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Development of an Acoustic Method for Predicting Wear of Commercial Cutting Tools

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Abstract
The system of forecasting or predicting wear of cutting tools in different turning operations of work pieces using acoustic method is studied. This work is based on the analysis of the conditions characteristics of the mechanical processing, laws of wearing and decomposition of cutting tools on the basic characteristics of the cutting process. The paper presents and studies research methods of the efficiency of cutting tools during turning operations. This work also researches the physical, chemical and mechanical phenomena occurring at the micro-level that lead to a change in the properties of the materials at the macro-level and this change is largely unpredictable due to the random nature of the motion of atoms and particulars at first glance and the scattered arrangement of the primary properties of products intended for the same purpose.

Keywords: acoustic method, composite material, cutting tools, turning process, vibration, wear prediction.

Introduction

Until now, the mechanical treatment of materials by pressure and cutting has remained one of the most important shaping operations in technological processes. Along with the formation of the characteristics of metal products, large volumes of materials, such as wood, printing materials, plastics, glass, composite materials, etc., are processed by mechanical means the efficiency of machining processes is the basis for the production of competitive products. an increase in productivity, flexibility, reliability and efficiency while ensuring the quality and accuracy of the products obtained is currently associated with a scientifically based choice of optimal tool materials, geometric parameters of tools and cutting conditions, and the introduction of systems control over the condition of the tool, etc.

Physical, chemical and mechanical phenomena occurring at the micro-level lead to a change in the properties of the material at the macro-level, and this change is largely unpredictable due to the random nature of the movement of atoms and the seemingly insignificant spread of the primary properties of products intended for the same purpose maintaining a given level of reliability in this case is possible by timely adjusting the technical condition of the machine, through the use of effective diagnostic methods, in particular, vibration diagnostics methods [1]. Moreover, it is necessary to approach this problem more broadly and apply diagnostics not only to monitor the state of the machine, as such, but also to monitor the state of the cutting tool used in the process of its manufacture.

Recommendations for optimization of machining processes are based on modern concepts of material deformation processes [2]. At the same time, many of the observed physical regularities during mechanical deformation still have no explanation from the standpoint of the mechanics of a deformable solid. Despite the increasing number of publications with a mathematical description of certain machining processes, a unified theory, which, in full accordance with the level of modern science, would make it possible with sufficient accuracy and reliability to assess the influence of various factors on the results, the process has not yet been created. This is largely due to the fact that most scientists who are engaged in the mechanical processing of materials do not have sufficient training in the field of solid mechanics and the theory of plasticity.

Taking this into consideration, the subject of concern in our article is the use of a linear-deformable half-space of stress and strain to explain the stress state of the surface layer of the product during wear of the cutting tool.

Materials

An important factor in the efficiency of machining is the ability to provide a stable physical-chemical-mechanical state of the surface layer of the product [3]. Practice shows that this task is quite difficult, thus the level of residual stresses can vary significantly within the same machined surface. In combination with fluctuations in the physicochemical state of the surface layer at the Nano-level, this leads to the appearance on the treated surface and in the near-surface layer of foci with an increased tendency to cracking, corrosion, adhesion and abrasion of the product. As a result, the presence of areas with variable properties creates the prerequisites for premature failure of the part during operation, especially under conditions of alternating loads and temperatures, high pressures and friction rates.

The physical essence of the formation of a surface layer with inhomogeneous properties is due, on the one hand, to the specific features of the development of deformation of the processed material, and, on the other hand, to its probabilistic nature. The first feature is the scheme of loading the material being processed, which can be supplemented by an explanation of the deformation and the phenomena of destruction and wear of the cutting tool that accompany it.

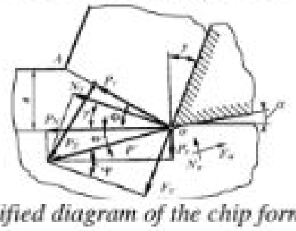

Fig.1.1. Simplified diagram of the chip formation process

Many scientists for theoretical research and analysis of experimental data in the machining of materials by cutting adopted a simplified chip formation scheme with one shear plane (Fig. 1.1) [4]. A characteristic feature of the contact interaction of the cutting tool with the chips and the work piece is the difficult friction conditions on the front and rear surfaces of the tool, caused by high temperature and contact loads. The forces acting on the front surface of the blade N_λ and F_λ are calculated by the formulas:

$$F_\gamma = P_{z0}\sin\gamma + P_{y0}\cos\gamma$$
$$N_\gamma = P_{z0}\cos\gamma - P_{y0}\sin\gamma \quad (1)$$

where; P_Z and P_Y are the components of the chip formation force; N_α, F_α - normal and tangential forces acting on the back surface.

The friction force F_α can be found using the expression:

$$F_\alpha = \mu \cdot N_\alpha, \qquad (2)$$

where μ is the coefficient of friction along the rear surface.

Often, to assess the friction conditions, the average coefficient of friction μ_c is used, which is determined by the ratio of the friction force F to the force of normal pressure N [5]:

$$\mu_C = \mu_0 + \mu_A = \mu_0 + \frac{q_F}{q_N}, \qquad (3)$$

where μ_o *is* the true coefficient of friction determined by the atomic-molecular interaction; μ_A - adhesive component.

S.S. Silin proposed the following formula for calculating the average coefficient of friction μ_c [1]:

$$\mu_C = \frac{\cos\gamma + \sin\gamma - B \cdot (\cos\gamma - \sin\gamma)}{\cos\gamma - \sin\gamma + B \cdot (\cos\gamma + \sin\gamma)}, \qquad (4)$$

where γ is the front angle of the cutter; - value characterizing the degree of plastic deformation of the metal of the removed allowance and the surface layer of the work piece; φ - angle of inclination of the conventional shear plane.

Experimentally, the angle φ can be determined by the formulas

$$tg\Phi = \frac{\cos\gamma}{\xi - \sin\gamma} \text{ Or } \sin\Phi = \frac{\cos\gamma}{\sqrt{\xi^2 - 2 \cdot \xi \cdot \sin\gamma + 1}}, \qquad (5)$$

where ξ is the coefficient of shrinkage of the chips, numerically equal to the coefficient of thickening of the chips Kα = αC/α or the coefficient of its shortening KL = L / LC (L is the cut length; LC is the length of the chips).

The normal force N_α acting on the rear surface of the cutting blade is determined from the expression:

$$N_\alpha = \frac{P_Y \cdot (1 + \mu \cdot tg\gamma) - P_Z \cdot (\mu - tg\gamma)}{1 + 2 \cdot \mu \cdot tg\gamma - \mu^2}, \qquad (6)$$

The average normal stress q_N on the back surface can be determined by the formula:

$$q_N = \frac{N_\alpha}{A_\alpha} = \frac{N_\alpha}{b \cdot (h_3 + C_\alpha^0)}, \qquad (7)$$

where A_α is the area of the contact pad along the back surface ($\boxed{A_\alpha = C_\alpha \cdot b}$ where C_α is the length of the contact along the back surface); *b* is the width of the cut layer; h_3 is the size of the wear area on the flank surface; N_α is contact length in the absence of wear. According to A.M. Rosenberg and O.A. Rosenberg the value q_N can be taken for carbide tools equal to 0.1 mm [6].

Any cutting tool always has a cutting-edge rounding radius *ρ*, the value of which depends on the properties of the tool material and the technology for preparing the working surfaces.

For a blade sharp-cut instrument from diamond and cubical barium nitride the ρ= 1 ... 3 microns, from hard tungsten-cobalt alloys ρ = 10 ... 16 microns, from hard alloys of the TK group ρ = 20 ... 30 microns, from high-speed steels ρ = 8 ... 10 μm [3].

The nature of the loading determines the shape and size of the presumed fracture zone (shaded area in Fig. 1.2); the zone in which the acting stresses are close to the ultimate tensile strength of the processed material. Point B is shown as the coordinate of a possible nucleus of a ductile fracture crack dividing the processed material into chips and the surface layer of the part. It is usually above the theoretical cutoff line AA A. The value Δh of the material, which rises by the rounded part of the cutting edge, is related to the rounding radius ρ by the ratio $\Delta h \geq (0{,}3 \ldots 0{,}5)\rho$.

The material, which is located above the AA' line, is crumpled, creating additional hardening of the surface layer, and partially elastic is restored after passing the tool, even with constant parameters of the cutting mode and the tool, the coordinate of point B - the point of separation of the work piece material - will be a random variable and, accordingly, the layer thickness соответственноh will change, creating the prerequisites for inhomogeneous hardening of the surface layer and height fluctuations micro-roughness on the treated surface. The position of the material separation point is limited by the size of the fracture zone near the cutting edge. The larger the source of destruction, the higher the likelihood that the specified point will move further and further from the AA' line. Accordingly, the fluctuations in the thickness of the crumpled layer Δh and the characteristics of the hardening substructure will increase. Thus, the larger the fracture zone in the cutting zone, the higher the probability of the formation of a surface layer with unstable properties along the length of the treatment in turn, the size of the fracture site is associated with the intensity and nature of the distribution of stresses on the processed material, acting from the cutting tool.

Contact interactions of the cutting edge of the tool with the material being processed is characterized by the value of the contact stress σK arising at the point of their contact (Fig. 1.3).

The average value of the contact voltage is determined by the following formula.

$$\bar{\sigma}_K = \frac{P}{2 \cdot R \cdot L_B}, \qquad (9)$$

where L_B is the length of the cut; P is the effort developed during cutting; R is the radius of the cutting edge.

The diagram of stresses arising at the contact area of the tool with the work piece material is shown in Fig. 1.3. The parameters of the contact area are shown in Fig. 1.2. The tool contour is described by the following equations.

$$f(x) = \begin{cases} -\dfrac{(x-c)^2}{2R}, x \geq b, \\ x tg\varepsilon + d, x < b, \end{cases} \qquad (10)$$

where $c = b + R tg\varepsilon$,

$d = -btg\varepsilon - \frac{(b-c)^2}{2R}$

Normal stresses in the contact area are determined by the formula:

$$\sigma_{y|y=0} = -\frac{2P}{\pi}\left(a^2 \arccos\frac{b}{a} - b\sqrt{a^2-b^2}\right)^{-1} \times$$
$$\times\left(\arccos\frac{b}{a}\sqrt{a^2-x^2} + (x-b)\ln\frac{\left[\sqrt{(a+b)(a-x)} + \sqrt{(a-b)(a+x)}\right]^2}{2a|b-x|}\right). \quad (11)$$

The ratio a/b is determined from the transcendental equation:

$$\sqrt{1-\left(\frac{b}{a}\right)^2} - \frac{b}{a}\arccos\frac{b}{a} = \pi\frac{R}{a}tg\varepsilon \quad (12)$$

Fig. 1.2. Area of contact of the tool with the work piece material:
a - the size of the contact zone, ε is the angle of inclination of the cutting edge, R - the radius of the cutting edge,
b - transition of the straight-line generatrix of the blade into curvilinear (rounded), c - the point where the maximum contact stresses act, P-cutting force.

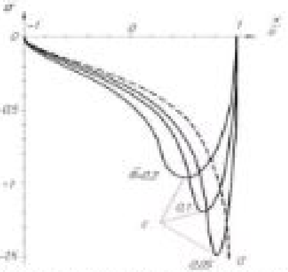

Fig. 1.3. Dimensionless diagrams of normal stresses in the contact area

$\left(\bar{\sigma} = \frac{a}{P}\sigma_y|_{y=0},\ \bar{R} = \frac{R}{a}tg\varepsilon\right)$

From Fig. 1.3 it follows that as the tool becomes blunt (increasing the radius of the cutting edge), the voltage value decreases and its maximum (point C) approaches the center of the contact area. The nature of the change in the maximum value of the diagram (point C, Fig. 1.3) as the radius R grows is shown in Fig. 1.4. Correspondingly, the average contact voltage also decreases.

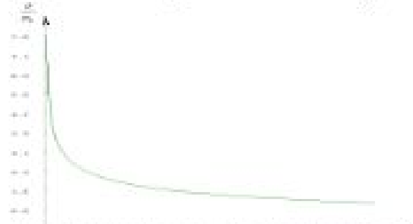

Fig. 1.4. Change in the maximum stress diagram (point C, Fig. 1.3) depending on the increase in the radius R of the cutting edge of the tool

Let us express the amount of wear of the cutting-edge h through its radius R (Fig. 1.4)

$$h = \frac{R}{tg\frac{\beta}{2}} - R. \qquad (13)$$

Substituting (9) into (13), we obtain an expression linking the amount of wear with the average contact stress

$$h = \frac{P}{2 \cdot L_K \cdot \bar{\sigma}_K} \cdot \left(ctg\frac{\beta}{2} - 1 \right). \qquad (14)$$

From (14) it follows that the value of the cutting-edge wear h is inversely proportional to the value of the averaged contact stress

$$h \approx \frac{1}{\bar{\sigma}_K}. \qquad (15)$$

The level of wear of the instrument can be determined by the following formula:

$$dh(t) = \frac{h(t) - h_0}{h_0}. \qquad (16)$$

where *h(t)* is the current amount of wear; h_0 is the initial value of the h parameter.

In practice, it is practically impossible to quickly assess the technical condition of the cutting tool using formula (16), so here it is necessary to use indirect methods that are widely used in technical diagnostics of machines. For example, you can estimate the degree of tool wear by the magnitude of the acoustic signal that is generated by the machining process of the material.

The amplitude of the sound pressure is directly proportional to the amplitude of deformation of the surface of the processed material. This deformation, in turn, is proportional to the magnitude of the contact stress created in the material being processed by the cutting tool. According to (15), the values of contact stress and wear are inversely proportional to each other.

$$A \sim \sigma К \sim 1/h . \qquad (17)$$

With this formula (16) will become the following:

$$dh(t) = \frac{A_0 - A(t)}{A(t)}. \qquad (18)$$

where *A(t)* is the current value of the amplitude of the sound pressure; A_0 is the initial value of the amplitude of the sound pressure (pressure generated by a sharp instrument).

Expression (18) allows you to control the degree of wear according to the results of regular monitoring of the magnitude of the acoustic signal generated by the process of machining the material. However, knowledge of the current degree of tool wear is not enough, it is also necessary to determine the operating time of the *Tzat* tool before its next sharpening. This parameter is determined in the process of approximating the results of monitoring the acoustic signal by a graph of a curve reflecting the mechanics of the tool cutting edge wear. This curve describes the process of decreasing the amplitude of the acoustic signal with the wear of the tool.

The approximation procedure is performed using a computer by minimizing the following functional.

$$U = \sum_{i=0}^{m}\left[A(t_i) - A_0[1 - \alpha\left(\frac{t_i - t_0}{T_{зап} - t_i}\right)^n]\right]^2, \qquad (19)$$

where α, n are the parameters of the analytical dependence.

Having determined the parameters $T_{зап}$, α and n, expression (18)) can be represented in the following form.

$dh(t) =$ (20)

These theoretical positions have been verified experimentally.

Research methods

Experimental setup

To study the operability of the system for diagnosing the state of the tool and to study the effect of tool wear on the AI, an experimental setup was developed on the basis of a universal lathe-cutting machine type II611P, with the following characteristics.

Name of Parameter	**Unit.**	**Value**
Largest diameter of material that can be installed on the lathe	mm	250
The distance between the centers	mm	500
Height of the center	mm	130
Largest diameter of the rod	mm	24
Largest diameter over the lower part of the support	mm	125
Largest diameter turning piece	mm	500
Pitch of the cut metric thread	mm	0.2…48
Pitch of the cut modular thread	modules	0.2…30
Pitch of the cut Inch thread	inch	24…0.5
Number of cutting tools in the tool holder	pieces	4
Largest width of the tool holder	mm	16
Largest height of the tool holder	mm	16
Largest longitudinal displcement by hand	mm	500
Largest tranverse displcement by hand	mm	180
Longitudinal displcement of limb division value	mm	0.1
Transverse displcement of limb division value	mm	0.02
Displacement on one round of limb of longitudinal displacement	mm	20
Displacement on one round of limb of transverse displacement	mm	3
Number of turns of the spindle motor	rmp	1430
Power of the spindle motor	kWt	3
Type of the spindle motor		4A100S4

The general view of the experimental setup is shown in Fig. 2.1. The work piece is processed by the tool; the registration of the AI signal was carried out using a receiver (microphone) placed at the required point in the processing system space.

The AI receiver attaches to the computer's sound card. The signal coming from the microphone is converted from analog to digital using an analog-to-digital converter installed on the sound card. The obtained data are stored in the computer memory using the Wave program for further processing by a specially developed program.

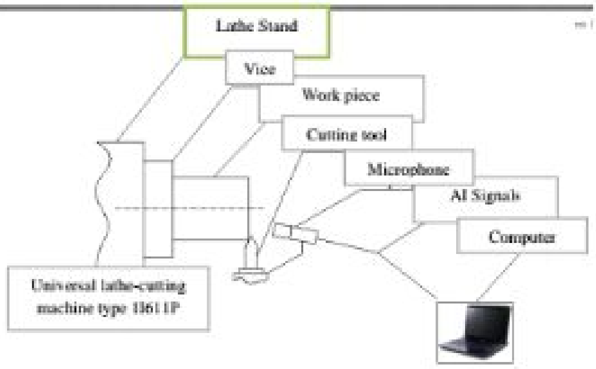

Fig. 2.1. The scheme of the experimental setup

During the experiments, it was found that the dynamic range of amplitudes perceived by the AI sensor depends both on the place of its attachment and on the method. This is due to the fact that acoustic waves that arise when cutting in metal, with increasing distance get damp.

Stable results were obtained by attaching the sensor to the body using a special device. In this case, the sensor attachment point was equipped with a soft gasket. The use of a soft gasket for fixing the sensor did not reduce the dynamic properties of the signal in comparison with its rigid fixing.

Thus, the sensor reacted only to acoustic vibrations arising during the turning of parts, machine vibration did not affect it. To carry out the experiments, we used right-hand boring cutters T15K6 and an angle of insertion with plasticity equal to 10 °. The cutter section in most cases of work piece processing was (hxb = 16x12) mm made of P6M5 material made in accordance with GOST 1050-88. The parameters of the cutters are shown in the figure. The choice of high-speed steel cutters as a material was determined by the need to blunt the cutter on the experimental work piece during several tool passes. Turning was carried out without the use of coolant. Machining was carried out with different spindle speeds and feeds per cutter at a constant depth of cut.

The blanks used in the experiment were made of steel. The size of the work pieces was 15 mm in diameter and 100 mm in length.

The amplitude-frequency characteristics (AFC) of the turning process signal taken with a microphone in the Adobe Audition 3.0 environment, one of which is shown in Fig. 2.2, made it possible to conclude that they can be used to analyze the state of the cutting tool. In a real system machine-device-tool-part, at medium cutting conditions, after a short time interval from the beginning of cutting, lasting a few seconds, a stationary self-oscillating mode is established. This is due to the high inertia of the machine-device-tool-part system, since self-oscillations cannot occur immediately after the tool is cut into the work piece, but some time passes before they occur.

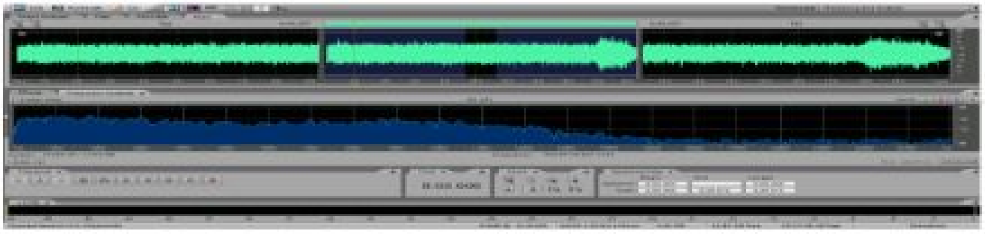

Fig. 2.2. Vibration spectrum image

Highlighting informative bands

It is known that various elements of the technological system and the cutting process itself "make noise" in different ways at different frequencies. Therefore, it is necessary to select a frequency band, the vibration amplitude in which depends only on the elements of the cutting mode and the amount of tool wear. To solve this problem, an experimental plan was built, in which the feed and frequency were varied within 0.18-1.5 min-1, 250-2000 rpm, respectively. This was required to find the optimal conditions under which the cutter would wear out in 1-3 passes over the work piece surface. Such modes were n = 2000 rpm, Pz = 1.44 min-1, t = 0.5 mm, and the spectra of the AI signal were constructed under conditions of shop noise and at steady-state cutting for each point of the experiment plan

Fig. 2.3. Acoustic emission spectrum of the turning process

These spectra were superimposed on each other, as shown in Fig. 2.3 and the areas characterized by an increase in signal amplitude with changing tool wear were highlighted.

Results and discussion

As a result of the research carried out, it was found that when turning the work piece, there is only one wide informative frequency band - from 700 Hz to 1200

Hz - sensitive to changes in tool wear. The experimental results are shown in Tables 1, 2 and 3.

Table 1. Results of experiment with sharpened tool

Tests	Frequency of rotation of spindle n_p, min^{-1}	Instrument displacement towards work piece S, mm/round	Average value of Decibel, dB
1	250	0.18	54.5
2	315	0.23	55.1
3	400	0.29	56
4	500	0.36	57.5
5	1000	0.72	57.8
6	1600	1.15	60.5
7	2000	1.44	61.5

Table 2. Results of experiment with unsharpened tool

Tests	Frequency of rotation of spindle np, min-1	Instrument displacement towards work piece S, mm/round	Average value of Decibel, dB
1	250	0.18	55.5
2	315	0.23	56.5
3	400	0.29	57.4
4	500	0.36	58
5	1000	0.72	58.5
6	1600	1.15	60.5
7	2000	1.44	62

Table 3. Results of experiment with worn out tool

Tests	Frequency of rotation of spindle n_p, min^{-1}	Instrument displacement towards work piece S, mm/round	Average value of Decibel, dB
1	250	0.18	57
2	315	0.23	57.8
3	400	0.29	58.2
4	500	0.36	59
5	1000	0.72	62
6	1600	1.15	65.5
7	2000	1.44	67

Note: The duller the tool and the more the feed and the spindle speed, you get a curved line, instead of a flat boring surface.

Conclusion

The results of this study can be used not only for practical technological applications, but also in the educational process for a significant increase in the level of training of specialists in the field of machining of materials by cutting.

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РАЗРАБОТКА АКУСТИЧЕСКОГО МЕТОДА ДЛЯ ПРОГНОЗИРОВАНИЯ ИЗНОСА ТОКАРНЫХ РЕЗЦОВ

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Аннотация. Разработана система прогнозирования акустическим методом износа инструмента при различных токарных обработках детали. В данной работе на основе анализа влияния условий механической обработки, закономерностей изнашивания и разрушения инструмента на основные характристики процесса резания разработаны и приведены методики исследования работоспособности металлорежущего инструмента при ПТТ. В данной работе исследованы физические, химические и механические явления, происходящие на микроуровне, приводят к изменению свойств материала и на макроуровне, и это изменение в значительной степени непредсказуемо из-за случайного характера движения атомов и ничтожного, на первый взгляд, разброса первичных свойств изделий, предназначенных для одной и той же цели.

Ключевые слова: акустический метод, композитный материал, режушие инструменты, токарный процесс, вибрация, прогноз износа.