Using vibration cutting for finish turning hard materials

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Abstract. With the development of the facilities new materials with higher strength and performance characteristics are developed. But as these characteristics increase, others, such as machinability, deteriorate. In view of this, the question about the most sustainable method of machining, in particular cutting, came up. One of such methods is machining with the use of vibration cutting. The process of vibration cutting consists in superimposing on common kinematic scheme of machining the additional vibrating movement of a tool or workpiece, which is characterized by the direction, shape, amplitude and frequency of vibrations. Superimposing of vibrations on the tool or treated material during drilling, turning, grinding, forming and pressing provides a considerable physical effect of cutting force reducing and friction forces reducing, it facilitates the processes of flow deformations, increases the tools life and improves the quality of machining.

1. Introduction
The use of vibration cutting for machining of hard-to-machine materials provides the increasing of tool life period and steady chip breaking. For this reason, the investigation of surface layer condition and roughness parameters becomes a critical task. By comparison of roughnesses, obtained during traditional and vibration cutting providing simultaneous vibrational impact on tangential and normal component of cutting forces [1] it is discovered that at the modes providing substantial increase of the tool life period, the height of micro-roughnesses is in the interval $Ra = 12.5 – 6.3$ microns. Among other things, during vibration cutting waviness in longitudinal section occurs on the machined surface with increasing of vibrational amplitude. It starts to appear especially clearly at vibration amplitudes at which the maximum period of cutter life was observed, thus vibro-turning of any vibration intensity provides chip crushing on pieces in length no more than 10 mm.

2. Equipment
The experiments were carried out on a special experimental unit.

The unit casing (figure 1) represents a box structure, consisting of front 1 and back 2 plates, which are connected between each other with top plate 3. On the top plate 3 there are mounting holes for installation of vibrator 4 and electric motor on adjustable base frame 5 (it is not specified on the drawing). Two lugs 6 are welded to the front plate 1 to create the cutter axis pin. The cutter axis pin is connected to the eccentric shaft 8 through the cutter oscillation mechanism 7.

Unit fixation in a tool clamp of the machine (figure 2) is made by guide plate clamping, lateral 9 and transverse 10, with the tool clamp screws.
The vibrator (figure 3) represents the casing 1 with roller tapered bearings 5 installed in it. The casing 1 is closed from both sides with covers 2 and 3, which, in turn, are fixed to the casing 1 with bolts 4. The eccentric shaft 6 is mounted in the bearings 5. The rotation from electric motor is transmitted to the shaft 6 through the pulley 8 fixed on the shaft 6 by a washer 9 and a nut 10. Between the end face of the bearing 5 inner ring and the end face of the pulley 8 there is a distance sleeve 7, designed to adjust the clearance in the bearings 5.

![Figure 1. General view of vibration cutting unit.](image1)

![Figure 2. Unit fixing elements.](image2)

![Figure 3. Vibrator design.](image3)

The problem of vibrations impact on the machine mechanisms was solved by the changing the plane of vibrations. In the new design, the vibrations are preset vertically perpendicular to the transverse stroke of the saddle feed. Vibrations set in this direction will have less influence on the machine mechanisms what in turn will have a positive effect on the accuracy characteristics of the machine and the cutting process.
3. Experiments
In the work [2] the authors revealed that the greatest lifetime period $T = 68$ min is observed at cutting speed $V = 80$ m/min, vibration amplitude $A = 70$ microns and vibration frequency of cutting tool corner $f = 100$ Hz. Cutting tool is a cutter equipped with a plate made of hard alloy metal Ti5Co10.

Based on the obtained data the authors revealed a dominant factors and variability intervals which have influence on the tool life period. Ground on the complete factorial experiment the regression equation was found and model optimization was made by gradient motion as per Box-Wilson method.

Based on the model optimization results a series of experiments was carried out to study the roughness parameters at the maximum tool life period at cutting speed $V = 85$ m/min.

The purpose of the experiment was to determine the change in the amplitude of vibrations at different frequencies on the character of roughness change and chip crushing. The tests were made on the samples made of steel 12Cr18Ni10Ti at cutting speed of 85 m/min, feed of 0.26 mm/rev, cutter plate material – hard alloy metal of grade IC907 produced by Israel company ISCAR.

The model of chip formation at the finish vibration turning of corrosion-resistant chromium-nickel steel of austenitic class 12Cr18Ni10Ti was considered. Lathe machining of this steel is accompanied by formation of “endless” flow chips. When using such cutting tool without chip breaker the machining of such materials causes the problems related to chips removal. One of such chip crushing method is the use of vibration cutting.

Vibration cutting is characterized by parameters such as amplitude and frequency of vibrations, which, in turn, affect the shape and mechanical properties of the chips. In the result of the investigations carried out in relation to vibration cutting, the authors obtained different types of chips (figure 4), corresponding to different vibration modes.

From the given types of chips it is validly to assume that the greater the value of amplitude and frequency of vibrations is, the higher is the value of vibrational influence in the cutting zone on the cut layer and the more intensive the process of chip crushing is going on. Vibration trajectory of the cutter corner presenting the conditional scheme of vibration impact in the cutting zone is given on the figure 5.

![Figure 4. Types of chips: a) – traditional turning; b), c), d) – cutting with vibrations.](image-url)
The presented scheme of the change in the trajectory of the cutter corner for one period of vibration has shown that the dominant main impact is on the tangential component, and the auxiliary one on the normal component.

The experiments were carried out in a wide range of vibration amplitudes at different vibration frequencies that allowed to define the parameters of the factors influencing on the chip formation process. It was revealed that major factors which characterize the vibration impact in the cutting zone are vibro-cutting speed, vibrational acceleration and dispersion of energy in cutting zone for the period of one cycle of vibrations.

During development of the chip forming model at vibro-cutting the impact of specified factors on the chip forming process during vibro-cutting were summed up with the conditional scheme of the cutting process for traditional turning proposed by N.V. Talantov [3], who discovered that according to the conditional scheme the transformation of the cut layer into a flow chips happens in the result of successively and continuously removed during the shift endlessly thin layers of material $\Delta c$ on the conditional shear plane $OL$ (figure 6).

![Conditional scheme of cutting process](image1)

**Figure 5.** Cutter corner vibration trajectory.

**Figure 6.** Conditional scheme of cutting process.
The experiments showed [4], that the process takes place without breaking the bond between shifted layers, i.e. without breaking a uniformity of the chip material.

It would be appropriate to assume that the conditional shear plane OL in the vibration process of the tool corner and the rotation of the workpiece, will be shifted, thereby changing the direction of vectors and the magnitude of forces acting during cutting.

Comparison of the conditional scheme of the cutting process and the action of the vibration impact force in the cutting zone will allow to develop an adequate mathematical model that characterizes the real scheme of the chip formation process and contact interaction during the vibration cutting.

4. Results
Optimization of vibration cutting parameters consists in finding of such values of amplitudes and vibration frequencies which ensure obtaining of crushed chips and minimal surface roughness. Based on the research findings [5, 6] it was revealed that the optimal amplitude for provision of steady chip crushing and obtaining the minimum surface roughness is 100 microns. The searching of optimal range of values is made by method of gradient motion for developed mathematical model of generalized function of vibration impact at amplitude of 100 microns, at changing of vibration frequency from 0 to 50 Hz in increments of 5 Hz.

Mathematical model of generalized function of vibration impact was found by polynomial method at research in a range of amplitudes from 10 to 100 microns

\[ Ra = 3.393 + 0.000786(A\omega) - 0.000000312(A^2\omega^2) + 0.000000641(A\omega^2) \]  

From the diagram presented in figure 7, it is obvious that two functions have a significant influence on the surface roughness. The speed of vibration \(B_1A\omega\) increases the roughness and the energy dispersion \(B_2A^2\omega^2\), on the contrary, decreases. However, numerical value of energy component prevails over the vibration speed and acceleration \(B_3A\omega^2\). Analyzing the curve corresponding to the calculated roughness values, it is obvious that the roughness decreases with increasing frequency of vibrations.

![Figure 7. Calculated dependence of vibration impact function on vibration frequency at A = 100 microns.](image-url)
To confirm the detected dependence of roughness on vibration frequency at the amplitude of $A = 100$ microns, it was decided to conduct control experiments in the field of optimization. The results of experimental studies conducted at the vibration amplitude of $A = 100$ microns in the field of optimization, confirmed the adequacy of the mathematical model. The results of surface roughness measurements are given on the figure 8.

![Figure 8](image)

**Figure 8.** Dependence of vibration impact function and experimental roughness on vibration frequency at $A = 100$ microns.

The values of roughness calculated on developed mathematical model for the amplitude $A = 100$ microns and obtained in the results of experiments made in the field of optimization confirmed the adequacy of the developed mathematical model for $A = 100$ microns. The experimental values of surface roughness obtained in the field of optimization were estimated according to the Student criterion for 5% level of significance. All the values are included in the confidential interval. At the same time, a sustainable chip crushing was provided (figure 9).

![Figure 9](image)

**Figure 9.** Types of the chips in machining of the steel 12Cr18Ni10Ti with amplitude $A = 100$ microns: a – $f = 35$ Hz; b – $f = 45$ Hz; c – $f = 50$ Hz.

5. **Conclusions**

The results of investigations presented in this work shown the possibility of vibration cutting use for finish turning of the workpieces made of hard-to-machine materials. The presented results do not reveal completely a physical base of vibration turning that requires additional researches. Based on the results presented in this work, intermediate conclusions can be drawn:

- On the basis of natural experiment results regression analysis the mathematical model was developed which determines the complex influence of the vibration parameters at vibration turning on the roughness of the machined surface.
- As a result of the vibration turning modes optimization it was established that in order to obtain the minimum value of the roughness it is necessary to use the vibration frequency in the range
from 5 to 15 Hz and from 40 to 60 Hz at the amplitude $A = 100$ microns. Thus the roughness reduction is provided by maximal impact of the energy component of vibration impact generalized function and high vibration frequency prevents the process of build-up forming.

- Therefore superimposing of forced rocking vibrations on the cutter corner facilitates a breaking of removal at the shift of endlessly thin layers of material $\Delta c$ during shifting at the shear conventional plane OL (figure 6), which explains the process of chips crushing during vibration cutting [7].

- The developed mathematical model in the form of a generalized function of vibration influence for the amplitude $A = 100$ microns according to the polynomial method, which takes into account the influence of three main factors of vibration impact in the cutting zone, allows to describe the dependence of surface roughness on the amplitude-frequency parameters at vibration cutting and reveals the physical basis of the process of vibration cutting.

References

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