FORECASTING THE CUTTING TOOL LIFE CONSIDERING AS A BLOW-UP MODE ITS OPERATION

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The article considers a method for real-time forecasting the cutting tool life, considering as a blow-up mode its operation.

The method based on the selection of a log-periodic component in the audio signal accompanying the cutting process. The model of this component contains as the main parameter the time taken as the tool life. To ensure the process control efficiency, when making a decision to stop the cutting process, the residual tool life is determined, which is equal to the difference between the tool life prediction and the current part processing duration.

KEYWORDS

Cutting process, tool life, log-periodic component, direct and indirect control methods, cutting sound, blow-up modes theory

1 INTRODUCTION

Intense competition in the international and domestic markets required the automation of the metalworking process, in particular, the turning process. This means increased productivity and improved product quality.

The turning quality depends on the cutting tool quality, numerically characterized by the duration of its defect-free operation, called tool life *T*. Process reliability, tool costs control and downtime depend on accurate tool life predictions [Bozek 2021]. Cutting tool life prediction is the most urgent task in machining performed on automated technological systems. Unpredictable tool wear or breakage results in product defect. The cost of this defect is especially high in the manufacture of labor-intensive large-sized products.

Continuous monitoring of the tool state is necessary to assess the possibility of its further use in turning, both in the processing of this part and subsequent parts [Murcinkova 2013]. The moment of the limit state approaching can be estimated by fixing technological indicators, for example: the quality deterioration of the machined surface, chip change, vibrations, excessive heat in the part. Also, the assessment of tool life is possible by the magnitude of the change in the geometric dimensions of the cutting part of the tool, for example, by the amount of wear of the leading or trailing edges, as well as by the deviation of the part dimensions from the given drawing tolerances [Balara 2018, Duplakova 2018, Flegner 2019 and 2020, Monkova 2013, Murcinkova 2021, Baron 2016, Mrkvica 2012, Zaborowski 2007, Chaus 2018, Vagaska 2017 and 2021, Straka 2018a,b, Modrak 2019, Michalik 2014, Olejarova 2017].

The control type is also important: direct or indirect. With direct control, it is necessary to constantly measure the geometric dimensions of the tool and work piece, which requires interruption of the machining process. However, knowledge of the current tool dimensions and the part also requires knowledge of their change dynamics; otherwise, the sudden tool destruction and the part defect are possible.

To solve this problem, continuous tool condition monitoring is used. It is carried out directly during the part processing in order to timely replace the worn tool and prevent emergency situations in case of its sudden breakage.

As a rule, such control is carried out by indirect methods. The disadvantage of indirect methods is the need for preliminary "training" of the control system at the stage of preparation for the manufacture of a new part in terms of geometry, dimensions and material [Rimar 2016, Panda 2011, 2012, 2013, Valicek 2016, Hlavac 2018, Sedlackova 2019, Kurdel 2014 and 2022, Labun 2017 and 2019, Jurko 2011, 2012, 2013, Pollak 2019 and 2020, Svetlik 2014, Zaloga 2020, Krenicky 2020 and 2022, Vasilko 2019]. The studies carried out at the same time, which are significant in terms of volume and science intensity, are described in the literature review cited in this article.

However, the results of these studies are applicable only for the period of a smooth and relatively slow change in the process of machining a part by cutting, not allowing predicting the moment of its sharp change. Such modes of changing the cutting process are harbingers of tool breakage and the appearance of part defects. Such modes of operation of real systems are called blow-up modes [Podlazov 2009].

The model of a system operating in blowup mode is a log-periodic function [Sornette 2003]. This function describes oscillations with a continuously increasing frequency, theoretically reaching infinity. The control of the oscillation period of this function makes it possible to predict the moment of exacerbation of the simulated phenomenon long before its onset. Traditionally, two methods for determining tool life T are used. They differ in the type of initial theoretical model used. The first method considers models with one or another measure of accuracy, describing the mechanics of the tool contact interaction with the work piece machined surface. The second method uses statistical models that characterize the probability of achieving the required tool life *T* in the cutting process.

At the same time, the original theoretical model is transformed in a certain way by introducing into it the quantities controlled during cutting: speed V_C, feed *f* and depth of cut a_C, as well as parameters that indirectly characterize the cutting process and are most easily measurable, for example, vibration or acoustic signals. When using the first method, the historically first initial theoretical model was the model proposed by Frederick Taylor in 1906 [Taylor 1906]. In [Johansson 2017a] the expression for the equivalent chip thickness is considered, which is a function of feed *f*, depth of cut a_C, main cutting angle κ, and tool nose radius *r*. Thus, the number of parameters describing the cutting conditions increases from one in the original F. Taylor equation to five. Next, to determine the tool life *T,* regression equations are composed. To calculate the tool life *T* in [Stahl 2014], as the initial theoretical model, the model characterizing the volumetric wear during contact interaction proposed in [Archard 1953] is used. This approach to determining the tool life makes it possible to consider, in contrast to the empirical F. Taylor's formula, the contact interaction physics of the tool with the work piece machined surface. In [Colding 1959, Johansson 2017b] proposed expression, which allows estimated the desired tool life *T* as a function of the equivalent chip thickness.

To determine the unknowns of a given function, it is proposed to perform the regression analysis operation [Dasgupta 2016]. To solve this problem the Taguchi method [Efimov 2005] was used. This made it possible to reduce the experiments number *n* from 27 to 9 in a three-level full-factor experiment. In [Aramesha 2014], the Weibull distribution is used as the initial statistical model. This distribution is characterized by two parameters. In practice, these parameters are determined by the results of processing a statistically representative number of the same type of cutting inserts used in the same cutting conditions in the manufacture of parts of the same configuration and material. In [Sourath 2018], the log-normal distribution is used as the initial model. According to the authors, this distribution more accurately describes the tool life changes statistics compared to the F. Taylor's model.

The statistical nature of the initial models does not allow to control the current manufacturing a particular work piece in the second method of tool life control, because with a certain probability degree, statistical models do not exclude part defects. In this regard, the combined approach is of particular interest, considered in [Innocent 2008]. It allows you to correct the calculated parameters of the tool life statistical model based on the results of online measurement of an indirect sign - the level of tool vibration. This allows you to flexibly adjust the model to the loads actually acting on the tool. Also, periodic interruption of the cutting process is not required to determine, for example, the actual wear value *VB* and compare it with a threshold level VB_{MAX}. In this regard, the authors [Innocent 2008] called this method "no-threshold". The Weibull distribution is used as a statistical model in [Innocent 2008]. In this case, the reliability function uses an indirect sign of the tool state, which is continuously monitored during the cutting process - its vibration level S instead of the time t. This method plays the role of a bridge from the existing methods for determining tool life T to the one considered in this article.

2 RESEARCH METHODOLOGY

The blow-up mode's theory is applied to develop a method for predicting tool life, which is considered in the article [Podlazov 2009]. The blow-up mode is described by a dynamic law, in which the controlled parameter increases sharply (theoretically, to infinity) over a finite time period [Podlazov 2009].

Traditionally, as a controlled parameter that limits the tool life *T*, the value of its wear *Vb* is considered. However, without interrupting the cutting process, the amount of wear cannot be controlled, which requires the indirect methods for monitoring the metalworking process.

The research materials presented in this article were obtained using the sound level generated by the cutting process as a controlled parameter. This parameter was used as initial information for cutting control, as a blow-up mode.

Such modes are described by the following equation

$$\frac{dx}{dt} = x^{1+1/\alpha}. \tag{1}$$

The equation solution increases without limit as we approach the peaking moment t_f:

$$x(t) \sim (t_f - t)^{-\alpha}. \tag{2}$$

To obtain a solution acceptable for practice (2), we pass from the real exponent α to the complex one $\alpha + \beta i$, which allows us to obtain an equation of the following form:

$$x(t) = \operatorname{Re} \sum_k a_k (t_f - t)^{-\alpha + k\beta i} = (t_f - t)^{-\alpha} \cdot F(\log(t_f - t)). \tag{3}$$

The function $F(\cdot)$ is described by several multiple harmonics, characterizing in the general case the significant nonlinearity of systems developing in the blow-up mode. However, in practice [Sornette 2003], the function $F(\cdot)$ is limited to one first harmonic:

$$x(t) = (t_f - t)^{-\alpha} \cdot \left(a_0 + a_1 \cos\left(\beta \cdot Ln \frac{t_f - t}{\tau}\right)\right). \tag{4}$$

The parameters of formula (4) have the following meaning: a_0 and a_1 are the amplitudes, respectively, of the main trend and fluctuations around it, β are their indifference measured frequency, and τ is the measured phase. This expression is a smooth trend, on which log-periodic fluctuations are superimposed, which serve as precursor of approaching the blow-up momentt_f. Taking $t \to t_f$ the oscillation frequency tends to infinity, which meets the dynamic law requirements followed by the blow-up mode. The continuous increase in the log-periodic oscillations frequency allows them to react sensitively to the course of catastrophically developing processes long before the blow-up moment.

If we consider the exhaustion moment of the tool life *T* as the blow-up moment t_f, then the materials cutting can be attributed to the blow-up modes. At the same time, to improve the quality of predicting tool life, it is necessary to isolate the sensitive log-periodic part of the recorded signal. In practice, this means that the total signal periodic component must be separated from the smooth trend and its behavior should be analyzed separately throughout the entire cutting process.

The periodic component model should be subjected to direct analysis, which fully describes the complex polyharmonic in structure of the actually recorded signal.

The cutting mode refers to the blow-up mode [Podlazov 2009], when the cutting mode characteristics during the part processing can change, bringing its dimensions and surface roughness to unacceptable values according to the drawing. These changes can be indirectly controlled by the information signal magnitude generated during metalworking.

The information signal is the sum A_{SUM} of the smooth (trend) B_{TR} and the variable B_{VC} components.

$$A_{SUM} = B_{TR} + B_{VC} \tag{5}$$

According to (4), at $T = t_f$ B_{TR} is determined from the following expression

$$B_{TR} = a_0 \cdot (T - t)^{-\alpha}. \tag{5}$$

The variable component B_{VC} is extracted from the information (total) signal A_{SUM} by decomposing it into empirical modes [Myasnikova 2011].

$$B_{VC} = -0.25 A_{SUM_{i-1}} + 0.5 A_{SUM_i} - 0.25 A_{SUM_{i+1}}. \tag{6}$$

The variable component B_{VC}, according to (4), is determined from the following expression

$$B_{VC} = a_1 \cdot (T - t)^{-\alpha} \cdot \cos\left(\beta \cdot Ln \frac{T - t}{\tau}\right). \tag{7}$$

For the convenience of further research, expression (7) should be reduced to the classical form of the log-periodic function (8), considering it as a B_{VCM} model of the variable component B_{VC}.

$$B_{VCM} = A_0 \cos(\omega \cdot Ln(T-t) - \phi),$$

$$A_0 = a_1 \cdot (T-t)^{-\alpha};\ \omega = \beta;\ \phi = \beta \cdot Ln(\tau). \quad (8)$$

Expression (8) contains five unknown parameters: $T, \omega, \phi, a_1, \alpha$. The first three parameters are determined by solving the system of two nonlinear equations (9).

$$\begin{cases} ln(T-t_n) - ln(T-t_{n+1}) = \dfrac{2\pi}{\omega}, \\ ln(T-t_{n+1}) - ln(T-t_{n+2}) = \dfrac{2\pi}{\omega}. \end{cases} \quad (9)$$

Equations (9) are based on the knowledge of the time t_n, which account for the extremes A_{EXT} of the variable component B_{CV}. To search for these extrema, the following algorithm is used

– at least three local extremes stand out in the variable component B_{VC}. They are separated from each other in phase by an angle 2π, and there are consecutive and identical in sign (maximum or minimum);

–the time t is marked when extremes occur (t_n, t_{n+1}, t_{n+2});

–the parameter ρ is calculated that characterizes the relationship between the extreme's occurrence time.

$$\rho = \frac{t_{n+1} - t_n}{t_{n+2} - t_{n+1}}, \rho > 1. \quad (10)$$

Parameter ρ must exceed one. This indicates a decrease in the period of its oscillations, characteristic of the log-periodic function, over time. A decrease in the period leads to an increase in the oscillation frequency of the log-periodic function in the limit to infinity. This function feature was the basis for choosing it as a model B_{VCM} (8) for describing systems operating in the blowup mode [Sornette 2003].

The set of extrema forms an array composed of discrete values of A_{EXT} extrema of the variable component B_{VC}. The solution of system (9) gives the following expressions for the first three unknowns of equation (8) [Urentsov 2008]:

$$T = \frac{t_{n+1}^2 - t_{n+2} t_n}{2t_{n+1} - t_{n+2} - t_n},$$

$$\omega = 2\pi / ln(\rho), \quad (11)$$

$$\phi = \pi - \omega \cdot ln(T - t_{n+2}).$$

To check the correctness of the obtained unknown values (7) and, if necessary, to refine them, the difference between the components of the array of extreme values A_{EXT} and their model B_{VCM} (8) is minimized. At the same time, the parameters a_1 and α are determined.

$$\sum_i^m (A_{EXTi} - B_{CVMi})^2 \Rightarrow min. \quad (12)$$

In practice, the array of extreme values A_{EXT} contains a number of components, indicating the polyharmonic nature of the oscillations of the variable component B_{CV}. Therefore, when refining the values of parameters (11), as a model A_{EXTM} (predictive model) describing an array of extreme values A_{EXT}, one should use a trigonometric polynomial composed of log-periodic functions (Fourier series).

$$A_{EXTM} = \frac{a_0}{2} + \sum_{k=1}^{m} \begin{bmatrix} a_k \cos(k \cdot \omega \cdot Ln(T-t)) \\ + b_k \sin(k \cdot \omega \cdot Ln(T-t)) \end{bmatrix}. \quad (13)$$

The coefficients of the series a_0, a_k, b_k are determined from the following expressions

$$\begin{cases} a_0 = \dfrac{1}{t_0 - t_m} \displaystyle\int_{t_0}^{t_m} A_{EXT} \cdot \dfrac{1}{T-t} dt, \\ a_k = \dfrac{2}{t_0 - t_m} \displaystyle\int_{t_0}^{t_m} A_{EXT} \cdot \cos\left(k \cdot \dfrac{2\pi}{t_0 - t_m} \cdot Ln(T-t)\right) \cdot \dfrac{1}{T-t} dt, \\ b_k = \dfrac{2}{t_0 - t_m} \displaystyle\int_{t_0}^{t_m} A_{EXT} \cdot \sin\left(k \cdot \dfrac{2\pi}{t_0 - t_m} \cdot Ln(T-t)\right) \cdot \dfrac{1}{T-t} dt. \end{cases} \quad (14)$$

When managing the technological systems operation, it is effective to manage not by the durability absolute value, by comparing it with the duration of part required by the technology processing, but by the durability residual value

$$T_{RES} = T - t. \quad (15)$$

3 RESEARCH RESULTS

The purpose of the experiments was to test the method of defect-free parts turning. To achieve this purpose, tool life T_{RES} was simultaneously predicted, and the machined surface quality was controlled in real time. This problem was solved using an indirect method of monitoring the tool performance degree and changing the state of the machined surface of the part, performed by the sound level generated during the cutting process.

Table 1. Type of processing, cutting modes and tool and part materials

Type of processing	Cutting mode			Material	
	ac, mm	*f*, mm/rev	*Vc*, m/min	tool	part
Roughing	3	0.8	80	T14K8	St45
Finishing	0.5	0.3	150	T15K6	30HGSA

The experiment was carried out during roughing and finishing in cutting modes and using the tool materials and workpiece given in Table 1. Turning was carried out on a 16K20T1 CNC machine.

3.1 Roughing

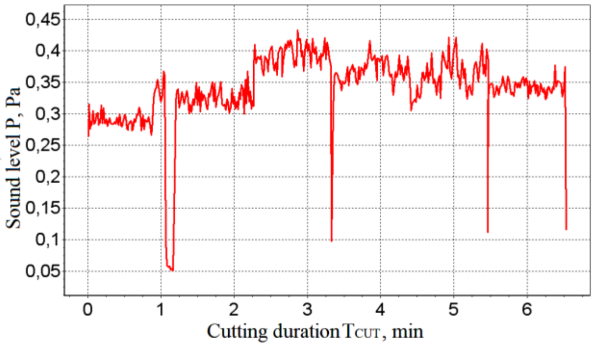

Figure 1. Graph of sound pressure level at the roughing process

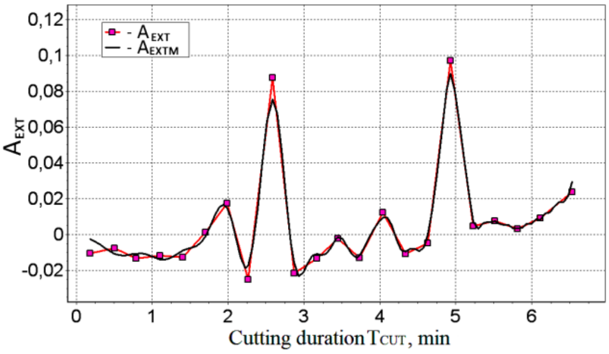

Figure 2. Approximation by the predictive model A_{EXTM} of the extremes A_{EX}

The method testing results of defect-free turning with a rough type of cutting is shown in Figs. 1-3. The graph of change in sound pressure P (A_{SUM}) at the roughing process is shown in Fig. 1. Approximation of the graph of the extremes A_{EX} by the predictive model (13) is shown in Fig. 2. Change in residual tool life prediction T_{RES} during rough cutting is shown in Fig. 3.

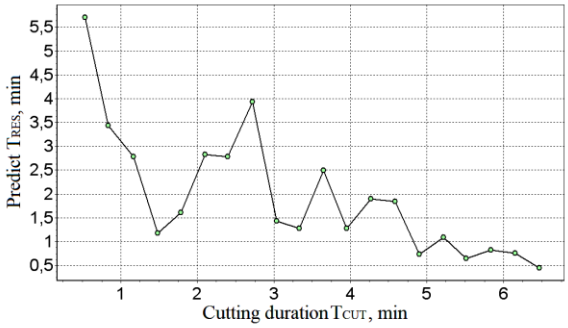

Figure 3. Residual tool life during rough cutting

3.2 Finishing

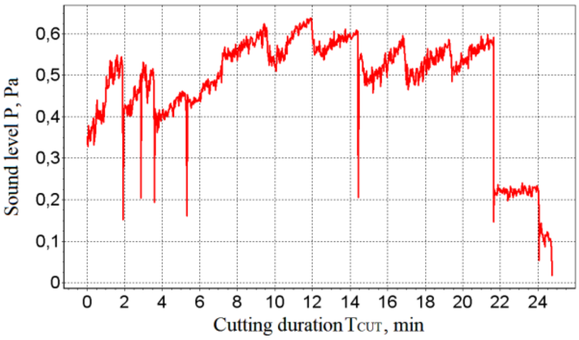

Figure 4. Graph of sound pressure level at the finishing process

The method testing results of defect-free turning with a finish type of cutting is shown in Fig. 4-6. The graph of change in sound pressure P (A_{SUM}) in the finishing cutting process is shown in Fig. 4.

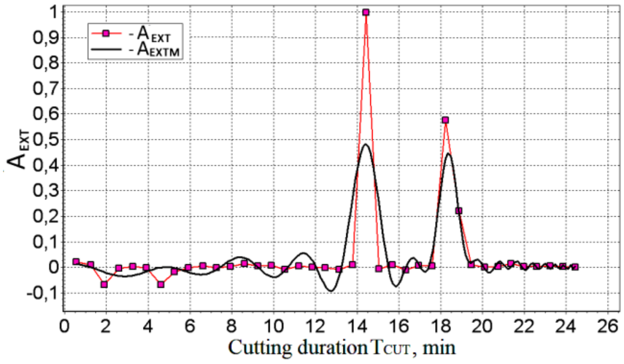

Figure 5. Approximation by the predictive model A_{EXTM} of the extremes A_{EX}

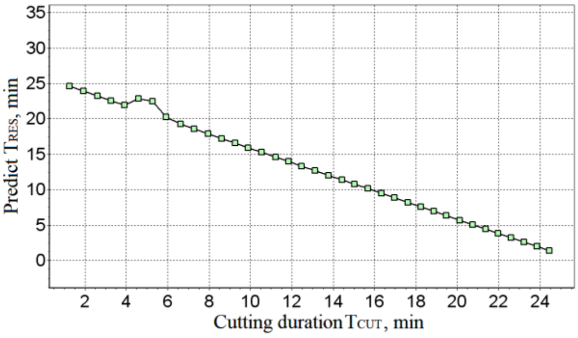

Figure 6. Residual tool life during finish cutting

Approximation of the graph of the extremes A_{EX} by the predictive model (13) during finishing turning is shown in Fig. 5. Change in residual tool life prediction T_{RES} during finish cutting is presented in Fig. 6.

4 CONCLUSIONS

The results show that the sound pressure level (Fig. 1 and 4), as a quality control parameter for controlling the technological system operation, is quite stable throughout the entire process of performing a technological operation. At the same time, the pressure values for finishing and rough turning differ in direct proportion to the difference between the cutting speeds used for these types of processing V_C.

In this case, the sound signal is the total A_{SUM} signal, which is subjected to further processing in accordance with the algorithm described in this article.

Graphs of the extremes A_{EX} (Figs. 2 and 5) have a rather complex form, which indicates their polyharmonic origin. This confirms the correctness of the choice of the polyharmonic Fourier series as a predictive model. The high quality of control is clearly confirmed by the high quality of approximation of the extremes A_{EX} graphs by their predictive models.

The tool life prediction (Fig. 3 and 6) corresponds to the tool life actually realized in the experiment. For clarity, in Figs. 3 and 6 shows the change in the residual tool life in the turning process T_{RES}. It tends to zero as it approaches the end of the part processing process.

The article considers the control of the technical systems operation, based on the blow-up mode theory on the example of technological metalworking systems.

The scientific results novelty presented in the article lies in the fact that for the first time in the practice of monitoring the metalworking process, the technological system operation is controlled by the actual tool state.

The practical significance of the results obtained lies in the fact that the method of actual tool life online determination makes it possible to implement in practice tool life prediction method based on blow-up mode theory.

Prospects for further research are aimed at developing a software product that reflects the process system control algorithm based on the actual tool state and creating an automated control system on CNC machines based on this.

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