Vibroacoustic monitoring of the intermetallic phase formation when electron-beam technology surface alloying

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Abstract. Synthesis of intermetallic phases of AlNi system using surface alloying technology on the surface of aluminum alloy products is not highly stable, so it seems appropriate to use diagnostic systems. In such cases, the method of vibroacoustic signal registration can be used, since it allows to control the kinetics of the process and phase transformations associated with the change in volume. Under the action of a low-energy high-current electron beam, the appearance of a vibroacoustic wave is due to the effect of thermoelasticity in a thin surface layer capable of providing a reaction of self-propagating high-temperature synthesis between a thin film of a titanium or nickel alloy and an aluminum substrate. Tracking changes in the effective value of the vibroacoustic signal make it possible to clearly state the formation of the intermetallic phase and select rational modes of irradiation.

1. Introduction
Among the many ways to modify the surface of aluminum details, for example, bodies of gadgets, against abrasion there are three ways to improve operational characteristics used in the materials industry. The first method is the development, as a rule, of new high-strength, high-doped alloys. It is quite expensive since the bulk alloying involves the use of a sufficiently large amount of deficient metals. Application to alloys of special metal coatings having wear resistance and corrosion resistance, as well as decorative coatings is the second way. The third way is the surface alloying. For surface alloying can be used anodizing, diffusion chromium plating, nickel-phosphorus coatings, nitriding and other methods of chemical-thermal treatment [1]. Moreover as an alternative to traditional methods can be the creation of an alloyed surface layer with increased wear resistance using the reaction of self-propagating high-temperature synthesis (SHS) [2].

In this case, it is possible to create a near-surface layer having a thickness of several micrometers, which increases wear resistance, by initiating an exothermic chemical reaction between the aluminum base and the metallic film deposited thereon with the formation of intermetallic compounds on the surface. The latter are a class of materials, the use of which in various fields of technology is rapidly expanding due to the unique complex properties [3], including high melting point, increased mechanical strength, and heat resistance.

This paper presents experiments on the hardening of the aluminum alloy (1.3% Cu, 0.26% Fe) plate surface by intermetallic phases of the NiAl system. The aluminum plate was coated with a thickness of about 0.2 microns of heat-resistant nickel alloy NiCr20TiAl. Subsequently, the plate with a metal coating applied to it was exposed to a series of pulses of a wide-aperture low-energy high-current
electron beam with a duration of about 5 µs. Chemical reactions between the metal film and the aluminum base were initiated.

2. Experimental
Processing was carried out in the installation "RITM-SP" which is a combination of a source of a low-energy high-current electron beam (LEHCEB) "RITM" and two magnetron sputtering systems on a single vacuum chamber [2]. The installation allows obtaining a beam of microsecond duration with a current density of up to 10,000 A/cm² at an accelerating voltage of 15–30 kV. The area of one-time processing is about 50 cm². The operating pulses were given at the generator charging voltage values from 18 to 24 kV, which corresponded to the irradiation energy density from 4.2 to 6 J/cm² [4, 5].

The formation of the structure in the near-surface layer of the material is largely due to the pulsed nature of the action in the microsecond range [6]. Here, the main factors of the surface alloying process are the energy of the electron beam, which depends on the accelerating voltage and the thickness of the deposited thin film. The dependence of the modified layer thickness on the accelerating voltage has a pronounced extreme character. Irradiation with insufficient energy in the beam is not able to initiate the SHS process, and its excess leads to evaporation of most of the film.

However, the control of the surface electron-beam alloying process of significantly complicates the instability of the electron beam pulse parameters and the process of its interaction with the processed material, which leads to some random changes in quality indicators that occur spontaneously, regardless of the control system. In this situation, it is proposed to use the acoustic emission method to monitor the process [7–9].

The pulsing action of the electron beam on the sample causes a vibroacoustic wave associated with the effect of thermoelasticity in a thin surface layer heated to the evaporation temperature of the substance in the vacuum. The recoil impulse due to the evaporation of the material in the irradiation zone also contributes. The high vibroacoustic activity of the resulting process is shown experimentally [10].

3. Results and discussion
The initial signal, passing through the elastic system, transforms by the amplitude-frequency characteristic of the observation channel. Experiments have shown that in this case, the components in the frequency range up to 40 kHz stand out against the background of noise. Low-frequency components up to 1 kHz, including all kinds of noise caused by the operation of the units of the "RITM-SP" unit, were also excluded from consideration. The recorded vibroacoustic signal was subjected to time and frequency analysis, to obtain information about the processes occurring on the irradiated sample. Effective (mean square) values of the amplitude of these signals filtered in different frequency ranges were taken as parameters of the vibroacoustic signal reflecting the kinetics of the processes on the workpiece surface. The width of the analyzed frequency bands approximately corresponded to the width of the octave band. Due to the discreteness of the spectra obtained, the analysis in narrower frequency ranges could have a significant spread associated with energy fluctuations in the electron beam and some variability of the amplitude-frequency characteristic of the elastic system.

It is observed that the amplitude of the vibroacoustic signal for the case of a coated sample increases significantly, starting from the third-fourth pulse. Analysis of optical images confirmed that the formation of intermetallic phases on the surface of the aluminum plate under irradiation by the first pulse, as a rule, does not occur. The film (figure 1(a)) is partly evaporated and partly mixed with the base and crystallizes in the form of extensive dendrite crystals (b). With further irradiation, in place of these crystals appear intermetallic phase inclusions up to several microns in size (c).

In figure 2 shows the recording of vibroacoustic signal and the effective values of its amplitude in octaves 32, 16, and 2–4 kHz, the irradiation of plates of pure aluminum (a), (c) and coated (b), (d). It is seen that in the presence of an alloying coating in the processes of changing the structure of the sample surface, short discrete pulses prevail, giving a contribution to energy at higher frequencies, which is in good agreement with [11, 12]. The growth of high-frequency energy in the spectrum of the vibroacoustic signal is accompanied by an increase in the content of the intermetallic phase.
Figure 1. The structure of the metal film of NiCr20TiAl alloy: (a) before the action of the electron beam; (b) after the action of the first pulse of the electron beam; (c) after irradiation with five pulses.

Figure 2. Records of vibroacoustic signal and effective values of its amplitude in octaves 32 (1), 16 (2) and 2–4 (3) kHz at irradiation of pure aluminum plates (a), (c) and plates coated with NiCr20TiAl alloy (b), (d) at the time of intermetallic phase formation.

Figure 3. The comparison of the amplitude spectra of the vibroacoustic signal during the pulse exposure in the range 1–15 kHz (a) and 15–25 kHz (b) for the coated plate (1) and uncoated (2).
The main signal energy was released in the first 40 ms. In figure 3 the signal spectra for low (a) and high (b) frequencies are shown.

When irradiating an aluminum alloy without coating, there is a clear predominance of low-frequency energy. On records of effective values of signal amplitude in the range of 2–4 kHz (figure 2(c), (d)) it can be seen that the irradiation of the plate without coating gives an amplitude eight times greater. This suggests that the process of formation of the intermetallic phase takes place without the “rough” pulses that accompany the processes of melting and recrystallization in aluminum.

Vibroacoustic signals accompanying the processes in materials subjected to electron beam effects have a complex varies spectrum. To effectively control the results of irradiation of various materials in an automated mode, a deterministic algorithm for processing vibroacoustic information is required, which allows evaluating the quality of the results in real time. In this case, quite a limited set of diagnostic parameters, the digital values of which allow monitoring the quality of the process and deciding on its repetition or change of the initial parameters.

For example, the analysis of vibroacoustic signals during irradiation of coated plates and a clean plate in the coordinates E (coefficient of kurtosis) – Alf/Ahf (the ratio of amplitudes in the bands of low and high frequencies in the neighborhood of the maximum signal in an octave of 16 kHz) makes it possible to unambiguously judge the passage of the reaction of intermetallic compounds (figure 4). Due to the change like the vibroacoustic signal on the chart, clusters of points are formed that are distinguishable in these coordinates. The oval shows a cluster of pulsed electron-beam effects, where the successful passage of the synthesis was recorded.

![Figure 4](image)

**Figure 4.** Graphical representation of the results of the analysis of vibroacoustic signals in the coordinates E (coefficient of kurtosis)/Alf/Ahf (the ratio of the amplitudes in the low frequency band to the amplitudes in the high frequency band in the neighborhood of the maximum signal in octave 16 kHz); number near the point means a sequence of pulses.

4. **Conclusions**

The experimental results indicate the possibility of obtaining on the upper layers of the aluminum alloy, modified by surface alloying. Such layers, which made it possible to increase the wear resistance of products, were obtained by initiating chemical reactions between the substrate and a thin Ni-based film deposited thereon. At that, in the reaction products, there was found a formation of a new phase component, particularly a NiAl intermetallic compound.

The formation of a structure in the near-surface layer of material, in our case, is due to a pulsed nature of exposure in a microsecond range. Here, the factors of the microalloying process shall be represented by the energy of the electron beam, dependent on the accelerating voltage, and the thickness of the thin film applied on the surface of the object. Irradiation with insufficient energy in
the beam cannot initiate a NiAl formation process, while the excess thereof results in evaporation of most of the film.

Monitoring of the vibroacoustic signal makes it possible to observe the course of transformations occurring during surface electron-beam alloying, including estimating the sufficiency of the power of the supplied electron radiation pulses.

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