The role of current characteristics of the arc evaporator in formation of the surface metal-coating composite

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Abstract. The influence of current characteristics of the vacuum arc evaporator on the interaction process of plasma streams with the surface under treatment during generation of the physicochemical properties of the formed metal-coating composite is considered. It is shown that the interaction of plasma streams with the processed surface provides surface heating, defects elimination, change in energy properties, and mass transfer of plasma stream elements activating surface diffusion processes whose intensity is evaluated by the arc current magnitude and location of the processed surface relative to the cathode axis.

1. Introduction
Plasma streams affecting the surface form the processes, the effectiveness of which is determined by the energy of components of elemental composition of gas-metal plasma streams. The result of such effects are the processes associated with surface layer heating, layerwise controlled removal of a defective absorbent-oxide layer, deposition of plasma stream elements, surface plasma-chemical reactions, interdiffusion saturation of the surface layer with elements of the plasma stream and the substrate [1–3].

The sequence of plasma stream effects on the surface being processed and their interaction generate technological stages of the surface treatment processes. Development of a wide range of external multilayer, multicomponent, gradient, nanostructured coatings is accompanied by changes in the chemical composition of the surface layer, chemical activity, structural and phase composition of the surface. Generation of the deposited coating properties depends on many factors including components ratio of gas-metal plasma stream determined by the current characteristics of the arc evaporator. This is especially urgent in formation of coatings where the system of obtained properties depends upon the change in the ratio of plasma chemical reaction components achieved through the variation in arc current of the evaporator and parameters of gaseous medium pressure.

2. Materials and experimental procedure
Model specimens made of 40H steel (150×30×2 mm) produced to manufacturing technology were investigated. Effects of titanium–nitrogen plasma stream on the surface under investigation were realized during vacuum ion-plasma treatment in a universal vacuum ion-plasma unit RADUGA developed and manufactured by JSC NIAT. The deposition process of titanium plasma stream...
occurred when one evaporator operated in nitrogen atmosphere with constant values of residual pressure \((P = 3 \cdot 10^{-1} \text{ Pa})\), reference voltage value \((U_{\text{ref}} = -100 \text{ V})\) and time of plasma stream effect (30 min). The variable value was the arc current \((J_{\text{arc}} = 60, 100, 150 \text{ A})\). Titanium plasma deposition was preceded by electron heating to the temperature of 360 °C and ion etching of the surface under treatment by argon plasma \((U_{\text{ref}} = -500 \text{ V}, 3 \text{ min})\).

Investigation of the initial parameters of the processed surface layer and evaluation of the properties variation after manufacturing effects as well as interactions with the titanium–nitrogen plasma stream were conducted using the following devices and equipment: change of the element chemical composition was carried out with Alpha-2000 class V portable metal and alloy analyzer made by Innox-X Systems company; evaluation of the change in the energy state of the surface layer was done by contact potential difference method according to the change of the value of reduced surface potential \(V_p \) (mV); surface layer hardness was investigated using a MicroMet 5101 device with loading from 0.1 to 2 N to measure surface hardness; layer-by-layer analysis of the quantitative change in the chemical composition of the surface layer was performed by a glow discharge atomic emission spectrometer GDS 850A (LECO). The depth of the layer-by-layer analysis measurement range was 0.01 to 25 μm.

3. Experimental results and discussion

The process of metal plasma stream generation is fundamental in formation of any type of coatings using the vacuum ion-plasma processing method. Separation of plasma stream generated by the electric arc evaporator into electron-ion components makes it possible to enhance significantly the capabilities of manufacturing effects of the streams during processing. Impact of the electron flow (anode – processed part connection scheme) has allowed for improving effectiveness of the stage of processed surface heating, which consists in its uniformity and speed, herewith the maximum value is obtained at the end of the heating stage, figure 1.

Temperature elevation of the processed surface is determined by its kinetic interaction with the electron component of plasma stream and transferred in that case by electron release energy. Subsequent effects of plasma stream on the surface being processed change its heating temperature since the value of reference current obtains prevalent significance. Transfer to the stage of ion etching in conditions of the semi-self-maintained gas discharge leads to temperature lowering in the surface layer at the cost of reduction in plasma stream energy caused by decrease of the reference voltage value. Realization of the deposition stage of plasma stream elements is associated with decrease in the reference voltage value that makes for further decrease with the following stabilization of the surface temperature. Variation of the current values of the evaporator in the range of 65 to 150 A actually does not influence the stage behavior of the change in the temperature dependence upon realization of the manufacturing effect stages.

Temperature of the surface layer and the presence of primary energy of plasma stream ions at the stage of deposition promote mass transfer of plasma stream elements on the substrate under treatment.
and interdiffusion of elements both of the substrate and the plasma stream, which are determining factors for the composite formation process. Variation of the arc current within the range of 60 to 150 A with all the rest process parameters being constant considerably affected the character of change in properties of the formed surface layer. This is due to the fact that the increase of the arc current enhances the density of plasma stream in the vacuum chamber volume and consequently increases the mass of the deposited element (Ti) in the coating, figure 1. With rise in arc current the non-uniformity of mass distribution of the deposited plasma elements along the specimen length also increases. The presence of gas-metal components (Ti–N) in the plasma stream results in their interaction with the processed surface and occurrence of plasma chemical reaction processes at the surface to form Ti–N system compounds.

According to the state diagram (Ti–N) the given system possesses a large domain of existence of titanium–nitrogen compounds with a variable hardness value determined by the ratio of plasma stream components (titanium and nitrogen) entering into a reaction. Dissolving in the titanium the nitrogen forms interstitial solid solutions, which transit into chemical compounds as the nitrogen concentration increases. Growth of the arc current value promotes change in the correlation of plasma stream components (titanium and nitrogen) as well as increases the mass transfer of titanium, which in turn increases the thickness of the coating under formation. An increase in hardness values in relation to the arc current, Figure 2, most likely depends on the factors that are determined by the growth of thickness of the generated coating rather than the change in the correlation of the stream components.

The change in the energy state of the surface evaluated by value of the reduced surface potential (V_p, mV) has demonstrated a weak dependence on the arc current value. It is connected with formation of identical structural state in the surface layer, figure 3.

![Figure 2](image2.png)

**Figure 2.** Variation of hardness in the surface layer of the 40H alloy formed during interaction with the Ti–N system plasma stream in relation to the arc current.

![Figure 3](image3.png)

**Figure 3.** Effect of the arc current on variation of the reduced surface potential V_p of the 40H steel along the specimen length: 1 – specimen area 70 mm above the center; 2 – central area of the specimen; 3 – specimen area 70 mm lower than the center.
Layer-by-layer analysis that records changes of the element composition in the surface layer formed, when affected by the TiN system plasma stream on the 40H steel surface, has shown that arc current significantly influences diffusion processes along with correlation of plasma stream elements entering into a plasma chemical reaction that forms coatings, figure 4. Deposition of the TiN functional coating is associated with the increase of the Ti mass transfer on the substrate, especially in the area along the cathode axis. The most intense increase of Ti along the entire length of the specimen is observed at the high value of arc current (150 A).

![Figure 4. Distribution of the surface layer elements of the 40H steel formed under the influence of the Ti–N system plasma stream in relation to the arc current: (a) – $J_{\text{arc}} = 60$ A; (b) – $J_{\text{arc}} = 150$ A (processed surface is 70 mm higher than the cathode axis).]

4. Conclusions
Variation in the arc current in the range of 60 to 150A caused titanium mass transfer to increase 3.5 times with a moderate spread in values along the specimen length. The resultant dependence of the change in mass transfer value of the Ti–N system plasma stream elements on the arc current provided an increase in thickness of the formed coatings and improvement in values of surface hardness during their interaction with the surface being processed.

Energy state of the surface layer evaluated by values of the reduced surface potential demonstrated that the coating, which was formed with different current arc characteristics, had virtually a constant value of $V_p$ with minor deviations. Such character of $V_p$ value variation is indicative of the similar structural state at the surface.

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elements entering into a plasma chemical reaction that forms coatings. At the top part of the area under investigation (70 mm above the cathode axis) we observe correlation dependences of the coating thickness growth, the depth of interdiffusion of elements of both the substrate and plasma on values of the arc current. To the maximum arc current corresponds the maximum titanium mass transfer and the maximum effectiveness of diffusion processes. Along the cathode axis and in the lower part of the area under investigation (70 mm below the cathode axis) correlation dependences established above completely remain, however, effectiveness of their interaction with the substrate is slightly reduced (coating thickness, depth of interdiffusion of substrate and plasma elements).

References
[1] Ilyin A A, Plikhunov V V, Petrov L M, Ivanchuk S B and Gavrilov A S 2006 Congress abstracts of 5th International Congress IAC’06 (Moscow) pp 160–1
[2] Plikhunov V V, Petrov L M, Ivanchuk S B and Gavrilov A S 2008 Proceedings of the VII scientific conference on hydroaviation “Hydro-Air Show-2008” (Gelendzhik) pp 233–8
[3] Plikhunov V V and Petrov L M 2010 Proceedings of the IX scientific conference on hydroaviation “Hydro-Air Show-2010” (Gelendzhik) pp 206–11