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Effectiveness of inert plasma gases in formation of modified structures in the surface layer of a cermet composite under pulsed electron irradiation

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ABSTRACT

The work studies the effect of argon, krypton and xenon used for pulsed electron irradiation in gas discharge plasma on structure formation, microhardness, wear resistance and friction coefficient of surface layers of 50%TiC/50%(Ni–20%Cr) cermet composite. The paper theoretically shows the decrease in ionization energy of plasma gas increasing the temperature and heating depth of the surface layer of a cermet composite. Experiments have established that the application of heavier plasma gases with lower ionization energy increases the depth of the layer where dissolution of TiC particles occurs, boosts wear resistance and microhardness, lowers the friction coefficient on the cermet composite surface.

1. Introduction

High-energy processing of metal materials and articles to modify their structure, physical and strength properties of surface layers is one of relevant fields of modern materials science in elaboration of technologies of surface strengthening for required operating conditions. The designated purpose of high-energy processing is the creation of modified structural and phase states of a material determining new higher level of physical and strength properties of surface layers [1].

Among the known methods of high-energy processing, a special place is held by the method of pulsed electron irradiation in inert gas plasma that is characterized be the widest modification capabilities of structural and phase state of material surface layer by forming in them amorphous, nano- and submicrocrystalline structures to the depth from several to dozens of micrometers [2, 3]. Pulsed electron irradiation of materials is carried out on setups with solid explosive emission cathode (copper wire) generating microsecond (from 2 up to 5 μs) electron beam current pulses with the energy density up to 20 J/cm^2 [4] or on setups with plasma cathode generating submillisecond irradiation pulses (from 50 up to 200 μs) with the energy density from 20 to 100 J/cm^2 [5].

An inherent part of electron irradiation of materials is plasma formation in the setup chamber trough ionization of plasma gas atoms. Plasma is needed to form an electron beam in the chamber in the gas atmosphere at low pressure. In the case of installation with a plasma cathode, the plasma of the inert gas is simultaneously a source of electrons. Ions of the inert gas, along with electrons, interact with the surface of the irradiated material and additionally contribute to the modification of the structure and phase composition of the surface layer.

A typical plasma gas for electron irradiation is inert gas argon. Along with argon, such gases as krypton and xenon are of appreciable interest, which significantly differ from argon in atomic mass [6] and ionization energy [7] (Table 1).

Presumably, at equal and constant plasma gas pressure in electron irradiation setup chamber, the effect of pulsed electron irradiation on the intensity and quality of structural and phase state modification in the cermet composite surface layer will depend on the atomic mass and ionization energy of the plasma gas.

This work was aimed at theoretical and experimental investigation of the modification efficiency of the surface layer structure of a cermet composite under pulsed electron irradiation depending on the choice of inert plasma gas out of argon, krypton and xenon.

2. Material and methods

As the model material, the experiments involved TiC/(Ni-Cr) cermet composite with the ratio of ceramic and metal components of 50:50. The choice of the composite with such formula is conditioned by high content of metallic binder, which enables more scrutinous assessment of the effect of electron irradiation in plasmas of various inert gases on

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Table 1
Values of atomic masses and ionization energy of the plasma gases.

Gas	Atomic mass, g/mol	Ionization energy E_{ig}, kJ/mol
Ar	39.948	1519.6
Kr	83.798	1350.0
Xe	131.29	1170.0

the character and intensity of interphase interaction of the components and peculiarities of structure modification of the composite surface layer.

The pulsed electron irradiation of cermet composite specimens was performed in argon, krypton and xenon plasmas with electron energy of 25 keV with irradiation pulse duration of 100, 150 and 200 μs, pulse energy density of 40 J/cm^2 and pulse repetition rate of 10 s^{-1}. The microstructure of surface layers of cermet composite specimens was studied on Carl Zeiss Supra 55 Sapphire scanning electron microscope at acceleration voltage of 20 kV.

The size of titanium carbide particles in the initial material was measured as the particle diameter (maximum distance between the boundaries) using SEM images. 150 particles were measured to obtain particle size distribution.

The microhardness of the composite surface layer was measured by a microhardness tester by forcing the pyramidal diamond penetrator at the load of 2 N. The friction coefficient of the composite surface was measured by high temperature tribometer (CSEM Instruments, Switzerland). The counterbody was a diamond cone. The measurements were done by rotation of the specimen, the counterbody being immovable; the load on diamond cone was 5 N, the end number of specimen revs was 2500. A micrometric system Micromesure System (STILS, France) was used for continuous recording of friction forces with consequent conversion into absolute values of friction coefficient. After the cutting, Micromeasure Station 3D profilometer (STIL, France) was used to measure the profile of the cross-cutting of the surface of cermet specimens by diamond counterbody with numerical determination of the cutting groove depth.

3. Results

3.1. Mathematical model and quantitative estimations

Let us consider a specimen of cermet composite represented by a round plate with radius r and thickness X. The plate suffers pulsed electron irradiation from one of its side surfaces. Let us assume the energy density distribution along the electron beam cross-section to be uniform. In this case, the equation that describes the temperature distribution in the irradiated specimen in one-dimensional approximation can be written as.

$$c\rho\frac{\partial T}{\partial t} = \lambda\frac{\partial^2 T}{\partial x^2} - \frac{\chi}{r}(T - T_0) - \frac{\varepsilon}{r}(T^4 - T_0^4) \tag{1}$$

where T is temperature; t is time; c and λ are heat capacity and heat conductivity of the specimen; ρ is the specimen density; χ is convective heat emission coefficient; ε is irradiation heat emission coefficient; T_0 is initial temperature of the cermet composite (293 K); x is axial coordinate ($0 \le x \le X$). In first approximation, the specimen thermophysical properties can be regarded as constant and not depending on temperature and structural transformations. According to additivity law,

$$c = v_{Ni-Cr}c_{Ni-Cr} + v_{TiC}c_{TiC} \tag{2}$$

$$\lambda = v_{Ni-Cr}\lambda_{Ni-Cr} + v_{TiC}\lambda_{TiC} \tag{3}$$

$$\rho = v_{Ni-Cr}\rho_{Ni-Cr} + v_{TiC}\rho_{TiC} \tag{4}$$

$$c_{Ni-Cr} = (c_{Ni}a_{Ni} + c_{Cr}a_{Cr})/(a_{Ni} + a_{Cr}) \tag{5}$$

$$c_{TiC} = (c_{Ti}a_{Ti} + c_C a_C)/(a_{Ti} + a_C) \tag{6}$$

$$\lambda_{Ni-Cr} = (\lambda_{Ni}a_{Ni} + \lambda_{Cr}a_{Cr})/(a_{Ni} + a_{Cr}) \tag{7}$$

$$\lambda_{TiC} = (\lambda_{Ti}a_{Ti} + \lambda_C a_C)/(a_{Ti} + a_C) \tag{8}$$

$$\rho_{Ni-Cr} = (\rho_{Ni}a_{Ni} + \rho_{Cr}a_{Cr})/(a_{Ni} + a_{Cr}) \tag{9}$$

$$\rho_{TiC} = (\rho_{Ti}a_{Ti} + \rho_C a_C)/(a_{Ti} + a_C) \tag{10}$$

where c_j, λ_j, ρ_j, v_j, a_j are heat capacity, heat conductivity, density, and relative mass fraction and atomic mass of the j-th component in the composite cermet alloy (in this case, nickel-chrome binder (j = Ni-Cr) or titanium carbide (j = TiC), or chemical element (j = Ni, Cr, Ti, C)).

The boundary conditions in the case of single electron pulse will be represented as:on the electron irradiated surface ($x = 0$).

$$-\lambda\frac{\partial T}{\partial x} = \begin{cases} E_S(g)/t_i > 0, & 0 < t \le t_i \\ 0, & t > t_i \end{cases} \tag{11}$$

where t_i is pulse duration; $E_S(g)$ is effective energy density in electron beam in inert gas plasma.on the face.

When ($x = X$)

$$-\lambda\frac{\partial T}{\partial x} = \chi(T - T_0) + \varepsilon(T^4 - T_0^4) \tag{12}$$

Let us determine parameter $E_S(g)$. For this end let us assume that the additional ion flow formed under electron energy deposition in inert gas plasma will promote the increase in effective (total) irradiation density which in first approximation is as follows:

$$E_S(g) \approx E_S(\mathrm{Ar}) + \Delta E(g) \tag{13}$$

where E_S(Ar)is the energy density of electron irradiation in argon plasma, $\Delta E(g)$is the increment of energy density due to additional ionization in krypton and xenon plasma (g = Kr, Xe).

Then let us assume that the lesser the inert gas ionization energy, the more inert gas ions form in electron-plasma flow and, correspondingly, the larger $\Delta E(g)$is. Hence, the drop in gas ionization energy and increase of $\Delta E(g)$ will augment the effective density of material irradiation energy $E_S(g)$. Since, in accordance with Table 1, $E_{iAr} > E_{iKr} > E_{iXe}$; then in this case, the following condition will be met:

$0 < \Delta E(\mathrm{Kr}) < \Delta E(\mathrm{Xe})$or

$$E_S(\mathrm{Ar}) < E_S(\mathrm{Kr}) < E_S(\mathrm{Xe}) \tag{14}$$

The numerical calculations were made using the system of eqs. (1), (11)–(12) and additional relations (13) and (14) in approximation of constant heat capacity and heat conductivity of a cermet composite. The values of thermophysical characteristics and parameters for the 50% TiC / 50% (Ni-20% Cr) constituents included in the composite were taken from [8–12]:

$c_{NiCr} = 452$ J/kg·K
$c_{TiC} = 408$ J/kg·K
$\lambda_{NiCr} = 88.5$ J/s·K·m
$\lambda_{TiC} = 42$ J/s·K·m
$\rho_{NiCr} = 8800$ kg/m^3
$v_{NiCr} = v_{TiC} = 0.5$
$\chi = 10$ J/s·K·m^2
$\varepsilon = 3 \cdot 10^{-7}$ J/s·K^{4}m^2
$T_0 = 300$ K,
$r = 0.01$ m,
$X = 0.001$ m.

Fig. 1 presents the temperature profiles of the cermet specimen surface heated by electron beam depending on effective irradiation energy density $E_S(g)$.

It is evident from Fig. 1 that the heating intensity and the heating temperature of the surface layer increase with the increase in the effective energy density of electron irradiation (in the transition from irradiation in argon plasma to irradiation in krypton and xenon plasma).