its content.

The layer-by-layer etching of the surface of the irradiated steel and the observation with an electron microscope indicate that the cellular structure formed by grain blocks separated by layers of the quasi-amorphous phase spreads up to a depth of $\sim 10\,\mu\mathrm{m}$ and then gradually transforms to cells separated by a network of dislocations, the density of which gradually decreases. At depths exceeding $25\,\mu\mathrm{m}$, this structure disappears. At such depths, the appearance of niobium carbonitrides was detected. Their absence in the upper layer apparently indicates a very high temperature at this place arising at the moment of impact of a plasma bunch.

The dislocation structure with the fragmentation of grains into blocks, arising as a result of the action of thermal plasma shocks, is qualitatively similar to the dislocation structures formed on thermal hardening of metals. Their formation makes it possible to explain the changes in the mechanical characteristics of austenitic steels indicated above.

CONCLUSIONS

Pulse flows of plasma of a high specific power $(\sim 100-1000\,\mathrm{GJ/m^2})$ impacting commercially pure vanadium and niobium substantially change the surface microstructure but practically do not affect the mechanical characteristics. As for the extensively used Kh16N15M3B and Kh18N10T structural austenitic steels, their strength and, especially, plasticity are reduced.

The described conditions of irradiation do not model those in thermonuclear reactors at the times of plasma instabilities or during disruptions of a plasma pinch. In the last case, the duration of a pulse and the specific energy release per unit square must exceed the corresponding values in the described experiments by several orders of magnitude. Therefore, the effects observed in thermonuclear reactors may turn out to be many times stronger.

On the other hand, the steel samples had a small thickness $(200\,\mu\mathrm{m})$, so that structural changes reached depths comparable to the total depth of a sample. For massive materials with samples $3-6\,\mathrm{mm}$ in thickness, the effect of the appearance of structures penetrating to relatively small depths may turn out to be insufficient in order to affect the mechanical properties of steels to any noticeable extent.

To answer the question of how power plasma impacts can really affect the mechanical properties of austenitic steels in thermonuclear reactors during service, it is necessary to perform further investigations of samples with thicknesses close to real ones and under irradiation conditions closest to those expected in thermonuclear reactors.

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