UKRAINIAN JOURNAL OF MECHANICAL ENGINEERING AND MATERIALS SCIENCE
Vol. 2, No. 1, 2016

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RESEARCH OF INFLUENCE OF OSCILLATIONS OF TOOL-PART SYSTEM ON ROUGHNESS OF SURFACE LAYER DURING HIGH-SPEED FRICTION STRENGTHENING

Received: March 30, 2016 / Revised: May 24, 2016 / Accepted: August 24, 2016

Abstract. During the discontinued friction strengthening except of the high-speed friction the processes of high-frequency shock loadings appears in the tool-part contact zone. The vibrations occur in the machine elastic system. During the vibrations of elastic systems, in the material of elastic elements and in the connecting units of the structure parts the energy dissipation into the ambient medium takes place. The energy dissipation of vibrations occurs due to the influence of the inelastic resistance forces on which the energy of the oscillatory system is spent. The vibrations of the tool-part system during the friction strengthening are similar to forced oscillations. However, for some particles of the part these oscillations are damped ones because the tool moves along the surface. The vibrations of the elastic system of the machine during the discontinued friction strengthening in the first approximation may be considered as free oscillations. For their investigation let us use the method of shock (impact) perturbation with a help of special measuring hammer which allows defining of the damping coefficient. With a help of the accelerometer and the hammer the shock (impact) curve and the registration curve of the tool-part vibrations were obtained. The obtained registration curve of tool-part vibrations was expanded into the Fourier series and with a help of MatLab program the obtained signal was filtered. Due to determination of the amplitude of vibrations and the oscillation period the logarithmic decrement of damping was defined. This parameter may be used for determination of the dynamic parameters of the oscillatory system of the converted machine.

For defining the oscillations which arises in the part being machined we used the dynamometer, in which the piezo-crystal sensor was rigidly fixed. This sensor allows the readout of oscillations along three directions (along vertical, horizontal and transversal axis).

Experimental research showed that the amplitude increased with increasing the number of processing modes and the oscillation character has exact wave-like form. The working process along the longitudinal direction has step-wise character. The single contact zone is heated to high temperatures; the metal softens; the friction coefficient decreases and the step-wise transportation of the part along the longitudal direction is being carried out. These phenomena are also confirmed by the figure of the machined surface and by the results of investigation of the topography of the machined surface. It is also experimentally determined that horizontal and vertical displacements of the spindle and the table vibrate with the frequencies close to resonance ones. With increasing of the tool rotation speed these vibrations have the character of damped ones and this phenomenon allows reducing the parameters of roughness, undulation and flatness of the surfaces being strengthened.

Introduction

Shape inaccuracy, roughness and undulation of the surface, which is being processed during friction strengthening, depend on various things, one of which is the oscillation of the machine-tool-device-part system. On this stage of manufacture development, it is necessary to provide optimal geometrical parameters of surface and quality of surface layer. The shape of the surface layer is an important factor, which determines the operational characteristics of the product. That is why the necessity of researching the degree of influence of tool-part system oscillations on parameters, which characterize the quality of processing, arises.

Problem statement and analysis of information sources on the subject of the article

One of the most important factors, which influence the quality of part surface processing, is dynamic state of machine, which is determined by the character of oscillation processes in its units. The level and the frequency of vibrational and acoustic oscillations during processing are important criteria of normal machine operation. These criteria are general indicators of its dynamic characteristics, which significantly influence the formation of quality parameters of processed surface. The main unit of metal cutting machine is spindle unit, which influence the parameters of the whole machine. Vibrations, which take place in spindle unit, negatively influence the precision and purity of processing, tool stability etc.

The velocity of spindle rotation, which influences physical processes in the contact area between the rolling bodies, also influences its damping features. At the same time damping may also depend on the oil viscosity. The level of oscillations of no-load operation, which is a random process, increases with the increasing of rotation frequency of the spindle. The level of oscillations has wide spectrum and consists of frequencies, which are close to the frequency of spindle natural oscillation. The intensity of these oscillations increases and the oscillation attenuation decrement is being reduced during the increasing of the rotation frequency. This phenomenon may observed at small amplitudes of natural oscillations, which are commensurate with the oscillations of no-load operation [1–3].

The oscillations are carried out by two components. The first of them is the oscillations of the machine-device-tool-part system as a result of rotation of its component elements. The reason of these oscillations consists in specific characteristics of the system rigidity, which influence system kinematics by forming small oscillations. The second component of oscillations of the tool-part system is oscillations, which arise as a result of dynamic and periodically repeated hits of the tool about processed surface. This component is crucial for further strengthening process and characterizes the structure of the surface.

Elastic oscillations spread in the material of the tool and the workpiece during the hit. These localized in the medium volume oscillations attenuate over time and are characterized by some damping coefficient.

During these oscillations the original structure of highly deformed metal is being formed on the workpiece surface, which particularly together with the chemical and thermal influence provides certain operational characteristics of the surface [2; 3].

Such errors, as undulation and deviations from the geometrical shape, arise during the friction strengthening as a result of oscillations of machine-tool-part technological system. These oscillations differ in moderate intensity in energy respect and have random character. The oscillations of the dynamic system, which occurs during the strengthening, influence the changing of the force in the contact zone and the temperature difference. When researching of the system oscillations it is necessary to determine methods of their decreasing or elimination. The subsystem of the tool, which consists of disc tool and drive, subsystems of the workpiece and elastic machine system. Disc tool, its shape and process kinematics have a tendency to oscillations and vibrations. The machine is a complicated structure and through its static and dynamic features influence oscillations during strengthening [3–5].

For decreasing oscillations and vibrations of the machine elastic system high requirements of dynamic quality of its units are set. Especially this concerns spindle units of the machine. Its dynamic quality is determined by the level of oscillations of the spindle front end (radial and axial), permissible range of rotation frequencies, frequencies of natural oscillations and damping features. The spindle unit is fixed on elastic supports that allow his rotation with the frequency, which is larger than critical velocity and sometimes larger than second critical angular velocity. In such spindle unit instead of static rigidity the dynamic rigidity is being created during the operating modes, which provides the necessary precision of parts processing. The precision of spindle rotation depend on such characteristics: friction losses in bearings, their temperature and durability [2–4].

In order to ensure high precision indexes of the process it is necessary to accurately define the ratio of the groove width to the working ledge length of the disk and the number of grooves. The elastic system operates in resonant mode and the maximal amplitude of its oscillations arises when the frequency of the external disturbance is the same as the frequency of natural oscillations of the system. High amplitudes of oscillations are undesirable not only because of the opportunity of elastic system operating in resonant mode, but also because of deterioration of the quality of the surface layer. During the machine operating in non-resonant mode the amplitude of oscillations decreases and the process of strengthening is being carried out if common mode. Therefore, we can say that periodic changing of oscillations amplitude causes the change of disturbance frequency. This, in its turn, leads to unstable operation of the machine. In addition, it is necessary to mention, that during the operating on the frequencies, which are close to the resonant frequencies of the elastic system, the strengthening process proceeds in unfavorable conditions [3–5].

Periodic changing of the disturbance force during the intermittent process of strengthening leads to the changing of the system rigidity. The rigidity is characterized by the features of the machine elastic system in an open state and is determined by its structure. The amplitude of the natural oscillations remains to be limited or increase in time depending on system components. The oscillations with increasing amplitudes are the most dangerous because they lead to resonance [5].

Statement of purpose and problems of research

The aim of this research is to investigate the vibrations of the machine elastic system which arises during high-speed discontinuous friction strengthening and to analyze their influence on forming the characteristics of the quality and accuracy of strengthened layers.

Main material presentation

During the friction strengthening by the instrument with intermitted working surface the area of tool-part contact is being loaded not only with shear deformation but also with hit loading. When the flat part of the working surface of the tool is passing through the contact zone the high-speed friction take place on the processing surface. The contact zone perceives the shear deformation. When the groove passes the contact zone of the working surface of the tool, it is being unloaded. Under the influence of elastic deformation, the elastic system of the machine begins to oscillate. At the time when the groove passes through the contact zone, it does not perceive any load. When the following flat surface of the working part of the tool passes through contact zone, first, the hit loading takes place, and then the shear deformation takes place in the contact zone.

The tool-part contact zone is being quickly heated due to the high-speed strengthening up to the temperature, which is larger than the phase transition point. Metal in the contact zone is being softened and the friction coefficient is decreasing. Complicatedly strained state of metal is being received in the contact zone.

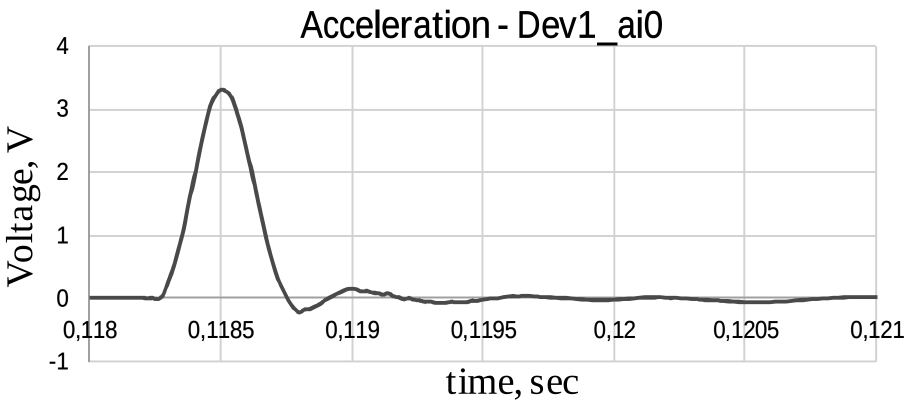
Nowadays the most widespread method of analysis of oscillations is strike disturbance. Oscillations, which arise after the strike, have transitional, short-term process of energy transmission. The spectrum of the strike force is continuous, with maximum amplitude at 31 kHz and with further its reduction during the frequency increasing [5; 6].

To determine the damping coefficient piezoelectric accelerometer and strike hammer of M355B15 model made by PCB was used (Fig. 1). This hammer consists of the frame, piezoelectric dynamometer and strike element. Strike element is rapidly changing and set at the end of the hammer cap. By changing the material of strike part it is possible to change the duration of the impulse and hence to change the frequency range of the spectrum of perturbations. Piezoelectric dynamometer provides measuring of electrical signals, which allow to determine the amplitude and the frequency of the applied force. Using the accelerometer and the hammer the strike curve and the registration curve of oscillations of disc-tool were taken down (Fig. 2).

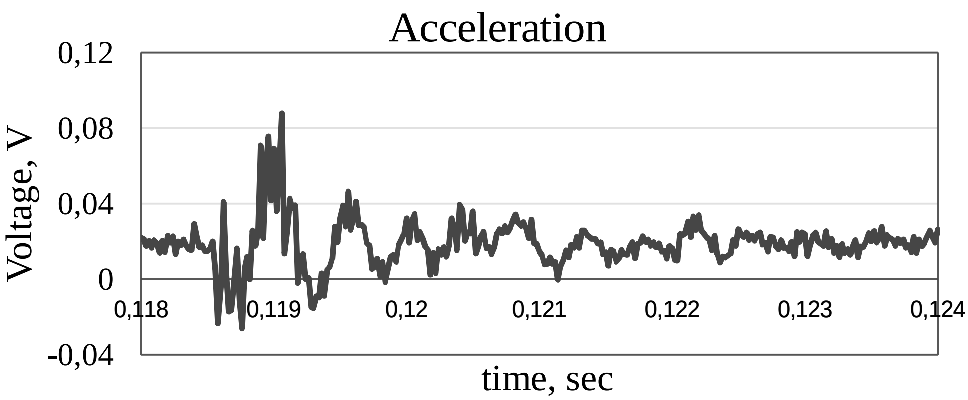
Obtained registration curve of oscillations of disc-tool was expanded into Fourier series. With a help of MatLab program obtained signal was filtered and the noises were separated (Fig. 3) [8]. For filtering the signal the Butterworth filter was used.

Using MatLab computer program, the following input parameters were selected: n (filter order) and W_n (limiting maximal normalizing frequency). Using these parameters after automatic selection of the coefficients b and n, the amplitude-frequency characteristic of the filter covered necessary frequencies of the signal [8; 9].

Fig. 1. *Strike hammer of M355B15 model made by PCB firm*



a



b

Fig. 2. *Registration curve of the hammer strike (a) and registration curve of oscillations of disc-tool (b)*

Let us take the following parameters for selecting the coefficients of the Butterworth filter: $n=5$, $W_n=0.1$. The following calculated polynomial coefficients of the $H(s)$ transfer function were obtained: $b(1)=5.9796\cdot10^{-5}$, $b(2)=2.9898\cdot10^{-4}$, $b(3)=5.9796\cdot10^{-4}$, $b(4)=5.9796\cdot10^{-4}$, $b(5)=2.9898\cdot10^{-4}$, $b(4)=5.9796\cdot10^{-5}$, $a(1)=1$, $a(2)=-3.9845$, $a(3)=6.4348$, $a(4)=-5.2536$, $a(5)=2.1651$, $a(6)=-0.3599$.

Based on the previously selected coefficients the signal is being filtered from too high frequencies, which are mainly classified as noise.

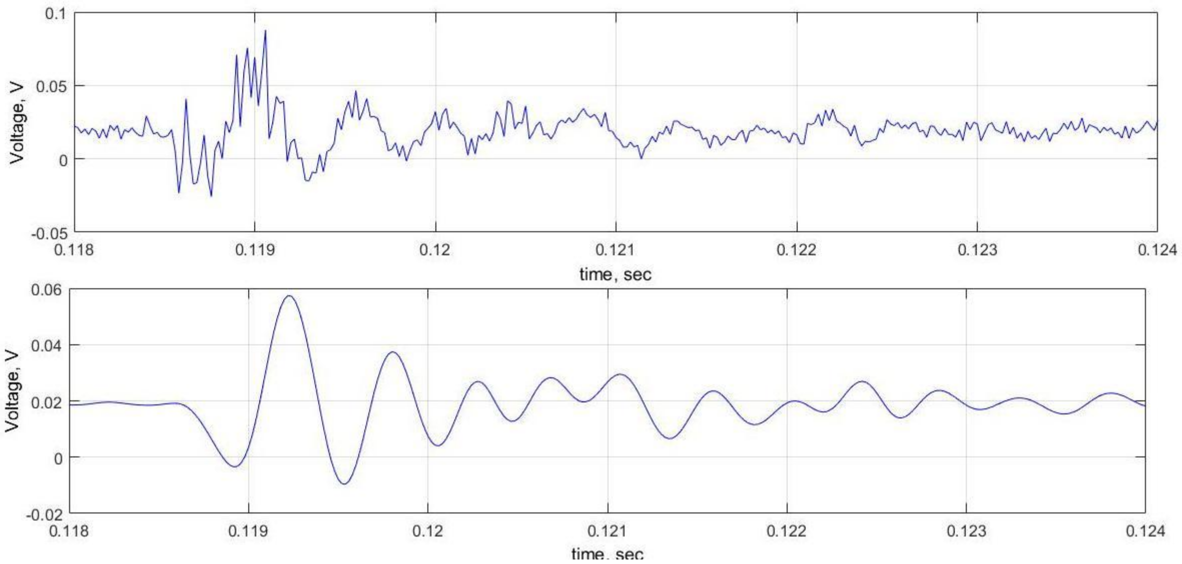


***Fig. 3.** Registration curve expanded into Fourier series in the MatLab program*

Let us determine the amplitude and the period of the oscillations of the registration curve (Fig. 4). In this case, logarithmic damping decrement of oscillations is:

$$l = ln\frac{A_1}{A_{1+i}} = ln\frac{0,067}{0,0414} = 0,481,$$

where A_1, A_{1+i} are the amplitudes of two neighboring peaks of damped free oscillations.

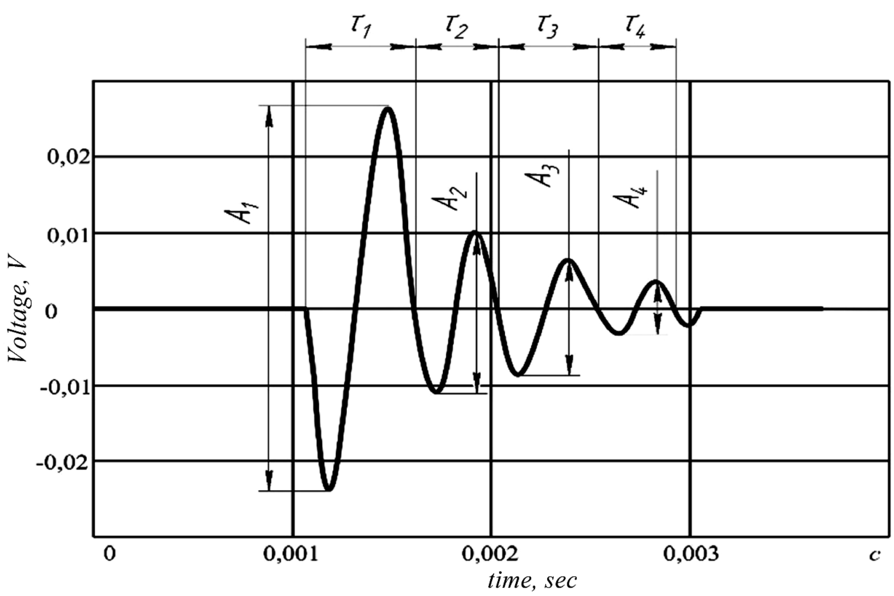


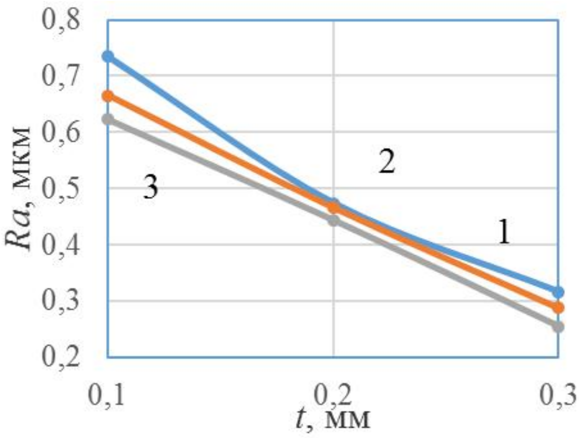
***Fig. 4.** Damped oscillations of disc-tool*

Obtained value of logarithmic damping decrement will be used for determination of dynamic parameters of the oscillation system of the modernized machine, which is designed for friction strengthening of flat surfaces of machine parts.

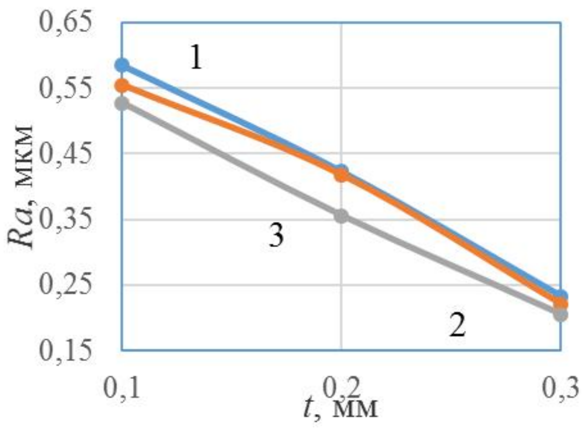
For determination of the oscillations, which arise in machined part, the piezo crystalline sensor (accelerometer) of M353B15 model made by PCB firm was rigidly fixed on the frame of the dynamometer. This sensor allows taking down (filming) oscillations along three directions: vertical, horizontal and transversal (*x*-, *y*-, *z*-axes). The machined workpieces were rigidly fixed in the dynamometer.

The experimental research showed that the amplitude of oscillations of investigated workpieces increased with raising of machining regimes of the workpieces made of 40X steel. The character of oscillations has clear wavy pattern. The process of machining in the transversal direction has stepwise character. The zone of single contact is being heated to high temperatures, the metal is being softened, the friction coefficient is decreasing and the stepwise displacement of the part is being held in the longitudinal direction. These facts are also confirmed by the figure of the machined surface and the research results of the machined surface topography. During the friction strengthening of 40X steel on the following machining regimes: vertical feed – 0.3 mm, transversal feed – 2.5 mm per double table course, rotation speed of the tool – 80 m per sec, maximal displacement along vertical axis was about 3.5 µm, along the horizontal axis – 3 µm and along the transversal axis – 1.5 µm. The frequency of oscillations was about 5 kHz (Fig. 6).

The experimental research of strengthened surfaces of workpieces, made of 40X steel, in hardened and low tempered state showed that machining regimes significantly affect the value of arithmetic mean deviation of the surface profile. Thus, at the primary processing regimes (vertical feed – 0.1 mm, transversal feed – 1.25 mm per double table course and rotation speed of the tool – 60 m per sec) the arithmetic mean deviation of the surface profile is $R_a = 0.74$ µm . With the increasing of vertical and transversal feeds and rotation speed of the tool the arithmetic mean deviation of the surface profile R_a decreases (Fig. 5). Especially the increasing of vertical feed affects this process. The increasing of rotation speed of the tool does not significantly influence the value of arithmetic mean deviation of the surface profile R_a. It should be noted that at the higher values of rotation speed of the tool the R_a parameter is slightly larger than at the lower speeds.



a

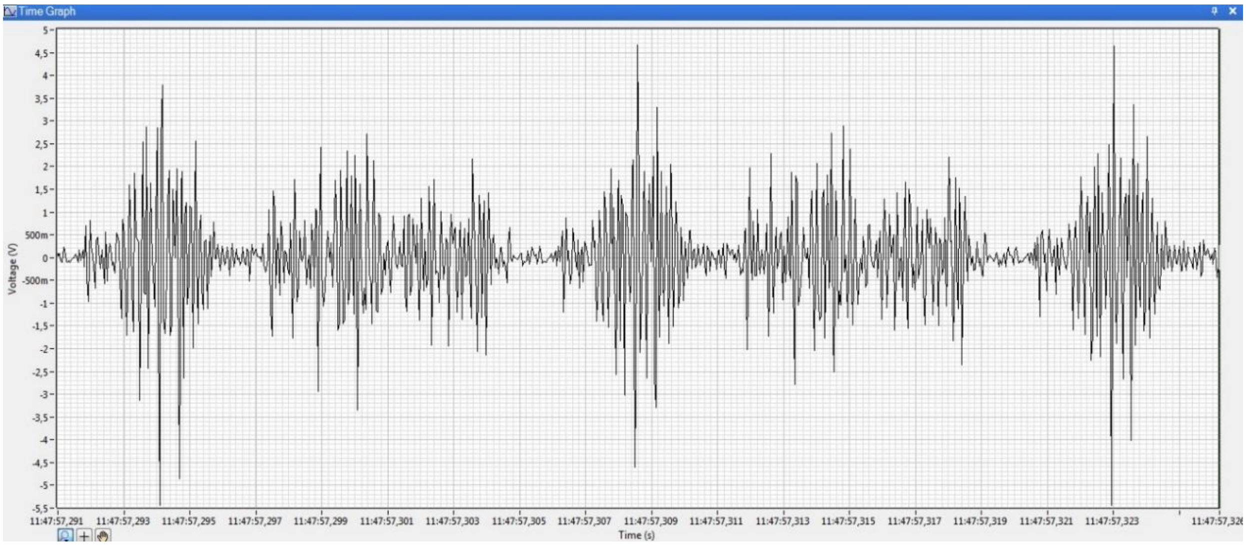


b

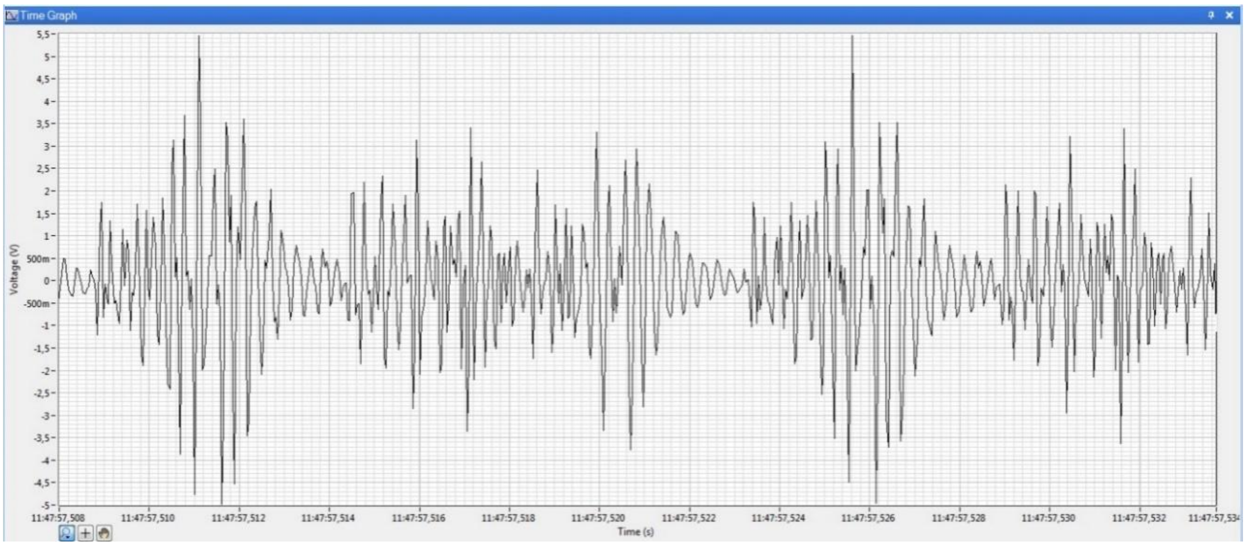
Fig. 5. *Dependence of the arithmetic mean deviation of the surface profile from the machining regimes of the 40X steel: a –* $s_n = 1.25$ mm per double table cource; *b –* $s_n = 2.5$ mm per double table cource; *1 – V = 60 m per sec; 2 – V = 70 m per sec; 3 – V = 80 m per sec*

Conclusions

It was experimentally investigated that vertical and horizontal displacements of the spindle and the table and reactions of the table oscillate on frequencies which are close to resonant ones. When the rotation speed of the tool increases from 60 to 80 m per sec they have the character of damped oscillations.



a



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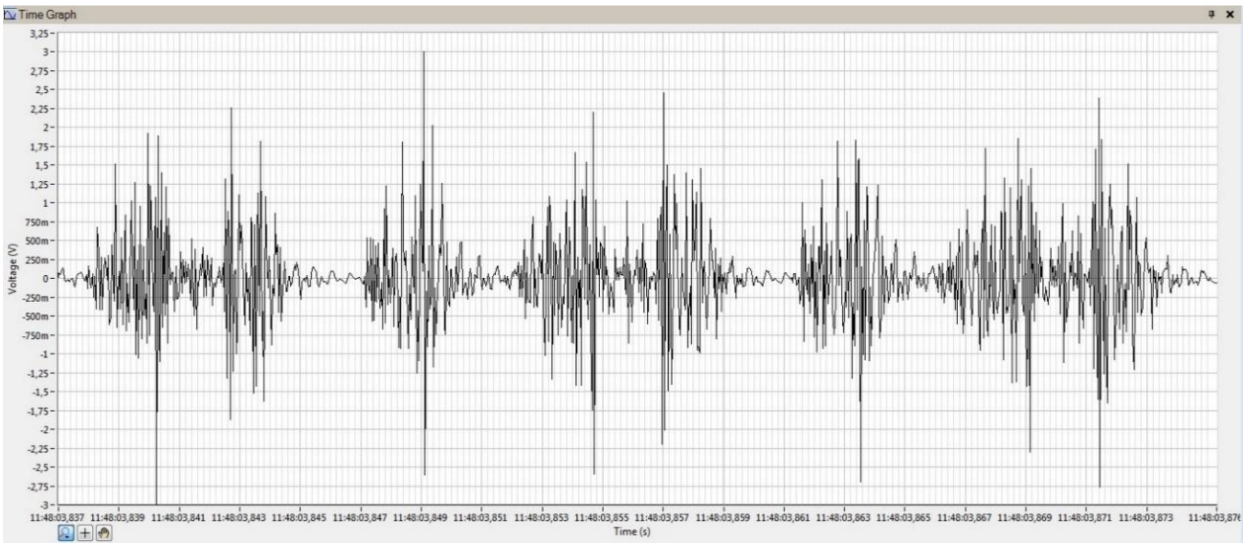

c

Fig. 6. *Oscillations of the part during friction strengthening of the 40X steel:*
a – vertical direction; b – horizontal direction; c – transversal direction

The amplitude of spindle oscillations decreases according to the exponential curve, and the coefficient of damping of the amplitude of oscillations increases with the increasing of spindle rigidity and stabilizing influence of gyroscopic moments. For increasing the stabilizing influence of gyroscopic moments it is necessary to increase angular velocity of spindle and moment of inertia of spindle and tool. To improve the quality of machined surface it is necessary to decrease static and dynamic imbalance of spindle with mandrel and disc, decrease the mandrel radius, increase gyroscopic moment from precession motion of the spindle-mandrel.

The quality of surfaces of flat parts is significantly influenced by the machining regimes and parameters of the working part of the tool. Increasing the rotation speed of the tool up to 80 m per sec allows decreasing of parameters of rigidity, undulation and flatness of strengthened surfaces. Thus, the arithmetic mean deviation of the surface profile, obtained for the 40X steel, decreased to $R_a = 0.26$ μm and the undulation decreased to 3 μm.

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