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Characterization of material's defects after electrical discharge machining and research into their technological parameters using vibroacoutstic diagnostics

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ABSTRACT

The electrical discharge machining is still one of the widest spread machining methods for manufacturing the parts from ceramics, nanoceramics, composites, nanocomposites and other high strength materials based on ceramic or metallic matrix. The defect after electrical discharge machining is often accompanied by processing. In this work, the characterization of the defects in the material was studied. The description of the assets' development for the process of diagnostics and the main effects of the technological parameters via the method of vibroacoustic diagnostics is provided. Among the most widespread on-line diagnostic methods for technological processes in modern production, vibrodiagnostics is one of the most preferable methods in the case of working area optic access absence. The results of the project, received by experimental implementation of the research, allow extending significantly the present knowledge about physical processes of the material disruption under the influence of the electrical current pulses and permit to develop the common technological recommendations to apply the developed diagnostic and measuring means and techniques in the conditions of the real manufacturing. The application of the results will increase reliability and safety of operation and maintenance of technological systems and will improve the quality of the responsible parts, produced by EDM method. Copyright © 2016 VBRI Press.

Keywords: Wire electrical discharge machining; material's defects; vibroacoustic diagnostics.

Introduction

The electrical discharge machining (EDM) is one of the most effective methods for manufacturing the parts from ceramics, nanoceramics, composites, nanocomposites and other high strength materials based on ceramic or metallic matrix [**1-4**]. More over the electrical discharge machining is one of the most precise machining methods; modern machines have the accuracy up to ± 1 μm and feeding step up to 80-100 nm [**5-8**]. From four to six independent axes extend significantly the fields of the EDM application [**9-13**]. The usage of ecological dielectric liquid makes the process safer for the health of an operator and the environment [**14-15**]. All these advantages make EDM an indispensable machining operation for production of the high-precision parts from hard-machining materials, which has complex three dimensional shape and internal cooling channels [**16-18**], for example, the parts as twisted turbine blades. EDM is based on the destruction of the conductive material under the action of electric discharges between non-core electrode and the electrode-workpiece [**19-20**]. Meanwhile the practice shows during manufacturing of the work-piece on the wire electrical discharge machine the wire electrode stuck in the body of work-piece is often occurred. It happens during the manufacturing of narrow slots 0.5 × 1.0 mm with round angles R 0.25 mm and height of the cut up to 200 mm. It can be a reason of non-stable cutting process, frequent short circuits, wire electrode break, damage of diamond nozzles, damage of machine working area, poor quality machined surfaces of the part, poor quality of the end product [**21-23**].

In another case of machining of a large-dimensioned work-piece with weight up to 300 kg, while separation of two interdependent parts by complex spatial contour, it is necessary to control the process of final cut of the straps between the parts before their end separation to avoid uncontrolled collapse of the internal part in the middle of the wire electrical discharge machine with the purpose to avoid its catastrophic damage.

During the final separation of a part from a work-piece by EDM cutting the special acoustic signal is occurred, which can be deducted by an experienced machine operator. To avoid the described negative consequences, he makes frequently a pause in machining manually or by CNC-program. During this pause he controls the position of the parts and, if it is necessary, re-fixates a part or a work-piece to obtain better control of the final separation.

In the modern machinery diagnostic assets are widely spread. Nowadays the assets of the on-line control and diagnostics for technological processes are particularly urgent and topical. They can be separated in two main groups: optical and acoustic. Optical assets found their application for the technological methods, where the character of physical processes in a zone of contact between a tool (cutting tool, plasma jet, laser beam, electron beam, water jet, etc.) and a work-piece can be deducted visually. Due to these assets the nature of the contact and its temperature fields in the working area can be defined.

During electrical erosion interaction of a wire electrode tool and a work-piece occurs in full submersion of the work zone into dielectric. The working area is so small and far away from the dielectric surface that the application of the optic assets is not possible. The vibroacoustic signals accompanied the EDM process can be indicated by special assets such as accelerometers [**24-26**].

The vibroacoustic diagnostic methods are used mainly for mechanical machining processes. These processes are characterized by special acoustic sound during machining, which occurs because of beating a tool by a part. This beating is occurs because of wear of the tool. By the character of the vibration during beating the severity of the processes, the wear of the cutting tool and the approximate period of time before damage of the tool can be defined. For this purpose, the accelerometers are placed maximum close to the working area (to a tool and a work-piece). The vibroacoustic signals during the processing are characterized by the relative amplitude of different frequency components [**27-28**].

The obtained additional data in this research will be used for the monitoring of the sample processing for the research of the effects of the technological parameters on the final quality and functionality of the product. The explanation of some physical effects, which have the influence on the materials' defects, will be achieved in the study by vibroacoustic diagnostics of EDM processing. The relevant assets will be developed to achieve the main task of the research. The important data will be obtained by an accelerometer placed on the upper rail of the machine. The gap of the vibroacoustic octaves of the processing and the choice reaction time will be also indicated by the study.

The problem of the material defects obtained after EDM and their research as well as the development of the vibroacoustic assets for diagnostic of electrical erosion processes will give a possibility to develop a complex of measures, which could improve the quality of responsible parts produced by EDM and reduce negative consequences of this technological process. Based on described above the urgency of the stated problem is concluded.

Novelty of current study enclose the new knowledge about physical processes occur during electrical discharge machining of materials by developed vibrodiagnostic assets, the classification of main material surface defects after EDM, the development of vibrodiagnostics assets for the purposes of the current study, the new knowledge about sub-surface layer of materials after EDM processing.

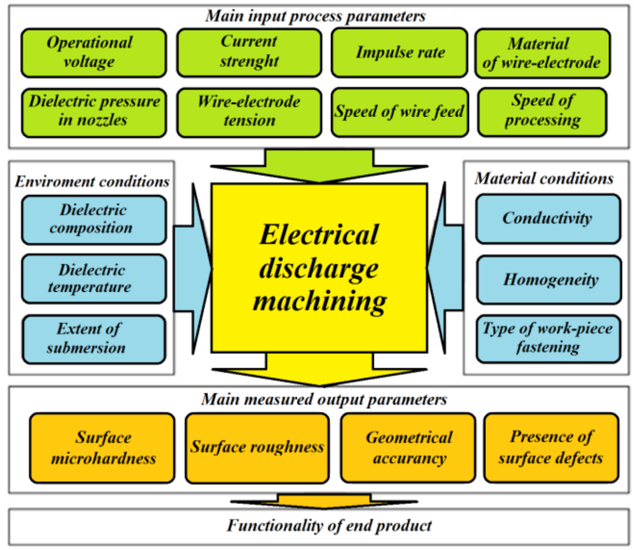

Fig. 1. Functional correlations of input factors (parameters) and output parameters of the electrical discharge treatment.

Experimental

There exist approximately 16 initial input factors (conditions) that define the nature of electric discharge processes influencing the quality of work-piece treatment (**Fig. 1**), as well as the functionality of the final product [**3**]. The nature of discharge pulse is characterized by main input factors of the treatment process such as voltage in inter-electrode space, electric current, electric pulse frequency (of electric discharge cycle), tool electrode tension, and the pressure of dielectric material in the nozzles. It is known that these factors significantly influence the treatment stability and, as a consequence, may affect the nature of vibrations during the treatment [**4**]. It is also necessary to ensure that sensors for measuring vibroacoustic signals are firmly fastened in order to accurately record the information during the treatment.

Table 1. Experiment performance plan.

Experiment No.	1; 2; 3	4; 5; 6	7; 8; 9	10; 11; 12	13; 14; 15	16	17	18	19	20
Material	12X18H10T stainless steel					D16 aluminum alloy				
Vo(V)	0	+1	-1	0	0	0	+1	-1	0	0
Wt (N)	0	0	0	+1	-1	0	0	0	+1	-1

Remarks: 1) Vo, V: -1 – 55; 0 – 60; +1 – 65; 2) Wt, N: -1 – 30; 0 – 35; +1 – 40.

In order to achieve the current goal, two key factors have been chosen that then varied to gain the new understanding of the influence extent of input factors on the nature of vibrations during the process of electrical discharge treatment and prior to the collapse of the work-piece/screenings: cutting voltage Vo and tension of the tool electrode Wt. It was decided to vary these parameters within the following ranges: Vo – 55 to 65 V with a 5 V pitch, Wt – from 30 to 40 N with a 5 N pitch (**Table 1**).

The 12X18H10T stainless steel and D16 aluminum alloy were as work-piece materials.

In order to analyze the technological parameters of products using vibroacoustic diagnostics of electrical discharge treatment and to obtain information about the nature of vibrations in the process of work-piece separation during the treatment, the operation of electric discharge cutting has been chosen. During this operation, a long work-piece (with length of the work-piece exceeding cutting width by 5.7 times) must be placed so that one of its ends is fastened to the working surface of the lathe, and its other longer part freely hangs over the treatment area. Presumably, such fastening scheme can be characterized by high vibration during cutting. For this experiment, two work-pieces from different materials were used: 12X18H10T stainless steel (tool steel for making mold parts, AISI 321) and D16 aluminum alloy (to assess the impact of unit weight on the nature of vibrations during the electrical discharge treatment) with 200 × 20 × 16 mm dimensions. During the treatment, work-pieces with 2 × 20 mm and 10 × 20 mm dimensions were cut out, without taking spark gap into account, for which a PNC program was prepared in a manual mode.

Table 2. Parameters of electrical discharge machine Seibu M500-S.

Name of parameter	Value
Max dimension of work-piece, mm	800x650x300
Max weight of work-piece, kg	800
Main axis movements X x Y x Z, mm	500x350x310
Wire diameter, mm	0.1…0.3
Max angle of cut, degree	± 10
Max obtained accuracy, μm	±1…2
Max obtained roughness Ra, μm	0,4
Dielectric liquid	Deionized water
Dimensions of machine, mm	1810x2245x2070
Weight, kg	3500

The work-piece treatment has been performed using the electrical discharge equipment *Seibu M-500S* (Japan) (**Table 2**). The brass wire with 0.25 mm diameter has been used as a tool electrode. Before the end of the cutting procedure, one minute before the collapse of the work-piece, a signal from the accelerometer had been recorded for future analysis.

The vibroacoustic signal has been recorded by two accelerometers installed on the working surface for work-piece fastening and on the upper slide of the tool electrode (**Fig. 2**). Such placement has been chosen to control vibrations of both the tool and the work-piece in order to determine the most informative sensor placement.

The work-piece dimensions have been measured using the micrometer *Brown & Sharpe* (Switzerland), with measuring error of 2 μm. The samples have been weighed using laboratory scales *METTLER TOLEDO (EL104)* with measurement range from 0.0001 to 120 g. and the error of 0.0001 g. The experimental sample surface photographs were obtained using *Olympus bx51m* optic microscope equipped with conoscopic and orthoscopic projection lenses with 10 to 500 times magnification, 5x, 10x, 20x, 50x lenses, 12 V halogen lighting, 90 to 150 mm. working distance. The surface roughness of experimental samples has been measured using the surface waviness recorder/roughness indicator *Hommel Tester* (Germany). The technical characteristics such as measuring range depending on a used probe, – 8, 80, 800, 8000 μm (resolution from 1 to 1,000 nm.); lowest displayed value – 0.001 μm; measuring error – 2 %. To obtain the images of the sample surface with high spatial resolution, as well as the information about its composition, structure, and properties of near-surface layers, the scanning electronic microscope VEGA 3 LMH (*Czech Republic*) has been used (magnification up to 1,000,000 times).

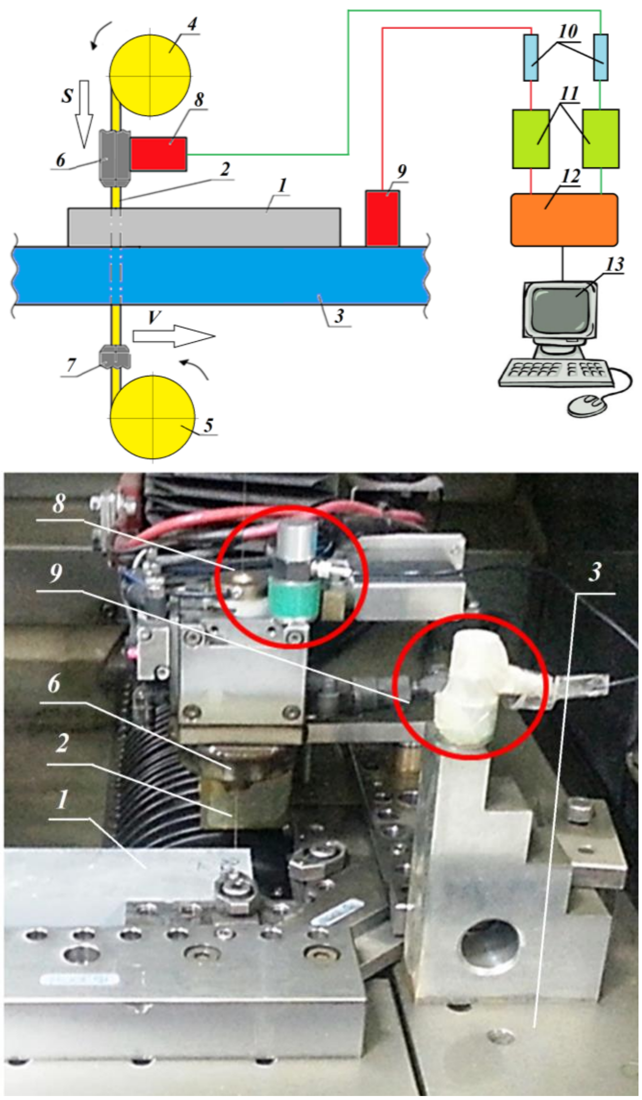

Fig. 2. Position of accelerometers on Seibu M-500: 1 – work-piece; 2 – tool-electrode; 3 – work table; 4 – feeding bobbin; 5 – receiving bobbin; 6 – upper guide; 7 – lower guide; 8 and 9 – accelerometers; S – speed of wire-electrode feed; V – speed of wire-electrode cut.

Results and discussion

After amplification, signals from the accelerometer have been sent to the ADC and recorded into a computer. The accelerometer signal sampling frequency is 20 kHz, which allows performing spectral analysis within the range up to 10 kHz.

A work-piece has been positioned manually: a relative coordinate system of the program has been set in relation to the fastened work-piece by means of a contact of the side surface with a wire in two points.

In the zero position of the program coordinate system relative to the work-piece, the tool electrode has been removed from the work-piece in order to avoid short-circuiting and to stabilize the treatment process for tool penetration into the work-piece body. The treatment has been performed with full tank of the electrical discharge machine and using preliminary holding of the work-piece in a dielectric material for 10 minutes (to avoid further thermal fluctuations of geometric parameters of the work-piece during the treatment).

It has been discovered that fluctuation amplitude surge detected by accelerometers happens during the undercutting of final crosspieces and accompanies the following collapse of the part, which leads to the formation of defects on the treated surfaces (approximately, 10 sec. before the end of the treatment). However, the weight and dimensions of the part may influence this parameter. The recording has been done for 60 sec. Alterations of the signal coming from the upper slide start five seconds before the collapse of the part. The vibroacoustic signals have been processed on a computer and presented as octave and amplitude ranges. When the first cuts of the experiment have been performed, it was discovered that the nature of vibrations from the accelerometer installed on the upper slide was more symmetrical than those from the working surface. The symmetry of the vibroacoustic signal is the evidence of the absence of electrical and electromagnetic interference. Hereinafter, diagnostics have been performed by the signal from the upper accelerometer.

At the end of the treatment, the loss of the process' stability has been observed. During the whole treatment process, the vibrosignal has been gradually increasing, and then a small surge appeared, then its break, and then another series of surges before the final collapse. This may be the evidence of a gradual decrease in the crosspiece between cut samples and the main body of the fastened work-piece during the treatment and, therefore, hanging of a larger piece of the material over the treatment area on a thin crosspiece being affected by plastic strain, including that under its own weight. When the sample starts to deform in such a way, it drives the tool electrode to the main body of the work-piece and short-circuit appears, causing burning on adjacent treated surfaces. At this moment, collapse is already imminent. The signal surges by the end of the treatment show the mechanical nature of fractures during work-piece collapse, which consist of a plastic strain and breaking fracture. At this moment, there appears warping of the sample relative to the work-piece accompanied by a series of short-circuits.

Fig. 3 shows high-frequency ranges of vibroacoustic signals 30 seconds before the end of the operation (range 1) and during the last second (range 2). It is apparent that in the 8 kHz area separate range components increase by four times. Such alterations of vibroacoustic signal components are sufficient to organize treatment process monitoring, information processing, and to take the respective steps to prevent short-circuits. Excess amplitudes of the vibroacoustic signal show the instability of a spark gap, due to which there is a danger of obtaining low quality of the treated surface. This is the basis for the change of manufacturing modes towards the decrease in perturbation of the tool electrode.

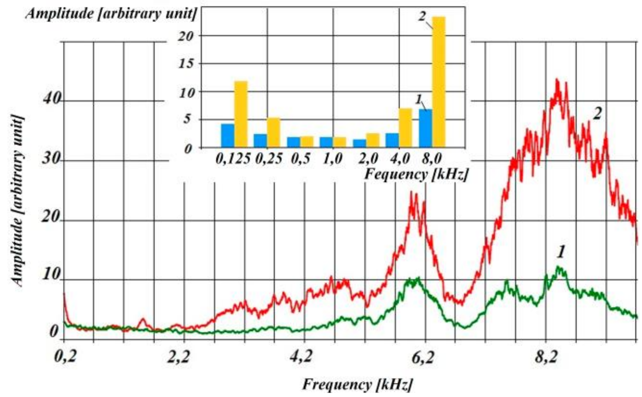

Fig. 3. High frequency ranges of vibroacoustic signals 30 seconds before the end of the operation (range 1) and during the last second of the operation (range 2).

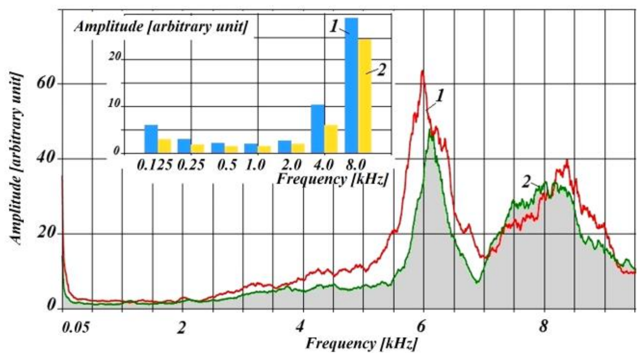

Fig. 4. High frequency ranges of vibroacoustic signals during the last second before the end of the operation for wire tension 15 % less (range 1) and 15 % more than normal (range 2).

It is inconvenient to use frequency bands to implement vibroacoustic signal amplitude monitoring system, because such a signal may prove to be unstable in case of the change of treatment modes and conditions. It is more convenient to monitor the effective value of the vibroacoustic signal amplitude in a wider frequency range, for example, octave-wide range. **Fig. 3** shows the main ranges of vibroacoustic signals 30 seconds before the end of the operation and during the last second. For example, in the 8 kHz octave band effective amplitude varies by more than three times, and in the 4 kHz – by 2.5 times. Such amplitude variation range is already enough to assess the situation and make a timely decision.

Fig. 4 shows the influence of wire tension on the character of the wire vibration. The amplitude of the vibration is slowly growing with reducing of the wire tension. After the samples have been cut, spark gap was measured. As a result of spark gap measuring, conclusions on more appropriate values of technological parameters for finishing electrical discharge treatment of samples have been made, which would further decrease material loss, value of the technological spark gap, and ensure a relatively better quality of the treated surface for the single passage, which should, without doubt, positively affect the geometric precision of the final product. Minimal spark gap for stainless steel equals 170 µm, for aluminum alloy – 196 µm. Thus, optimal technological treatment factors have been determined.

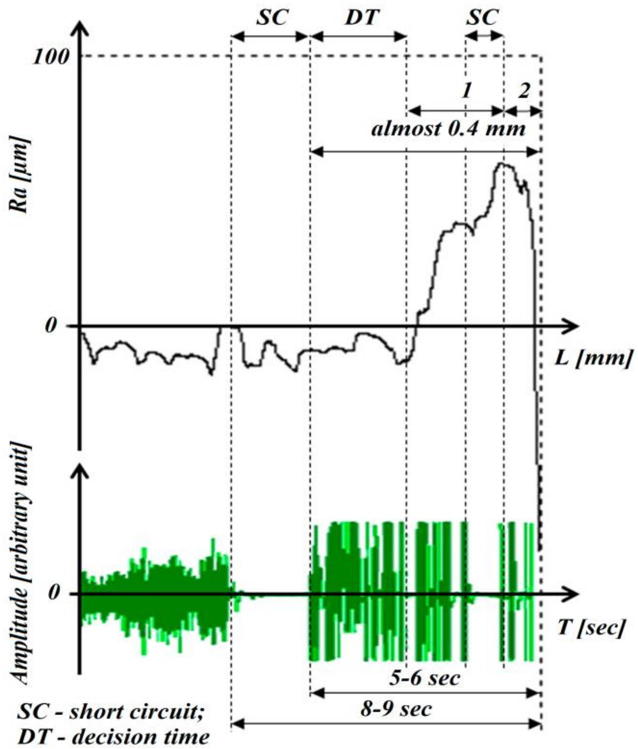

Fig. 5. Surface waviness record of the treated surface of the D16 aluminum alloy sample, and the results of VA signal recording 15 sec before the crosspiece separation, where SC are short-circuit areas during the contact of the tool electrode with the sample; DT – decision time; 1 – the plastically strained area of the sample; 2 – the area of the sample fractured by breaking (chipping point).

The vibroacoustic signal recording has been compared to weighing results of the samples and surface waviness record of the treated surfaces.

When registering a vibroacoustic signal 5 seconds before the end of the stainless steel part treatment (≈24.5 g) and its collapse (≈4.28 g), a substantial (12 to 15 %) increase of the RMS vibration amplitude value at 8000 Hz frequency appears during the collapse of a large sample, which is definitely due to its heavy weight. When treating an aluminum sample, such tendency is not apparent.

Ra roughness, which is a mean value of absolute values (modules) of profile deviations within the set length, has been measured using a surface waviness/roughness recorder. A probe followed the surface of the part from its middle in the direction of the tool electrode movement.

The vibroacoustic signal recording length has been analyzed, totaling 300 sec for stainless steel, which is, approximately, 10 mm of the work-piece cutting surface (according to chosen treatment modes, where the tool electrode moving speed was determined as V_{te}=0.03 mm/sec), and 150 sec for aluminum alloy, which is also 10 mm (V_{te}=0.07 mm/sec). The signal vibrations broke 5-6 seconds before the end of the treatment, whereas the surface waviness record of the area clearly shows the lack of plastic strains or breaking deformations at such treatment stage. After that, the signal nature was changed for consistently more intensive and irregular, which may indirectly show the beginning of the process of mechanical breakdown of the sample crosspiece: the surface waviness record clearly shows a plastically strained area and an area deformed by breaking (**Fig. 5**).

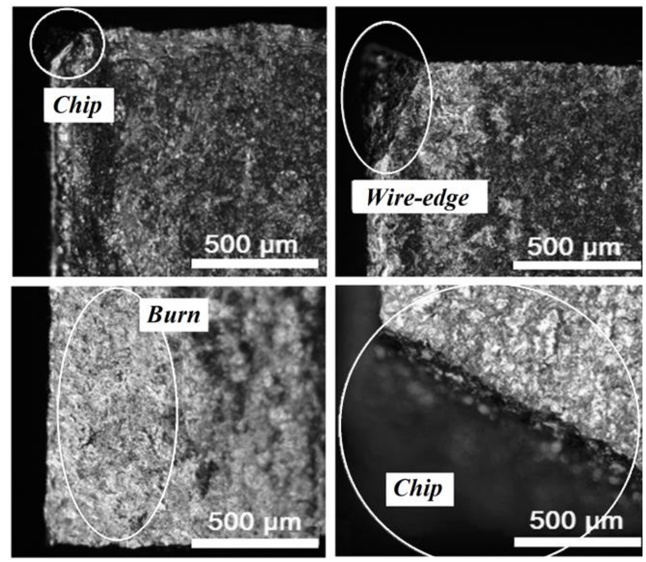

Fig. 6. Surface defects of the parts produced from stainless steel 12X18H10T (AISI 321) obtained by optical microscopy.

For illustrative purpose of the demonstration, the surface of aluminum alloy has been chosen, which had a clearly visible plastically strained area of the sample before the chipping. The results obtained may be the evidence of the possibility of vibroacoustic diagnostics of electrical discharge treatment in a continuous mode, with the possibility to control technological factors of the treatment process (in this case, decision time is approximately 2-4 seconds for the samples with 2.0 to 25 g weight), reducing their values by 15 to 20 % at the moment of vibroacoustic signal surge.

In order to study experimental samples for defects, the surfaces treated by electrical discharge have been photographed using an optical microscope. On the photographs of the surface, two types of defects have been detected based on mechanical impact (chips, burrs) and heat impact (burns, scratches) (**Fig. 6**).

Additionally, the treated surfaces of the samples using VEGA 3 LMH electron microscope have been photographed, which showed that the surface has been flowed and consisted of hardened droplets of melt pool generated from the impact of a discharge channel during the treatment. On the surface of the part made of aluminum alloy, multiple plastic chips of viscous nature can be seen.

The analysis of the chemical composition of the cross sections of samples (**Fig. 7**) has shown that at 4 µm distance from the work-piece surface, the depletion of material after electric discharge treatment can be seen. The presence of copper and zinc in the near-surface layer can be explained by the composition of the tool electrode material (brass).

Based on developed method and relative assets a die plate of injection mould for production of plastic parts for medical purposes was produced (**Fig. 8**). The internal spatial contours with the inclination of the vertical surfaces up to 0.5 degree were obtained by electrical discharge machining with mentioned parameters.

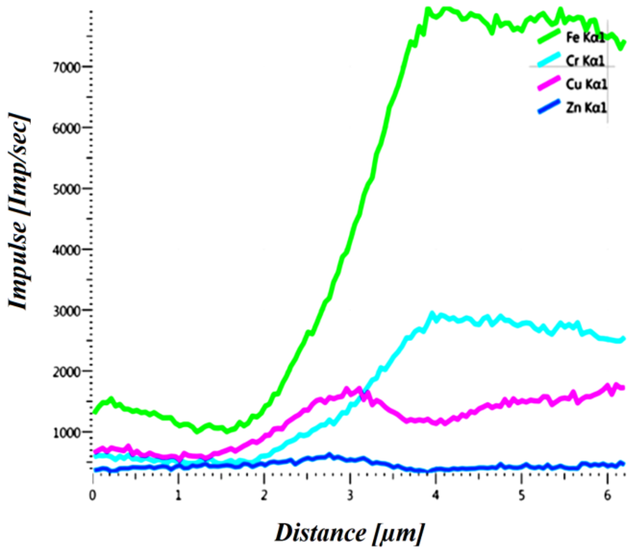

Fig. 7. Distribution of chemical elements on the sample of stainless steel 12X18H10T (AISI 321) obtained by scanning electronic microscopy.

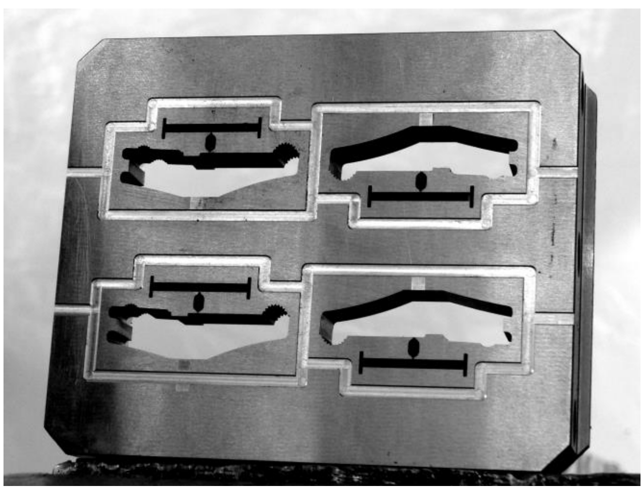

Fig. 8. Die plate for injection plastic mould produced from stainless steel 12X18H10T (AISI 321).

Conclusion

The experimental researches show that vibroacoustic diagnostics informatively demonstrates the nature of physical phenomena occurring in the treatment area between the electrode and the work piece. The octave ranges are preferable for the continuous diagnostics of the technological process. The decision time for the development of electrical discharge machining adaptive control assets has been determined, which can be used for the machining of responsible parts for instrumental usage in order to reduce the negative effects of the technology.

During the realization of the project the new knowledge about electrical erosion processes and about possibilities of improvement of quality of responsible parts and about reliability of technological systems of the EDM machine was obtained. The task to research the possibility of automation the surface quality control process was solved. Based on the implemented research the creation of new science intensive solutions for diagnostic problems of modern electrical discharge machines with the development of scientific and technological bases was done.

Acknowledgements

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