STUDY OF THE HIGH VOLTAGE ATMOSPHERIC PRESSURE DISCHARGE AND ITS USE FOR SURFACE PROCESSING

S. A. Zhdanok, É. M. Vasil'eva,
and L. A. Sergeeva

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The possibility of using a high voltage atmospheric pressure discharge for chemothermal processing of surfaces is demonstrated by experimental study.

At the present time the process of interaction of a nonequilibrium plasma with a material surface for the purpose of changing physicochemical properties is being used ever more widely. Among the large number of discharge types used for creation of the nonequilibrium plasma, special attention has been given to uhf, hf, and glow discharges [1-6], a characteristic feature of which is their use of reduced pressures. Instruments based on use of other discharge forms, for example, the high voltage atmospheric pressure discharge, have been studied little.

Theoretical studies of plasmochemical processes [1] have shown that these occur at greatest efficiency under nonequilibrium conditions with an electron temperature of T_e = 1–2 eV, which corresponds to values of the gas discharge parameter $E/N \sim 2 \cdot 10^{-16}$ V·cm², characterizing the ratio hf the electric field intensity E to the gas density N in the discharge zone. In this case the energy contribution to the system $Q < 1.5$ eV/mol ($Q = UI/G$).

The processes of CO_2 dissociation and nitrogen oxidation in an atmospheric pressure high voltage discharge were studied in [7, 8]. The goal of the present study is to investigate the atmospheric pressure high voltage discharge and its use for chemothermal processing.

A diagram of the experimental equipment used for realizing the atmospheric pressure high voltage discharge is shown in Fig. 1. Initiation of the high voltage discharge in chamber 4 occurs by a method similar to that of [9], in which a dependent atmospheric pressure discharge is maintained by gas injection from the pre-ionizer. Under the conditions of our experiments after discharge ignition in chamber 4 the pre-ionizer 1 was shut off after 5-10 sec. The length of the discharge zone 1 in the chamber between electrodes 3 and 5 was varied by moving electrode 5. In our study of the atmospheric pressure high voltage discharge the geometric parameters of the discharge zone were varied over the ranges: d = 1.0-9.0 mm, interelectrode distance 1 = 15-100 mm. The discharge burn voltage comprised U = 2-15 kV, with a current I = 30-70 mA, and gas flow rate of 100-600 liter/hr. By varying the gas discharge parameters, discharge zone length, and gas flow rate during the experiments the temperature of the gas flow at the exit of the discharge zone was changed over the limits t = 350-1450°C. Temperature was measured by a platinum–platinum/rhodium thermocouple.

The properties of the low temperature plasma maintained by the external electric field define the current-voltage characteristic (CVC) of the discharge. Typical CVC's of the atmospheric pressure high voltage discharge are shown in Fig. 2. It is evident from the figure that with increase in gas flow rate at one and the same load current the burn voltage increases. With increase in current for constant flow rate the gas temperature increases, its resistance decreases, and the voltage falls. For identical load currents, gas flow rates, and one and the same reactor geometrical characteristics the lowest discharge voltages occur for nitrogen, and the highest for carbon dioxide. The curves are all decreasing, i.e., the discharge studied was independent.

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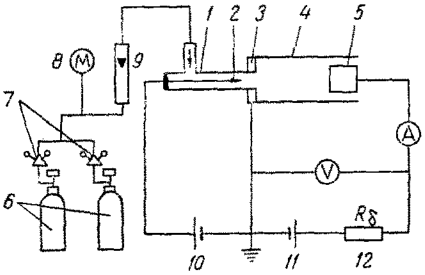

Fig. 1

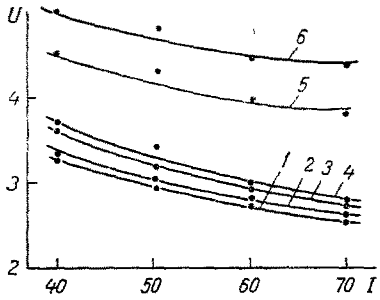

Fig. 2

Fig. 1. Diagram of experimental equipment: 1) pre-ionizer; 2) discharge chamber; 3, 4, 5) electrodes; 6) gas reservoirs; 7) reservoir valves; 8) manometer; 9) rotameter; 10) pre-ionizer power supply; 11) plasmotron power supply; 12) ballast resistance.

Fig. 2. Discharge curent-voltage characteristics for discharge zone diameter $d = 6.0$ mm and length $\ell = 25$ mm; 1, 3) nitrogen; 2, 4) air; 5, 6) carbon dioxide; 1, 3, 5) 400 liter/hr; 2, 4, 6) 550.

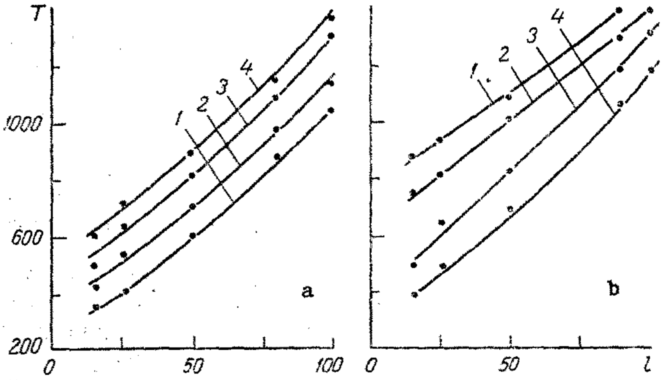

Fig. 3. Temperature T, °C vs discharge chamber length ℓ, mm: a) for constant gas flow rate G = 500 liter/h at various discharge currents: 1) I = 30 mA; 2) 40; 3) 55; 4) 70; b) for constant current I = 55 mA and gas flow rates: 1) G = 180 liter/hr; 2) 310; 3) 500; 4) 620.

Figure 3 shows experimental dependence of nitrogen flow temperature at the output of the discharge zone on discharge chamber length. As is evident from the figure the discharge current (Fig. 3a) and the gas flow rate (Fig. 3b) have significant effects on the flow temperature, i.e., the process of temperature regulation is flexible, which is of great significance in chemothermal surface processing [3].

Thus, as follows from the CVC and the temperature measurements, under the experimental conditions discharge conditions are realized under which E/N lies in the range $(1.5\text{-}3.0)\cdot 10^{-16}\ \mathrm{V\cdot cm^2}$, with energy contribution Q = 0.2-1.5 eV/mol, i.e., according to [1] conditions are achieved under which chemical reactions are stimulated by oscillatory excitation of the ground state of the reacting molecules with the highest energetic efficiency. In connection with this, it would be of interest to use the gas flow excited in the atmospheric pressure high voltage discharge for chemothermal processing in order to intensify that process. Current industrial methods of chemothermal processing require lengthy times and large energy expenditures. Thus, in gas (furnace) nitrogenization of type 38 KhMYuA steel 48 hr are require to achieve a diffusion depth of 0.5 mm, while nitrogenization in a glow discharge reduces the required time to 10 hr [3]. But, despite the significant time reduction achieved by the glow discharge its speed remains quite slow. This is because of the low working pressure (6-8 torr) [4]. According to currently accepted concepts of this process, it is precisely the presence in the working medium of ionized atomic nitrogen* which pro-

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*At present the mechanisms of nitrogenization in a plasma have not been fully studied. New data have appeared [11] in which it is shown that an important role in surface processing is played by bombardment not by ions, but by neutral ions and molecules.

TABLE 1. Experimental Data on Chemothermal Processing of 38 KhMYuA Steel Specimens in High Voltage Discharge

Specimen No.	Q, eV/mole	E/N, V·cm^2	Processing time, min	Depth of ordered layer, μm
1	0,64	$2{,}1\cdot 10^{-16}$	10	180
2			20	310
3			30	420
4			40	480
5			50	500

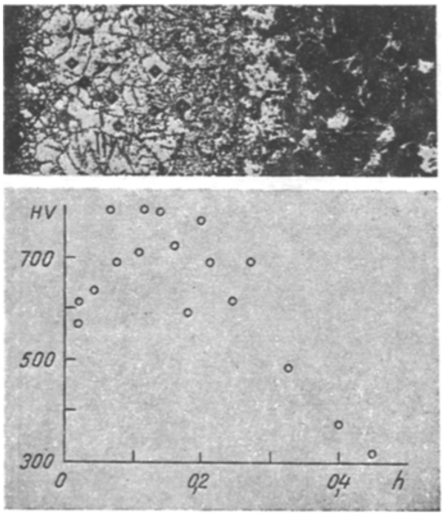

Fig. 4. Microstructure and depth distribution of hardness in steel nitrogenized in atmospheric pressure high voltage discharge. h, mm.

duces all the advantages of nitrogenization in a glow discharge, although because of the low pressure the amount present is insignificant. Increase in pressure in the glow discharge leads to an increase in ionized particles, but the fraction of atomic nitrogen decreases [4], not allowing an increase in the nitrogenization rate in such a discharge.

In the atmospheric pressure high voltage discharge of the present study, as was shown above, the major portion of energy goes to excitation of molecules of the working gas, which in turn leads to significant increase in the rate of molecular dissociation, i.e., to formation of energetically active atoms at the surface, the concentration of which is significantly greater than in a glow discharge, which leads to intensification of the process of surface saturation by the working gas.

Specimens of steel in the form of cylinders Ø 10 × 10 mm were processed in a nitrogen flow excited by the atmospheric pressure high voltage discharge. Metallographic studies and x-ray phase analysis of the specimens were performed by A. A. Susin, A. A. Val'ko, and E. I. Mosunov at the Industrial Machinery Branch of the Academy of Sciences of the Belorussian SSR.

Table 1 presents experimental rsults on chemothermal processing of 38 KhMYuA steel specimens in a nitrogen flow excited in an atmospheric pressure high voltage discharge. Thus, an ordered layer 0.5 mm deep was produced over 50 min, while as indicated above the same required 10 hr in a glow discharge. Nitrogenization of steels with 0.5-0.6% carbon [10] in an atmospheric pressure high voltage discharge permitted production of an ordered layer with hardness of HV 550-700 and depth of 0.3-0.5 mm over 30-50 min. Figure 4 shows the microstructure and hardness distribution over depth for a layer processed in the high voltage discharge.

As is evident from Fig. 4, before processing the steel had a pearlite-ferrite structure. Processing in the plasma flow for 30 min with subsequent cooling in a nitrogen flow permitted hardening the surface to 0.26-0.3 mm (with traces of hardening to 0.35 mm). The microstructure of the hardened layer is martensite with residual asutenite. The surface showed some products of a non-martensitic type in the form of dark regions along the grain boundaries. In the surface layers there are also light-colored nitride formations, and at a depth above 0.15 mm, small inclusions of a ferrite phase. The marked scattering in microhardness values is due to the significant difference of its values for the different structural components (the microhardness of martensite is HV 800-850, that of the residual austenite, HV 400-500). Qualitative x-ray phase analysis revealed the presence of nitrode formations with a structure of the Fe_2N–Fe_3N transitional type.

The process realized herein is energy-efficient. In nitridization in a glow discharge the energy expenditures comprise 0.14 kW·hr/cm^2, while in the high voltage discharge we have 0.06 kW·hr/m^2 (with hardened layer depth of 0.5 mm in both cases).

Thus, the studies performed permit the conclusion that chemothermal processing of surfaces in a high voltage atmospheric pressure discharge is characterized by higher energy efficiency than the same process in a glow discharge, leading to a significant reduction in the time required for chemothermal processing.

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