Capabilities of vibration cutting at turning of hard-to-cut materials and built-up surfaces

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Abstract. The article describes the results of vibration turning research for cutting the parts produced of austenitic steel of high ductility and strength, as well as for the machining of the surfaces reworked by the method of build-up welding. Lathe turning with a superposition of pendular-type harmonic vibrations to the cutting tool is one of the productive cutting methods of austenitic steel, from which parts of mining machines and equipment are made, and built-up surfaces as a result of repair of various parts of mining equipment. Selection of optimal amplitude-frequency parameters of cutting tool vibration allows to increase a period of tool material lifetime, to ensure constant process of chip breaking and helps to reduce a cutting force. When turning the materials with generation of pendular vibrations in cutting zone, some phenomena occur that are not observed during cutting without vibrations. Based on the results of tests of vibration turning the main facts were defined, which have the greatest influence on lifetime of cutting tools during cutting of austenitic class steels and built-up surfaces, it is expedient to consider: vibration velocity, vibration acceleration, vibrating influence energy dispersion. The concept of the vibration impact generalized function (VIGF) was introduced, which allows to describe mathematically three main factors of pendulum vibrations influence in the cutting zone. The equation of the mathematical model of vibration turning with VIGF is presented, which describes the dependence of the tool lifetime period on vibration parameters. The process of generation and breaking of the chips when turning the hard-to-cut materials is studied. The fields of temperature distribution in the cutting zone at turning are investigated.

1. Introduction

The characteristics of mining machinery and equipment operating conditions establish strict requirements to mechanical characteristics of steel grades used for manufacturing of various parts. For example, increased wear resistance and durability, with the obligated maintaining of sufficient viscosity, the possibility of operation at high temperatures and in conditions of aggressive environment. Steels with such feature sets, as a rule, are referred to the group of hard-to-cut materials.

One of the steel grades widely used for production of mining machinery and equipment parts is steel 110G13L which is distinguished by its high manganese content in the chemical composition. The steel 110G13L is widely used for manufacture of mine-mill, crushing, metallurgical, transportation equipment parts: the body and lining of jet-type and ball mills, jaws and cones of crushers, chain tracks of excavators, tractors and machines, teeth and front walls of buckets of mining excavators, railway cross pieces and other heavy-duty parts operating under conditions of shock loads and high abrasion [1-4].
Due to the hard operating conditions of mine-mill equipment there are situations when production of new parts that failed requires high time expenditures. On that basis, reconditioning of piece working surface by the method of arc surfacing is effectively used in maintenance shops.

The advantage of this reconditioning method is the reduced maintenance downtime of the equipment. One of the main advantages of such reconditioning method is a possibility of further usage of the workpiece without applying a heat treatment due to the use of electrode materials with a complex chemical composition. The use of such electrode materials allows to obtain the properties of built-up surfaces close to the properties of original material. It is necessary to take into account that the surface obtained by the method of building-up welding, has an uneven structure, which is caused by built-up joints overlapping areas. The structure and properties of the built-up layers are similar to the properties of the piece surface obtained by casting method. Thus, the use of vibration turning for machining the built-up surfaces is relevant, because there is a similarity to the piece treatment on cast surface where the use of vibration cutting showed the high efficiency.

Lathe turning with the superposition of pendular-type harmonic vibrations to the cutting tool is one of the productive cutting methods of austenitic-type steels and built-up surfaces, providing increased lifetime of metal-cutting tools and stable breaking of workpiece material cut-off layer in the form of discontinuous chips.

The main feature of vibration turning is the generation of tangential vibrations of the pendulum type at the tip of the cutting tool, directly in the cutting zone, including normal and tangential components of vibrations, which are characterized by the amplitude, frequency and form of vibrations. The study of vibration turning parameters consists in finding the boundaries of the stability range of forced low-frequency vibrations.

Based on the analysis of the performed experiments it was discovered that vibration strength has considerable influence on the period of metal-cutting tool lifetime and the volume of the removed metal from workpiece surface.

Despite the dependence of cutting mode elements on vibrations intensity, the extremal dependence of metal-cutting tool lifetime period on vibration amplitude is noted. Such character of dependences means that for realization of high vibration cutting process capacity it is necessary to define the optimal matching of amplitude-frequency vibration parameters, named vibration velocity [5-9].

2. Investigation of tool lifetime period

From the analysis of work results [7] the correspondence of max period of cutting tool lifetime \( T = 68 \) min and cutting speed equal to \( v = 80 \) m/min was noted. Such confority was noted at the following amplitude-frequency parameters: \( A = 70 \) microns and \( f = 100 \) Hz, tool material is hard alloy of grade Ti5Co10.

Further investigations directed on studying the dependence of vibration turning and cutting tool lifetime allowed to define the dominating factors in the greatest degree influencing: the speed of cutting and vibration acceleration. The mathematical model equation, which allows to describe the period of tool lifetime, included only these two factors [7, 8].

Further investigations directed to the optimization of the mathematical model allowed to formulate a conclusion that energy dispersion in a cutting zone at vibrating impact also has considerable influence on its adequacy.

Therefore, it is expedient to take into account the vibration impact of the factors in the cutting zone, which have the greatest influence on the development of the model: vibration velocities and accelerations, and dispersion of vibration energy in the cutting zone. Coefficient values at VIGF factors \( F(A, \omega) \) were found based on the database obtained as a result of experiments, using the polynomial method and are presented in the equation:

\[
Y = T = 25.46 + 22.75(A\omega) + 0.36(A\omega^2) – 14129.56(A^2\omega^2)
\]

where \( A\omega \) – vibration velocity;
\( A \omega^2 \) – vibration acceleration, characterizes the effects of vibration forces in the cutting area during turning;

\( A^2 \omega^2 \) – parameter, that determines the influence of the vibration dispersion energy in the cutting area during turning [10].

The subsequent study of the mathematical model for determination of the VIGF character was oriented to evaluation of fractional dependence range of each vibration parameter which had the maximum impact on the function contributory factors.

In the result of parametric calculations at changing the amplitude and vibration frequency it was defined that the values, on the basis of which the mathematical model equation was calculated, were within the range corresponding to the maximum period of cutting tool lifetime and were limited to the maximum possible technical parameters of the experimental unit for vibration turning.

From the results of the equation model parameters calculations it is noticed that achievement of the maximum period of the cutting tool lifetime is possible at assuring of a certain ratio of low amplitudes values and high values of fluctuations frequencies.

Comparison of the obtained experimental and calculated values allowed to make a conclusion about adequacy of mathematical model. The values of cutting tool lifetime obtained in the course of experiments did not exceed the limits of the confidence interval calculated according to the Student’s criterion. The data obtained will allow us to determine the direction of further research aimed at optimizing the mathematical model [10].

Theoretical studies of mathematical model of roughness dependence on vibration cutting parameters showed that with increasing the vibration value, the roughness of the machined surface deteriorates, in contrast to the period of tool life, which increases [8, 10].

3. Investigation of chips breaking

Lathe turning of austenitic class steels of type 110G13L, 12Cr18Ni10Ti, etc. takes place with constant formation of continuous chips in the form of endless tape.

Nowadays there are various methods of machining such as vibration cutting with different vibration frequencies of cutting tool, machining with the use of advanced plastic deformation, plasma-mechanical treatment, machining with preheating, use in the cutting process of surface-active materials. Application of listed methods of machining, except for vibration cutting in the range of low frequencies (up to 200 Hz) requires significant material costs and energy resources. The presented methods of machining do not allow to get high quality of machined surface at preset level of roughness.

The amplitude-frequency parameters in a form of vibration impact considerably influence on the properties and geometry of processed material chips. Based on the work results of group of authors focused on studying the vibrating turning of cryogenic structural steel of 12Cr18Ni10Ti grade, which also belongs to the austenitic class, different types of chips formed during various vibration modes are known (Figure 1).

The presented elements of chips during their detailed studying provide evidence of vibration force increase at vibration amplitude increase, as well as determine the intensity of chip breaking process.

The experiments covered a great range of amplitude-frequency parameters of pendulum vibrations. Investigation of such vibration area allowed determining the most dependent factors of chip formation and breaking process.

The intensity of chips forming and breaking processes completely depends on vibration velocity and cutting speed. It should be noted that it is necessary to ensure a ratio at which the vibration velocity is much higher than the cutting speed. Maintaining such a ratio allows us to draw a conclusion that at generation of vibrations in the cutting zone, the process of turning at ultra-high speeds with simultaneous provision of a similar process of chip formation happens. A confirmation of that conclusion can be found on the chip fragments when cutting structural cryogenic steel of austenitic class 12Cr18Ni10Ti, which are shown in Figure 2. The cutting modes in which the machining was performed were as follows: cutting speed 82 m/min; chip load per revolution 0.26 mm/rev; cutting depth 0.5 mm.
Figure 1. Types of the chips: a – conventional turning process; b – vibration turning (A = 5…10 micron; f = 5…10 Hz); c – vibration turning (A = 30…50 micron; f = 15…25 Hz); d – vibration turning (A = 70…100 micron; f = 50…70 Hz)

Detailed examination of provided elements of the chips gave the opportunity to define the value of chip edge melting when turning with vibration generation in the cutting zone. The measurement of melting value showed difference of about 2…3 mm, while the melting at vibrations is less.

At the moment of the working vibration motion there is a summation of the vibration velocity and cutting speed, which causes the process of turning at ultra-high speeds.

Figure 2. Pictures of chip elements: a – when turning without vibrations; b – at vibration turning (A = 5…10 micron; f = 5…10 Hz)
4. Investigation of temperature fields

As the vibration cutting is a productive cutting method of workpieces produced from hard-to-cut materials, which are widely used in designing and subsequent production of equipment for ore processing and metal production, the use of optimum vibration turning parameters increases the tool lifetime and ensures a reliable chip breaking process. The cutting of hard-to-cut materials by turning with superposition of pendular-type harmonic vibrations to the cutting tool tip is accompanied by the formation in the cutting zone of processes opposite to conventional turning.

Thus, the study of temperature fields change and the stress-strain state of the tool and the workpiece, depending on the parameters of vibration turning, is relevant. In this connection, a number of experiments on vibration turning were simulated using the finite element method in the DEFORM 2D software package.

In accordance with the design of the experiment, two turning processes were simulated, the cutting modes of which corresponded to the full-scale experiments [11-17]:

• Conventional cutting: \( v = 88 \text{ m/min}, t = 0.5 \text{ mm}, f = 0.26 \text{ mm/rev}; \)
• Vibration cutting: \( v = 88 \text{ m/min}, t = 0.5 \text{ mm}, f = 0.26 \text{ mm/rev}, \) amplitude-frequency parameters of vibration – \( A = 100 \text{ micron} \) and \( f = 50 \text{ Hz}. \)

The workpiece is an austenitic cryogenic structural steel as per American standard AISI-321, which is a close analogue of the steel 12Cr18Ni10Ti. Material of the tool – hard alloy WC (tungsten carbide). The workpiece was given the properties of a ductile material with Brinell hardness of 170 HB, and the tool had the properties of a "completely" rigid body. The initial temperature of the workpiece and the tool was 20 °C [11-17].

Based on the results of turning processes simulation, it was found that the maximum temperature is inherent in the vibration cutting process, where \( T = 356 \text{ °C}, \) as opposed to the non-vibration cutting process, where \( T = 313 \text{ °C}. \) Temperature distribution in the contact zone for two cutting processes is different. For example, the temperature of the chip body was 200...240 °C for non-vibration cutting, and 190...230 °C for vibration cutting. It is worthwhile noting that in the contact zone of workpiece cut-off layer with the surface of the cutter, the temperature was 230...270 °C. The depth of temperature distribution in the body of the cutting tool did not have significant differences. Such phenomenon is caused by the temperature of the heating zones on the main surfaces of the cutter (Figure 3).

As a result of the analysis of the temperature distribution zones on the surface of the cutting tool, it has been determined that there are three heating zones for conventional cutting, with a total temperature range from 56 to 166 °C. At vibration cutting, the tip of the cutting tool has two heating sections, with temperatures ranging from 62 to 146 °C. This feature can be attributed to the interruption of workpiece material constant contact with the cutting tool. Thus, temperature decrease on the cutting tool tip increases the tool's service life.

The analysis of the obtained calculated temperature values in the cutting zone and on the inner surface of the material cut-off layer allows to formulate a statement about the melting of material cut-off layer
in the form of the chips [15]. During the cutting process the constant contact between the tool and the workpiece material ensures a constant high temperature in the chip body (Figure 3a), which in turn ensures its ductility and flow type. During vibration cutting an interruption of the permanent contact between the cutting tool and the workpiece to be machined happens periodically. This phenomenon causes a heat decrease in the chip body, a decrease in its ductility and a change of type.

From the turning processes simulation results it is obvious that the use of vibration cutting contributes to a decrease in temperature at the cutter tip. It is necessary to take into account the intensity of heat decrease which depends on certain optimal ratio of amplitude and frequency of vibration cutting. Thus, to ensure the temperature decrease, the vibration amplitude shall be \( A = 80 \ldots 120 \) micron and vibration frequency depending on the cutting speed, shall be at a ratio of the workpiece rotation speed not less than 5:1.

5. Conclusion

As a result of computer simulation by the finite element method of cutting processes with and without cutting tool vibrations, the following is valid:

- Calculation of forces and values of workpiece removed material plastic deformation when simulating the vibration cutting had found a confirmation of their change from the vibrational impact of the cutting tool with the workpiece material, according to the periodic law [15];
- The results of stress simulation in the near-cutter zone confirm the phenomenon of conditions creating for the exhaustion of the ductility reserve of the machined material due to periodic vibration impact [15];
- Vibration turning decreases the wear degree during the treatment of built-up surfaces and steels of austenitic class;
- Vibration turning ensures the interruption of diffusion-viscous interaction between the contact zone of the tool and the workpiece, providing an increase of tool lifetime period, which is confirmed by the results of temperature calculations in the areas of tool contact with machined workpiece and the cutting tool tip [11].
- Based on the presented results of simulation by the method of finite elements it is possible to make the conclusion about the impact of main parameters on VIGF:
- Vibration turning increases the cutting modes range of values for built-up surfaces and the steels of austenitic class;
- Vibration turning increases the lifetime of metal working tools;
- Turning of high viscosity materials with cutting tool vibrations forms the conditions under which the ductility resource is excluded and the removed layer is destroyed subsequently.

Thus, summarizing the obtained results of research, it is legitimate to formulate a conclusion that the use of vibration turning, with reference to the technological processes of manufacturing and repair of parts made of hard-to-cut materials for mining machinery and equipment is an actual task.

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