Cutting tool wear monitoring using the diagnostic capabilities of modern CNC machines

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Abstract. The article discusses the automation of the tool wear monitoring for collecting statistics on the cutting process and taking into account its variability in the design of technological processes for the manufacture of engineering products. It is proposed to use the diagnostic capabilities of modern CNC machines. The main methods of tool wear monitoring are considered: a direct method using optical or electromechanical methods or an indirect method using measurement of the load of drive motors or oscillations of a technological system. The automation of the direct tool wear monitoring method on the Heidenhain TNC 620 CNC system is presented. The change in load on a main motion drive during a tool wear is shown on a practical example. The experimental setup for estimating cutting tool wear by vibration level is proposed.

1. Introduction

In the context of Russia's integration into the world economic system, ensuring sufficient free access to its markets for foreign competitors, a strategically important task is to increase the level of competitiveness of engineering products. At present, the engineering industry has a low level of competitiveness both within Russia and on the international market. With a comparable quality of engineering products, domestic counterparts, as a rule, are more expensive due to the high cost of their production.

To reduce the cost of domestic engineering products and increase its competitiveness on this basis, it is necessary to increase the efficiency of all processes executed during its production. One of the most important technological processes in the production of engineering products is machining. According to expert estimates, 15% of the cost of parts and machines produced in the world is provided by the machining operation using a cutting tool. Despite the constant development of new machining technologies in mechanical engineering, traditional metal cutting now and in the coming decades will remain the main method of manufacturing parts and machines.

The effectiveness of machining with a cutting tool is largely determined by the cutting modes assigned based on the known tool life equations and the period of restoring or replacing the cutting tool. However, despite the fact that machining are probabilistic in nature, modern mechanical engineering uses tool life equations that describe only the dependence of the average tool life of a cutting tool on cutting modes, for example [1-3], and not taking into account the stochastic nature of cutting tool wear [4], which depending on many factors: cutting modes, cutting properties of tools, type of machining, hardness of machined parts, value of machining allowance [5], pre-existing mode
of deformation [6], vibration [7], geometric errors of machine, coolant, etc. This circumstance does not allow to take into account the variability of the machining during the appointment of cutting modes and the period of restoration or replacement of the cutting tool [4]. As a result the dispersion of the cutting tool life within one batch of tools can reach up to 15-35% [8].

Design decisions in the design of a manufacturing process for engineering products, taken only on the basis of average values of the cutting tool life without taking into account the variability of the machining, can lead to significant errors in the assignment of manufacturing process parameters and an increase in production costs, and, consequently, to an increase prices and reduce the competitiveness of products. Thus, it is necessary to take into account the machining variability to improve the efficiency of engineering production and this is an important scientific problem. To evaluate the variability of the machining, it is required to organize the collection of statistics on the wear of the cutting tool during the processing of a batch of parts [9].

Modern machine tools with numerical control (CNC) have extensive diagnostic capabilities that allow evaluating a wear cutting tool directly by using optical or electromechanical methods or indirectly, for example, by measuring the load of drive motors [10, 11] or oscillations of a technological system [12, 13].

2. Direct control method of cutting tool wear

Modern machine equipment is equipped with a number of standard industrial systems for direct monitoring of cutting tool wear, which can be used to automate the collection of cutting tool wear statistics for evaluating the variability of the machining.

Electromechanical sensors are mainly of three types depending on the method of signal transmission: wired, infrared and wireless, but the measuring body is the same for all. Optical sensors are divided into two types: combined (bracket, into the slot of which the tool passes and is scanned with a laser) and modular sensors consisting of two parts (receiver and transmitter), which are installed at different ends of the machine's bed in case there is no space to install the combined sensor.

The main manufacturers of sensors are Heidenhain, Renishaw and Blum. The main industrial systems for cutting tools wear monitoring manufactured by these companies are presented in table 1.

Table 1. Major measuring systems for direct control of cutting tool wear at CNC machines

| Manufacturer | Electromechanical system | Optical system |
|--------------|-------------------------|---------------|
|              | Wired                   | Wireless      | Combined   | Modular    |
| Renishaw     | TS27R, TS34, Primo LTS  | OTS           | RTS, Primo Radio 3D Tool Setter | NC4, NCPCB TRS2 |
| Heidenhain   | TT 160                  | TT 460        | TT 460     |            |
| Blum         | Z-Nano, Z-Pico, ZX-Speed, TC76 | Z-Nano IR, ZX-Speed IR TC 53-20 | Z-Nano RC, ZX-Speed RC TC 63-20 | Micro Single NT |
The procedure of direct wear monitoring using these systems is as follows: after a certain tool life, the CNC command is called to measure wear, the wear is directly measured by the sensor, the obtained values are written to the CNC tool table, and from this table information is read and transmitted to an external computer. Let’s consider an example of such monitoring using the Heidenhain TNC 620 CNC system. To measure the tool length call the TCH PROBE 31 or TCH PROBE 480 measurement cycle. When measuring a tool with a BLUM laser, the measurement results are saved into parameters Q190-193, from where they can be read using the appropriate command. The tool measurement results obtained with the TT 460 sensor are stored in parameter Q199: Q199 = 0.0 if the instrument is within tolerance; Q199 = 1.0 if the tool is worn and Q199 = 2.0 if the tool is broken. The deviation of the actual value from the value specified during the automatic tool measurement with the TT 460 is stored in parameter Q115 when measuring the tool length and Q116 when measuring the tool radius.

To automate the direct monitoring of cutting tool wear using industrial measuring systems, a fragment of the control program for the Heidenhain CNC system has been developed, which operates as follows. At the beginning of the part processing, a specially prepared table count.tab opens, from which the number of machined parts and the prediction of the tool life of the current cutting tool are read. After processing the part, the number of machined parts is increased by 1 and written back into the count.tab table. The cutting tool wear is measured with a TT 460 sensor and it is checked whether the tool needs to be replaced or not. If the tool needs to be replaced, the number of machined parts is reset to zero, and the message “The tolerance for tool breakage exceeded” is displayed and the machining stops. After the measurement, the results are recorded in the tresult.txt file and a pause is made in the program for 30 seconds to process the measurement results and predict a new tool replacement period using an external program. The results of the prediction of the external program are recorded in the table predict.tab. After that this prediction is read and write it to the count.tab table.

The developed fragment of the control program can be automatically added when the control program for CNC machine is generated by modifying the post-processor of the CAM system. In this paper, the postprocessor of the SprutCAM system was modified (figure 1, a) and the control program generated by this way was verified on the TNC 620 CNC system (figure. 1, b).
Using the radial wear $h_r$ measured in this way, it is possible to estimate the change in the radius at the tip of the cutting tool or the cutting insert of the modular milling cutter $Δr$ and the flank wear $VB$ using the following formulas:

$$Δr = \frac{h_r \cdot \sin(ε/2)}{1 - \sin(ε/2)}, \quad VB = \frac{h_r}{\tan α},$$ (1)

where $ε$ is the angle at the tip of the cutter or cutting insert, $α$ is the end relief angle of the cutter or cutting insert.

3. Monitoring the cutting tool wear by measuring the load of drive motors

The physical essence of this control method is that a change in the load on the drives leads to a change in the current strength. During machining the cutting tool has to overcome resistance to remove metal from the surface of the workpiece. Due to the cutting tool wear, its geometry changes, which leads to an increase in cutting force. This leads to an increase in cutting power. As a result, the load on the drive motors of the machine increases, and the current strength increases as well. The current sensor installed on the machine measure its changes and transfers the value to the CNC computer system. In Figure 2 shows a functional diagram of the measurement of the load on the drive motor.

![Figure 2. Functional diagram of the measurement of the load on the drive motors](image)

4. Monitoring of cutting tool wear by measuring vibration of the technological system

Changes in the machining process due to wear are accompanied by a corresponding change in the vibration of the technological system. The vibration change accordingly with the stages of tool wear and will provide an objective picture of the state of the cutting tool.

During machining the technological system makes forced oscillations under the action of cutting forces. According to the well-known d’Alembert principle,

$$\vec{F}_i + \vec{F}_d + \vec{F}_e + \vec{F}_R = 0,$$ (2)

where $\vec{F}_i$ is the force of inertia, $\vec{F}_d$ is the force of resistance (damping), $\vec{F}_e$ is the force of elasticity of the system, $\vec{F}_R$ is the cutting force. The cutting force $\vec{F}_R$ and its projections $P_y$ and $P_z$ are non-linear values depending on the cutting modes and actual cutting conditions. When turning the tangential component of the cutting force can be estimated by the formula

$$P_z = C_{pz} \cdot a_p \cdot f_n \cdot v_c \cdot K_{pz},$$ (3)

where $C_{pz}$, $xz$, $yz$, $nz$ are empirical coefficient and exponents, $a_p$ is the cutting depth, $f_n$ is the feed per revolution, $v_c$ is the cutting speed, $K_{pz}$ is the correction factor that takes into account the actual cutting conditions, including the radius at the tip of the cutting tool $r$. The cutting force will
fluctuate due to various factors during machining. First, due to auto-oscillations caused by the deviation of the machining allowance at the beginning of processing and in subsequent operations due to technological heredity [14, 15]. Secondly, as the cutting edge is worn, the geometry of the cutting tool and, accordingly, the value of the coefficient $K_{pc}$ will change. Given these circumstances, equation (2) can be represented as

$$P_z = C_{pc} \cdot a_p(t) \cdot f_a \cdot \nu_c \cdot K_{pc}(r_0, \Delta r),$$

where $r_0$ is the initial value of the radius at the tip of the cutting tool. Taking into account the analytical expressions for inertia, resistance, and elasticity known from the literature [16], the motion in the XOZ plane can be described by a differential equation

$$m \frac{d^2 z(t)}{dt^2} + \eta_0 \frac{dz(t)}{dt} + Cz(t) = C_{pc} \cdot a_p(t) \cdot f_a \cdot \nu_c \cdot K_{pc}(r_0, \Delta r),$$

where $m$ is the reduced mass of the system, $\eta_0$ is the damping coefficient, $C$ is the stiffness coefficient.

To control the change in the vibration level as the cutting tool is worn, it is necessary to develop a special device that can be installed on the CNC machine during its normal operation. The first step in creating such a device is to design an experimental setup for testing the proposed model. A common method for solving this problem is the use of vibration and acceleration sensors. This method provides reliability and resistance to external influences. To obtain a complete picture of the machining process, it is proposed to use several sensors located at key points of the technological system (figure 3).

**Figure 3.** Measuring setup of vibration control during turning
1 – rotary vibration sensor, 2 – tool holder with vibration and acceleration sensors, 3 – tailstock with acceleration sensor

The signals collected from the sensors must go through a series of processing to convert them into a convenient form for analysis. To reduce the noise of the original signal, a Kalman filter is applied [17, 18]. Then the received signal is integrated for transition from acceleration to amplitude of vibration. Wavelet analysis allows to accurately determine the frequency characteristics of the received signal over time and their changes, as well as to identify non-stationarity in the operation of the technological system [12, 19]. It should be considered that the vibration of the technological system varies over a wide range and carries generalized information about the machining process,
therefore it is necessary to extract from the vibration signals that information that reflects the wear processes of the cutting tool.

5. Monitoring of cutting tool wear by measuring vibration of the technological system
An example of the results of wear control using the direct control method when machining with three tools from the same batch is shown in figure 4.

![Figure 4](image)

Figure 4. The results of measuring the radial wear of the cutting tool using a direct control system

In order to verify the proposed theoretical assumptions about the possibility of controlling the cutting tool wear on the load on the main motion drive, experimental measurements of the load on the main motion drive under the conditions of the existing production on the serially manufactured part were carried out. Its machining consists in longitudinal turning by a cutting tool with a replaceable carbide insert ISCAR CCMT 120408-SM IC907 from Ø160 mm to Ø90h12 mm.

Machining of parts was carried out under the following cutting modes: cutting speed of 160 m/min, cutting depth of 1.5 mm. The results of cutting inserts wear monitoring before and after processing of a batch of 12 parts are presented in table 2, and the results of measuring the load on the main motion drive during machining in figure 5.

| Insert № | Cutting edge radius, mm before machining | Cutting edge radius, mm after machining |
|----------|----------------------------------------|---------------------------------------|
| 1        | 0.8013                                 | 0.8893                                |
| 2        | 0.8004                                 | 0.8890                                |
| 3        | 0.8001                                 | 0.8893                                |
| 4        | 0.8013                                 | 0.8799                                |
| 5        | 0.8005                                 | 0.8882                                |
| 6        | 0.8002                                 | 0.8900                                |
| 7        | 0.8013                                 | 0.8802                                |
| 8        | 0.8004                                 | 0.8887                                |

| Insert № | Cutting edge radius, mm before machining | Cutting edge radius, mm after machining |
|----------|----------------------------------------|---------------------------------------|
| 9        | 0.8015                                 | 0.8853                                |
| 10       | 0.8011                                 | 0.8889                                |
| 11       | 0.8013                                 | 0.8886                                |
| 12       | 0.8020                                 | 0.9882                                |
| 13       | 0.8003                                 | 0.8874                                |
| 14       | 0.8007                                 | 0.8875                                |
| 15       | 0.8002                                 | 0.8882                                |
6. Discussion

The collected statistics on the wear of the cutting tool confirms the variability of the cutting process and, consequently, the variation of tool life. Analysis of the results showed that the correlation between the change in the radius at the tip of the tool and the increase in cutting power is 0.95, which confirms the possibility of using control of cutting power to estimate the wear of the cutting tool. The increase in cutting forces at the end of the tool life is about 2–2.3 times. The change in cutting forces leads to a change in vibration during machining as the cutting tool is worn.

Tool wear non-monotonously affects the level of vibration intensity. When working with a sharp instrument in the first minutes there are intense vibrations. With increasing flank wear, the oscillation amplitude decreases. The decrease in the amplitude of oscillation occurs to the level of wear $VB = 0.15$ mm. A further increase in wear again leads to an increase in vibration. At the end of the cutting tool life period, a sudden increase in cutting forces and, accordingly, an oscillation amplitude occurs.

7. Conclusion

The article proposes a method of usage of the existing diagnostic capabilities of CNC machines for statistics collecting about cutting tool wear during machining. The direct measuring using optical or electromechanical methods and indirect measuring using power measurement of drive motors and oscillations of the technological system are proposed as a monitoring technics.

Automation of statistics collection by direct measuring using existing systems is possible by writing a fragment of the control program to control the wear of the cutting tool and automatically integrating it into the control program for the CNC machine by upgrading the post-processor of the CAM system. This approach has practically been verified using the Heidenhain TNC 620 CNC system and the CAM system SprutCAM. Based on the radial wear of the cutting tool, it is possible to calculate the flank wear and the change in the geometry of the cutting blade.

Change of the cutting forces due to changes in the geometry of the cutting tool as wear leads to a change in the level of vibration, which can also serve as a method of indirect control of the state of the cutting tool. To control the cutting forces, the built-in diagnostics of drive motors was used, and to control the vibration – an experimental setup using accelerometers placed on key components of the process equipment. As a result of the study, it was found that there is a strong connection between the state of the cutting tool and the cutting force, as well as the vibration of the technological system caused by it.

By collecting statistics on the wear of the cutting tool during machining, it is possible to determine the state of the cutting tool in specific working conditions. The use of existing diagnostic capabilities
of modern CNC machines and devices that may appear in the near future will allow to evaluate and take into account the variability of the machining process, and, consequently, reduce production costs.

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