An Automated Control System for Machinery Parts Machining

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Abstract. The article deals with the problem of creating an automated system for controlling surface layer quality characteristics of machinery parts during machining. An automated system structure, its operation algorithm, mathematical support and work results are provided. The paper proves the necessity of using a self-learning mode in technological systems for providing set values of surface layer quality characteristics.

1. Introduction

Technological support of surface layer quality characteristics of machinery parts during machining consists in determining machining conditions (methods and modes of machining, machinery and tool performance etc.) of work surfaces of machinery parts providing set values with the smallest production cost [1] and their adjustment in workshop environment.

Experience has shown that in most cases during actual processing cutting parameters are usually set up according to standards. However, cutting conditions in actual processing greatly differ from those of standards in which the following aspects are not taken into account: machinery condition, a range of properties of the material being machined and the tool material, fluctuations of machining allowance, etc. It is even more difficult to provide set values of surface layer quality characteristics in case of machining new materials or using new tool materials as data on their cutting conditions are either not available or do not conform to field operating conditions. The latter are usually taken into account by the operator in the workplace according to one’s intuition and experience. Besides, the operator is more interested in the increase of manufacturing productivity rather than in working costs or compliance with the drawing. That is why the problem of creating an automated system for controlling surface layer quality characteristics of machinery parts during machining is of vital importance [2-5].

2. Statement of a problem

The task of the Automated Control System is to define cutting parameters directly in the workplace and to update them during machining for providing set values of surface layer quality characteristics.

The operation of the Automated Control System in the mode of adaptive control over surface layer quality characteristics is based on mathematical model [2-5] making a connection between output parameters of the process under control and its input control action. Nowadays there are theoretical and empirical dependences which make it possible to predict surface layer quality characteristics of the machined surface. Theoretical equations are of a general character and have practically no limits, but they do not take into account random factors and have lower accuracy. Empirical dependences have narrow specific application; they predict output parameters of the process in the predetermined
experimental conditions rather accurately. However, the analysis has shown that such dependences exist not for all work materials and machining conditions. The situation is even more difficult when machining new materials, using new tool materials, introducing new technological processes, i.e. when reference data are not available or do not conform to field operating conditions. There is uncertainty in providing set quality characteristics of machined surfaces between the existing initial information on the object under control – the cutting process- and the required machined surface finish (initial information includes data on tool geometry, tool and workpiece material, machinery parameters etc.). That is why it becomes necessary to carry out additional experiments which is economically unprofitable for manufacturing enterprises under tough competition when the lead time is substantially reduced. In his paper Professor Tsypkin Y.Z. writes that in case of initial uncertainty the only way out is to eliminate it by means of teaching or self-learning of the system in the process of control and to use the obtained information.

3. Results

The operation of the Automated Control System during its self-learning consists in obtaining mathematical model connecting surface layer quality characteristics with the machining conditions and in using the obtained model for controlling the technological system regarding any quality parameter. Hence, the Automated Control System should incorporate a computing device, a two-way communication channel with the technological system, control sensors of output parameters of the cutting process and also algorithmic software. A functional diagram of the Automated Control System for controlling surface layer quality characteristics of machinery parts is represented in figure 1.

The system incorporates the following elements: a metal-cutting machine; a sensor measuring the main constituent of the cutting force (Sensor Pz); a sensor measuring the current temperature in the cutting zone (Sensor T); a surface finish control sensor (Sensor Ra); sensor interface with a PC and NC unit. In most cases CNC units are only designed for controlling the process of workpiece machining. That is why, for building the Automated Control System with the self-learning mode on the basis of the CNC unit it is necessary to use the PC with the corresponding software implementing the system operation algorithm.

The interface incorporated in the system is intended for the data exchange between Sensor Pz and Sensor T and PC and CNC unit interface. The computed correction values of feed and speed are transmitted from the PC through the interface controller to the CNC unit.

Programmable logic of the machine is capable of setting up the CNC unit in such a way that it is possible to change cutting feeds and speeds in an automatic mode by means of external programmed control over spindle feed and speed adjustment. Spindle feeds and speeds vary over a range from 0 % to 127 % from initial values (initial values are 100 %) with the minimum programmable movement of 1 %.
Nowadays not only hardware but also software and algorithmic support are critical for creating the Systems of Automated Control over technological equipment. That is why the operation algorithm should be considered as an integral part of the self-learning system.

The Automated Control System provides two modes: ‘Self-learning’ (STP) and ‘Adaptive Control’ (ADC). A ‘Self-learning’ mode is intended for parametric identification of mathematical models and storing the results of self-learning in the system database. For parametric identification of mathematical models an active experiment using the Automated Control System is carried out directly in the workplace. The obtained data are handled statistically and parameters for mathematical models are set up and stored in the system database alongside with initial data. Initial data include the following information: the cutting edge geometry, the cutting edge material, the workpiece material and its hardness, required surface layer quality characteristics and machining allowance for the required quality parameter.

During the experiment the Automated Control System automatically determines surface finish value Ra by direct measuring; the values of surface microhardness and surface residual stress are measured indirectly using the values as the main constituent of cutting force Pz and temperature in the cutting zone. The value of complex parameter Cx is calculated on the basis of the obtained data.

An ‘Adaptive Control’ mode is used to provide the set values of surface layer quality characteristics or complex parameter Cx. Thus, the adaptive control over the specified technological system parameter is carried out. In this mode the measurement data are transmitted from sensors set up near the cutting zone; the obtained information is then studied and on the basis of this study a decision on technological system control is made.

To ensure the operation of the Automated Control System in the mode of adaptive control over surface layer quality characteristics of machinery parts the corresponding process control law is used [6]. In case of changing of the workpiece material and its hardness, the cutting edge material and geometry, self-learning of the technological process should be carried out again if there are no data on the changed parameters in the system database.

The operation algorithm of the Automated Control System includes the following main system operation modes: 1) initial data input and study; 2) knowledge database; 3) learning; 4) operation.
The mode ‘Initial Data Input and Study’ is intended for inputting and analyzing the data before machining. Initial data include: the workpiece material, tool geometry, cutting modes, technological system rigidity, and the surface layer quality characteristic. It is also necessary to obtain its required value. Preceding from the input data the system identifies the availability of the corresponding mathematical model in the system.

The mode “Knowledge Database” is intended for collecting and storing information on machined materials, cutting conditions and corresponding mathematical models. Thus, knowledge database contains mathematical models for each material being machined and each cutting condition. In case the appropriate model is not available, the system switches on to the mode ‘Learning’.

The task of the mode ‘Learning’ is to carry out an experiment and to obtain a mathematical model. To fulfill this task a test part – prototype – is machined on the machine tool, while the tool, its geometry, the test part material and the cutting depth should correspond to those employed in machining of the next workpiece batch. The prototype is divided into zones and each zone is then automatically machined according to preset cutting parameters. Surface layer quality characteristics are automatically controlled by the system during machining.

The mode “Operation” implements an algorithm of adaptive control over the technological system to ensure the preset values of surface layer quality characteristics. On the basis of the input initial data and required surface layer quality characteristics the system software picks up necessary parameters of mathematical models from the database, chooses corresponding process control law [6], calculates initial feed values F and workpiece rotational speed S for the required surface layer quality characteristics.

Engineering research on self-learning of the Automated Control System of surface layer quality characteristics was carried out. The process task of the system self-learning was a parametric identification of mathematical models specifying: surface finish $Ra$, the values of surface microhardness $H\mu$ and surface residual stress $\sigma$ and the value of complex parameter $C_x$ after turning. Several process tasks for different workpiece materials and machining conditions were solved. Initial data and obtained results are given as an example.

Initial data for task №1: workpiece material is steel 20Mn5, workpiece material hardness is HB=280, cutting edge material is Т15К6. Cutting plate geometry is the following: clearance angle - 8°, cutting angle – 7°, major cutting edge angle – 95°, minor cutting edge angle – 15°, tip radius – 0.5 mm, edge radius – 20 μm, cutting parameters:

Longitudinal feed S:
- $S_{\text{min}} = 0.10$ mm/rev;
- $S_{\text{max}} = 0.4$ mm/rev;

Cutting Speed V:
- $V_{\text{min}} = 100$ m/min;
- $V_{\text{max}} = 200$ m/min;

Depth of Cut: t=0.4 mm.

The result of parametric identification in the self-learning automatic control system, when processing a workpiece of steel 20Mn5, is mathematical models (1-4)

\[
Ra = 6.098 \cdot S^{0.384} \cdot V^{-0.2017}, \text{μm} \quad (1)
\]

\[
H\mu = 132.27 \cdot S^{-0.147} \cdot V^{0.165}, \text{HV} \quad (2)
\]

\[
\sigma = 380.5 \cdot S^{-0.486} \cdot V^{-0.222}, \text{MPa} \quad (3)
\]

\[
C_x = 0.334 \cdot S^{-0.333} \cdot V^{-0.139} \quad (4)
\]

Initial data for task №2: Workpiece material is steel X12CrNiTi 10, workpiece material hardness is HB = 180, cutting edge material is BK8. The cutting plate geometry include: clearance angle – 9°, cutting angle – 6°, major cutting edge angle – 92°, minor cutting edge angle – 10°, tip radius – 0.2 mm, edge radius – 20μm, cutting parameters:
Longitudinal feed \( S \):
\[
S_{\text{min}} = 0.10 \text{ mm/rev}; \\
S_{\text{max}} = 0.25 \text{ mm/rev};
\]

Cutting Speed \( V \):
\[
V_{\text{min}} = 77 \text{ m/min}; \\
V_{\text{max}} = 124 \text{ m/min};
\]

Depth of Cut: \( t = 0.4 \text{ mm} \).

The resulting mathematical models of self-learning of the Automated Control System for processing steel workpiece X12CrNiTi 10 are as follows (5-8):

\[
Ra = 21.78 \cdot S^{1.355} \cdot V^{-0.073}, \mu m. \quad (5)
\]

\[
H\mu = 339.8 \cdot S^{-0.192} \cdot V^{-0.046}, \text{HV} \quad (6)
\]

\[
\sigma_T = 32.09 \cdot S^{0.93} \cdot V^{1.004}, \text{MPa} \quad (7)
\]

\[
C_X = 0.123 \cdot S^{-0.241} \cdot V^{0.154} \quad (8)
\]

In the process of self-learning of the Automated Control System surface finish Ra of the machined surface was measured by a laser optic sensor in an automatic unmanned mode under the monitor program control of the Automated Control System.

On finishing of the self-learning process the obtained parameters of mathematical models are stored in the computer database.

The operation of the Automated Control System was tested in an ADC mode with simultaneous provision of the following parameters of surface layer quality characteristics: \( Ra = 1.6 \mu m, H\mu = 420 \text{ HV}, \sigma_T = 450 \text{ MPa} \). This set of parameters corresponds to determined complex parameter \( C_X = 0.432 \). So, the task can be formulated as follows: it is necessary to obtain the pre-set value of complex parameter \( C_X \) using the adaptive control mode of the Automated Control System.

The initial data for the ADC mode are:
- required parameter \( C_X \): 0.432
- required diameter tolerance: \( \pm 15 \% \)
- workpiece material steel: X12CrNiTi 10
- workpiece material hardness, HB: 290
- cutting edge material: BK8
- clearance angle: 9°
- cutting angle: 6°
- major cutting edge angle: 92°
- minor cutting edge angle: 10°
- tip radius: 0.2 mm
- edge radius: 20 \( \mu m \)
- depth of cut: \( t = 0.4 \text{ mm} \)

While testing the operation of the Automated Control System in the ADC mode five workpieces were machined. After the test parts machining surface finish Ra, and microhardness \( H\mu \) of the machined parts were measured. Surface finish Ra was measured with profilometer MarSurf PS1. Microhardness was defined with a microhardness tester. Value \( \sigma_T \) was calculated. On the basis of measured parameters Ra and H\mu and calculated value \( \sigma_T \) complex parameter \( C_X \) was produced. The average values of the obtained parameters are: \( C_X = 0.44, Ra = 1.36 \mu m, H\mu = 421 \text{ HV}, \sigma_T = 432 \text{ MPa} \).

### 4. Conclusions

The obtained research results show that surface finish value Ra – feeds and speeds are equal – is different for different machining parameters (workpiece hardness, the workpiece material, the cutting edge geometry: the clearance angle, the cutting angle, the major cutting edge angle and the tip radius), that is why it is necessary to carry out the system’s self-learning.
It was found that in machining of one and the same material (but with only changing cutting edge geometry, i.e. clearance angle and cutting angle) the value of surface finish does not change much, the maximum error is 2.3 %. This means that for machining of one and the same material using a tool with different geometry of clearance and cutting angles the technological system self-learning can only be carried out for the tool geometry.

The obtained results prove the efficiency of the Automated Control System in the modes of self-learning and adaptive control over surface layer quality characteristics.

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