Vibroacoustic Monitoring Features of Radiation-Beam Technologies by the Case Study of Laser, Electrical Discharge, and Electron-Beam Machining

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Abstract: A feature of radiation-beam technologies is similar processes associated with phase transformations and chemical reactions that cause changes in the volume of matter, accompanied by the vibroacoustic energy release distributed through the equipment flexible system in a wide frequency range (up to 40 kHz and high for 150 ms). The vibroacoustic signal amplitude accompanying radiation-beam technologies depends on the power density and process performance. The accelerated growth of the high-frequency components of the vibroacoustic signal is associated with the activation of the processes of volumetric boiling and evaporation/sublimation of the material. The \( K_f \) parameter, introduced as the ratio of the effective amplitudes of the low-frequency and high-frequency ranges of the vibroacoustic signal, monitors the results of high-energy flows’ impact on the material in the direction of vaporization/sublimation. The \( K_f \) parameter decrease tendency shows an increase in the proportion of the substance evaporated during laser treatment. The \( K_f \) parameter control allows the indication of the short-circuit approach in electric discharge machining, which allows increased productivity and reliability of processing. The monitoring of the \( K_f \) parameter helps to select rational processing modes, preventing excessive evaporation, providing the necessary intensity of the impact power to trigger the necessary chemical reactions in surface electron-beam alloying.

Keywords: electrical discharge machining; electron beam; diagnostic parameter; laser; vibroacoustic monitoring

1. Introduction

Modern trends in the development of technologies suggest automatic monitoring systems controlling the flow of manufacturing processes [1,2] and provide information on deviations of the current conditions from the optimal modes and warn about developing defects and emergencies. Simultaneously, there is a multiplicity of approaches to the algorithms for monitoring and selecting diagnostic parameters [3,4]. For example, information on the power consumed by the drives or on the parameters of the vibroacoustic (VA) signals accompanying cutting is used for the current control of metal-cutting equipment [5,6]. Other types of monitoring are usually available in the laboratory or only after completing the machining process.

There is much less information on monitoring methods implemented in processes related to radiation-beam technologies (RBT), based on the products’ surface’s impact by concentrated heat flows of energy with a high power density. Such technologies include exposure to plasma jets, laser radiation, electron or ion beams, which, although they differ like energy carriers, are associated with rapid heating and cooling of the surface layer due to plasma formation on the product’s surface [7,8]. Therefore, it is quite possible to assume some commonality of the effects of exposure to materials and the common properties...
of diagnostic signals accompanying these processes. Such an assumption allows getting hints and significantly reducing experiments since checking an established pattern is less expensive than search research by trials and errors.

In the case of RBT, processes are usually carried out in closed working areas, in vacuum chambers, the workpiece immersed in the working fluid even the presence of an operator often does not allow for effective control of the accompanying situations processing \[9,10\]. Power parameters are practically absent there, and their measurement itself is not available. The temperature characteristics could provide more information, but the qualitative measurement of thermal fields in the dynamics arising from millisecond thermal pulses is also not available. Unfortunately, the electrical characteristics of the processes are also clearly not enough for complete information about the accompanying phenomena. Although there are examples of successful adaptive control, such as electrical discharge machining, which is carried out by monitoring electrical parameters, there are proposed methods to supplement the existing monitoring by vibration signals in a wide frequency range \[11–14\]. Until recently, there was not enough information about the monitoring of processes in a vacuum chamber under electron-beam exposure of metals, which is explained by the complexity of equipment installation, but there are works on the study of phase transformations occurring in a vacuum \[15–17\].

Information about thermoelastic stresses, deformations, intergranular friction, and vapor recoil displayed in the phenomenon of acoustic emission, the essence of which is the process of emitting elastic waves during thermal expansion or compression of the material, phase, structural and chemical transformations, the occurrence of cracks, when the material is exposed to load pulses. The occurrence of elastic waves in structural adjustment processes is typical for processes with low (for example, martensitic transformations) \[18\] and high (diffusion processes) \[19\] activation energies. The main advantage of the acoustic emission method is that it allows getting information about the object of research in real-time when the installation of sensors at a considerable distance from the processing area.

This article describes an attempt to determine the relationship between the parameters of vibroacoustic signals and significant RBT parameters that affect the quality and performance of processing to create systems for monitoring and correcting processing modes. The commonality of such technologies lies in the fact that with an increase of thermal exposure intensity, the proportion of the evaporated/sublimated substance increases, reflected in the outstripping growth of the high-frequency components of the vibroacoustic signal. The effect is observed, although different carriers cause heat flows in the described technologies. This fact allows describing several technologies at once, for which the heat flow power and power density are essential. It is established that the processes accompanying laser, electrical discharge, and electron beam technologies generate vibroacoustic signals in the frequency range up to 40 kHz, which fade for a period of up to 150 ms and positively correlate with the power density of the supplied pulses.

During laser processing in the described experiments, the power and power density are proportional since the diameter of the spot in the focal plane has not changed. It is possible to maintain the power of the process quite accurately in electrical discharge machining, but the power density will vary significantly due to the presence of erosion products or the occurrence of short circuits. In electron-beam alloying, the supplied power and the power density are proportional to the charging voltage. Nevertheless, here random factors interfere, which change the real power density, despite the voltage constancy. It leads to the thermal effect is different. Thanks to vibroacoustic (VA) monitoring, express information about the progress of the technological process in real-time can be received and adjusted. The novelty is the proposal to use the ratio of the effective amplitudes of the vibroacoustic signal taken in the low-frequency and high-frequency ranges of its spectrum. It is experimentally shown that a decrease in this ratio correlates with an increase in the evaporated/sublimated substance proportion to estimate the increase in the proportion of a substance in the evaporation/sublimation state after the supply of thermal pulses. When
using the described connection, the parameters of the VA signals are different, which is
due to the distinctive features of the processes being implemented.

2. Materials and Methods

Vibrations in the processing area were measured using a piezoelectric accelerometer
KD35 (ViCont, Moscow, Russia), operating in a wide frequency range (from a few Hz
to hundreds of kHz, considering non-linear frequency ranges). It converts the vibration
acceleration of the surface on which it is mounted into an electrical signal. It is necessary
to consider a valid signal in the processing area and interference from other mechanisms
during installation (for example, noise from the operation of drives, pumps).

The accelerometer is installed on the object using a magnet. The signal must im-
mediately amplify to reduce the interference. This function is performed by the PM-3
preamps (Izmeritel, Rostov, Russia), which can be installed directly on the accelerometer or
separately but at a minimum distance. Then the signal was transmitted at a distance of
several meters to the VSHV-003 amplifier (ViCont, Moscow, Russia), where the gain needed
for registration was selected. The signal was digitized using an L-CARD analog-to-digital
converter (ADC) (L-Card, Moscow, Russia) and recorded in the computer’s memory for
further analysis. The frequency of signal polling in the ADC depends on its capabilities and
the required frequency analysis range. One or more channels are organized, formed using
single-channel amplifiers depending on the tasks to be solved. Figure 1 shows a diagram
of the organization of two channels for registering VA signals from two accelerometers.

![Equipment structure connection diagram.](image)

The optimal gain factors were monitored to avoid overloads and ensure a good signal-
to-noise ratio according to the indicators of the amplifying equipment and the monitor.
This control is primary and further refined. The recorded signals were processed using
special software.

The concept of the amplitude-frequency response (AFR) is used in vibroacoustic
diagnostics often. There is the dependence of the transmission coefficient in the observation
channel on the frequency of the input action. The transmission coefficient is defined as
the vibration acceleration and force amplitudes ratio for a specific frequency if a force
action is used as the input signal. The vibration acceleration amplitude is used as the
output signal (as at the accelerometer output). The content of the transmission coefficient
may change if other parameters are controlled at the input and output. Researchers are
often interested in vibration velocity or vibration displacement as an output signal. In
this case, the output signal from the accelerometer is integrated once or twice. However,
the integration procedure may be associated with a decline in signal quality. They are
analyzed in the time and frequency domains by spectral analysis techniques to expand the
information capabilities of vibration signals.
Experiments conducted with the laser equipment model U15 (RMI) (RMI, Lafayette, LA, USA), with an input power of 15 W, assess the dependence of the parameters of the VA signals on the pulse action energy. A solid-state laser marker with a diode pump is designed for marking metals and their alloys, silicon, and ceramic surfaces.

Experiments to monitor the laser sintering of powder materials are conducted on the two kW laser machine TruLaser Cell 3008 (Trumpf, Hanover, Germany) with high-performance CW laser with welding optics.

Experimental studies were carried out on wire electrical discharge machines CUT 30P and CUT 1000 Agie Charmilles (GF, Biel, Switzerland). Parallel recordings of the VA signal and the discharge current were made when cutting plates made of conductive ceramics Al₂O₃-30%TiC [20–22] and hard alloy WC-6%Co.

The work was carried out on an experimental stand (Figure 2).

![Figure 2. The mechanical part of the electrical discharge machining stand.](image)

A series of experiments on irradiation of steel, hard alloy, and aluminum samples were carried out to detect changes in the spectrum of vibroacoustic signals during electron-beam processing. For this purpose, the RHYTHM-SP (Microsplav, Tomsk, Russia) installation was used, a source of low-energy high-current electron beams (LEHCEB) RHYTHM combined with two magnetron sputtering systems on a single vacuum chamber [23]. The installation allows the deposition of films of different materials on the surface of the desired product and the subsequent liquid-phase mixing of the film and substrate materials by an intense pulsed electron beam. In this case, the thickness of the surface alloys formed can range from fractions to tens of micrometers. Combining electron-beam surface treatment, coating, and subsequent remelting with the base with an electron beam in one working cycle makes it possible to obtain alloys of controlled composition and structure on the surface of products of various shapes.

The generation of LEHCEB involves the emission of electrons from the explosion-emission cathode, forming a beam in a plasma-filled diode and further transportation in the plasma channel. Such a generation scheme makes it possible to obtain a beam of 5 µs duration with a current density of up to 104 A/cm² at an accelerating voltage of 15 to 30 kV. The area of one-time processing is about 50 cm².

As a result, the impact of charged particle beams on the object by plasma flows, the surface layer of the alloy was heated at high speed (up to 10⁶ s⁻¹) to temperatures exceeding the melting point of the components, followed by cooling at an extremely high speed (10⁴–10⁷ s⁻¹). The temperature in the near-surface layer reaches values that exceed the melting point of the system components. Due to the high-temperature difference and the complex stress state of the material, the cascades of atoms shift, and a large
concentration of structural defects occurs, which causes intense diffusion fluxes of atoms. High-speed thermal cycling is accompanied by the interfacial interaction of the components according to non-equilibrium state diagrams and leads to a non-equilibrium structure.

The essence of the method is to melt the surface of the processed material together with alloying components, which are pre-applied to the treated area using a magnetron. A coating with a given chemical composition applied to the samples’ surface fused into it and now forms a single whole with the base.

3. Results and Discussion

3.1. Investigation of the Effect of Laser Radiation Power on Performance and Vibroacoustic Signals

One of the essential properties of the diagnostic parameter is its relationship with the performance of the technological process. An experiment was conducted to evaluate the relationship between the VA signal parameters and the performance of the process. The productivity is estimated as the volume of material produced due to exposure to laser pulses of different power [24]. The plate made of AISI 410 stainless steel was processed.

Figures 3 and 4 show the dependencies of the signal amplitude and performance on the laser power. The presence of these dependencies allows the formation of a general function of the signal amplitude VA on the performance.

![Graph of experimental dependences of the VA signal amplitude on the power output (N) of laser radiation for the effective amplitude (A) of the VA signal in a wide frequency band and the octave band of 16 kHz (A\textsuperscript{16}).](image)

**Figure 3.** Experimental dependences of the VA signal amplitude on the power output (N) of laser radiation for the effective amplitude (A) of the VA signal in a wide frequency band and the octave band of 16 kHz (A\textsuperscript{16}).

![Graph of experimental dependence of the performance (P) on the power output (N) of the laser radiation.](image)

**Figure 4.** Experimental dependence of the performance (P) on the power output (N) of the laser radiation.

There will be no removal of the material due to the lack of energy for melting the material at the minimum values of the laser radiation power output. However, it is possible to construct an approximate dependence of the signal amplitude VA on the performance P at power output at N > 20% based on the dependencies in Figures 3 and 4 in the form:

\[
A = C \cdot P^\beta
\] (1)
where $A$ is the amplitude of the high-frequency VA signal; $C$ is a constant depending on the selected frequency range and the characteristics of the accelerometer in the octave of 16 kHz; $\beta$ is the exponent of performance, the values of which are in the range of 1.14–1.16 for this example. It is possible to monitor the current performance of laser processing and adjust the laser beam focus position when the workpiece changes, having the dependence (1).

Another frequency range may be chosen. Figure 5 shows the spectra of the VA signal at different laser power outputs in the range of 12–20 kHz. It can be seen that everywhere there is a monotonous increase in the amplitude of the VA signal with an increase in the laser power output. The local maxima corresponding to the own frequencies of the workpiece do not change their position when the laser power changes, which speaks in favor of the linear model of a dynamic system with this processing technology. Thus, the dependence (1) can be applied to other frequency ranges, but the coefficients $\beta$ will be obtained differently. For monitoring, the monotony of the amplitude change and the information content of the signal parameter VA is essential, which is estimated by the magnitude of the amplitude increment per unit of power change.

![Figure 5. Vibroacoustic signal spectra at different laser radiation power outputs.](image)

Spectral maxima can occur in the spectrum of the VA signal. Such maxima are associated with the natural frequencies of the technological system and the forced frequencies caused by laser pulses. Figure 6 shows an example of a spectrum in the lower frequency range compared to Figure 5. The frequency of the applied pulses was 10 kHz with a duration of 10 ns. In addition, periodic modulation with a frequency of about 33 Hz occurred in the laser radiation.

![Figure 6. Examples of the VA signal recording in a spectrum range of 9.5–10.5 kHz under pulsed laser exposure.](image)
The central spectral maximum is located at the pulse frequency. The side components, by a multiple of the laser pulse modulation frequency (33 Hz), are separated from this maximum. It can be seen that each pulse of laser radiation is reflected in the VA signal. The modulation of the pulse series is visible. There may be other forced frequencies that occur during processing in the spectrum of the VA signal, for example, components associated with the operation of the machine drives.

How the material is removed in laser processing is crucial: by melting or sublimation. The surface quality is higher with sublimation, but this requires more energy consumption. It can be assumed that the sublimation mode is accompanied by intense vaporization with recoil pulses from the vaporized substance. The recoil pulses are shorter than those generated during melting. The presence of short pulses will create a VA signal in a higher frequency range. Figure 7 shows the spectra of the VA signals that accompanied the operation of the laser at different power levels. It can be seen that with an increase in the radiation power of 1.5 times, the signal amplitudes in the high-frequency region significantly increased.

![Figure 7. The VA spectra during laser processing with a power output of 60% (1) and 40% (2).](image)

Figure 8 shows the $K_f$ graphs representing the changes in the ratio of low-frequency effective amplitudes to high-frequency amplitudes over time. The dependencies can be constructed by taking the effective values of the amplitudes for each operation with a specific laser power output. It can be seen that $K_f$ decreases with increasing laser power output due to the rapid growth of the high-frequency component of vibrations associated with the advanced activation of sublimation processes.

Laser sintering of powder materials also requires monitoring since deviations from the optimal combination of speed and power of the laser beam can violate the quality indicators of the resulting part [25]. These indicators include the strength and uniformity of the resulting product, the consumption of energy and powder material, and the performance of the operation. Sintering a metal powder is different from laser cutting a monolithic billet, but the results obtained are interesting compared to previous data.

Figure 9 shows the VA signal spectra obtained by sintering a layer of AISI 410 steel powder with different beam travel speeds. The spectra for better visualization are presented separately for the low-frequency and high-frequency ranges. It can be seen that an increase in the speed of the beam movement leads to an increase in the amplitude of the VA signal in almost the entire frequency range, but this increase is more noticeable in the high-frequency region, especially in the range of 10–20 kHz.

Figure 10 shows microphotographs of the tracks obtained by sintering the steel 410 powder at different speeds. When the beam moves at a low speed (Figure 10, Microphotograph 1), a large amount of powder is fused, the track is more expansive, and the consumption of the powder is significant. The increase in the beam speed by 2.5 times (Figure 10, Microphotograph 2) reduces the width of the track without breaking its continuity. When the speed increases by another two times, the track becomes thinner, but its uniformity is noticeably disturbed. Microphotograph 4 shows the track obtained under the conditions of Microphotograph 2, but with a power reduced by two times. The inhomogeneity of the track and the areas with breaks are striking.
Figure 8. The change in the average square value of the VA signal amplitude in the octave bands 8 kHz (green) and 16 kHz (blue) and their ratio $K_f$ (black) with changes in the power output N% of laser pulses.

Figure 9. Spectra of the VA signal in the low (a) and high (b) frequency ranges when sintering an AISI 410 steel powder layer with different laser beam speeds: (1)—10 mm/s; (2)—25 mm/s; (3)—50 mm/s.

Figure 10 shows microphotographs of the tracks obtained by sintering the steel 410 powder with different beam travel speeds. The spectra for better visualization are presented separately for the low-frequency and high-frequency ranges. It can be seen that an increase in the speed of the beam movement leads to an increase in the amplitude of the VA signal in almost the entire frequency range, but this increase is more noticeable in the high-frequency region, especially in the range of 10–20 kHz. The given graphs show how the frequency component of the VA signal indicates an outstripping growth of the boiling track. As a working hypothesis, we can assume that the outstripping growth of the high-frequency component is explained by the fact that a larger volume of surface powder particles melted per time unit at a high beam speed making the sublimation the most outstanding contribution to sublimation. At high beam speed and insufficient power, the powder does not have time to fuse with the substrate, as shown in Figure 10, Microphotograph 4.

Figure 11 shows the dependences of the effective amplitudes in the low-frequency and high-frequency ranges and their relationship $K_f$ to the beam speed. With increasing speed, the amplitudes increase at all frequencies, but the growth is faster at high frequencies, which leads to a monotonous drop in $K_f$. This dependence between the amplitude and the speed is explained by the fact that a larger volume of surface powder particles melted per time unit at a high beam movement making the most outstanding contribution to sublimation. At high beam speed and insufficient power, the powder does not have time to fuse with the substrate, as shown in Figure 10, Microphotograph 4.

Figure 12 shows the VA signal handling results accompanying laser sintering processes with the same beam speed but different power output. It can be seen that in the entire frequency range, the amplitude at high power is higher. When the laser power is reduced to 50 W, the amplitude of the high-frequency component decreases more strongly, which leads to an increase in $K_f$ values and a corresponding deterioration in the quality of the track. As a working hypothesis, we can assume that the outstripping growth of the high-frequency component of the VA signal indicates an outstripping growth of the boiling...
and evaporation/sublimation process. It is possible to limit the boiling and evaporation processes by changing the process mode if pre-set the \( K_f \) limit.

![Microphotographs of laser sintering tracks with different modes: (a)—power 100 W, speed 10 mm/s; (b)—power 100 W, speed 25 mm/s; (c)—power 100 W, speed 50 mm/s; (d)—power 50 W, speed 25 mm/s.](image)

**Figure 10.** Microphotographs of laser sintering tracks with different modes: (a)—power 100 W, speed 10 mm/s; (b)—power 100 W, speed 25 mm/s; (c)—power 100 W, speed 50 mm/s; (d)—power 50 W, speed 25 mm/s.

![Graph showing the changes in the effective amplitude of the VA signal in the frequency bands of 0.4–6 kHz (red), 10–20 kHz (blue), and their ratio \( K_f \) (black) with changes in the speed \( V \) of the laser beam.](image)

**Figure 11.** The changes in the effective amplitude of the VA signal in the frequency bands of 0.4–6 kHz (red), 10–20 kHz (blue), and their ratio \( K_f \) (black) with changes in the speed \( V \) of the laser beam.

![Graph showing VA signals during laser sintering with the same speed and different laser power output: (1)—100 W, (2)—50 W.](image)

**Figure 12.** VA signals during laser sintering with the same speed and different laser power output: (1)—100 W, (2)—50 W.

The parameters of the accompanying VA signals uniquely respond to changes in the intensity of laser radiation and changes in the scanning speed of the laser beam. The positioning of the focal plane relative to the surface of the workpiece affects the intensity of...
the energy flow, and, therefore, the evaporation processes, which is displayed in the VA signals in the form of monotonic dependencies and makes it possible to use vibroacoustic diagnostic methods for monitoring the quality of laser processing.

3.2. Analysis of Vibroacoustic Signals during Electrical Discharge Machining

The processing of materials on electrical discharge equipment is faced with short circuits, wire electrode breaks, the appearance of chips and burrs when separating the part [26,27]. These phenomena can cause the unsatisfactory quality of the cut and lead to a defective final product. Methods and means of VA diagnostics allow the expansion of knowledge on the physics of the technological process and create a set of measures that make it possible to improve the quality of the machined surfaces. Hence, the research aims to identify the relationship of the parameters of the VA signals accompanying the electrical discharge machining (EDM) with the current process parameters.

The EDM principle is based on the destruction and removal of the material by the thermal action of a pulsed electric discharge directed to the workpiece surface placed in the dielectric medium (liquid such as deionized water and hydrocarbons, or air) [28]. Under the action of electric discharges, material removal occurs, leaving the pattern of single wells covered with the deposed secondary structures of secondary material on the surface. The size and density of wells are determined by the EDM modes, including the parameters and methods of generating discharges (operational voltage is responsible for size and current is for density), the properties of the workpiece (mainly electrical resistance), and working medium [29–32]. The same phenomena are present in laser processing and based on this idea, the vibroacoustic signals accompanying the EDM will have similar properties. Among these properties, it is essential to note the monotonic relationship of the VA signals amplitude with the processing performance and the change in the ratio of amplitudes in the low-frequency and high-frequency ranges of the VA signal when the ratio of the volumes of molten and vaporized materials changes.

The radiation power was changed to assess the relationship of the VA signals with laser processing performance. Unfortunately, this is not provided for by the functions of the equipment on the Agie Charmilles EDM. However, it is possible to change the performance of the process by changing the frequency of the discharge pulses. Figure 13 shows the VA signal spectra at different EDM frequencies. The hard alloy WC-6%Co was processed according to the mode: U = 80 V, I = 2 A, current pulse duration of 0.01 ms, the pulse repetition frequency of 35 kHz, S_{sol} = 40%.

![Figure 13](image_url)

**Figure 13.** The spectra of VA signals during EDM processing at different power outputs of the energy impact when WC-6%Co cutting.

Let us compare Figures 5 and 13. There are many similarities in the behavior of the curves.

From the spectra in Figures 5 and 13, it can be concluded that changes in the energy fluxes power do not change the position of the spectral maxima of the VA signals both during laser processing and during EDM. The spectral maxima are determined exclusively by the own frequencies of the elastic system. Moreover, since there is no
direct contact between the tool and the workpiece during processing (as in cutting processing), the dynamic characteristics do not change with increasing impact power. That is, the frequency response of the process does not change. The monotonous growth of the amplitude with an increase in the impact power is not violated anywhere, although the increase in the amplitude of the VA signals in different frequency ranges is not strictly proportional. For EDM, this position is actual for the same state of the discharge gap. The variable concentration of erosion products in the discharge gap distinguishes EDM from other RBT technologies. This feature makes it much more difficult to obtain information about the happening processes since the concentration of erosion products at any given time remains unknown.

The data presented in Figure 13 were obtained under the assumption that the discharge gap had a minimum concentration of erosion products. In this case, the VA signals were recorded at the beginning of machining, when the working fluid was still clean. The practice had established that when there is a pure discharge gap, maximum performance is observed, and when the maximum concentration of erosion products increases, productivity falls to the minimum values. When there is a further increase in the concentration, a short circuit occurs, the material of the workpiece is not destroyed, and the energy is spent on heating the electrodes. The temperature field extends only to a part of the wire electrode diameter in an ideal EDM process. The temperature field captures the entire body of the electrode tool, which threatens a sharp decrease in the elastic modulus of the electrode material, melting and breakage under tension forces when the discharges are localized.

Figure 14 shows an example of short-circuit VA signals during the processing of conductive ceramic Al₂O₃-30% TiC (the voltage—72 V, the pulse repetition frequency—25 kHz, the pulse duration—2.7 µS, the rewinding speed—7 m/min, the wire tension force—0.3 N). A short circuit does not lead to rapid breakage of the electrode due to the high electrical resistance of the material. This effect allows us to better consider the characteristics of the VA signal.

![VA signals and discharge current](image)

**Figure 14.** Recording of the VA signals and the discharge current at the site of a short circuit during Al₂O₃-30%TiC ceramics electrical discharge machining.

It can be seen that, in the short-circuit section of the VA, the signal becomes barely noticeable against the background of regular machining. The current amplitude increases several times. When a metal alloy was used as a blank electrode, the current increase was more significant; this would lead to a break in the wire electrode. The breakage was avoided. With the help of forced washing of the discharge gap, it was possible to get rid of the excess amount of erosion products, and the machining continued.
A signal with a relatively small amplitude was still present during the short circuit period. The low rewinding speed of the wire conductor generated a wide-spectrum but small-amplitude VA signal. The fact that the amplitude of the VA signal significantly exceeds the amplitudes accompanying the friction contact during the short-circuit period in the entire frequency range during the ordinary course of the EDM process allows the use of the VA signal as an indicator of short-circuits for the emergency reverse of the electrode in order to relax the discharge gap and restore the discharge gap.

Processing conductive ceramics with frequent short circuits with a long duration does not always lead to a break in the wire electrode but is also characterized by other troubles. Cracks and chips may occur directly next to the incision on the Al$_2$O$_3$-30\% TiC plate [33,34].

The processing mode was as follows when processing an aluminum plate on an experimental stand (Figure 2). Discharge pulses with a voltage of 100 V and current amplitude of 80 A were applied at a frequency of 1 kHz, but with a different duty cycle. The duration of the voltage pulses varied from 10\% of the period between the pulses to 90\%. In this case, the discharge current, voltage, and VA signal were recorded (Figure 15). The VA signal was recorded from an accelerometer mounted on the workpiece attachment unit outside the working fluid. A well of a complex shape, the volume of which was estimated to determine the electrical discharge machining performance, formed due to the impact of the discharge current on the aluminum alloy plate.

![Figure 15](image1.png)

**Figure 15.** Example of recording voltage, current, and vibration signals during electrical discharge machining with a pulse width of 10\% (recording time of 0.3 s).

Signal amplitude root-mean-square values (RMS) were used when processing the experimental data. Figure 16 shows an example of recording the RMS of the VA signal in the range of 1–10 kHz and the RMS of the discharge current. The records are different. The RMS of the current changes are more minor than the RMS of the VA signal because not all discharge pulses entirely give their energy to the workpiece. Part of the pulse energy interacts with the products of erosion, weakening the impact on the workpiece.

![Figure 16](image2.png)

**Figure 16.** Changes in the RMS of the VA signal (range of 1–10 kHz) and the discharge current (pulse duration of 80\%).

Figure 17 shows the spectra of the VA signals at different duty cycles of the discharge pulses. It can be seen that the amplitude of the VA signal increases by order of magnitude in the region of 3 kHz, with an increase in the pulse duration by eight times.
Figure 15. Example of recording voltage, current, and vibration signals during electrical discharge machining with a pulse width of 10% (recording time of 0.3 s).

Signal amplitude root-mean-square values (RMS) were used when processing the experimental data. Figure 16 shows an example of recording the RMS of the VA signal in the range of 1–10 kHz and the RMS of the discharge current. The records are different. The RMS of the current changes are more minor than the RMS of the VA signal because not all discharge pulses entirely give their energy to the workpiece. Part of the pulse energy interacts with the products of erosion, weakening the impact on the workpiece.

Figure 16. Changes in the RMS of the VA signal (range of 1–10 kHz) and the discharge current (pulse duration of 80%).

Figure 17. Comparison of the VA spectra of signals accompanying the operation of discharge pulses with different duty cycles: pulse widths of 10% and 80%.

The RMS of the VA signal amplitude in the range of 1–10 kHz ($A_E$) was calculated for seven experiments with different duty cycles. The energy VA of the signal ($W$) for the EDM period in each experiment was calculated by the formula:

$$W = A_E^2 \cdot T$$

where $T$ is the processing time.

The valuable work ($Q$) carried out during the EDM experiment was calculated in the volume of the removed material. The coefficients of the linear approximation were calculated using the least-squares method. The dependency has the form:

$$W = 3.24 \cdot Q + 44.8$$

The linear approximation of the oscillation energy on the amount of valuable work dependence is shown in Figure 18.

The VA energy of the signal released during the entire processing period changes almost linearly with an increase in the electrical discharge machining performance. The amplitude of the VA signal will increase slightly more slowly since the energy of the oscillations is proportional to the square amplitude of the oscillations. Therefore, it is possible to get a dependency of the form from Equation (3).

$$A = C \cdot Q^{0.47}$$

Figure 18. Dependence of the oscillation energy on the amount of valuable work.
The exponent in Equation (4) is smaller than in Equation (1), but the monotony of the dependence is preserved. The monotonous growth of the effective amplitude of the VA signal with an increase in the performance of the EDM process can be taken as a basis for creating monitoring systems and adaptive control of such technological operations. Of course, it is necessary to carefully select the frequency range, where the information content of the diagnostic parameter will be the greatest.

It was shown above how the \( K_f \) coefficient changed with increasing laser radiation intensity. A similar relationship should be observed in EDM. Figure 19 shows the RMS records of the amplitudes of the VA signals (a) and the spectra of the VA signals (b) for a segment of the hard alloy WC-6%Co. The amplitudes were recorded for the ranges of 1.4–2.8 kHz and 10–20 kHz. In both ranges, changes in amplitudes have opposite tendencies: for high frequencies to decrease, for low frequencies to increase. Due to the influence of the random component associated with the concentration of erosion products, these trends do not appear in a strictly monotonous form, but their presence is noticeable. The \( K_f \) coefficient increases unevenly throughout the entire processing process. It increases by order of magnitude in 3 s before the break. If the machine control system considered the change in this coefficient, it would be possible to prevent electrode breakage. It was enough to make a short-term stop of the supply for enhanced washing of the discharge gap. The spectra in Figure 19b confirm this trend. When the moment of wire tool breakage approaches, the amplitudes at high frequencies fall, and ones at low frequencies (less than 5 kHz) increase.

A change in the energy flux intensity in laser radiation is associated with a change in the \( K_f \) coefficient. The mechanism for changing the intensity of laser radiation could change the beam’s diameter on the machined surface due to the displacement of the focal plane. If the area of the beam spot increased, the intensity of the energy flow decreased. It led to a change in the ratio of the vapor and liquid phases. The decrease in the vapor phase led to a decrease in the proportion of short pulses and decreased amplitude of the vibrations high-frequency component. Simultaneously, the heating zone of the substance expanded, which provided an additional contribution to the low-frequency component.

In EDM, the mechanism for changing the ratio of the vapor and liquid phases is somewhat different, but its essence again consists of changing the intensity of the energy flow. One of the prominent roles in these changes is the concentration of erosion products in the discharge gap. The energy flow enters the surface of a larger area with an increase in the concentration of erosion products due to the energy expenditure for its destruction. The electrodes are closed through arrays of erosion products, the energy is distributed over such a large area that the material evaporation/sublimation completely stops, and its removal stops in an extreme short-circuit situation (the discharge gap conditions are violated). For these reasons, short-circuit pulses do not produce valuable work but cause thermal stresses and local deformations that cause the propagation of elastic waves. The spectrum of these waves covers a lower frequency range compared to the recoil pulses from vaporization processes.
Typical consequences of the impact on the electrodes of energy flow with reduced values of the intensity of the energy flow during a short circuit are cauterization on the material’s surface, reflow in the form of cracks on the machined surface. These phenomena are particularly noticeable when processing conductive ceramics. There is no rapid breakage of the wire tool to observe the picture in more detail. There are visible deposits of brass on the edges of the machined surface, which were obtained due to the short circuits. Spectral analysis of the chemical composition of the trace on the ceramic sample shows that the copper and zinc of a tool electrode are adsorbed on the machined surfaces [34].

Figure 20 shows just one example of change in the $K_f$ coefficient from the processing time of the $\text{Al}_2\text{O}_3$-30% TiC ceramic, caused by the contamination of the discharge gap by erosion products.

3.3. Vibroacoustic Monitoring of Electron Beam Alloying

Electron beam alloying technologies are related to RBT in the same way as laser processing and electric discharge machining since they are based on concentrated energy flow processing material. The thermal energy is transmitted by a 5 $\mu$s electron beam and acts immediately on a vast area (about 50 cm$^2$), where the target-blank is located. The patterns of VA signal change should correspond to the results described above.

Vacuum coating methods are widely used at present, and, in some cases, they are the only effective technological solution for increasing the durability and wear resistance of
mechanical engineering products. Of great interest are promising methods for obtaining coatings using modern vacuum technologies, such as electron-beam alloying.

![Graph showing the change in the effective amplitude of the VA signal](image)

**Figure 20.** The change in the effective amplitude of the VA signal in the frequency bands of 0.4–6 kHz, 10–20 kHz, and their ratio $K_f$ over time due to contamination of the interelectrode gap by erosion products during cutting of Al$_2$O$_3$-30% TiC ceramics.

It is necessary to develop monitoring systems to improve the control of electron-beam doping processes. These systems should obtain information about thermoelastic stresses and deformations, intergranular friction, and the recoil of vapors of the irradiated material. The control of the surface alloying process is complicated by a sufficiently large number of control factors determined primarily by sufficient energy for the heat treatment of the surface layer thickness (melting and partial evaporation/sublimation), which must be introduced. The main factors include the charging voltage value, which determines the beam's specific energy and the film's thickness with alloying components deposited using magnetron sputtering.

However, the instability of the electron beam parameters and the process of interaction with the processed material, and the random distribution of the beam energy over the irradiated surface lead to significant results spontaneously, regardless of the control system. This problem violates the strict repeatability of the surface alloying process, primarily since no single observable parameter reflects its kinetics.

In addition, electron-beam alloying processes differ in that they are carried out in chambers with a high vacuum. Unfortunately, the placement of any equipment inside the chamber is significantly complicated due to the impossibility of introducing shielded cables through the vacuum inlet and the powerful electromagnetic effect during the passage of an electronic pulse. The impact of the pulse can lead to unacceptable interference in the operation of the equipment and its damage.

When pulsed by electron beams, the surface layer is subjected to a thermal shock, which creates a volumetric expansion and motion of a thermoelastic wave in the material. The substance density jump forms a perturbation in the flexible system that propagates in all directions at the speed of sound. This perturbation gradually fades in space and time, but it can record vibrations of the surfaces of adjacent parts of the structure.

Another reason for the occurrence of VA activity is the impulses of the reactive vapor pressure of the material. Also, the source of VA signals changes in the microstructure of the substance surface layer, accompanied by a variation in its volume and deformation.

Since the installation of vibration measuring equipment inside the vacuum chamber and next to it causes several difficulties described above, a flexible waveguide in the form
A flexible system supplemented with a waveguide will change its dynamic characteristics, frequency response, and transmission coefficients at different frequencies. Immediately there is a whole series of questions: How does the cross-sectional area of the waveguide affect the transmission coefficients of the elastic system, and where are the permissible limits of variation of this cross-section? How does the tension of the wire waveguide affect the change in its characteristics? How critically does the sealing of the vacuum inlet affect the properties of the waveguide? The main question is, how effective is the use of VA signals recorded at the output of the waveguide to display the features of the processes occurring in the vacuum chamber?

On a qualitative level, it is clear that with a decrease in the waveguide cross-section and an increase in its length, the dynamic compliance (transmission coefficients) will decrease, but the rate of these changes for different frequency ranges remained unclear. It was found that the presence of tension changes the position of the spectral maxima as a result of experiments with changing the tension of flexible waveguides of different cross-sections. However, the transmission coefficient significantly changes for a thin waveguide (cross-section of 1 mm²) only in the low-frequency region. The tension of up to 1.5 kg does not significantly affect the VA signal in the frequency range above 2 kHz for a 2.3 mm² cross-section waveguide.

The possibilities of vibroacoustic monitoring were evaluated when studying the surface electron-beam alloying of an aluminum plate with a chromium-nickel alloy and titanium. A plate was covered with a film about 0.2 µm thick by magnetron sputtering to ensure the formation of the surface alloy occurs under the action of an electron beam and to initiate a self-propagating high-temperature synthesis reaction on the sample surface.

There were high-frequency VA signal spectra for pure aluminum, aluminum with a Ni₇₇Cr₂₃ film, and aluminum with a Ti film as shown in Figure 21. It can be seen that the largest amplitudes were obtained when doping a plate with a NiCr coating, the smallest when exposed to electron beams on aluminum with a Ti coating.

![Figure 21](image)

**Figure 21.** Comparison of the VA signal spectra during electron-beam alloying of an aluminum plate coated with a metal film: (1)—pure aluminum; (2)—aluminum with a NiCr film; (3)—aluminum with a Ti film.

Irradiation of the aluminum surface leads to melting and evaporation of the metal, accompanied by a temporary increase in the volume of the material, an increase in internal stresses that generate VA energy in the aggregate. In films, the base and coating metals react to form intermetallic compounds, accompanied by a structural rearrangement of the
surface layer, which changes the local volumes and generates additional elastic waves in the workpiece material leads to an increase in the spectral components on the receiving plate. The experiment is interesting because, due to the high thermal conductivity of aluminum, the temperature on the surface of the workpiece, limited by the evaporation temperature of aluminum in a vacuum, often does not reach the value necessary to initiate the synthesis of intermetallic compounds during electron-beam processing. Besides, the wetting properties and the presence of oxide films can further increase the required temperature.

The passive behavior of the plate with a titanium coating was explained by the fact that after magnetron sputtering, before being placed in a vacuum chamber, the titanium coating was in contact with air oxygen, forming compounds that did not always enter into chemical reactions.

It was noticed that the amplitude of the vibroacoustic signal increases significantly, starting from the third or fourth pulse. The analysis of optical images confirmed that the formation of intermetallic phases on the surface of the aluminum plate during the first pulse irradiation, as a rule, does not occur. The film partially evaporates, mixes with the base, and crystallizes in the form of long dendritic crystals (Figure 22a). However, the resulting surface alloy has a higher melting and evaporation temperature making it possible to initiate the intermetallic formation reaction upon further irradiation. Intermetallic inclusions of the NiAl phase with a size of up to several microns appear (Figure 22b).

The surfaces of the samples examined using the Thixomet image analyzer to estimate the proportion of intermetallic compounds were obtained, the crystals of which were visible with an optical microscope.

Figure 22. Structure of the surface of an aluminum plate alloyed with a Ni$_{77}$Cr$_{23}$ alloy: (a) after exposure to the first pulse of the electron beam; (b) after irradiation with five pulses.

Figure 23 shows the recording of the original vibroacoustic signal and the envelope of its high-frequency component in the range of 35–40 kHz. The primary energy of the VA signal is allocated in the initial 40 ms. In the presence of an alloying coating in the processes of changing the structure of the sample surface, short discrete pulses predominate in the high-frequency component of the VA signal, between which there are signal dips almost to the level of interference. These bursts of the VA signal can be attributed to processes that increase the proportion of high-frequency components. This behavior may indicate the emergence of some new reaction centers, which appear at different times by the local peaks of the high-frequency component of the VA signal (envelope 2 in Figure 24) and identify the moments of activation of the chemical reaction. There is reason to believe that the reaction is distributed over the irradiated surface in new centers. An increase in the proportion of high-frequency components in the VA signal spectrum corresponds to an increase in the intermetallic phase.
Figure 22. Structure of the surface of an aluminum plate alloyed with a Ni\textsubscript{77}Cr\textsubscript{23} alloy: (a) after exposure to the first pulse of the electron beam; (b) after irradiation with five pulses.

Figure 23. The initial recording of the VA signal (1); the RMS envelope of the VA signal in the range of 35–40 kHz in an averaging period of 0.14 ms (2). The primary energy of the VA signal is allocated in the initial 40 ms. In the presence of an alloying coating in the processes of changing the structure of the sample surface, short discrete pulses predominate in the high-frequency component of the VA signal, between which there are signal dips almost to the level of interference. These bursts of the VA signal can be attributed to processes that increase the proportion of high-frequency components. This behavior may indicate the emergence of some new reaction centers, which appear at different times by the local peaks of the high-frequency component of the VA signal (envelope 2 in Figure 24) and identify the moments of activation of the chemical reaction. There is reason to believe that the reaction is distributed over the irradiated surface in new centers. An increase in the proportion of high-frequency components in the VA signal spectrum corresponds to an increase in the intermetallic phase.

Figure 24. VA signal in different frequency ranges under irradiation of pure aluminum (a) and aluminum with Ni\textsubscript{77}Cr\textsubscript{23} coating (b).

The features of the behavior of VA processes in different frequency ranges under electron-beam action on an uncoated and coated aluminum plate are shown in the records of Figure 24a,b.
It can be seen that in the presence of coating, the ratio between amplitudes at low and high frequency ranges changes dramatically in favor of high-frequency ones. Under laser irradiation, such a change in the ratio of effective amplitudes indicated an increase in the proportion of the vaporized/sublimated substance. Accordingly, a similar assumption can be made here.

The envelopes of the signals are shown in Figure 25a,b to plot the time-to-time ratio of the amplitudes $K_f$.

![Figure 25. The envelopes of the VA signals in the low-frequency (1–13 kHz) and high-frequency (16.5–22 kHz) ranges and the $K_f$ coefficient when irradiated with pure aluminum (a) and aluminum with Ni$_{77}$Cr$_{23}$ coating (b).](image)

It follows from Figure 25 that the $K_f$ coefficient under irradiation of pure aluminum fluctuates by about 5, and in the presence of a NiCr coating, its values fall to 0.4 due to the sizable high-frequency component. These data indicate that the intermetallic phase formation proceeds without the rough pulses accompanying the melting and recrystallization of aluminum.

The obtained estimates of the intermetallic phase yield can be compared with the values of the RMS amplitude in the octave bands with the central frequencies of 16 and 32 kHz (Figure 26). It can be seen that with the increase in the amount of intermetallic phase formed, the amplitudes in both octaves increase, but the high-frequency signal grows faster. Figure 26 shows the change in the coefficient $K_f$. A rapid increase in the
amplitude of 32 kHz octave at an intermetallic phase content above 10% on the plate surface leads to a sharp drop in $K_f$. In the future, this effect can serve as a basis for optimizing the processing modes.

![Graph showing RMS amplitude changes in the octaves of 16, 32 kHz, and $K_f$ coefficient with the proportion of intermetallic compounds.](image)

**Figure 26.** RMS amplitude changes in the octaves of 16, 32 kHz, and $K_f$ coefficient with the proportion of intermetallic compounds.

The relationship between changes in the microstructure of the near-surface layer of steel occurs during surface treatment with electron beams and changes in the parameters of the vibroacoustic signal accompanying the process by the example of alloying pre-nitride ferrite steel [35] with a niobium alloy.

In order to eliminate extraneous noise as much as possible, the working table of the “RHYTHM-SP” installation was replaced with a sample of AISI 439 (8Cr17Ti) sheet made of nickel-free stainless ferrite steel. Then, a metal coating made of Nb$_{70}$Hf$_{22}$Ti$_{8}$ alloy was applied to some plates by magnetron sputtering, which was subsequently used as a surface alloying material. Irradiation of the electron beam causes the dissociation of iron nitrides. The released nitrogen atoms enter into an exothermic chemical reaction with the coating material to form a refractory nitride phase based on Nb and Hf, which are strong nitride-forming agents.

At the first stage, the experiments were carried out with steel samples without any additional processing to identify the rational modes of irradiation and the corresponding parameters of acoustic signals. The operating pulses are applied at different values of the charging voltage of the generator. The effective RMS values of these signals amplitude in two frequency bands taken as the parameters of the VA signal reflect the kinetics of the surface processes. These could be octave bands, for example, with center frequencies of 16 and 32 kHz, but there could also be bands with other boundaries selected after analyzing the composition of the VA signal spectra and evaluating the most variables in conditions ranges.

The VA signal in the range of 26–33 kHz was ahead of the low-frequency component by a maximum of 13–14 ms. The phenomenon may indicate that the recoil of vapors of the evaporated material occurs before the formation of waves of thermoelastic stresses. The lower component is still present on the recording for a long time when the high-frequency signal fades out. The estimation of the $K_f$ coefficient gave its value of 2.8 near the maximum of the high-frequency component since it is associated with the material evaporation/sublimation processes.

Processing the results of such experiments at different charging voltages allowed us to obtain the dependencies of the effective values of the VA signal in the 32 kHz octave in the range from 16 to 25 kV. It can be seen that after exceeding the set point of the charging voltage of 20 kV, there is a sharp increase in the amplitude of the high-frequency VA signal, which indicates an increase in the share of vaporized material. For a 25 kV voltage in the
32 kHz octave, the amplitude is 3–6 times higher than the signal at 16 kV. This phenomenon allowed us to limit the maximum values of the discharge voltage to 20–22 kV [36].

After irradiation of a coated sample with an electron beam, the coating and base materials were mixed, and an exothermic chemical reaction was initiated with the formation of nitride phases based on niobium and hafnium. Some of the atoms of the film dissolved in the iron, and some evaporated/sublimated. According to X-ray spectral analysis, the average niobium content was approximately 0.5% in the near-surface layer of the processed samples. A consequence of the new nitride phase formation is the depletion of the austenitic component with nitrogen. Austenite causes a martensitic transformation under conditions of rapid cooling after pulsed heating by electrons.

Figure 27 shows the recordings of the VA signal in the octave of 16 and 32 kHz, where the local amplitude maxima are visible. Three VA signal spectra are given in the exact figure, corresponding to these maxima for the octave of 16 kHz (a) and 32 kHz (b).

Both the formation of nitride phases and martensite in the near-surface layer of the sample are accompanied by a change in volume and contribute to plastic deformation,
which can be a sufficiently strong source of VA signals. The features of the effects of irradiation reflected changes in its parameters. Simultaneously, the low-frequency component of the VA signal practically does not change in amplitude, and the high-frequency component grows up to five times. If we consider the $K_f$ coefficient at the maximum of the high-frequency component, it falls to 0.37.

If in Figure 27a, the amplitude decreases uniformly over the entire octave, then, in Figure 27b, the amplitudes in the right part of the spectrum fade faster. It can be assumed that this behavior of the vibroacoustic signal is associated with the martensitic transformation that takes place in several stages, caused by the chemical reaction of the formation of a nitride phase based on niobium against the background of shock compression.

The presented examples show a variety of approaches to the formation of diagnostic parameters. Their choice is primarily determined by the tasks assigned to the monitoring system, which can be selecting pulse exposure modes, determining the required number of pulses, evaluating the quality of processing results, and the formation of cracks after the passage of pulses.

4. Conclusions

1. The peculiarity of radiation-beam technologies is that the effect of concentrated heat energy flows on the processed material generates similar processes: the transfer of heat energy to the processed material, heating of the local volume, the development of melting, volumetric boiling, and evaporation/sublimation of the material, accompanied by ionization. These processes are accompanied by phase transformations and chemical reactions that cause pulsed changes in local volumes of matter and corresponding dynamic interactions transmitted through the material of the workpiece and parts of technological equipment in the form of elastic stress waves.

2. Vibroacoustic signals generated by dynamic interactions in radiation-beam technologies in the frequency range up to 40 kHz were studied. Studies of this range are of great applied importance since the signals of this range are recorded at a much greater distance from the processing zone (up to 1–2 m) compared to the ranges above 100 kHz.

3. It is experimentally shown that the performance of radian beam technologies and the amplitudes of the accompanying vibroacoustic signals increase with an increase in the power density of heat flows acting on the material. The growth of amplitudes is observed in a wide frequency range, but the amplitudes rate of change in different frequency ranges is different. The outstripping growth of the vibroacoustic signal high-frequency components with an increase in the intensity of the energy flow is associated with activating the processes of volumetric boiling and evaporation of the processed material.

4. The parameter $K_f$ was introduced as the ratio of the effective amplitudes of the low-frequency and high-frequency ranges for monitoring the impact of high-energy flows on the material to assess the displacement of the observed process in the direction of changing the evaporation fraction.

5. The proposed hypothesis allows the development of vibroacoustic monitoring systems for radiation-beam technologies from common positions. For example, it is possible to track changes in the intensity of the impact of thermal energy flows on the material, which may occur due to:
- A shift in the focal plane setting during laser cutting,
- An increase in the concentration of erosion products in electrical discharge machining,
- Accidental changes in the intensity of the heat flow or errors in the assignment of exposure modes during electron-beam alloying.

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