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Alloying the surface of stainless steel Ti and Al with a modulated electron beam in a source with a plasma cathode

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Abstract. By irradiating the system “film(Ti)/film(Al)/(12H18N10T/AISI 304) substrate” with a modulated electron beam of low (up to 25 keV) energy with a total duration of up to 1 ms, the surface wear rate is reduced by ~1000 times at a constant high (0.73) dry friction coefficient and a slight change in surface microhardness. The samples were irradiated by an electron source with a grid plasma cathode based on a low-pressure arc. Impact modes were selected based on the results of numerical modeling in Comsol Multiphysics. Possible areas of application of this type of processing of steel parts for the industrial sector are indicated.

Keywords: plasma cathode, electron beam, steel 12H18N10T / AISI 304, alloying, surface modification, ultra-fast crystallization.

1. Introduction

The advantage of austenitic steels, including stainless steel 12H18N10T, is wear rate $660\cdot10^{-6}$ mm^3/Nm , high corrosion resistance. The disadvantage is low wear resistance. The cheapest and most technologically advanced way to increase the tribological properties of friction unit parts is surface hardening [1], for example, by ultra-fast melt quenching of Ti and Al in the surface layer of steel with the formation of solid intermetallic compounds. Electron beam alloying is a leader over other methods of introducing energy into the surface of a sample in terms of efficiency up to 90% due to low electron reflection, control and uniformity of heat flow [2] and has been repeatedly used to improve the mechanical properties of metals and alloys [3–5], as well as ceramics [6]. Since electrons with energy of less than 30 keV are used, the bremsstrahlung radiation arising from the interaction of the electron beam with the sample is completely shielded by the chamber walls.

The research question of this work is to analyze the structure and tribological properties of the surface of 12H18N10T steel modified by exposing the "film(Ti)/film(Al)/(12H18N10T) substrate" system to a pulsed electron beam.

2. Research methodology

The material tested was stainless steel 12H18N10T (AISI 304). The samples were coated with an Al film 5 μm thick, and then with a Ti film 5 μm thick using plasma-arc spraying using a QUINTA vacuum ion-plasma installation [7], which is part of the UNIKUUM complex a list of unique scientific installations in Russia [8]. The system “film(Ti)/film(Al)/(12H18N10T) substrate” was irradiated with an electron beam on a SOLO installation [8], whose electron source makes it possible to generate beams with a diameter of up to 5 cm, an energy of up to 25 keV, and an energy density of up to 100 J/cm^2 with a pulse duration of 20–1000 μs [9]. A unique feature of this type of electron sources is the possibility of low-inertia control of the beam current, which weakly depends on the accelerating voltage [10]. Thus, it is possible to dynamically control the beam power in the submillisecond range of pulse durations [3] and, consequently, the rate of energy supply to the surface of the target being processed within the beam current pulse [11]. Controlling the energy supply makes it possible to control the temperature field in the surface layer of the target and, consequently, its structure and phase state.

The irradiation modes were chosen so that the surface layer was heated above the melting point of aluminum (> 650 °C), but did not reach the melting point of steel and titanium (< 1500 °C), that is, it was at a level of about 1000 °C. It was expected that in this case, Ti and Al films would effectively diffuse into the steel surface.

With an average beam electron energy on the target of ~10 keV, thermal processes with pulse durations of 50–500 μs can be considered in a one-dimensional approximation, since the transverse size of the energy effect is significantly greater than the depth of propagation of the thermal field. Under these assumptions, heating assessment is reduced to solving the heat conduction equation (1), with boundary conditions (2), (3) and initial condition (4):

$$d\rho c\frac{\partial T}{\partial t}=d\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right), \tag{1}$$

$$\lambda\left.\frac{\partial T}{\partial x}\right|_{x=0}=q(t)=U(t)I(t)\frac{J}{\sum_i\left[U(t)I(t)(t_i-t_{i-1})\right]}, \tag{2}$$

$$\left.\frac{\partial T}{\partial x}\right|_{x\to\infty}=0, \tag{3}$$

$$T\big|_{t\to 0}=T_0, \tag{4}$$

where *d* is the thickness of the thin layer; *c* – specific heat capacity; ρ – density; λ – coefficient of thermal conductivity; *q*(*t*) – power density external heat source; *U*(*t*) and *I*(*t*) accelerating voltage and beam current; *J* – energy density for the entire pulse (from calorimetry data); t_i – time counts.

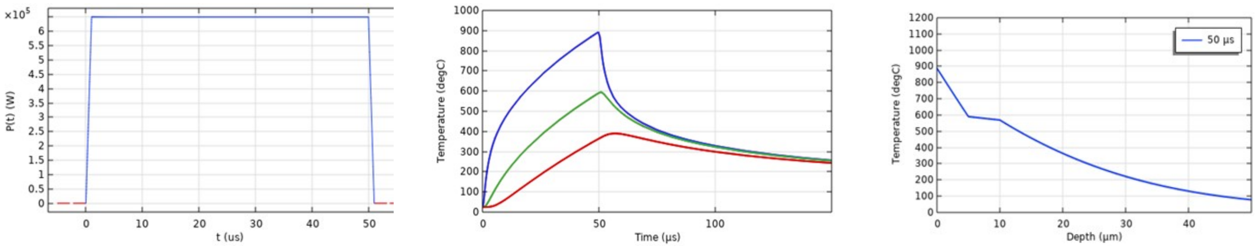
The mathematical model includes the presence of a two-phase zone, which in the “solid-liquid” system is characterized by the average volume fraction of the liquid phase θ. The phase transition occurs in the temperature range Δ*T*, in which the phase of the material is modeled by a smoothed function θ, varying from 1 to 0. The effective thermal conductivity of the solid-liquid system λ is related to the thermal conductivity of the solid λ_s and the thermal conductivity of the liquid λ_l (5). Similarly for density and heat capacity:

$$\lambda=(1-\theta)\lambda_s+\theta\lambda_l, \tag{5}$$

To take into account melting, the apparent heat capacity method is used, in which the latent heat of fusion *L* is included as an additional term in heat capacity (6) [12]:

$$c=c_S+L/\Delta T, \tag{6}$$

Irradiation was carried out at an argon pressure of 20 mPa, in a magnetic field in the sample area of 100 mT and 50 mT – in the emitter region. The beam energy density at the collector was 10 J/cm^2. Fig. 1 shows the calculation results in Comsol Multiphysics for trial mode – basics for modes No. 1–3 – Table 1.



(a) (b) (c)

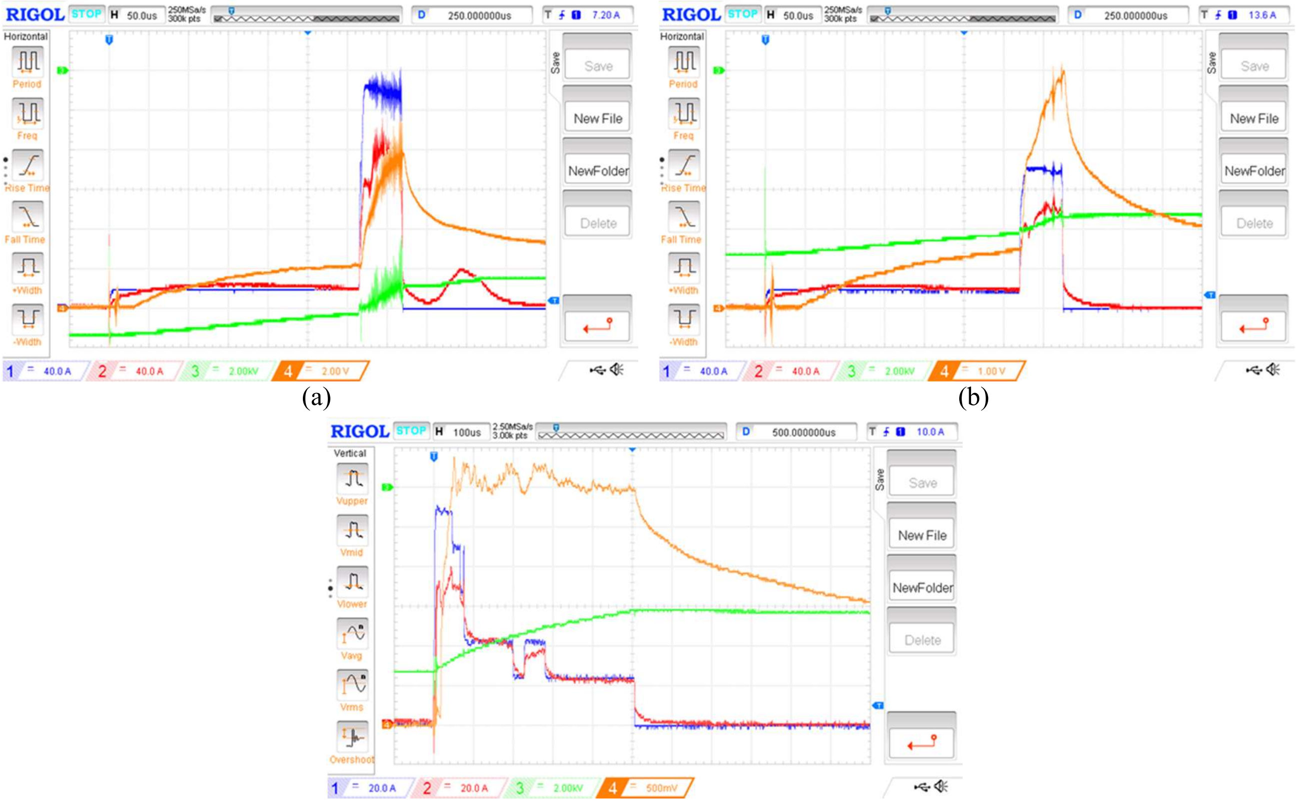
Fig. 1. Simulation of the trial mode: a – power dynamics in the accelerating gap circuit; b – temperature change during the pulse; c – temperature change in depth at the end of the pulse.

3. Results and discussions

Table 1 in Fig. 2 shows the results of studies of the surface properties of the film/substrate system after exposure to an electron beam with a power density varying during the pulse.

Table 1. Comparison of samples.

Characteristic	Irradiation mode No. 1	 No. 2	 No. 3
Oscillograms 1 – plasma cathode discharge current I_d, 40 A per cell, 2 – current in the accelerating gap I_g, 40 A per cell, 3 – accelerating voltage U_g, 2 kV per cell, 4 – temperature (T [°C] = 300+200×U [V]) Sweep 50 μs per cell.	Fig. 2a	Fig. 2b	Fig. 2c
Achievable temperature, °C	1900	1400	900–950
Duration of the main part of the pulse, μs	50	50	500
Preheating	320 μs to 700 °C	320us to 600 °C	–
Wear rate (original steel / with films) $\times 10^{-6}$, mm^3/Nm	0.53 (660/690)	740 (660/690)	720 (660/690)
Friction coefficient (original steel / with films)	0.73 (0.79/0.70)	0.64 (0.79/0.70)	0.60 (0.79/0.70)
Microhardness (initial/with films), kg/mm^2	545.4 (220/372.2)	264.6 (372.2)	367.9 (372.2)
Phases	$Fe_{0.6}Al_{0.4}$; $Ti_{0.84}$ $Fe_{0.16}$; $Fe_{1.25}Al_{0.75}$	–	Fe; $Ti_{0.02}Al_{0.98}$; Ti



(a) (b)

(c)

Fig. 2. Oscillograms of irradiation modes: a – mode No. 1, b – mode No. 2, c – mode No. 3.

Based on the results of studies of the structural and phase state of modified steel performed by transmission electron diffraction microscopy, it can be concluded that an increase in the mechanical (microhardness) and tribological (wear parameter) properties of the film (aluminum+titanium) system/(steel 12H18N10T) substrate is caused by the formation of a submicro-nanocrystalline multiphase structure containing inclusions of intermetallic phases such as Al_5NiFe, NiTi, Al_6Fe, $Al_{13}Fe_4$, CrNiTiFe.

4. Conclusion

A method has been developed for electron beam doping of the “film(Ti)/film(Al)/(12H18N10T) substrate system” with a modulated electron beam in a source with a SOLO plasma cathode based on a numerical model. This method of increasing the wear resistance of 12H18N10T steel is characterized by low costs of alloying elements and electricity, as well as cost, since alloying can be used as a post-processing of finished products. Modified steel can be used to make parts of tillage machines for agriculture, friction pairs for heavily loaded dry friction units, as an alternative to metal-ceramic friction materials.

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