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Occurrence of microstructures on steel surface under the influence of plasma focus discharge

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The surface of metals after irradiation by intense streams of argon plasma arising in the plasma focus was studied. Metal samples of steel, copper, tungsten and molybdenum were investigated. Different types of microstructures were recorded. The surfaces of steel samples contain micropores with sizes of $0.1-3\,\mu$m with a shape close to circular. On copper and tungsten plates the appearance of fine-dispersed structures with sizes of $0.5-20\,\mu$m is observed. The possible mechanisms of the appearance of these microstructures are discussed.

Keywords: plasma focus, intense plasma flows, micropores, filamentous discharge structure.

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Units of plasma focus type are used to create a dense high-temperature plasma resulting from the pinch effect [1–6]. In experiments using gaseous deuterium, significant neutron yields are observed as a result of thermonuclear reactions, reaching the value $\sim 1.5 \cdot 10^{10}$ neutron/pulse. At the pinch decay stage intense plasma flows are formed. It was found that the interaction of plasma focus particles with the surface of metals leads to the appearance of nanostructures [7]. This is discussed in the literature in view of its possible use for obtaining nanomaterials [8,9]. A study was made of a discharge of the plasma focus type during discharges in deuterium and neon using laser diagnostics [10]. An assumption was made about the presence in the current plasma sheath of a fibrous structure with an individual fiber diameter of about $100\,\mu$m, with a total number of these fibers of about 200.

In the present paper, the electrode system contained a central copper anode (Fig. 1), in the upper part of which the studied metal plate was placed in the form of a disk with a diameter of 12 mm and a height of 3 mm. The characteristic charging voltage of the capacitor bank was in the range of $24-26$ kV, the battery capacity was $12\,\mu$F, the amplitude value of the discharge current was $330-345$ kA at a discharge current period of $5.0\,\mu$s. The shape of the current pulse was a damped sinusoid with the number of periods $3-4$. The working pressure of argon in the chamber was $1.5-1.7$ Torr. After rounding the anode, the current sheath converges near the axis of the chamber, forming a dense plasma formation — plasma focus. According to plasma concentration measurements in the peripheral regions of the discharge, the particle flux density takes values in the region of $10^{20}-10^{21}$ atom/$(\text{cm}^2 \cdot \text{s})$ [4,5].

Images of the surface of steel plates, which were installed in the central part of the anode, are shown in Fig. 2. The surface microstructure was studied using Hitachi TM1000 and VEGA 3 SEM microscopes. On the metal surface there are separate areas where there are oval or irregular-shaped clumps $10-40\,\mu$m in size. The elemental composition of these formations, as a rule, contains iron (about 80%), aluminum (about 15%) and copper (about 5%). On some clumps, micropores of size $0.1-0.7\,\mu$m with a shape close to round are observed.

Let us consider micropores on the surface of steel plates (Fig. 2 and 3, *a*) with sizes in the range $0.1-3\,\mu$m. The shape of the pores is close to round. The pore layout is

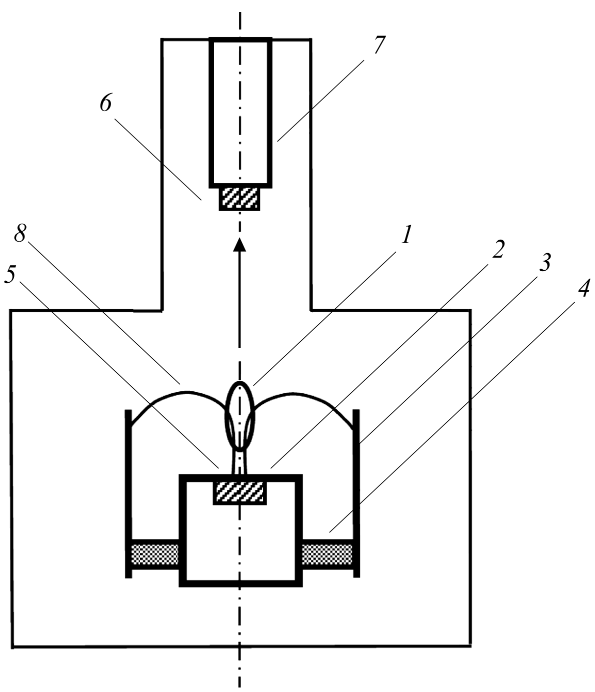

Figure 1. Scheme of the experiment on the plasma interaction with metals. *1* — plasma focus, *2* — anode, *3* — cathode, *4* — insulator, *5* — metal plate, *6* — metal sample, *7* — holder, *8* — current lines.

irregular. The surface of the original steel plate before the experiments is shown in Fig. 3, *b*. The original material of the plate surface — steel (St 45) — was not specially ground and contained microroughness up to $3\,\mu$m wide. The typical number of shots is 10–15. The elemental composition of the surface after plasma irradiation was as follows: iron — 93–95%, aluminum — 5–7%. Before plasma irradiation, the surface contained almost 99% of iron, taking into account the measurement error. The aluminum content appears to be related to the sputtering of the insulator made from corundum, which contains aluminum.

Let us assume that in some areas the current filamentation into small micron currents with a diameter of $0.1-3\,\mu$m occurs, they subsequently have a thermal effect and lead to the formation of a microporous surface structure. For metal surfaces in plasma the sputtering mechanism typical to the action of ion beams on the surface in vacuum can work [11]. Let us assume that the current through the steel insert is in the range of 500–5000 A. With filamentation of this current, the number of current filaments in the range of 500–1000 is acceptable. In this case, the value of the elementary current per one current filament will be in the range of 0.5–10 A. The time of current action (or its passage through the plate) for evaluation can be taken to be equal to half of the period $2.5\,\mu$s.

To estimate the formation energy of one pore, the volume of an iron cylinder with a diameter of $1\,\mu$m and height of $5\,\mu$m was taken. The amount of heat transferred to one pore at average elementary current 2 A, due to Joule heating, in this case is about $7.6 \cdot 10^{-5}$ J. As an estimate of the binding energy of atoms in iron crystal for the considered volume of matter, one can obtain a value of about $2.06 \cdot 10^{-6}$ J [12]. This energy can be used in the complete sputtering of the substance particles of the pore volume. For one pore the estimate for the Joule heat exceeds the estimate for the binding energy by about 37 times, which can be attributed to the energy loss during sputtering of the pore particles.

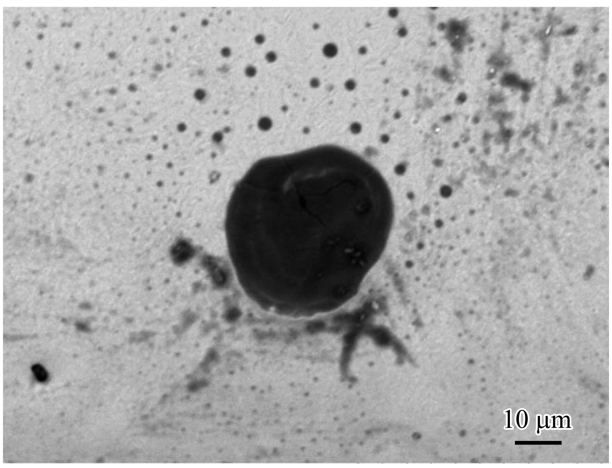

Figure 2. Structures on the steel surface: oval formation and micropores.

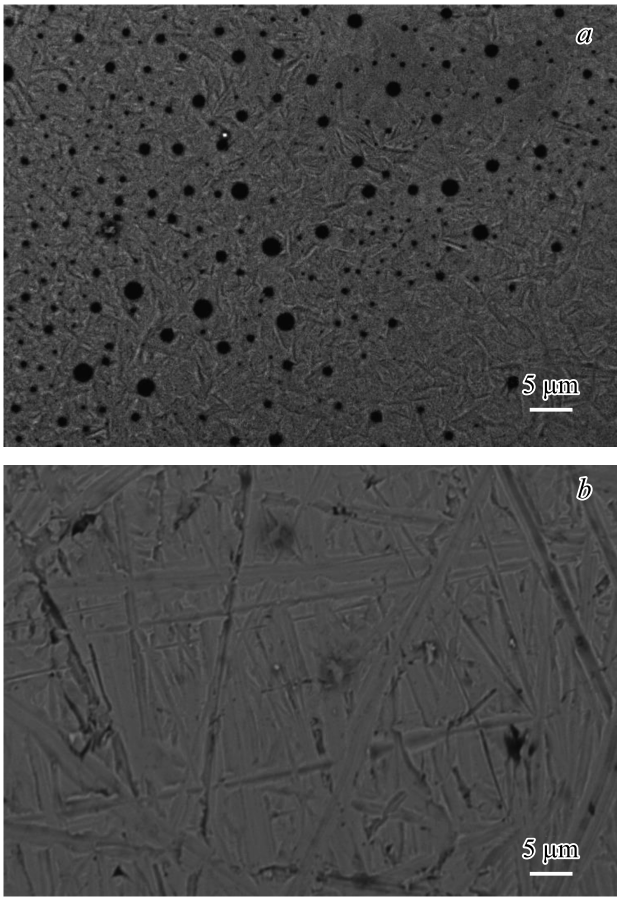

Figure 3. Image of the surface of steel plate. *a* — micropores of various diameters after plasma irradiation, *b* — initial surface before plasma irradiation.

When studying the interaction of argon plasma flows with copper plates *6* fixed in a holder *7* (Fig. 1), the following types of formations are observed: fine droplets with a size of $0.1-1\,\mu$m with shape close to spherical, and irregular clumps of size $1-20\,\mu$m. For samples of tungsten and molybdenum, upon irradiation with argon plasma, droplets of oval and irregular shape with a size of $0.5-4\,\mu$m appear.

Under the influence of intense flows of argon plasma created with the help of plasma focus, the micropores are observed on the surface of steel samples. It is assumed that the appearance of this microporous structure occurs during the filamentation of the discharge current into individual micron filaments with a diameter of $0.1-3\,\mu$m and a current value of 0.5–10 A. Sputtering of the pore substance is a specific mechanism that requires further detailed study.

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Conflict of interest

The authors declare that they have no conflict of interest.

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