
PHYSICAL FOUNDATIONS
OF STRENGTH AND PLASTICITY

Mechanism of Formation of the Coating/Substrate Interface during the Treatment of Conductors by an Electric Explosion Plasma

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Abstract—The Ti–Zr and Ti–Nb coatings fabricated by the electric explosion of conductors are studied by scanning electron microscopy, and the behavior of the coating/substrate interface is theoretically investigated. The results obtained are used to propose a mechanism for the interface relief formation. The wavy interface relief is assumed to be caused by the Rayleigh–Taylor instability. An analysis of a dispersion equation shows that the wavelength corresponding to the maximum increment is 0.92 μm for the Ti–Zr system and 1.67 μm for the Ti–Nb system. The distance between relief ridges detected in experiments is 2.5–8.7 μm for Ti–Zr and 5–11 μm for Ti–Nb. This difference is explained by the fact that the second maximum in the wavelength dependence of the instability increment can be observed in experiments.

Keywords: surface, Rayleigh–Taylor instability, electric-explosion deposition, interface relief

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INTRODUCTION

Artificial materials are widely used in modern medicine to replace damaged tissues and organs. They must operate for a long time, withstand erosion wear, and do not contain toxic elements [1]. Volume alloying for improving the properties of implanted materials is not always justified, since a material begins to degrade from its surface. Therefore, the surface of a part should be hardened first of all [2–4].

The required specifications can be met by surface modification, in particular, the formation of a coating on a working surface. Many methods of coating deposition onto the surface of an implant have been developed to date, and gas-phase chemical and physical deposition [5, 6] and the sol gel method [7] are noteworthy. Although these methods can be used to create coatings with the required properties, the process of their deposition is labor consuming.

Surface modification is often accompanied by coating separation, which is caused by mechanical stresses at the coating/substrate interface because of the difference between their elastic moduli [8, 9]. The stress distribution depends on the interface relief. As follows from [10, 11], a developed surface relief favors the dispersion of stress concentrators. As a result, the functional properties of a coating can be retained without the formation of extended localized plasticity bands in a matrix.

An alternative to the existing coating deposition methods can be an electric explosion of conductors [12–16]. This method can be used to create composite coatings having high adhesion and mechanical erosion resistance. To use this method widely and to search for the treatment conditions that ensure a developed coating/substrate interface relief, it is necessary to know the relief formation mechanism.

The authors of [17] proposed a mechanism, which is based on the appearance of the Rayleigh–Taylor instability, for mixing materials during electric explosion treatment. The essence of this instability consists in the fact that, if the boundary of two media moves at an acceleration directed normal to the interface from the lighter to the heavier medium, this boundary is unstable [18]. The development of the Rayleigh–Taylor instability is a complex process, which includes the formation of sharp protuberances, curtains, and bubbles [19]. Such relief elements were detected during the formation of composite coatings [12, 13, 16].

The purpose of this work is to study the mechanism of formation of the interface between a coating formed by electric explosion alloying and a titanium substrate. Titanium and its alloys are widely used to prepare implants due to their good compatibility with the human body. The Rayleigh–Taylor instability is assumed to occur at the interface during the electric explosion alloying of the titanium surface [12, 13, 16].

Table 1. Characteristics of the electric explosion device

Parameter	Value
Energy consumption, kJ	60
Discharge eigenfrequency, kHz	10
Maximum charge, kV	5
Charging voltage step, kV	0.1
Maximum capacity at the maximum charging voltage, cycles/h	10
Average consumed power in charging, kW	≤0.55
Battery capacity, μF	1008
Pulse duration, μs	100

EXPERIMENTAL

We studied $20 \times 20 \times 5$ -mm samples made of VT1-0 titanium. Zirconium and niobium foils 568 and 134 mg in weight, respectively, were used as conductors to be exploded. To form multiphase plasma jets, we used an EVU 60/10 device, which consists of an end-face coaxial plasma accelerator. The main characteristics of the device are given in Table 1 and the principle of its operation is comprehensively described in [20, 21].

The main parameters of the electric-explosion deposition of conductors are pulse duration τ and power density q absorbed during the thermal action on a surface. The conditions required for this process were specified by the charging voltage of the accelerator energy storage system ($U = 1.8$ kV), the plasma stream acceleration ($g = 6 \times 10^9$ m/s²), the nozzle channel diameter ($d = 20$ mm), and the distance from the nozzle exit section to a sample ($s = 20$ mm). To choose q for treatment ($q = 1.5$ gW/m²), we calculated the irradiated surface temperature using the model of heating by a flat thermal source [22].

The modified layers were analyzed by scanning electron microscopy (Zeiss EVO 50 XVP microscope).

RESULTS AND DISCUSSION

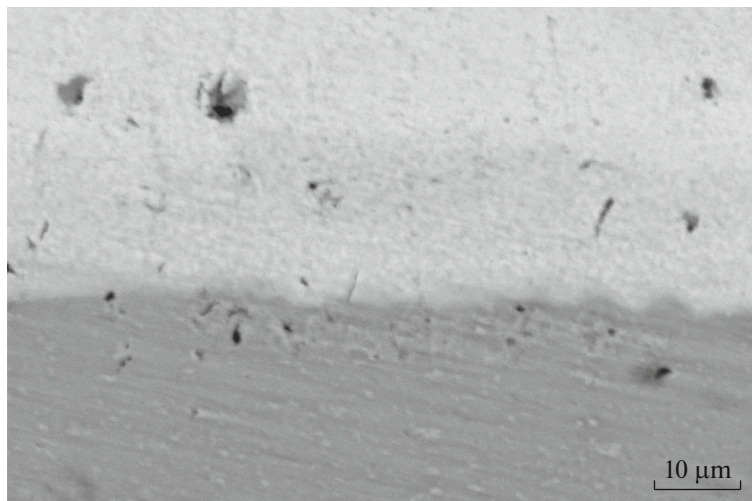
Under the chosen deposition conditions, the interface between Ti–Zr and Ti–Nb coatings and the base is wavy (Figs. 1, 2). The wavy character of the Ti–Nb coating is more pronounced. The shape of the ridges (indicated by the arrow in Fig. 2) is similar to the picture that is observed when the Rayleigh–Taylor instability was studied [18, 19]. It is logically to assume that this instability is the relief formation mechanism. The distance between ridges is 2.5–8.7 μm in the case of a Ti–Zr coating and 5–11 μm in the case of a Ti–Nb coating.

We now consider the initial stage of the Rayleigh–Taylor instability, when a flat interface loses its stability at small harmonic perturbations. The important parameters that characterize the instability at this stage are the critical wavelength at which the instability begins and the wavelength corresponding to the maximum instability [23]. To find these parameters, we have to analyze a dispersion equation for small harmonic perturbations. We analyze the dispersion equation obtained in [17],

$$a\omega^2 + 2b\omega + c = 0, \quad (1)$$

where $a = \rho_1 \coth(kh) + \rho_2 \coth(kH)$, $b = ik^2(\rho_1 \nu_1 \coth(kh))$, $c = g(\rho_2 - \rho_1) - \sigma_0 k^3$, ρ is the density, ν is the kinematic viscosity, σ is the surface tension, $\sigma_0 = |\sigma_1 - \sigma_2|$ is the interfacial surface tension, H is the coating thickness, h is the substrate thickness, g is the plasma stream acceleration, k is the wavenumber, and subscripts 1 and 2 belong to the substrate and the coating, respectively.

In the calculations, we use the approximation $H \rightarrow \infty$ and $h \rightarrow \infty$. Equation (1) was derived in the so-called viscous potential approximation [24], according to which viscosity effects are significant only at the interface. The electric explosion plasma incident on a sam-

**Fig. 1.** Structure of the Ti–Zr coating (cross section).

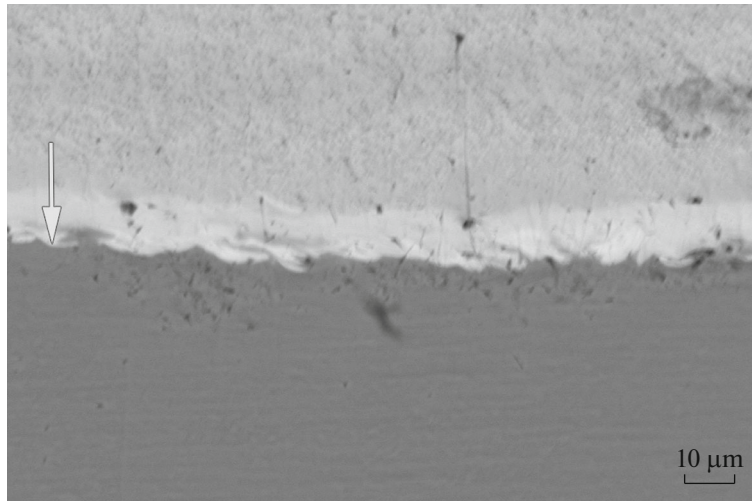


Fig. 2. Structure of the Ti–Nb coating (cross section).

ple is taken to be an ideal liquid, and the molten substrate layer is taken to be viscous. To find the increment, we write the cyclic frequency as a complex number $\omega = \omega_R + i\alpha$, where ω_R and α are the real and imaginary parts of the complex frequency, respectively. As a result, we have the set of equations¹

$$\begin{aligned} a\omega_R^2 - a\alpha^2 - b\alpha + c &= 0; \\ a\omega_R\alpha + b\omega_R &= 0. \end{aligned} \quad (2)$$

From the solution to Eq. (2), we find increment α ,

$$\alpha = \frac{\sqrt{-b^2 + ac}}{a}. \quad (3)$$

To calculate α , we estimate plasma stream velocity v and acceleration g . The plasma stream velocity at the nozzle exit section of the accelerator is calculated by the empirical formula [25]

$$v = 6.75 \times 10^3 \left(\frac{CU^2}{2\tau} \right)^m, \quad (4)$$

where C is the battery capacity, U is the charging voltage, m is the exponent dependent on the type of source ($m = 0.05$ for electric explosion sources), and τ is the pulse duration.

The stream acceleration is estimated as

$$g = \frac{v^2}{2s},$$

where s is the distance from the nozzle to the sample surface.

¹ If the imaginary part of the complex cyclic frequency (increment) is zero, the corresponding wavelength is critical. All wavelengths with $\lambda > \lambda_{cr}$ are unstable and lead to the formation of vortices. The wavelength at which the instability is maximal indicates the most probable size of vortex structures.

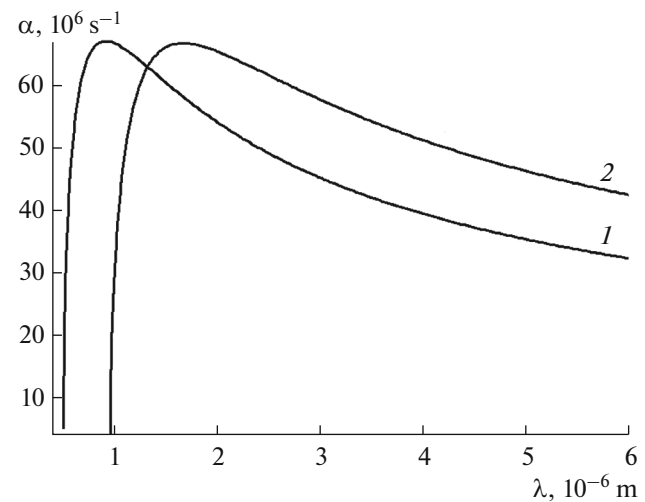


Fig. 3. Increment α vs. the wavelength for (1) Ti–Zr and (2) Ti–Nb systems.

Table 2 gives the physical characteristics of the materials used to find the wavelength dependence of the increment.

Figure 3 shows the increment as a function of the wavelength at the experimental treatment parameters. The wavelength of the maximum increment for the Ti–Zr pair is 0.92 μm (Fig. 3, curve 1) and 1.67 μm for

Table 2. Physical properties of the materials

Material	ρ , kg/m ³	ν , 10 ⁻⁷ m ² /s	σ , N/m
Titanium	4120	10.7	1.402
Zirconium	5800	8.16	1.492
Niobium	7580	5.92	1.9

ρ is density; ν , kinematic viscosity; and σ , surface tension.

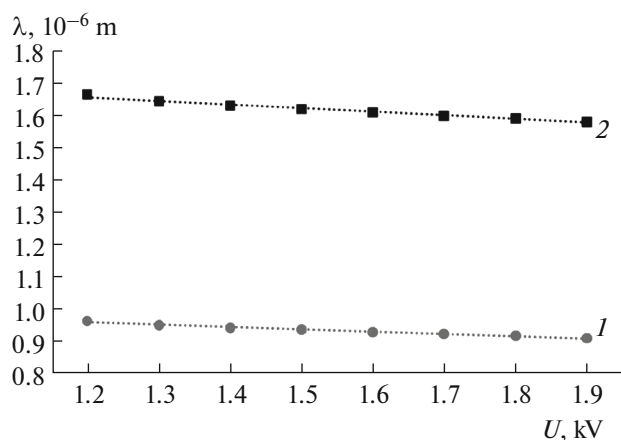


Fig. 4. Wavelength corresponding to the maximum increment vs. the charging voltage for the coatings of (1) Ti–Zr and (2) Ti–Nb systems.

the Ti–Nb pair (Fig. 3, curve 2). A smaller wavelength in the case of zirconium alloying is caused by lower interfacial surface tension. The calculated values are slightly smaller than the experimentally detected inter-ridge distances (see Figs. 1, 2). This difference could be explained by the fact that the temperature-gradient-induced effects manifest themselves during the coating–substrate interaction under real conditions. However, when Eq. (1) was derived in [16], the processes under study were assumed to occur under isothermal conditions. On the other hand, the viscous potential approximation used in this work and the assumption about an infinitely large layer thickness give only one maximum at short waves (see Fig. 3). A second maximum can appear at long wavelengths under experimental conditions. This maximum is likely to manifest itself in electron-microscopic images (see Figs. 1, 2).

Despite these differences, we can conclude that the Rayleigh–Taylor instability is the main mechanism of formation of the coating/substrate interface relief and the viscous potential approximation can be used to predict the surface relief geometry. Indeed, a decrease in the wavelength corresponding to the maximum increment points to a more developed surface relief.

The dependence of the wavelength corresponding to the maximum increment on the charging voltage is linear (Fig. 4). An increase in the charging voltage decreases the wavelength corresponding to the maximum increment. Thus, a developed surface relief forms at high charging voltages.

CONCLUSIONS

The formation of the coating/substrate interface relief during coating deposition by electric explosion of a conductor was studied for Ti–Zr and Ti–Nb systems. Using scanning electron microscopy, we showed

that a developed interface relief formed during electric explosion treatment. A relief formation mechanism, which is based on the appearance of the Rayleigh–Taylor instability during electric explosion treatment, was proposed. An analysis of the initial stage of this instability showed that the wavelength corresponding to the maximum increment was 1.67 μm for the Ti–Nb pair and 0.92 μm for the Ti–Zr pair. The dependence of the wavelength that corresponds to the maximum increment on the charging voltage is linear and can be used to choose the optimum conditions of electric-explosion coating deposition.

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