

MODEL OF MASS TRANSFER IN THE TITANIUM SURFACE LAYER AFTER COMPRESSION PLASMA FLOWS INFLUENCE

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Introduction

Compression plasma flows generated by a magneto-plasma compressor are perspective type of concentrated energy flows used for materials properties modification. Such plasma flows are characterized by a high concentration of charged particles and a small divergence of the plasma stream that are give risen by the own magnetic field. These peculiarities of the compression plasma flows provide the long time of stable existing of the flow that is up to 100 – 140 μ s. The last time the compression plasma flows became to be used not only for structure and properties materials modification but also for the alloying of them with other elements /1/. For this aim the plasma flow influences on a “coating/substrate” system. Variation both of the coating thickness and plasma flow energy can provide any elemental composition of the alloy that can not be reached in traditional methods.

In this account revealing the main mechanisms of mass transfer in the surface layers of the materials undergone plasma flow influence is an actual problem. In previous works /2/ the authors described the mass transfer as a convective mechanism. Nevertheless the quantitative parameters of this phenomenon were not determined.

The purpose of the presence work is determination of the main physical principles of heat and mass transfer in the surface layers of titanium alloyed with chromium atoms by means of compression plasma flows influence.

Experimental

A commercial pure titanium alloy was chosen as a substrate for the surface alloying. A chromium coating was deposited on the surface of the samples by arc-vacuum method. The thickness of the coating was 1 – 1.5 μ m.

The formed systems were undergone to the compression plasma flows generated in the nitrogen atmosphere at the residual pressure 400 Pa. The main varied parameter was an absorbed energy density that was changed from 13 to 23 J/cm².

The elemental distribution was analyzed by means of energy-dispersion X-ray microanalysis using the Rontec equipment.

Results and discussion

The X-ray microanalysis allowed to find that the chromium concentration in the surface layer of the titanium samples after plasma influence is decreased from 6.8 to 1.1 at. % with absorbed energy density rising from 13 to 23 J/cm². First of all the falling of chromium concentration is connected with increase of the depth of melted layer. The chromium distribution in the sample obtained from the analysis of the cross-section (Fig.1) shows that the chromium atoms penetrate inside the modified layer up to 10 – 20 μm in dependence on the absorbed energy density. Moreover, the alloyed layer is characterized by uniformly distribution of chromium atoms.

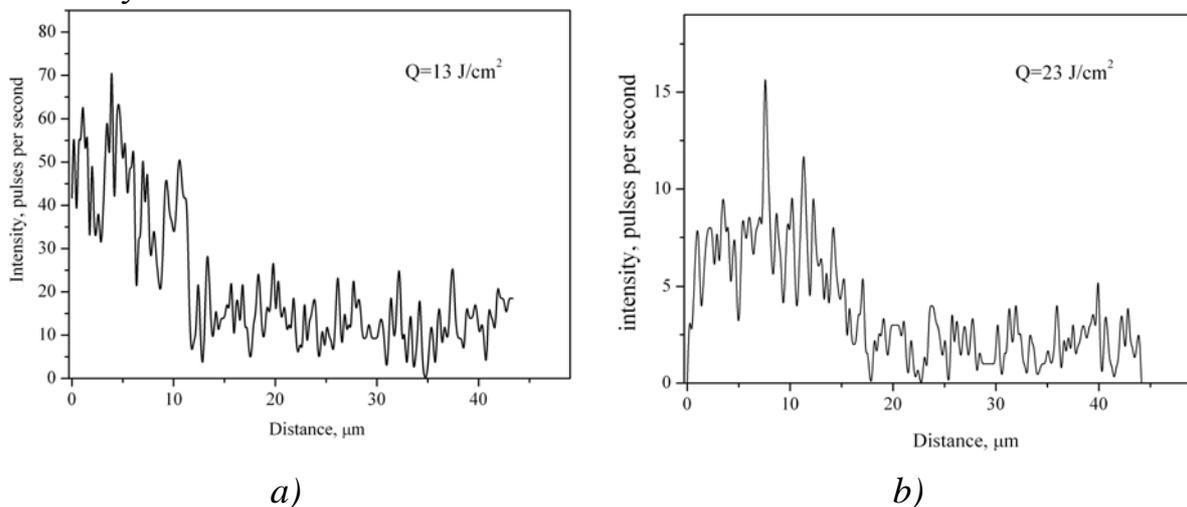


Fig. 1 – Chromium atoms distribution inside the modified layer after compression plasma flows influence at absorbed energy density 13 J/cm² (a) and 23 J/cm² (b)

The same results were found after compression plasma flows influence on molybdenum/titanium and zirconium/titanium systems that indicates on the sameness of mass transfer process in the surface layers.

The first model of mass transfer based on the diffusion mechanism does not allow to exactly describe the concentration of alloying elements and the depth of their penetration. In this case the penetration depth is not more than 2 μm and weakly depends on the absorbed energy density.

The adequate description of the experimental data can be reached in the mass transfer model based on the convective mechanism. In this model the motion of alloying elements atoms is connected with hydrodynamics flow of the melt that can be calculated from Navier-Stokes equation. The following equations must be solved:

$$\begin{aligned} \frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} &= -\nabla p + \nu \Delta \vec{v} + \left(\frac{\xi}{\rho} + \frac{\nu}{3} \right) \nabla (\nabla \cdot \vec{v}) \\ \frac{\partial \rho}{\partial t} + \nabla \cdot \vec{v} &= 0 \\ \frac{\partial C}{\partial t} + (\vec{v} \cdot \nabla) C &= \frac{\partial}{\partial x} \left(D \frac{\partial C}{\partial x} \right) \\ c\rho \frac{\partial T}{\partial t} + c\rho (\vec{v} \cdot \nabla) T &= \frac{\partial}{\partial x} \left(\kappa \frac{\partial T}{\partial x} \right) \end{aligned}$$

where \vec{v} – velocity of the melt, p – pressure in the melt, ν and ξ – viscosity of the liquid metal, ρ – melt density, C – alloying elements concentration, T – temperature, c – thermal capacity, κ – thermal conductivity.

The initial and boundary conditions for chromium atoms concentration:

$$\begin{aligned} C(x, 0) &= \begin{cases} 100, & x < d \\ 0, & x \geq d \end{cases} \\ \left. \frac{dC}{dx} \right|_{x=0} &= 0 \\ C(L, t) &= 0 \end{aligned}$$

where d – thickness of the chromium coating (2 μm), L – thickness of the sample (2 mm). These conditions take into account the absence of the external flow of chromium atoms.

The initial and boundary conditions for surface temperature:

$$\begin{aligned} T(x, 0) &= T_0 \\ -\kappa \left. \frac{dT}{dx} \right|_{x=0} &= W \\ T(L, t) &= T_0 \end{aligned}$$

where T_0 – initial temperature of the sample (300 K), W – absorbed power density (1.3–2.3 GW/m^2). The external flow of the heat energy is connected with the plasma flow interaction with the material.

The solving of the equation will be considered only in the direction normally to surface (along x -coordinate). To find an initial value of the velocity of the melt in the x -direction the law of indestructibility of impulse was used:

$$\int_0^{\tau} F(t) dt = \int_0^{v_1} m dv$$

where τ – pulse duration (100 μs), $F(t)$ – force that is connected with the external pressure of plasma flow p that was experimentally found. Then the initial velocity v_1 can be written as followed:

$$v_1 = \frac{p\tau}{\rho L}$$

After calculation the velocity v_1 equals to about 3 m/s. To describe of the type of the melt motion the Reynolds number was evaluated which equals to 10^1 . In this case the Navier-Stokes equation can be simplified and the system of main equations will be written as followed:

$$\frac{\partial v_x}{\partial t} = \nu \frac{\partial^2 v_x}{\partial x^2}$$

$$v_x(0) = v_1$$

$$\frac{\partial C}{\partial t} + v_x \frac{\partial C}{\partial x} = \frac{\partial}{\partial x} (D(T) \frac{\partial C}{\partial x})$$

$$c\rho \frac{\partial T}{\partial t} + c\rho v_x \frac{\partial T}{\partial x} = \frac{\partial}{\partial x} (\kappa \frac{\partial T}{\partial x})$$

The results of the simulation are represented on the Fig.2 that are correspond to the experimental data.

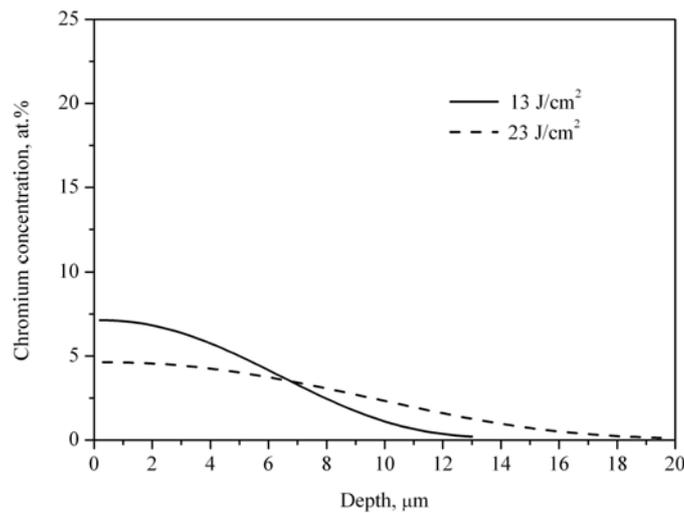


Fig. 2 – Chromium distribution in the titanium after compression plasma flows influence (simulation results)

Conclusions

The proposed model of mass transfer in the surface layers of titanium after compression plasma flows influence based on the convective mechanism allows to obtain the penetration depth of the alloying elements and their concentration.

References

1. **Uglov V.V.** Vacuum, 78 (2005) 489-493.
2. **Cherenda N.N.** Journal of Optoelectronics and Advanced Materials, 12 (2010) 749–753.