Study of physical and mechanical properties of steel after plasma modification of its surface

M Kh Gadzhiev, D V Tereshonok, M A Sargsyan, M V Ilichev and E E Son

Federal State Budgetary Institution of Science Joint Institute for High Temperatures RAS, Izhorskaya 13, building 2, Moscow

E-mail: makhach@mail.ru

On the basis of studies of the electrophysical characteristics of a low-temperature nitrogen plasma flow, a procedure for verifying the thermophysical properties and establishing regularities in the formation of the structure, phase composition, and properties of a metal when steels surface is exposed to plasma, plasma exposure modes were determined for modifying the surface of metals and alloys used in various applications, such as nuclear power plants.

1. Introduction
Increasing the fatigue and wear resistances of steel parts is a very important task due to the continuously increasing requirements for the reliability and durability of structures, especially in the nuclear power industry. One of the promising directions for increasing the operational durability of products is the use of plasma surface modification technology [1]. Plasma action leads to surface hardening of steel with a brief interaction time of the metal with low-temperature plasma. Keeping metal at temperatures above critical with a high rate of heating and cooling leads to phase and structural transformations of the surface. The use of nitrogen as a working gas simultaneously with quenching leads to nitriding of the surface layer of steel, which increases the level of operational properties of products [2-7].

2. Materials and methods
To study the effect of the plasma stream on the steel surface, we used an experimental stand (Fig. 1) based on a nitrogen low-temperature plasma generator (LTPG) with a flow converter and a processed sample made of 60G brand steel with a cross section of 50×50 mm and a length of 100 mm. The sample was cut in half in cross section to fit chromel-alumel thermocouples. Thermocouples were minted in pre-drilled holes 0.5 mm in diameter. The holes for thermocouples were located at a depth of 0.5, 1.0, 1.5, and 2.0 mm from the surface with a step of 4 mm [8]. The flow transducer was a hydrodynamic transition section in which a cylindrical jet of low-temperature plasma flowing out of the expanding channel of the LTPG is converted into a flat jet and supplied onto the treated workpiece surface [5, 6].

A DC plasma torch (Fig. 2) with a self-aligning arc length, vortex stabilization and an expanding channel of the output electrode was used as a generator of low-temperature plasma [6, 9]. The choice in favour of this type of plasma torch is due to the fact that such a design provides arc burning in a laminar flow at a high gas velocity at the nozzle inlet, an increase in arc stability.
over the entire range of current variation, at the same time the arc length decreases, and heat fluxes into the walls become more uniform, and the efficiency of heating the working medium increases with low heat losses in the water-cooled parts of the device. In addition, the expanding channel of the gas-discharge tract of the LTPG provides an increasing current-voltage characteristic (CVC) and a larger region of arc existence when compared to the channel with a constant cross-section (Figs. 3 and 4). The falling current-voltage characteristic leads to instabilities of the LTPG operation and low efficiency, due to which, to achieve the required average mass plasma temperature at the outlet, it is necessary to input more power, which affects the resource, energy efficiency and stability of the plasma torch operation. In such generators, to stabilize the arc and thermally insulate it from the channel walls, porous injection, axial flows or gas swirl are used, and various cavities, ledges, diaphragms, and interelectrode inserts are made, which complicates their design [10-13].

Figure 1. Schematic of the experimental stand: 1 - working body, 2 - spacer, 3 - thermocouple wires, 4 - clamp, 5 - flow converter, 6 - plasmatron.

Figure 2. Constructive schematics of LTPG.

Fig. 3. Dependency of CVC from nitrogen flow

Fig. 4. Dependency of CVC from nitrogen
rate for the expanding channel of the output electrode.

When the power of the LTPG arc was at 30-40 kW, the temperature of the nitrogen plasma flow incident on the steel surface was \( \sim 4 \text{ kK} \). The incident flow temperature was determined by processing the spectroscopic data obtained with the Specair program (\( T_e \sim 7500 \text{K} \), for \( N_2^+ \ T_{\text{trans}} = T_{\text{vib}} = T_{\text{rot}} \sim 4100 \text{K} \)). The maximum heat flux to the surface when exposed to nitrogen plasma at a speed of 20-40 cm/min is \( \sim 8000 \text{ kW/m}^2 \). The registration of the temperature changes dynamics at different depths of the steel under study made it possible to develop a method for verifying the thermophysical properties of steel, based on solving the three-dimensional equation of thermal conductivity, in which the coefficients of thermal conductivity and heat capacity are functions of temperature. The equation is solved numerically with the first order of accuracy in time and the second in space, similarly to how it was done in [8, 14-15]. The computational grid was uniform in each direction. Mesh convergence was investigated by changing the space step. On the lateral surfaces and boundaries free from plasma action, a condition was set in the form of radiation in accordance with the Stefan-Boltzmann law and a degree of emissivity at a level of 0.5-0.8. On the lower surface, the ambient temperature was set to \( T_0 = 300 \text{ K} \). The heat flux was poured in the form of a certain profile based on the approximation of experimental data. To test the developed procedure for verification of thermophysical properties, an experiment was also carried out on an installation for measuring the coefficient of thermal conductivity by the method of longitudinal heat flow with steel 60G and 12Kh18N10T [16]. The choice of steel 12Kh18N10T is associated with its recommendation as a reference material in studies of thermophysical properties and is widely used in materials of nuclear power engineering [17]. So, a satisfactory agreement was obtained between the calculations and the experiment on measuring the temperature at different depths from the heated surface. The three-dimensional non-stationary temperature fields obtained as a result of calculations make it possible to determine the optimal parameters of the plasma hardening regime for steel products.

3. Results and discussion

Short-term exposure to nitrogen plasma of the steel surface in one pass creates a wide strip with a uniform, hard and wear-resistant hardened layer. It was found that with an increase in heating power, gas flow rate and a decrease in speed, the depth of the heat-affected zone (HAZ) increases. A decrease in the processing speed leads to an increase in the hardness of the hardened surface, while when the heating power or the gas flow rate change, the hardness does not change significantly. While studying the microstructure of the heat-strengthened and transition layers (Figs. 5 and 6), five regions with different types of microstructure were revealed: 1 - a thin surface layer with austenitic microstructure \( \sim 30 \mu m \) thick. Intergrowth of truss-like martensite needles into the depth of this layer is observed; 2 - a structure of the low-tempered packet martensite with an average microhardness \( H_{0.981} = 6000 \text{ MPa} \). Layer thickness \( \sim 1 \text{ mm} \); 3 - a zone of an inhomogeneous intermediate structure, which is a mixture of troostomartensite sections with \( H_{0.981} = 4200 \text{ MPa} \) and structureless martensite with \( H_{0.981} = 6120 \text{ MPa} \) (the thickness of this layer is \( \sim 0.8 \text{ mm} \)); 4 - intermediate structure of troostosorbite with \( H_{0.981} = 3370 \text{ MPa} \); 5 - structure of the base metal - temper sorbitol with ferrite areas along the grain boundaries with \( H_{0.981} = 3230 \text{ MPa} \).

At the same time, a deep and smooth transition zone provides stronger adhesion of the hardened layer to the base metal and is one of the reasons for the increased resistance to fracture. An additional factor in increasing the level of properties of hardened steel is the relaxation of stresses arising during operation due to phase \( \gamma \rightarrow \alpha \) transformation in the layer of high-nitrogenous austenite.
Fig. 5. Microstructure of the hardened zones surface: 1 - a layer of nitrides and oxides; 2 - a layer of nitrogenous austenite; 3 - a layer of truss-like martensite.

Fig. 6. Distribution of microhardness along the depth of the hardened layer.

4. Conclusion
On the basis of studies of the physical and technical characteristics of the plasma torch and the establishment of regularities in the formation of the structure, phase composition, and properties under the action of a low-temperature nitrogen plasma flow on the steel surface, plasma exposure modes for modifying the surface of metals and alloys used in various applications, including atomic energy.

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