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EFFICIENCY OF KINEMATIC CHIP BREAKING ON A CNC LATHE

When turning many materials, especially such as high-alloyed steels and a some of non-ferrous metal alloys, long continuous chips are usually formed which clutter the working area of the machine tools and are dangerous for the workers. One of the effective and reliable methods of chip breaking during turning is vibration cutting, when the uniform motion of the cutter relative to the workpeace during the turning process is superimposed with an additional vibration motion of the cutter. The use of oscillating movements of the cutter in the direction of longitudinal feed is the most effective for chip breaking during longitudinal turning. To ensure the necessary amplitude-frequency range of cutter oscillations, the use of a toolholder with an elastic part in the form of a machined spring of cross slot configuration and directional stiffness. The toolholder is equipped with a mechanism of oscillating movements of the elastic part, which receives movement from the drive of the tool spindle of the machine tool. The development and research of the mathematical model of the cutting tool elastic system determined the conditions under which reliable chip breaking takes place regardless of the cutting modes and the properties of the processing material. The conducted experimental studies confirmed the effectiveness of the proposed toolholder with elastic elements for reliable chip breaking during longitudinal turning.

Key words: chip breaking, vibration cutting, mathematical simulation, toolholder with machined spring of cross slot configuration.

INTRODUCTION

The problem of controlling the chip formation process arose when using automated production, CNC machine tools and "unmanned" technologies in modern engineering. In the conditions of automated production, breaking and removal of chips becomes especially important when their accumulation disrupts the automatic cycle of the machine tool. During high-speed turning of structural steels, a long continuous chip is usually formed, which is wound around the toolholder and the processed workpeace, interferes with monitoring the machining process, clutters the workplace, is inconvenient to remove from the machine tool, and is dangerous for the workers.

ANALYSIS OF LITERATURE DATA AND FORMULATION OF THE PROBLEM

The chip breaking process on the machine tools is carried out depending on the nature of the interaction between the cutting tool and the processed workpeace and is divided into cutting with constant and variable parameters. When cutting with constant parameters, the invariance of the cutting speed, feed and depth is ensured within the limits of this technological operation. In this case, they mainly use methods of mechanical breaking of chips without the supply of additional energy, which is carried out by adjusting the cutting modes and geometry of the cutter, as well as with the help of notches and ledges, which that change the movement of the chips in the direction of its steeper twisting [1].

When cutting with variable parameters, the most effective is the method of vibration cutting, which consists in adding to the traditional forming movements the vibration movement of the cutting tool relative to the workpiece, as a result of which the cutter of the toolholder performs the sum of the feed and additional vibration movements. However, this method requires the introduction of additional mechanisms into the design of the machine tool to create oscillating movements of the cutting tool in the range of up to 200 Hz with amplitudes of up to 0.3 mm and synchronizing them with the rotation of the workpiece. At the same time, the cutting tool relative to the workpiece can oscillate parallel to the directions of axial and radial feeds and the cutting speed vector (tangential vibrations) [2, 3].

Turning with axial vibrations in the direction of longitudinal feed affects the change of the cut area and increases the roughness of the machined surface in relation to turning with uniform feed. Therefore, turning with axial vibrations is used for rough and semi-finish operations, which do not have strict requirements regarding the quality of the machined surface. When cutting with radial vibrations, the cutting tool relative to the workpiece performs oscillating movements in the direction of cross feed and is effective especially in operations with cross feed. A feature of the turning process with tangential vibrations is the practically constant dimensions of the longitudinal and cross sections of the cut, which makes the use of such vibrations of the cutter for kinematic breaking of chips inefficient.

Depending on the cutting modes and additional vibrations of the cutter, the kinematics of the cutting process with vibrations can provide a continuous or intermittent cutting process. In the latter case, regardless of the cutting conditions, a breaking chip form is obtained. In the case of a continuous process of cutting with vibrations, chip breaking will take place when the thickness of the chip fluctuates significantly, when its strength in the hollow during interaction with the rotating surface of the workpiece or a special projection of the cutter may become insufficient [4, 5].

The purpose of the research is to increase the efficiency of turning with chip breaking by using toolholders with machined spring of cross slot configuration of directional stiffness to ensure a given amplitude-frequency range of oscillatory movements of the cutter and modes of vibration-resistant cutting.

PURPOSE AND OBJECTIVES OF THE STUDY

During the processing of workpieces on a machine tool using vibration cutting, additional ones arising under the action of alternating loads and due to the properties of the elastic system of the machine tool are superimposed on the oscillations set by the vibration drive [6]. Both during vibration and during conventional cutting, three components of the cutting force $P(t)$ act on the cutter - axial $P_x(t)$, radial $P_y(t)$ and tangential $P_z(t)$, the current values of which, especially depending on the methods of vibration cutting, change during each cycle of the cutter oscillation. As a result, the total amplitude of cutter oscillations can cause the technological system of the machine tool to go beyond the limits of stable cutting. Considering this, there is a need to simulate the turning process with additional oscillations of the cutting tool in order to determine vibration-resistant cutting modes while ensuring effective chip breaking.

For the mathematical description of the elastic system of the machine tool in its technological system, the cutting tool system that exerts a dominant influence on the chip breaking process is highlighted. It is advisable to build the model of the elastic system of the cutting tool using the main coordinates, which will allow to completely separating the variables that determine the movement of the cutting tool in an arbitrary *xyz* plane. In Fig. 1 shows a generalized dynamic diagram of a lathe designed for modeling dynamic processes during chip breaking in turning. The elastic system of the cutting tool includes sub-systems of the cutter-carriage, the feed drive-carriage and the drive of oscillatory movements of the cutter.

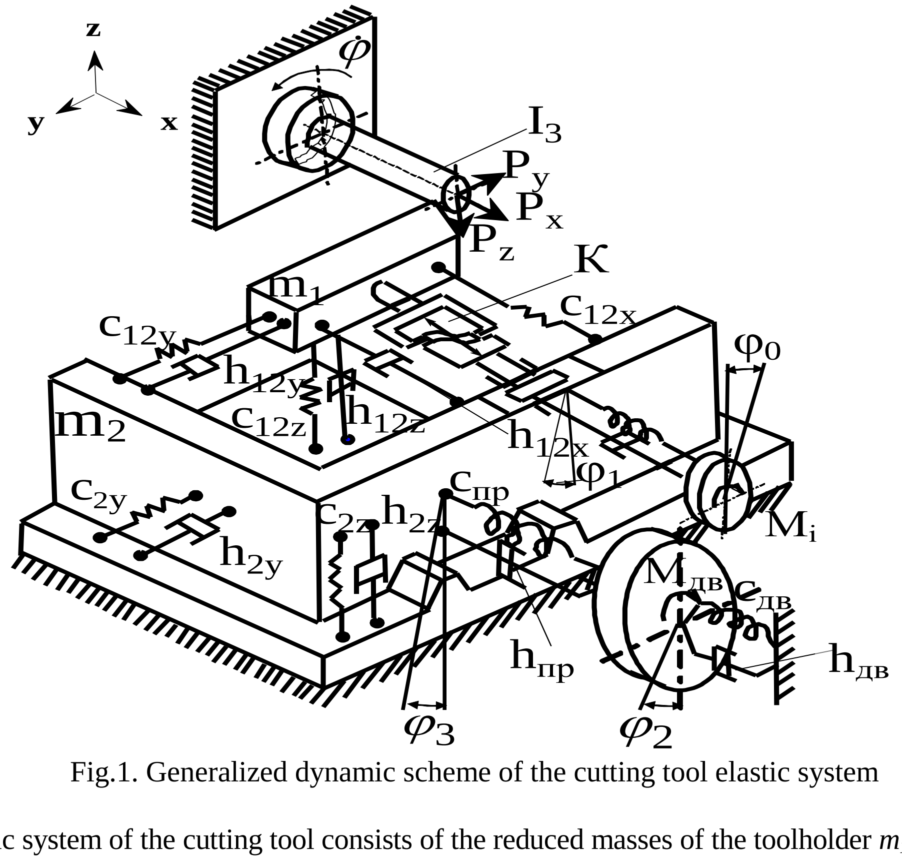


Fig.1. Generalized dynamic scheme of the cutting tool elastic system

The elastic system of the cutting tool consists of the reduced masses of the toolholder m_1 and the carriage m_2, connected to each other and the base of the machine tool by links with elastic and dissipative properties, on which the cutting force $P(t)$ acts. The system takes into account the reduced stiffness and damping coefficients of the toolholder - c_{12y}, h_{12y} and c_{12z}, h_{12z}, and the carriage - c_{2y}, h_{2y} and c_{2z}, h_{2z}, respectively, in the directions *Oy* and *Oz*; I_3 and I_0 - moments of inertia of the rotors of the feed drive motor and oscillatory movements of the cutter; φ_2, φ_3 - rotation angles of the engine rotor and the feed drive screw; h_{01}, h_{23}, c_{01}, c_{23} - total reduced coefficients of torsional damping and torsional stiffness of feed drives; h_{x12}, c_{x12} - total reduced coefficients of damping and stiffness of the toolholder in the *Ox* direction; M_{dv} and M_i - torques of the motors of the feed drive and the drive of the oscillating movements of the cutter; F_{TP} – the total frictional force in the slide carriage guides, screw gear, bearings and seals; $P_x(t)$ is the axial component of the cutting force (in the direction of longitudinal feed); $t_в$ – pitch of the lead screw. Mechanism K is designed to convert rotary motion into oscillating motion of the cutter along the Ox axis.

In modern CNC lathes, the feed drive consists of a high-torque motor, a belt (gear) transmission, a roller screw, and a feedback sensor. In addition, the carriage contains a tool accumulator - a turret head, in the working position of which there is a drive for rotating the tool spindle of the toolholders for drilling and milling operations. It is this drive that can be used as a source for oscillatory movements of the cutter.

The drive of oscillatory movements of the cutter is presented in the form of a reduced mass of the toolholder m_1, a vibration drive of the tooholder with a torque M_i, a reduced moment of inertia of the motor rotor I_0, the angles of rotation of the motor rotor and the drive shaft of the tool spindle - φ_0 and φ_1, which with the help of a transmission mechanism K transforms the rotational movement of a drive into oscillating movement of the elastically deformed part of the toolholder with the cutter.

The system of equations of motion of the cutting tool elastic system in the direction of longitudinal feed has the following form:

$$\begin{cases} J_3 \cdot \ddot{\varphi}_2 + h_{23}(\dot{\varphi}_3 - \dot{\varphi}_2) + c_{23}(\varphi_3 - \varphi_2) = M_{\partial в.} \\ m_2 \cdot \ddot{x}_2 + h_{x12}(\dot{\varphi}_3 - \dot{\varphi}_2) + c_{x12}(\varphi_3 - \varphi_2) - \\ - h_{23} \cdot \dfrac{2\pi}{t_{ГВ}}(\dot{\varphi}_3 - \dot{\varphi}_2) + c_{23}\dfrac{2\pi}{t_{ГВ}}(\varphi_3 - \varphi_2) = -F_{TP} \\ m_1 \cdot \ddot{x}_1 + h_{x12}(\dot{\varphi}_3 - \dot{\varphi}_2) - c_{x12}(\varphi_3 - \varphi_2) = -P_x \\ J_0 \cdot \ddot{\varphi}_1 + h_{01}(\dot{\varphi}_1 - \dot{\varphi}_0) + c_{01}(\varphi_1 - \varphi_0) = M_i \end{cases} \quad (1)$$

The cutting force $P(t)$ can be represented as [7] $P(t) = K_{piз} \cdot a(t) \cdot b(t)$, were $a(t)$ and $b(t)$ - time-varying thickness and width of the area of metal being cut, $K_{piз}$ - specific cutting force.

When cutting without vibrations, the distance $a(t)$ between the trajectories of the cutter end on two adjacent rotations of the workpeace is constant and equal to the axial feed S. When cutting with axial vibrations, this distance is variable and depends on both the feed and the amplitude of oscillations, phase angle and phase shift as [3]:

$$a(t) = S + A \cdot \sin\omega_i t - A\sin(\omega_i t - 2 \cdot \pi \cdot \omega_i / \omega_\partial), \quad (2)$$

were $\omega_i = \dot{\varphi}_2$ - circular frequency of oscillatory movements of the cutter; ω_∂ - angular velocity of the workpiece. The ratio ω_i/ω_∂ can be represented by the sum of the whole part k, which is the whole number of waves included in one revolution of the workpiece, and the fractional part q, that is: $\omega_i / \omega_\partial = k + q$. It is obvious that the relative position of the sinusoids of oscillations is determined only by the fractional part of the ratio ω_i/ω_∂. In particular, at $q = 0$, an increase in the amplitude A of the cutter vibrations does not ensure chip breaking due to the whole number of vibration waves that are included in one revolution of the workpiece and leave a constant value $a(t)$ at each subsequent revolution of the workpiece (machining on the previous trace). Therefore, it should be taken into account that the ratio ω_i/ω_∂ should not be a whole number to ensure chip breaking.

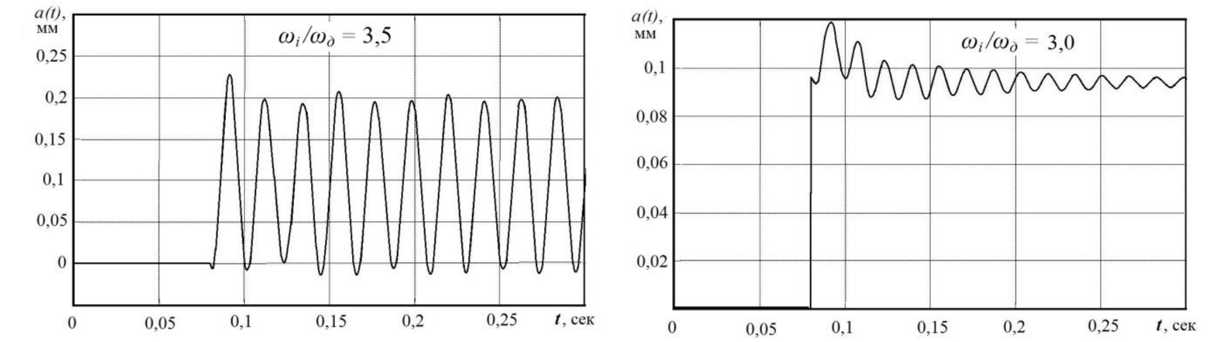
Cutting with axial vibrations affects the change of the cut area, which is proportional to $a(t)$, and increases the roughness of the machined surface in relation to cutting with a uniform feed. Therefore, cutting with axial vibrations is used for rough and semi-finished operations, which do not have strict requirements regarding the quality of the processed surface. From the analysis of the kinematics of vibration cutting, it follows that with axial vibrations of the cutter, chip breaking with a minimum amplitude is achieved only with a strictly defined ratio between the angular speed of the workpeace ω_∂ and the angular frequency of oscillations of the cutter ω_i , that is[8]:

$$\omega_i/\omega_\partial = k+0{,}5 \text{ та } A=0{,}5 \cdot S. \quad (3)$$

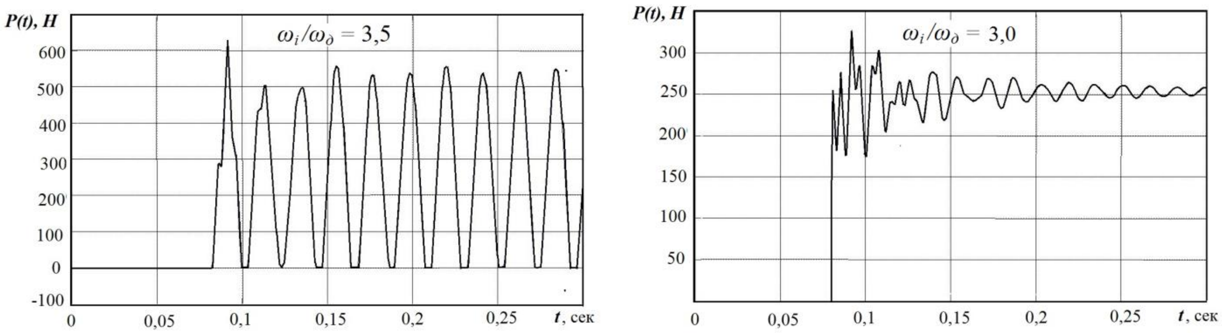
The simulation of the process of chip breaking in the direction of axial feed is carried out on the mathematical model of the cutting tool elastic system in the form of a system of differential equations (1), which takes into account the elastic-damping characteristics of the elements of the dynamic scheme and, using expression (2), the kinematic characteristics of the chip breaking process and the influence of one of sources of self-oscillations during cutting - machining on the previous trace (3).

RESEARCH RESULT

In Fig. 2 shows the results of the simulation of the chip breaking process in the form of graphs of the dependence of the current value of the thickness of the cut area *a(t)* and the cutting force *P(t)* from the frequency ratio ω_i/ω_∂. The graphs were calculated at the values of S = 0.1 mm/rev, A = 0.05 mm and at the ratio ω_i/ω_∂ = 3.5, which corresponds to condition (3), and at the ratio ω_i/ω_∂ = 3.0. Modeling of the breaking process under the condition ω_i/ω_∂ = 3.5 shows that its consideration ensures periodic crossing of the zero coordinate by the *a(t)* graph, which means periodic interruption of the cutting process (Fig. 2, a) and zeroing of the cutting force *P(t)* (Fig. 2, b). On the other hand, disregarding condition (3) and the effect of processing after the trace at the ratio ω_i/ω_∂ = 3.0, with all other parameters of the model being the same, a process of continuous cutting with variable parameters and slight fluctuations in the thickness of the cut area *a(t)* (Fig. 2 ,a) and cutting forces *P(t)* (Fig. 2, b) are observed without chip breaking.



a)



b)

Fig.2. The results of the simulation of the chip crushing process in the form of graphs of the current values of the cut area thickness *a(t)* (a) and the cutting force *P(t)* (b) taking into account the condition (3) for ω_i/ω_∂ = 3.5 and with an arbitrary ratio, for example ω_i/ω_∂ = 3.0

To implement the specified amplitude-frequency range of cutter oscillations, a toolholder with machined spring of cross slot configuration and with the axis of greatest stiffness oriented relative to the normal to the processed surface is proposed [10]. The use of such a machined spring for cutter oscillations provides an increase in the modes of stable chip breaking and the necessary amplitude-frequency range of vibration movements of the cutter due to the sufficient cyclic endurance of its elastic elements at maximum amplitudes of its oscillations.

In Fig.3 shows the kinematic diagram of the two-coordinate turret carriage 1, which has a turret head 2 with a 16-position faceplate 3. The faceplate 3 of the turret head in the working position is fixed on the gear semi-couplings 4 by a hydraulic cylinder 5. The rotation of the faceplate is carried out when the semi-couplings 4 are unfixed from the high-torque motor 6 through the gear pair 7. The rotation of the tool spindle 8 is also provided by the engine 6 through the toothed belt transmission 9, the toothed gear 10 and the clutch 11. The rotation of the tool spindle 8 of the toolholder for chip breaking is transmitted only after the faceplate is fixed, when the faceplate rotation drive is turned off.

In Fig. 4 shows the general view of the elastic elements (Fig. 4, a) and the polar diagram of the flexibility of the elastic part of the toolholder in the *yOz* plane (Fig. 4, b).

From Fig. 4,b, it can be seen that the special design of the elastic element of the toolholder in the form of a machined spring of cross slot configuration ensures the directionality of the axes of greatest and least flexibility in accordance with the recommendations that ensures the increased vibration resistance of processing with non-rigid tooling, i.e. that the angle of rotation of the main axes of stiffness *y'Oz'* (β = 15^0) was approximated in value to half the angle α (α=30^0 was taken in the calculations), which determines the direction of action of the cutting force *P*, that is $\beta = \alpha/2$ [7, 10].

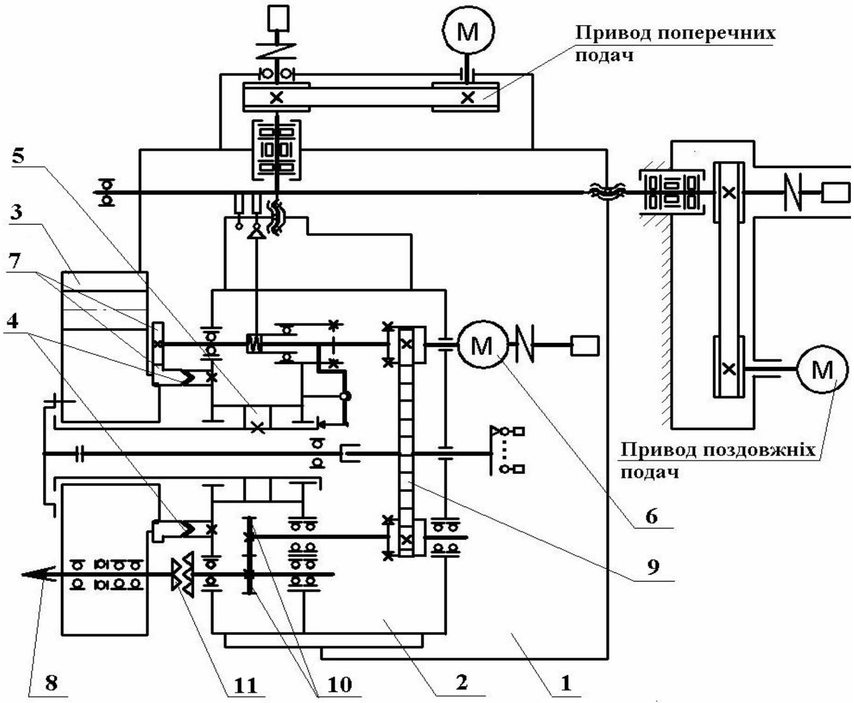


Fig.3. Kinematic scheme of the turret carriage of a CNC lathe

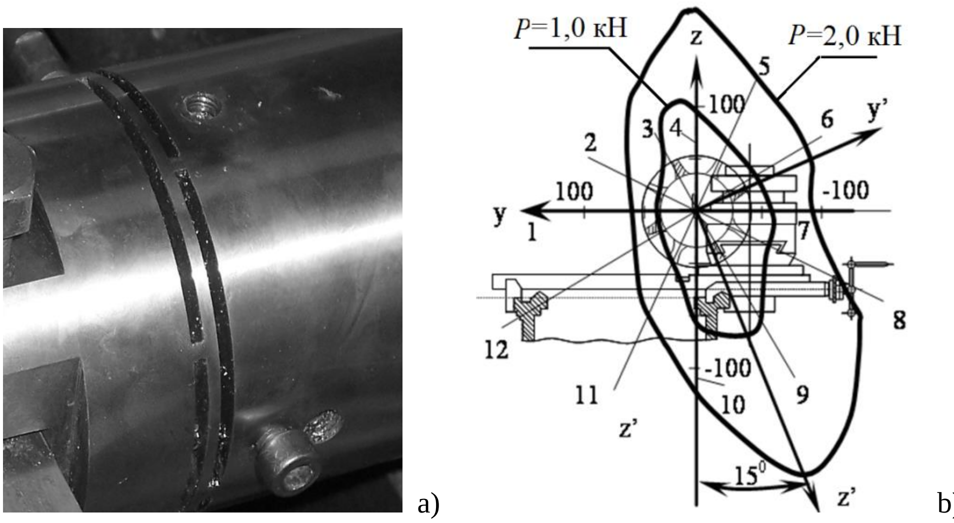


Fig.4. Machined spring of cross slot configuration of the toolholder (a) and experimental polar diagram of the flexibility of the elastic part of the toolholder (b)

Experimental research of the toolholder with elastic elements in the form of machined spring of cross slot configuration showed the following results: - stiffness in the directions of the components of the cutting force c_x = 67.5 N/μm, c_y = 23.45 N/μm, c_z = 11.18 N/μm. Frequencies of natural oscillations of the elastic part of the toolholder in the following directions: - P_x without pretension - 93 Hz, with pretension of 0.2 mm - 86 Hz; - P_y without pretension - 140 Hz, with pretension of 0.2 mm - 150 Hz; - P_z without pretension - 155 Hz, with pretension of 0.2 mm - 157 Hz. Increasing the value of the pretension did not lead to a significant change in the frequencies of natural oscillations.

The test for cutting workpieces made of steel 45 was carried out on a stand based on a 1A616 lathe equipped with an additional drive for rotating the tool spindle of the tooholder. In all cutting modes at feed S=0.16 mm/rev, range of cutting speeds V = 72-167 m/min., amplitude of cutter oscillations A = 0.08 mm, cutting depths t=0.25; 0.5; 0.75; 1.0; 1.25; 1.5; 1.75 mm and an odd ω_i/ω_o ratio, stable chip breaking was registered.

DISCUSSION OF THE RESULTS OF THE STUDY

Based on the analysis of known methods and devices for chip breaking during turning, it was established that the use of elastic elements for oscillating movements of the cutter is the most effective way to provide vibration processing with an amplitude of up to 0.5 mm and a frequency of up to 200 Hz for reliable chip crushing in a wide range of modes cutting.

The results of mathematical modeling established that the choice of the shape, location and stiffness of the elastic part of the toolholder relative to the direction of the external load on the cutting tool has a significant impact on the efficiency of the segmental chip formation process.

It is proposed to choose the parameters of the elastic elements of the toolholder, taking into account ensuring its maximum stiffness with minimal external loads for oscillatory movements of the cutter. At the same time, it is recommended to use oriented stiffness for the machined spring of cross slot configuration due to the special placement of jumpers between two rows of slots.

SUMMARY

According to the results of research, the effectiveness of using vibration cutting with low-frequency oscillations for reliable breaking of chips during turning processing has been confirmed. The most effective and reliable in longitudinal turning is the chip breaking process with axial vibrations of the cutter, taking into account the odd ratio of the spindle rotation frequency and the frequency of oscillatory movements of the cutter. Conducted research using a mathematical model of the cutting tool elastic system showed that when using axial vibrations of the cutter, the reliability of chip breaking is determined by the ratio of the amplitude of these vibrations and the amount of longitudinal feed of carriage.

The use of a toolholder with an elastic part in the form of machined spring of cross slot configuration and with the drive of its oscillating movements provides the necessary amplitude-frequency range of cutter oscillations for chip breaking in the direction of longitudinal feed. The positive effect of chip breaking compensates for some disadvantages associated with a slight decrease in the quality of the treated surfaces. The execution of the elastic part of the toolholder in the form of machined spring of directional stiffness ensures a sufficient level of vibration resistance of the cutting tool elastic system due to the reduction of the influence of the coordinate connection, that is, the condition when the cutter is pushed away from the processed surface of the workpiece when the cutting force increases.

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Шевченко О.В. Бєляєва А.Ю. Ефективність кінематичного дроблення стружки на токарному верстаті з ЧПК

При токарній обробці багатьох матеріалів, особливо таких, як високолеговані сталі і ряд сплавів кольорових металів, зазвичай утворюється зливна стружка, яка захаращує робочу зону верстата та є травмонебезпечною для робітника. Одним ефективних і надійних способів дроблення стружки при токарній обробці є вібраційне різання, коли на рівномірний рух інструменту відносно деталі в процесі точіння накладається додатковий вібраційний рух інструменту. При правильному виборі напряму коливань, їх частоти та амплітуди, вібраційне різання дозволяє надійно і ефективно дробити стружку. Найбільш ефективно при поздовжньому точінні відбувається дроблення стружки з використанням коливальних рухів різця в напрямку поздовжньої подачі. Результатами математичного моделювання на розробленій математичній моделі динамічної системи інструменту токарного верстата, що враховує конструктивні особливості вібраційного приводу з передаточним механізмом різцетримача у вигляді пружного елементу спеціальної просторової конфігурації для забезпечення направленого вібраційного руху різця, показано, що суттєвий вплив на ефективність процесу утворення сегментної стружки має вибір форми, місця розташування і величини жорсткості зони пружного корпуса різцетримача відносно напрямку зовнішнього навантаження на різальний інструмент. Для забезпечення необхідного амплітудно-частного діапазону коливань різця запропоновано використання різцетримача з пружною частиною у вигляді прорізної пружини направленої жорсткості та використання штатного приводу інструментального шпинделя верстата з ЧПК. Розробкою та дослідженням математичної моделі пружної системи інструменту визначені умови, при яких незалежно від режимів різання та властивостей оброблювального матеріалу відбувається надійне дроблення стружки.

Ключові слова: дроблення стружки, вібраційне різання, математична модель, прорізна пружина різцетримача.

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