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Diagnostics and Forecasting of Cutting Tool Wear at CNC Machines

L. I. Martinova, A. S. Grigoryev, and S. V. Sokolov
Moscow State Technological University "Stankin," Moscow, Russia

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Abstract—The problem of monitoring and forecasting the remaining cutting tool durability is formulated and an architectural model of a generalized diagnostic system and its software implementation are suggested. A diagnostic module/CNC system kernel protocol is specified and a universal solution to diagnosing and predicting cutting tool wear is presented being based on an external calculator.

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1. INTRODUCTION

Diagnostics and forecasting of cutting tool wear is a topical issue of CNC machining, where the process is carried out without an operator and the secured ending of a manufacturing step (or an operation) without changing the cutting tool and its breakage is required. The problem is that the durability of even one tool lot has a rather wide span. In addition, present-day machine builders use mostly composite cutting tools containing several cutting edges having different durability. All this increases the risk of a defect or a tool breakage under the process of cutting, which is not desired by the manufacturer especially in the context of using workpieces of expensive materials, and, besides, such situations are inadmissible in case of long-time machining: a hard defect of an almost finished piece caused by a tool breakage can cost too heavy expenses.

2. MONITORING AND FORECASTING THE REMAINING TOOL DURABILITY

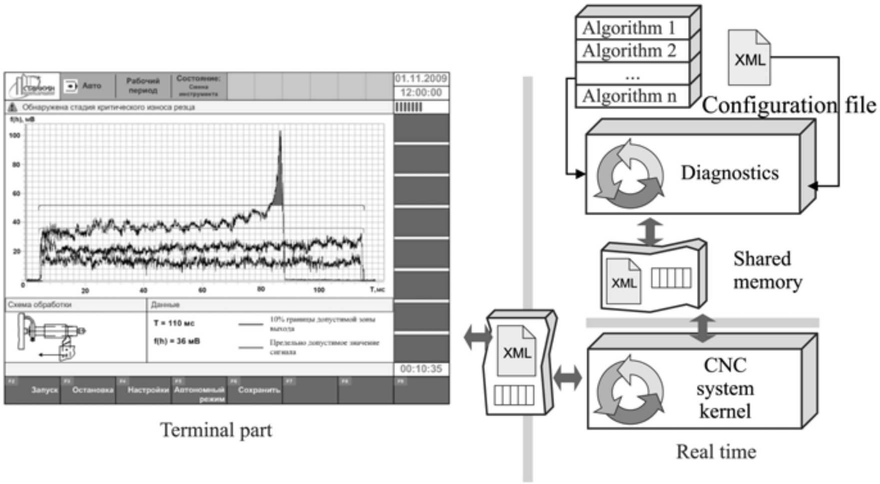
The problem of monitoring and forecasting the remaining tool durability is that the ending of a manufacturing step must be provided without changing the cutting tool. European and Japanese manufacturers use less than or equal to 70% of cutting tool life and then have to change the tool. This solution is not cheap but possible due to the range of cutting tool lot durability being within 20%. The range of Russian cutting tool lot duration makes up to 200% which does not allow applying such approaches. The solution to the problem is in monitoring and forecasting the remaining cutting tool durability directly during the process of machining that is in real time [1].

The variety of tasks of diagnostics involves different algorithms that use data from various sensors: strain gauges measuring the components of the cutting force, vibration sensors measuring the vibrations in the cutting zone, inductive sensors, or other ones. The task of a cutting tool diagnostic module integrated into a CNC system is to implement many variants of diagnostic algorithms with the purpose of making a decision on changing the tool in proper time.

Applicability of the decision is justified by the possibility of enhancing diagnostic module functionality without recompiling a CNC system kernel [2].

3. ARCHITECTURAL MODEL OF GENERALIZED DIAGNOSTIC SUBSYSTEM

Figure 1 displays an architectural model of a diagnostic subsystem included in a CNC system. As the model shows, the diagnostic module and the CNC system kernel start and run simultaneously



Обнаружена стадия критического износа резца

T = 110 мс

f(h) = 36 мВ

Fig. 1. A generalized structure of a diagnostic subsystem.

and the shared memory area is used for the interaction. That solution allows to secure the kernel in case of errors or hang-ups of the diagnostic module while running.

The diagnostic module operates in real time. The xml file contains possible diagnostic algorithms and parameters for their initialization. The process of diagnostics acts as framework for operating with these free-running diagnostic algorithms (initiation and execution). Each algorithm obtains the necessary data from sensors and yields control instructions into the CNC system kernel according to the interaction protocol.

The graphical part of the diagnostic module is implemented in the form of a component being integrated into an operator's interface. The diagnostic subsystem transfers data to the graphical component via the CNC system kernel by using the xml format. The graphical component of the diagnostics interprets the data from the diagnostic subsystem and displays them by graphical and text representation.

3.1. Software Implementation of Diagnostic Subsystem

The diagnostic subsystem is implemented as a single application meant for launching in real-time Linux and designed on the basis of open module architecture (Fig. 2).

The system includes the following modules:

—*the configuring one*, which controls the initiation of the required diagnostic algorithms and configuration via the xml file;

—*the data collection one*, which supervises the interaction between the diagnostic subsystem and physical sensors for collecting data on the process of machining. This module configures the operation algorithms and the sensors and reads and interprets the obtained data;

—*the data processing one*, which implements the operation of the cutting tool wear diagnostic algorithms chosen at the stage of configuring and produces a forecast on the remaining tool durability;

—*the output one*, which carries out the transfer of the results of diagnostic algorithm operation to a higher-level control system.

The division into modules allows to separate the diagnostic algorithms from the mechanisms implementing the sensor interaction and CNC system interaction. This makes the diagnostic system flexible and adaptable for different types of sensors and connecting to other CNC systems. The diagnostic system can be reconfigured without any change in its source code.

3.2. Diagnostic Subsystem Configuring Algorithm

(1) A name of the loaded module containing the diagnostic algorithm is read from the module configuration xml file.

(2) The library with the implemented module is loaded.

(3) A module object instance is created according to its unique identifier.

(4) The created module is added to the collection of modules within the component manager. Pointers to the modules are stored in the inside list of the component manager in the form of pointers to an abstract base class. Then a type of each module (the data collection one, the data processing one, and the output one) can be identified by functions of the base class and a pointer to the module will be modified to a standard interface for this module type.

The diagnostic subsystem modules carry out real-time exchange of data streams in the process of subsystem operation (real-time stream in Fig. 2). The real-time stream is meant for provision of just-in-time system responses, algorithm operation clocking, and data processing. For controlling diagnostic subsystem operation stability the watchdog stream is introduced; its priority is higher than that of the real-time stream and it monitors real-time stream operation and processes the cases of its failures and hang-ups.

The actions carried out in each real-time stream cycle are as follows (Fig. 2):

- receiving data from the data collection module (I),
- transferring the data to the data processing module (II),
- obtaining diagnostic results (III),

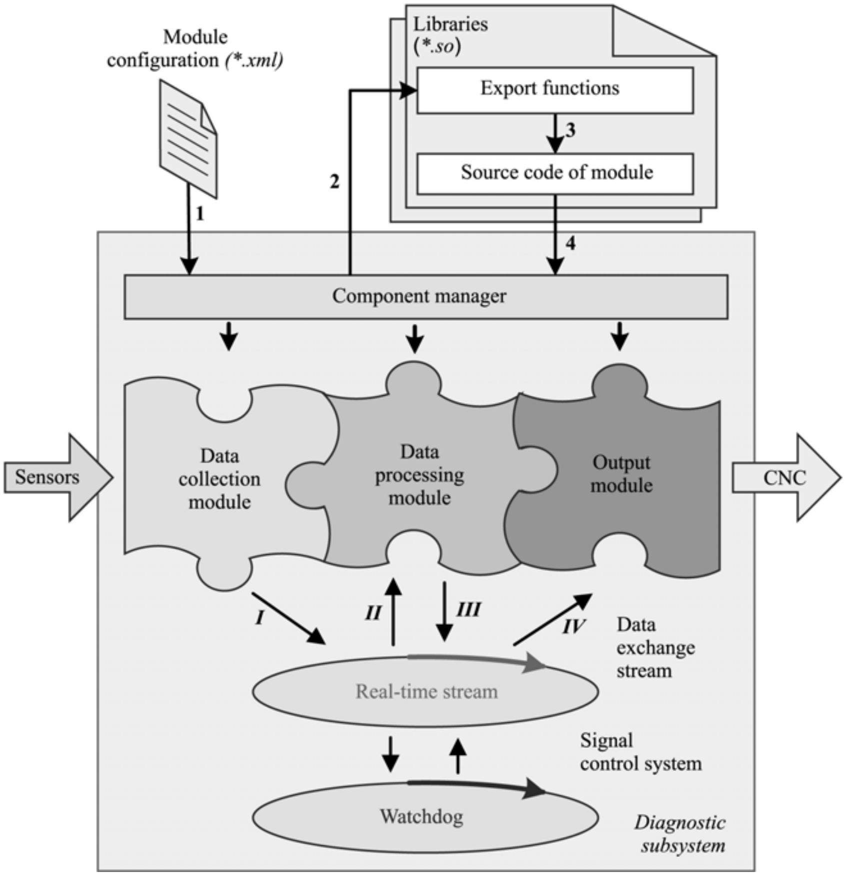


Fig. 2. Diagnostic subsystem architecture.

- transmitting the diagnostic results to the output module (IV).

Data being transferred at each stage of the information exchange have a specified format for provision of the required level of abstraction and interchangeability of the modules.

The data collection module and the output one contain their own low-priority streams which interact with physical information channels, as execution time of such actions fails to be predicted. Program queues are used for exchanging data with the real-time stream.

3.3. Diagnostic Module/CNC System Kernel Interaction Protocol

A diagnostic module/CNC system kernel interaction protocol appears to be generalization of controlling the cutting operation. The protocol contains a cutting tool position correction for wear compensation. Measurement of a wear rate in the cutting operation is conducted by an indirect method via diagnostic parameter checkout. A correction value is determined by a diagnostic algorithm based on the relationship between a parameter being under control and wear with the existing indeterminacy taken into account.

The protocol provides for producing a cutting tool change signal for guaranteeing the required quality of the product and preventing emergency situations. There can be two types of cutting tool change instructions. They are “finish the manufacturing process and change the cutting tool” and “change the cutting tool immediately.” The latter one can be interpreted as an emergency shutdown.

The protocol realizes *emergency shutdown* to prevent the machine mechanism failures, piece defects, and dangerous situations for the operator. The emergency shutdown instruction is to be issued in the exception cases related to a sudden cutting tool breakage, control program malfunction, growing imbalance, and other circumstances that make the controlled diagnostic parameters fall outside the emergency tolerable limits. It is necessary to consider that the emergency tolerable limits can be not only upper but also lower. For instance, lack of a cutting tool in an active position (due to some reasons) or a workpiece leads to the fact that in the beginning of the cutting operation there will be abnormally low values of the diagnostic parameters in the control program. This situation also requires shutting down the machine and calling the operator. The shutdown mode is conducted according to a strictly specified algorithm allowing to preserve the machined surface quality. For example, when receiving the emergency shutdown instruction, a shutdown of cutting tool supply takes place including that of the supply with an instant normal-to-surface tool withdrawal by a certain value, say, 0.3 mm. That withdrawal is needed to eliminate the formation of a band caused by elastic system deformations on the machined surface. A shutdown of the main drive gear follows a shutdown of the supply.

3.4. Universal Solution Based on External Calculator

A diagnostic module is a universal solution as it can be used for present-day CNC systems of different producers without changing their architecture. Monitoring and forecasting of cutting tool wear is carried out by an external calculator based on a PC of an industrial version (Fig. 3). Control signals enter the CNC system through a tool logic controller. The system is based on measuring cutting force components P_x, P_y, P_z, which define the current wear and forecast the remaining cutting tool durability.

A remaining durability forecast methodology is based on the dependence where three stages are revealed under rational conditions of each tool operation. The stages are wear-in, steady-state (normal) wear, and wear-out. In case of steady-state wear the experimental points are positioned randomly about a line and can be approximated by a linear function (Fig. 4).

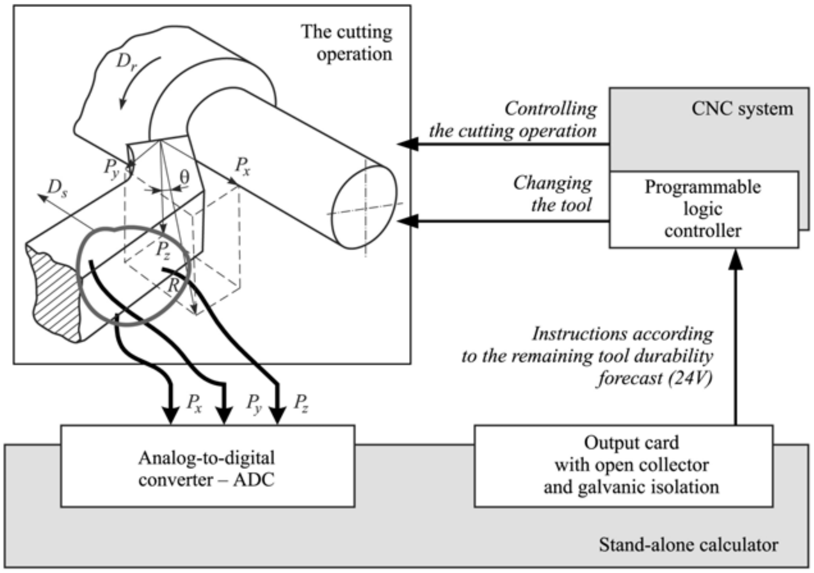


Fig. 3. Monitoring and forecasting of the remaining tool durability.

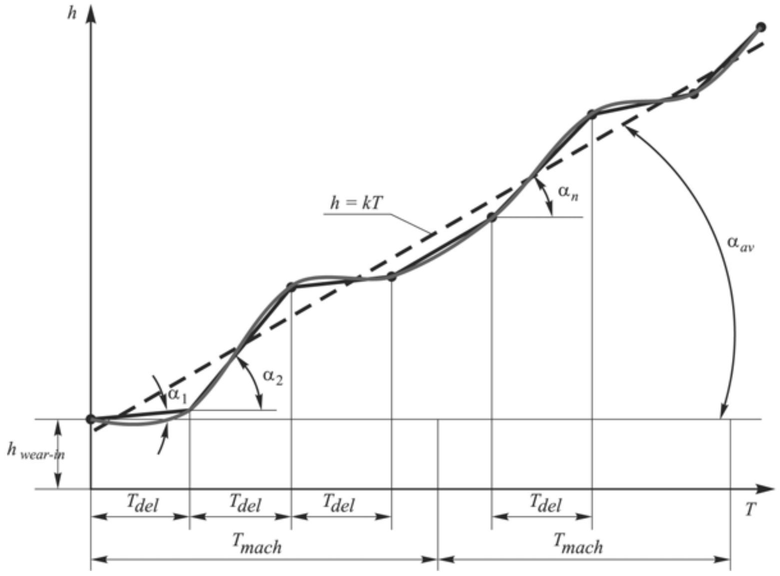


Fig. 4. The wear-time dependence in the stage of steady-state wear.

A value of wear hf_i is determined in a time instant T_i of tool operation, and hf_{i+1} is defined after a polling delay $T_{del} = T_{i+1} - T_i$. Then

$$\tan(\alpha_i) = (hf_{i+1} - hf_i)/T_{del}, \tag{1}$$

and the remaining durability is determined by the following formula:

$$T_{rem} = ([hf] - hf_{i+1})/\tan(\alpha), \tag{2}$$

where $[hf]$ is admissible tool flank wear, which has been detected in the preoperational period of diagnosing [3], proceeding from the requirements to provision of the piece quality parameter under the stipulated conditions of piece cutting.

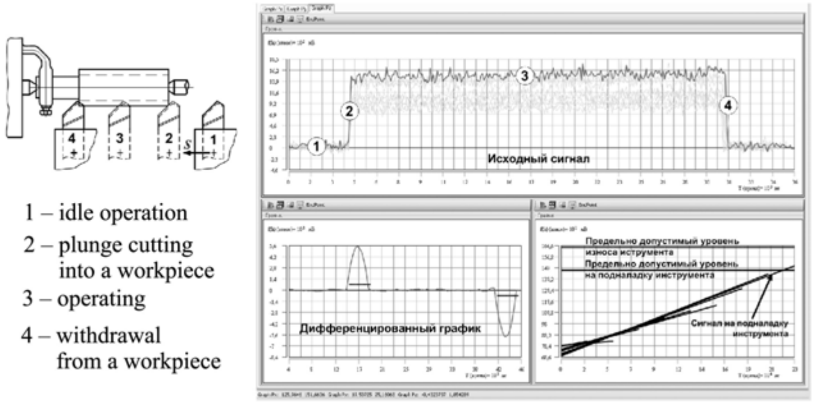


Fig. 5. Types of signals from a cutting force sensor while machining a piece.

Therefore, the algorithm of forecasting T_{rem} is expected to provide actions of determining $\tan(\alpha_i)$ and $\tan(\alpha_{av})$ in the whole period of tool life. Then as the wear gets closer to $[hf]$, the accuracy of forecast of T_{rem} improves.

An algorithm for forecasting the remaining durability has been developed in accordance with the described methodology [4]. Tool control algorithm initialization implies preparatory activities connected with enabling sensors and obtaining data from the user.

Then a cycle of collecting information from the tool control system sensors with the specified T_{del} get activated. The continuous data are shared between the zones (Fig. 5): idle cutting one (tool supply), plunge cutting one, cutting one, and tool withdrawal one. Only the cutting zone is used for solving the problem of tool wear control. Taking into account the data from the other zones is not required and can lead to a blunder in forecasting the remaining tool durability. In order to eliminate unnecessary information, algorithms for defining the beginning moment of the cutting operation when performing another step and a termination moment of the cutting operation are introduced.

If a cutting beginning signal is received and after further several plunge cutting signals the system state becomes unchanged, then a moment of steady-state cutting is fixed and data collection starts. Likewise, in case of receiving a set of tool withdrawal signals and further loss of signals, one may come to the conclusion that the machining process has ended. All the data being obtained in the process of idle cutting do not influence the forecast, but they are collected and analyzed by the algorithm of program zero correction.

It's worth considering that the data obtained in the process of machining the first piece must be excluded from forecasting algorithm operation since the tool undergoes running-in and a first-piece forecast may be false.

4. THE IMPLEMENTATION SPECIFICS

The designed diagnostic system has passed the development tests based on a 16K20 lathe with the Siemens Sinumerik 840D CNC system. Figure 6 demonstrates a simplified diagram of hookup of the diagntostic system using an external calculator.

Connection of the external stand-alone calculator and inputs/outputs of the S7-300 tool logic controller of the CNC system is carried out via a special device "USTIN," which converts an input TTL-level signal from the external calculator into a 24V-level one. A core control logic program has been adapted to the assigned problem and integrated into a PLC of the CNC system by means of a special software complex, which is the Simatic S7 Step7v.5.4SP3.1 communication board.

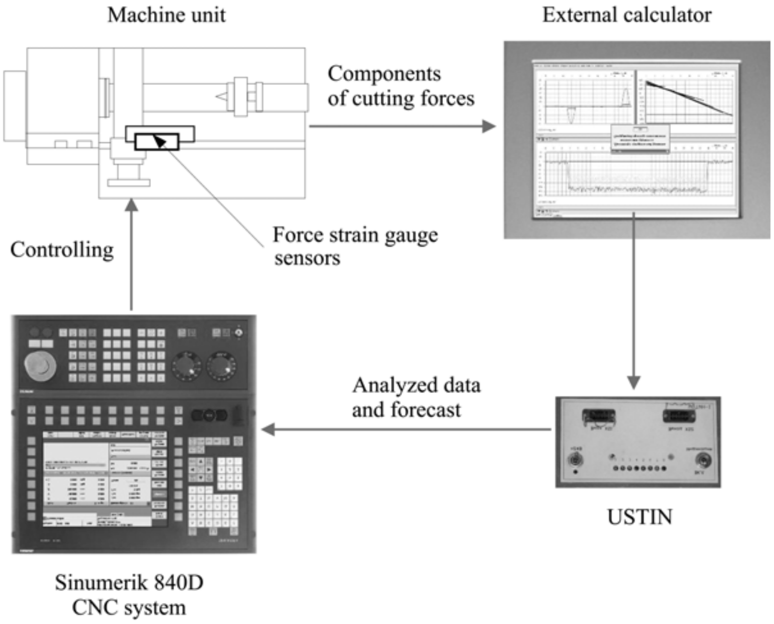


Fig. 6. A diagnostic system based on an external calculator.

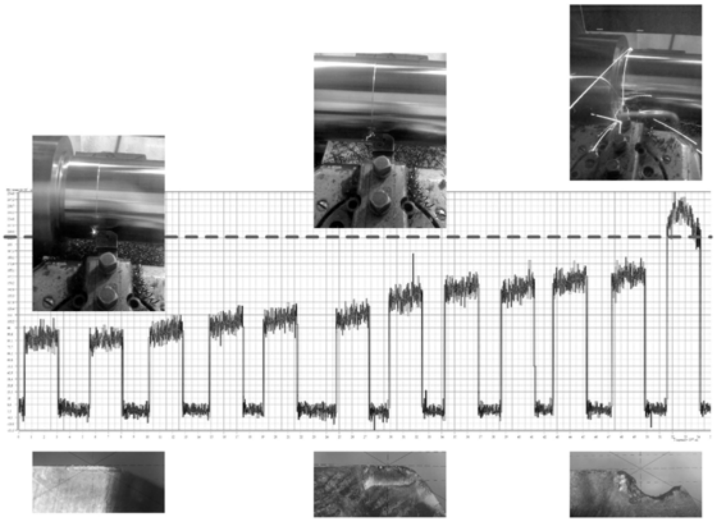


Fig. 7. The testing data obtained in the process of machining a piece of steel 45.

Figure 7 shows the testing results obtained in the process of machining a piece of steel 45. By using system variables (R parameters), a diagnostic module/CNC system kernel interaction protocol and adaptive control functions have been implemented in the Sinumerik CNC system.

Nowadays the implementation of the embedded version of a diagnostic system is under way within the framework of realization of the project Creation of a Universal Intelligent Complex for Mechanical Processing Equipment with CNC carried out according to the Federal Target program "National Technological Base" for 2007-2011.Wear is not evaluated by the parameters taken from the strain gauge sensors in this solution. It is appraised by interpretation of a force moment obtained from the drive gear controller. Such definition allows not to change the above algorithm for computing and forecasting. An application for the invention has been filed on receiving the study results.

5. CONCLUSION

A cutting tool wear forecast subsystem developed on the basis of algorithms for tool control and forecasting of its remaining durability makes it possible to keep a specified accuracy in a size of a piece and machining finish and reduce a ratio of a defect following a tool breakage before the end of piece surface machining (before the completion of a manufacturing step).

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