The object of this study was the substances that could be used to generate arc plasma. Conventional and promising plasma media were analyzed in order to identify the most universal one in terms of a set of properties for efficient energy transfer of material. It is shown that the mean-enthalpy media have a harmonious ratio of temperature and enthalpy and could provide a change in the energy state of the processed material with maximum efficiency. It is established that the most universal set of properties is demonstrated by the medium enthalpy plasma of the N-O-C-H system. The use of mixtures of air with hydrocarbons for its generation makes it possible to reach the average mass temperature of $(5...7)\cdot10^3$ *K and change the oxidative-reducing potential of the plasma medium over a wide range. Given this, heat treatment is possible with maximum preservation of the original composition of the material. Experimental studies of plasma flows of the N-O-C-H system confirmed the presence of reducing components capable of binding oxygen to air that is sucked into the jet. On rich mixtures, the oxygen content in the jet at a distance of 100 mm does not exceed 5 %.*

The positive effect of combined energy input into plasma-forming substance on the process of generation and formation of plasma jet has been proven. The use of energy of different physical nature makes it possible to maintain the local energy parameters of the plasma flow during material processing. This is due to the release of additional heat as a result of the interaction of plasma and plasma components with ambient air. The use of plasma of the N-O-C-H system in surface engineering technologies could expand the range of processed materials and reduce the operating costs of the process

Keywords: plasma-forming substance, plasma of the N-O-C-H system, reducing components of plasma, oxidative-reducing potential

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ANALYSIS OF TECHNOLOGICAL POSSIBILITIES OF N-O-C-H SYSTEM ARC PLASMA IN SURFACE ENGINEERING PROCESSES

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1. Introduction

Surface engineering techniques have become a necessary component of the process of manufacturing new articles and are widely used in repair industries. Additive technologies for manufacturing prototypes and serial product samples are created on the basis of surface engineering methods.

Among the methods of surface engineering, plasma technologies occupy a special place. This is due to a number of advantages of using low-temperature plasma. For plasma technologies, there are no restrictions on the unit power of devices and the melting temperature of the material being processed. There are wide possibilities for controlling the parameters of the process and full automation and computerization of the plasma processing of the material.

The industry employs a significant number of technological processes that use low-temperature plasma. The most widespread are conventional technologies of surface engineering, coating, and modification of surface layers. The processes of plasma cutting, spheroidization and powder production are actively developing. Over the past decade, additive technologies, plasma-chemical processes, plasma waste processing technologies have been dynamically evolving.

The composition of the plasma determines the structural features of the plasma generator (especially the arc one). The choice of the type and material of the plasma torch electrodes, the material of body parts and the cooling system of heat-stressed structural elements directly depends on the list of components in the plasma-forming gas.

At the same time, the effectiveness of surface engineering technologies using plasma devices is largely determined by the capabilities of plasma flows to target processing of the impact object. Processing is usually done by heating, forcing the surface of the object, and chemically interacting with the surface layers of the material. These possibilities can be provided by a specially defined composition of the plasma medium, which, in turn, is due to the composition of the initial plasma-forming substance.

Changing the composition of the plasma environment is one of the means of controlling the energy-spatial parameters of plasma flows along with changing other operating parameters of the process. Thus, scientific research into this area is relevant and important for practical industrial application. Scientifically justified choice of plasma-forming gas composition could improve the energy and resource capabilities of plasma generators, increase the competitiveness of plasma technologies, and expand the scope of their application.

2. Literature review and problem statement

The application of plasma coatings in most cases is carried out using universal standard equipment, designed for the use of inert and neutral gases [1]. This choice of plasma-forming substances is mainly due to the materials that were used in the manufacture of plasma generator electrodes. Changing the set of plasma-forming substances at the request of material processing technologies is not structurally provided for and is physically impossible. The universality of the plasma medium generated by the mentioned plasma torches is based on the assumption of plasma neutrality with respect to the material being processed. It is believed that the use of inert gases could ensure the preservation of the initial composition of the material used. In general, this is a complex task that involves preventing chemical interaction of the material with the active components of the medium in which the heating and acceleration of the starting material occurs. If the process is carried out in an open atmosphere, it is also necessary to protect the material from the active components of the surrounding gaseous environment. In [2], the results of the study of changes in the content of argon in the volume of the plasma jet, which is generated by an argon plasma torch, are reported. As can be seen from the data, the plasma flow, neutral at the initial stage of processing, subsequently becomes oxidizing for most materials due to the flow of air from the environment. Thus, the use of equipment on inert and neutral gases in coating technologies practically does not solve the problem of protecting the material from oxidation (in the case of operation in an open atmosphere). The results of the study of coatings applied using such a “neutral” plasma confirm the appearance of oxides in the coating composition due to burnout of the alloying components of the starting material [3].

Thermal emission cathodes used in plasma generators make it possible to complicate the plasma-forming substance by adding nitrogen or hydrogen to argon [4]. The use of new components in plasma-forming gas significantly complicates the system of equipment for generating plasma. There is a need for additional mixing, dosing, and control systems [5]. Given that these gases are kept in tanks, operating costs increase while the process of operation of plants becomes more complicated. In addition, the scarcity and high cost of these gases limits the geographical possibilities of their use. The addition of hydrogen is used to increase the enthalpy of the generated plasma and has virtually no effect on the ability of the plasma medium to protect the material being processed. This can be confirmed by studies, the results of which are given in [6]. The transition to hydrogen-containing plasma-forming media based on argon practically does not affect the oxidation process of the starting material.

To level the negative impact of the working environment, which, due to the mixing of air from the environment, becomes oxidative, additional organizational and structural measures are usually applied. For example, reducing the residence time of the material in the core of processing due to the transition to supersonic spraying modes partially solves the problem of reducing the oxide content [7]. But, at the same time, reducing the duration of the material in the high temperature region puts forward certain restrictions on the particle size of the material being processed (especially for materials with low thermal conductivity). The use of additional protective gas flows, which change the conditions for mixing the plasma flow with ambient air, allows for (30...40) % reduction in the burnout of alloying components of the material [8]. But the design of the plasma sprayer becomes significantly more complex and the requirements for the stability of the operating parameters of the process are tightened.

Based on the review of literary sources, it can be argued that the problem of creating and applying optimal (from the point of view of technology) plasma-forming media remains relevant and requires further scientific research. Neutral and inert plasma media under the conditions of the treatment process in an open atmosphere cannot be considered universal. The result of the research should be a reasoned assessment of the ability of plasma to affect the material effectively energetically with maximum preservation of its chemical composition. This task is closely related to the problem of designing plasma generators, which, without changing the structure, are able to generate plasma of different elemental composition, having a sufficient service life. By universalizing the plasma medium, there may be a complication of the initial composition of the substance used to create plasma.

3. The study materials and methods

The aim of this study is the evidence-based substantiation of the universality and prospects of using the plasma of the N-O-C-H system (from a mixture of air and hydrocarbons) for surface engineering processes. This will make it possible to offer cheap plasma-forming mixtures for plasma generation, capable of providing efficient processing of materials with maximum preservation of their original composition.

To accomplish the aim, the following tasks have been set:

– to prove the ability of the plasma of the N-O-C-H system to heat the processed material in the realistically achievable range of changes in the specific enthalpy of the medium;

– to experimentally confirm the ability of the plasma of the N-O-C-H system to protect the processed material from the negative effects of environmental oxygen.

4. The study materials and methods

The object of research is the properties of plasma media of the N-O-C-H system.

The hypothesis of the study assumes that the complication of the composition of the plasma-forming mixture by adding hydrocarbon gas could compensate for the negative effect of oxygen on the processed material due to the appearance of active reducing components of the plasma while maintaining the heating ability of the system.

Primary information can be provided by thermodynamic analysis of the plasma of the N-O-C-H system, which was carried out using the software package for modeling chemical and phase equilibrium at high temperatures «TERRA».

Experimental studies were conducted under laboratory conditions using experimental plasma generators employing a plasma-forming mixture of air with network natural gas or cylinder hydrocarbon gases (methane, propane-butane, etc.) [9].

To determine the local parameters of real plasma jets, a probe technique was used. The Gray probe was applied with transverse blowing of the working edge of the probe [9]. The local values of enthalpy, composition, and speed of movement in the high-temperature gas flow were determined.

The chemical composition of gas systems was determined by chromatographic method (chromatographs of type HL-3 and LHM-8-MD).

Systematization of the obtained experimental results, data analysis and processing, as well as the construction of graphical dependences were carried out using the statistical data analysis software STATISTICA 7.

5. Results of investigating the properties of plasma media of the N-O-C-H system

5. 1. Energy capabilities of plasma in surface engineering processes

In surface engineering technologies, a rather universal indicator of the ability of a low-temperature plasma flow to heat and accelerate the material being processed can be the amount of energy invested in a unit volume (mass) of plasma-forming gas.

Fig. 1 shows the estimation dependences of the temperature of a number of plasma-forming gas systems on the specific energy invested in the gas system [9].

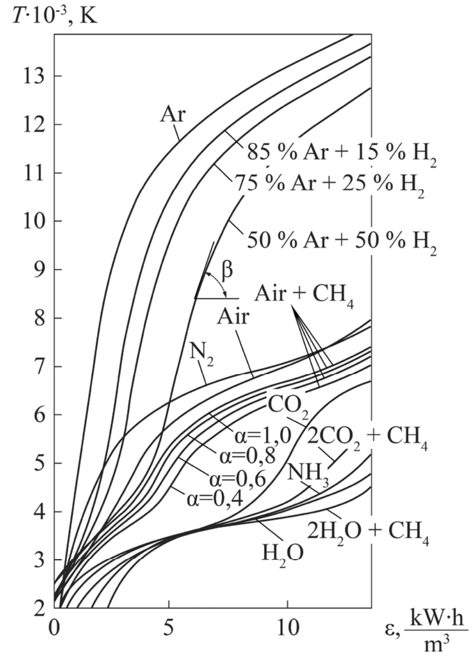


Fig. 1. Dependence of the average mass temperature of the plasma on the specific contribution of energy to the plasma-forming gas [9]

Conditionally, the derived dependences can be divided into three groups that correspond to a certain type (on an energy basis) of plasma media: low-enthalpy, medium-enthalpy, or high-enthalpy.

According to the above dependences, high-ethalpy media are characterized by relatively low temperatures and high enthalpy values (plasma of water, mixtures of water and carbon dioxide with hydrocarbons, ammonia). Low-enthalpy ones have diametrically opposite parameters – high temperature and relatively low enthalpy (plasma of argon and mixtures of argon with hydrogen). A compromise option can be medium-enthalpy plasma media, combining a fairly high temperature level (5…7)·10^3 K with high values of enthalpy of the working fluid (plasma of nitrogen, air, mixtures of air with hydrocarbon gases).

The most affordable and cheapest of these substances is atmospheric air, which is a mixture of gases of the N–O system (except for components with low air content – inert gases, CO, CO_2, water vapor, etc.).

Air plasma has a disadvantage that is quite critical for surface engineering technologies: such a plasma does not have the ability to change the oxidation-reducing potential of the working fluid because nitrogen is neutral and oxygen is the oxidizing component of the plasma. The relationship between them is unchanged, and there are no reducing components.

Complication of the chemical composition of the medium with additional components allows solving the mentioned problem of controlling the oxidation-reducing potential of the working fluid in surface engineering technologies. A fairly simple and effective solution can be the use of plasma-forming media of the N-O-C-H system. The practical implementation of this idea is possible by using cheap and affordable mixtures of air with saturated hydrocarbons [9].

The loss of the mobility factor compared to air (hydrocarbons are cylinder gases) and some increase in cost is compensated by the emergence of new components (hydrogen, carbon monoxide), which allow changing the oxidative-reducing potential of the active medium. In addition, the consumption of the hydrocarbon component is relatively low compared to air flow (up to (10…15) %).

According to thermodynamic calculations, the average mass temperature of the plasma of the N-O-C-H system lies within (5…7)·10^3 K (in the case of invested energy (5…12) kWh/m^3). Experimental studies of real plasma jets of the N-O-C-H system prove a certain uneven distribution of temperature in the plasma flow. In the central part of the stream, temperature values reach values by (1.3…1.5) times greater than the average mass value [9]. Although even the temperature level of (5…7)·10^3 K is quite sufficient to change the state of aggregation of any materials used industrially.

An important characteristic of the plasma medium is its ability to efficiently transfer heat to the material being processed.

During the processing of dispersed materials in plasma processing technologies of dispersed materials during the flow of particles by a stream of high-temperature gas, the value of the number Re usually ranges from 1 to 15 (flow close to laminar). This indicates that the share of the convective component in the process of heat transfer does not exceed 30 %. Thus, the heating of dispersed materials during plasma processing occurs mainly by the mechanism of thermal conductivity.

In the case of the potential for heating the passage of chemical reactions with a change in the composition of the medium (for complex plasma-forming mixtures), the concept of effective thermal conductivity coefficient is used.

It is determined by the thermal conductivity of the components and depends on the rate of change in their concentration due to dissociation and ionization reactions. The range of change in the effective coefficient of thermal conductivity due to chemical reactions is quite wide – it can vary by (10…12) times. In the temperature ranges where the processes of dissociation and ionization occur (in the case of lowering the temperature, reverse processes), the thermal conductivity coefficient of complex plasma-forming media has extremes (Fig. 2).

The maxima are in the temperature ranges where the greatest development of dissociation and ionization processes is observed. The nature of the gas mixture and its complexity determine the number of such temperature ranges and their location. The N-O-C-H system plasma, obtained from a mixture of air and methane, is characterized by maxima at temperatures where the maximum dissociation rates of the characteristic components of this plasma are: H_2O – 2800 K, CO_2 – 3500 K, H_2 – 4500 K, N_2 – 7000 K.

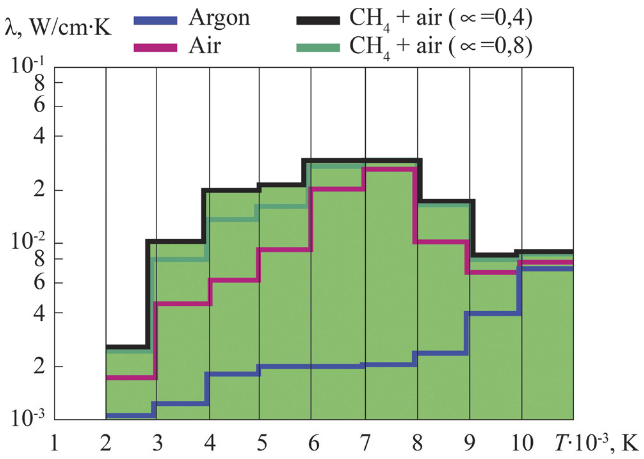


Fig. 2. The dependence of thermal conductivity of the N-O system plasma (air) and the N-O-C-H system plasma (mixture of air with hydrocarbon gases) on temperature

Such a change in the nature of the dependence of thermal conductivity coefficient λ on the temperature of the medium significantly increases the average value of the thermal conductivity coefficient in the temperature range, which is characteristic of the treatment processes of dispersed materials – $(3...10)\cdot10^3$ K. As shown by Fig. 2, the average value of λ for air is almost 5 times, and for the plasma of the system N-O-C-H is almost an order of magnitude higher than that of argon plasma.

Machining of massive parts (plasma hardening of surfaces, cutting, plasma-machining, etc.) occurs with the transfer of heat to the material mainly by the processes of convective and, partially, radiative heat transfer between the gas phase and the treated surface.

In this case, the coefficient of convective heat transfer in the contact zone depends not only on the gas velocity and thermal conductivity but also on the processes of recombination of dissociated plasma components. According to various sources, the heat flux to the surface of the material due to the recombination of dissociated components under such conditions can be an amount that is an order of magnitude higher than radiant and convective heat fluxes [7, 8].

The processed material takes energy quite intensively from the plasma with which it contacts. At the same time, this process is intensified due to the receipt of additional mass of cold gas from the environment (in the case of treatment in an open atmosphere). The consequence of energy withdrawal is a decrease in temperature and a change in heat transfer conditions between the plasma and the material being processed. From the point of view of maintaining the temperature pressure during the material taking energy from the working fluid (plasma), the best results are demonstrated by high-enthalpy and medium-enthalpy gas systems. Analyzing the estimation dependences of temperature on specific energy (Fig. 1), it is possible to estimate the ability of the medium to ensure the stability of the process of heating the material by determining the rate of temperature drop $\frac{\Delta T}{\Delta \varepsilon}$ during energy withdrawal in Fig. 3.

The rate of decrease in temperature in the plasma of the N-O-C-H system in the range (5000...7000) K is rather slow and does not exceed (180...200) K for every 1 kWh/m^3 taken from plasma due to dilution with air and the cost of heating the material. This situation occurs in the range of values characteristic of surface engineering technologies: (5...12) kWh/m^3.

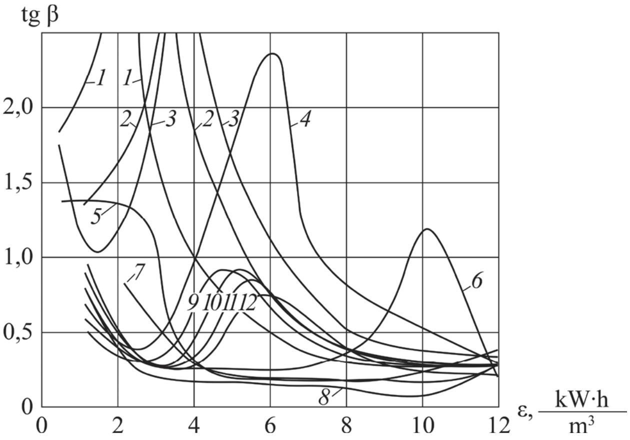


Fig. 3. The rate of drop in plasma temperature due to energy withdrawal: 1 – argon; 2 – argon+15 % hydrogen; 3 – argon+25 % hydrogen; 4 – argon+50 % hydrogen; 5 – nitrogen; 6 – carbon dioxide; 7 – ammonia; 8 – water; 9 – air+methane, α=1; 10 – air+methane, α=0.8; 11 – air+methane, α=0,6; 12 – air+methane, α=0.4; angle β (Fig. 1); α – oxidizer consumption factor

5. 2. Ability of the plasma medium to protect the material being processed

The plasma of the N-O-C-H system due to a possible change in the ratio between the components of the initial gas mixture (changes in the value of the oxidizer consumption coefficient) acquires the ability to change its oxidation-reducing potential. During heating of the initial gas mixture, oxygen binds to carbon into a thermally stable CO compound. At the same time, hydrogen is released, which, together with CO, become reducing components of the plasma medium. The content of reducing components changes by changing the volume composition of the initial plasma-forming mixture. This operation can be carried out according to the predefined algorithm during the technological process without stopping it.

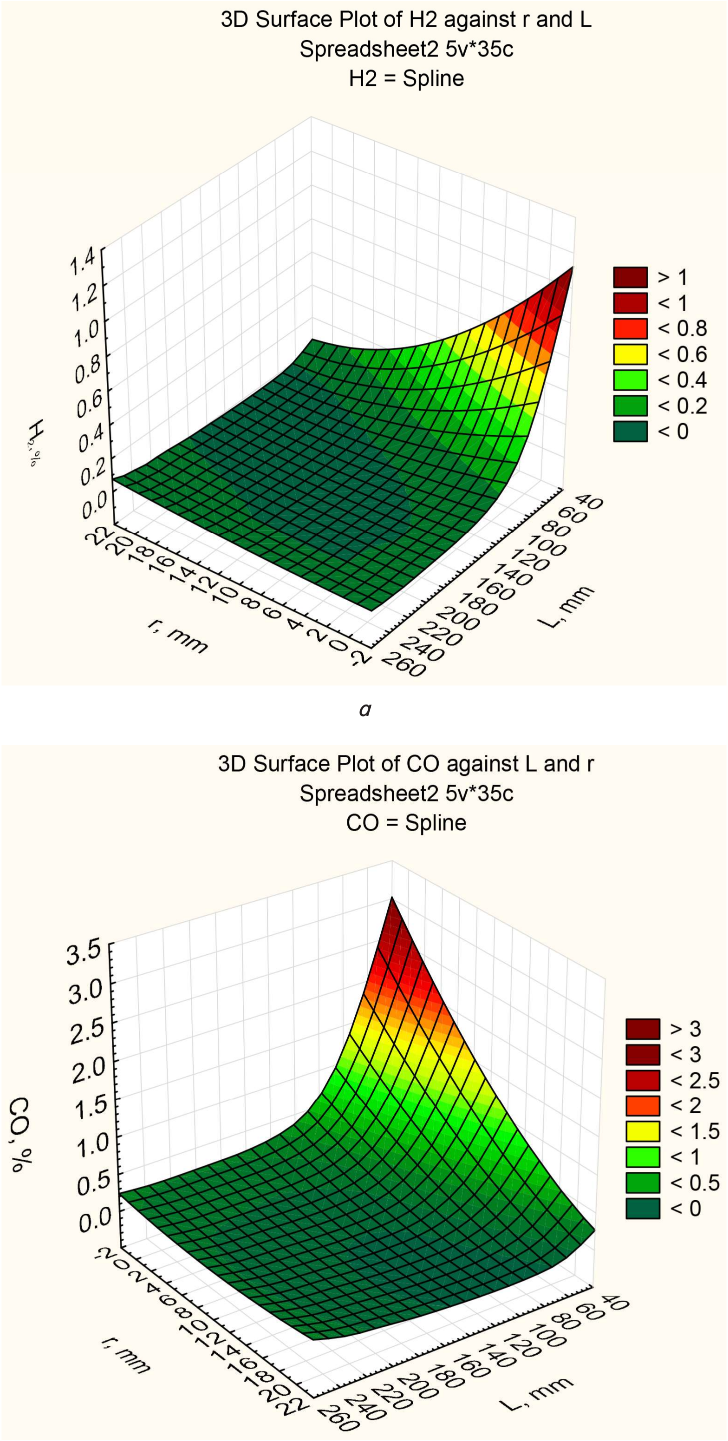
Experimental studies of the plasma jet of air mixtures with hydrocarbon gases confirm the presence of reducing components capable of binding oxygen to the air that is sucked into the jet and, under certain conditions, take oxygen from the material to be processed.

Fig. 4 shows the plasma distribution of reducing components H_2 and CO. Experimental values of the content of reducing components (hydrogen and carbon monoxide) were obtained by direct sampling of gas in the plasma stream using a probe. The probe is mounted on a three-coordinate manipulator. Measurements were carried out at fixed values of operating parameters: I=300 A, Q_Σ=4.91 m^3/h, α=0.48 (mixture of methane and air).

The results were obtained on the plasma sprayer P-100 with a single interelectrode insert, the design of which is described in [9].

As can be seen from the above figure, there is a decrease in the content of reducing components in the entire volume of the plasma jet, which is evidence of the active interaction of these reducing components with environmental oxygen.

The relative content of reducing components in plasma increases with the enrichment of the initial plasma-forming mixture. The limitation of the process of enrichment of the initial mixture with hydrocarbons can only be the danger of carbon formation in the solid state, provided that α<0.1 is reduced.



a

b

Fig. 4. Content of reducing components: *a* — hydrogen content; *b* — content of carbon monoxide in the volume of the plasma jet: *L* — distance from the cut of the nozzle down the stream; *r* — distance from the axis of the jet in its cross section; I=300 A; Q_{Σ}=4.91 m^3/h; α=0.48 (mixture of methane and air)

Fig. 5 shows the spatial distribution in the volume of the plasma stream of oxygen in the free state.

At the same time, in plasma flows of mixtures of air with hydrocarbons ("rich" mixtures with α<0.6), such oxygen concentration is registered only at distances of more than 200 mm.

The initially neutral flow of nitrogen plasma on the cut of the nozzle of the plasma torch is already at the processing distance (80...100) mm contain more than 16 % oxygen At the same time, the transition from plasma-forming nitrogen to a mixture of air and hydrocarbon gas (natural gas) can significantly reduce the oxygen content at all measurement distances (Fig. 6). The results were obtained by taking samples on the axis of the plasma jet at different distances from the cut of the nozzle of the P-100 plasma torch using a probe. The thermochemical cathode used in the P-100 plasma torch does not allow the use of inert gases, therefore, for comparison, the distribution of oxygen in the flow of argon plasma from [10] is given.

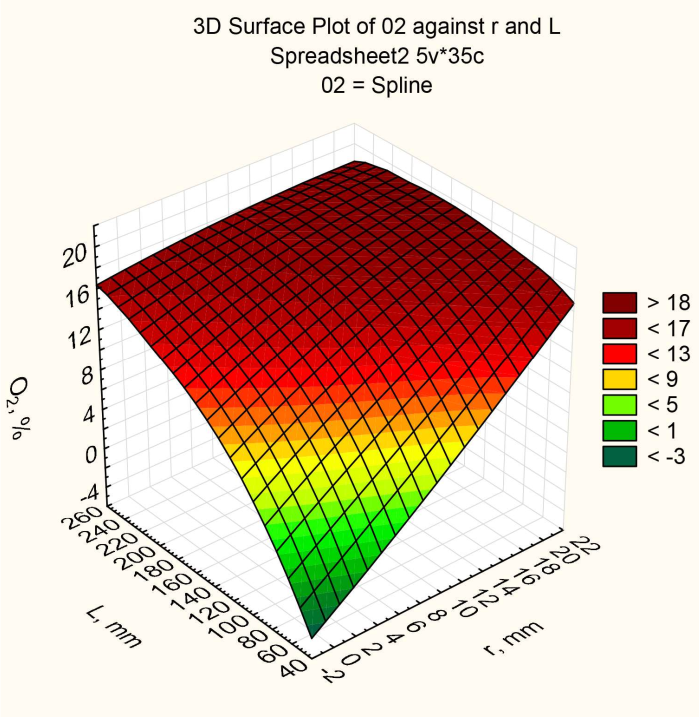


Fig. 5. The oxygen content in the plasma jet volume (plasma generation conditions are similar to those shown in Fig. 4)

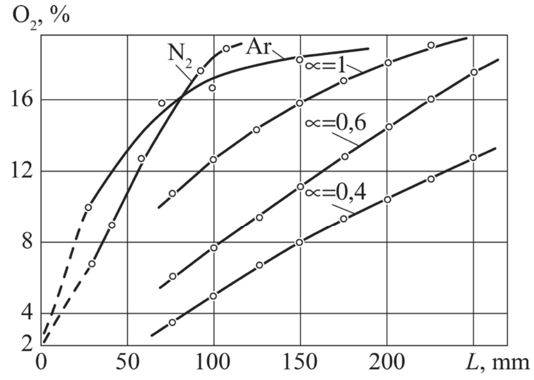


Fig. 6. Oxygen content along the axis of the plasma jet

Interesting and debatable is the possibility of reducing metal oxides during material processing by plasma of the N-O-C-H system.

Analysis of the potential reduction of oxides on the surface of metallic materials during their plasma treatment of the N-O-C-H system can be carried out using such a criterion as the generalized indicator of reducing properties of complex gas mixtures (CGM). The methodology for determining CGM is outlined in [11].

In the case of hydrocarbon use, the oxidation degree is numerically equal to the oxidizer consumption coefficient $\alpha = x_{(\text{N-O-C-H})}$. Equilibrium oxidation of the system $x_{e.}$ is determined taking into account the course of oxide reduction reactions. If $x_{e.} > x_{(\text{N-O-C-H})}$, the medium is reducing with respect to the oxide of the corresponding metal.

Fig. 7 shows the dependence of the equilibrium oxidation of the system (x_e) on the oxidizer consumption coefficient.

The results of calculations prove that the reduction of oxides is possible in the case of the use of "rich" mixtures of air with hydrocarbons (oxidizer consumption coefficient α<1). Materials such as, for example, oxides of chromium (CrO_3) and iron (Fe_2O_3) are reduced unconditionally in the range of change in α from 0.8 to 0.4. The reduction of oxides of molybdenum, tungsten, and iron (FeO) is possible only in the case of rather low values of the oxidizer consumption coefficient. Vanadium and chromium oxides (Cr_2O_3) cannot be reduced within the entire range of possible α change.

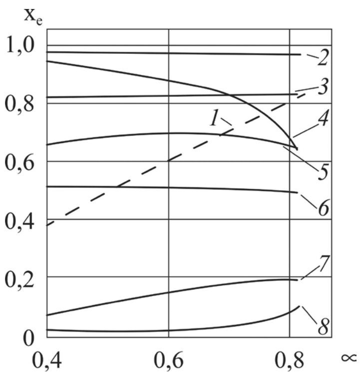


Fig. 7. Redox properties of plasma of the N-O-C-H system in relation to characteristic metal oxides: 1 – oxidation degree of CGM ($\alpha = x_{(\text{N-O-C-H})}$); 2 – CrO_3; 3 – Fe_2O_3; 4 – MoO_3; 5 – WO_3; 6 – FeO; 7 – V_2O_5; 8 – Cr_2O_3

6. Discussion of the study results

The results of the studies into the ability of potential plasma-forming media to effectively heat the processed material and protect it from the negative effects of the environment make it possible to formulate a set of requirements for plasma-forming substances.

The plasma-forming substance must:

– effectively perceive and accumulate external energy, converting it into thermal and kinetic energy of the plasma jet;

– be able to change the oxidation-reducing potential of the generated plasma environment due to the presence of appropriate components;

– not create a potential danger to service personnel and the environment;

– be affordable and cheap.

In turn, a plasma stream that is created from a plasma-forming substance that meets the above requirements must:

– provide local and average mass temperature sufficient for possible changes in the state of aggregation of processed materials;

– provide the necessary spatial structure of temperature, speed, and concentration fields;

– ensure efficient transfer of stored energy to the treated object;

– facilitate the passage in the desired direction of transformations (including chemical) in the processed material;

– have a wide range of changes in its energy and concentration characteristics by changing the operating parameters of plasma generation.

Taking into account the whole complex of requirements for plasma-forming substances and the plasma created from them, based on the results of research, it can be concluded that the plasma properties of the system N-O-C-H are universal. This conclusion is explained by the presence in the plasma of the whole system of components (N_2, H_2, CO_2, H_2O), which in different temperature ranges have maximum dissociation rates correlated with maxima of thermal conductivity. The mentioned thermal conductivity extremes are distributed over a wide temperature range (from 2800 K to 7000 K). Thus, a high level of thermal conductivity values is maintained within the entire active region along the plasma flux length (Fig. 2). At the same time, the appearance of hydrogen and carbon monoxide, which are reducing components of plasma, makes it possible to predict the active binding of oxygen into stable compounds. This assumption is confirmed by the results of experimental studies proving a decrease in the content of free oxygen in the plasma jet volume (Fig. 5, 6).

The plasma of such a system can be created from a mixture of air and hydrocarbons of the formula C_nH_{2n+2}. In the homologous series of saturated hydrocarbons in the gaseous state under normal conditions there are only methane, ethane, propane, and butane. These gases are not scarce and widespread. Taking into account the hydrocarbon content in the mixture, which does not exceed 20 %, the cost of the initial plasma-forming mixture will increase insignificantly.

Another argument for the prospects of using plasma-forming gas mixtures of the N-O-C-H system in surface engineering technologies may be the possibility of increasing the energy characteristics of plasma generators. This becomes possible due to the use of a combined supply of energy to the plasma-forming substance in the process of transferring it to a state of low-temperature plasma. Electrical energy is directly converted into heat during the interaction of an electric discharge with a gas-forming plasma-forming medium, and additional energy can be released during the interaction of the components of the plasma-forming mixture in the presence of a combustible component. The combustible component of the plasma-forming mixture (hydrocarbon gas) radically changes the energy balance of the plasma generator, and plasma generators using the above-mentioned energy flow scheme are transferred to the category of hybrid devices [12]. Hybrid devices for generating low-temperature plasma flows, in particular, plasma torches operating on gas systems N-O-C-H, have significantly wider possibilities for controlling the energy parameters of plasma flows [9]. An interesting point is the change in the meaning of the generally accepted concept of specific energy of plasma flow as a characteristic of the ability of a high-temperature medium to effectively heat the material being processed. In the case of using only electrical energy to generate plasma, all energy is simultaneously invested in the plasma-forming substance and at the active site of material processing it is almost impossible to correct the parameters of the jet. This circumstance impairs the technological capabilities of the working environment in case of necessity of volumetric processing of the material (coating technology, spheroidization of dispersed material, etc.). The energy of the plasma jet is spent on heating and accelerating the material being processed, and on heating the air sucked in from the environment. As a result, the initial value of specific energy ε begins to decrease rapidly throughout the entire volume of the plasma jet. To ensure the required energy level in the material processing zone, the initial values of ε are usually overestimated, which leads to excessive energy losses. In addition, it increases the risk of uncontrolled evaporation of the treated material in the region of the initial section of the plasma flow along the cut of the plasma generator nozzle.

When using the plasma of the N-O-C-H system, it is possible to generate plasma streams with the minimum required value of ε. The subsequent maintenance of this level is carried out due to the energy released in the stream due to the interaction of plasma components and plasma components with ambient air.

The analysis of plasma-forming media and the conclusions drawn relate mainly to surface engineering technologies that do not involve changes in the elemental composition of the surface layers of the material (plasma coating, spheroidization, plasma quenching, etc.). Nitriding and carbonization technologies can potentially also use the plasma of the N-O-C-H system (the elemental set of the medium allows the implementation of these processes). But for the effective application of such plasma, additional studies of the relationship between the plasma composition and the operating parameters of its application with the chemical composition of the surface layer of the material after passing through the target plasma-chemical reactions are required.

The disadvantages of the current study include the lack of results on the possible effect of hydrogen on the structure and properties of materials treated with the plasma of the N-O-C-H system. This may be the subject of further development of work on the introduction of plasma technologies with optimization of operating parameters, including the composition of the initial plasma-forming mixture.

7. Conclusions

1. The studies reported here have established that the medium enthalpy plasma of the N-O-C-H system provides a temperature level of $(5...7)\cdot10^3$ K in the range of specific energy values typical for surface engineering technologies. The rate of temperature drop due to heat withdrawal does not exceed (180...200) K for every 1 kWh/m^3, and the average value of the thermal conductivity coefficient is almost an order of magnitude higher than that of argon plasma. Due to this, it can be argued that the plasma of the N-O-C-H system is a sufficiently universal plasma environment for materials processing technologies in surface engineering.

2. A characteristic feature of the N-O-C-H system is the ability to change its oxidation-reducing potential by changing the ratio between the components of the plasma-forming mixture. The appearance of a thermally stable CO compound and

free hydrogen during heating enriches the plasma medium with reducing components. The consequence of this is a significant decrease in the oxygen content in the plasma stream. For example, at a distance of 100 mm, the oxygen content does not exceed 5 %. This indicates the active binding of environmental oxygen by the reducing components of the plasma.

Conflicts of interest

The author declares that he has no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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