Adaptive profile gear grinding boosts productivity of this operation on the CNC machine tools

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Abstract. The paper is devoted to solving an important scientific and technical problem of increasing the productivity of defect-free profile gear grinding on CNC machines through computer subsystems of grinding operation automated design, monitoring, and grinding diagnostics. The corresponding methodology and theoretical preconditions for these computer subsystems developments are provided to solve the following scientific problem. Despite of the increase in the productivity of gear grinding on CNC machines, a number of attendant factors have appeared that limit the gear grinding productivity: the time of the grinding stock measuring in the tooth spaces which is comparable with the time of gear grinding, the lack of methods for accounting the information about the grinding stock, etc. In this connection, the paper purpose is to indicate the ways of increasing the productivity of the profile defect-free gear grinding on CNC machines. For this purpose, a set of purposeful methods and means of innovative adaptive gear grinding technology has been developed. For example, a method for restoring information about the grinding stock is proposed with a limited number of measurements to ensure, for example, that the feed can be switched from accelerated one to working and vice versa. Mathematical models have been developed to convert the grinding stock uncertainty into the deterministic value of the grinding wheel retraction from the workpiece, etc.

Keywords: adaptability, gear grinding system, gear grinding stock, grinding stock model, designing, monitoring, diagnostics.

1 Introduction

The property of adaptability in the mechanical engineering is gaining increasing recognition due to the success of its application in practice of automated production on CNC machines. This was the result of a natural process of computer-aided design of high technologies and the corresponding both cutting and grinding machining systems, including the gear grinding systems on the basis of CNC machine tools. The basis of adaptive mechanical machining is its integration with on-machine measurement (monitoring) and process diagnostics (control), which are performed on the same equipment, i.e. without the error of the workpiece setting and with eliminating the influence of the human factor. As a consequence, it is possible to significantly increase the process productivity, including gear grinding on CNC machine tools.

That is why the proposed work, which is the result of many years of experimental and theoretical research, is among the topical in the mechanical engineering.

2 Analysis of the question status, the purpose and objectives of the study

The analysis of labor-intensiveness of the technological process of gears production has been made. A significant amount of time spent on grinding operation (up to 40-70%) is established. Therefore, the task of increasing the productivity of the gear grinding on CNC machines is actual and important, despite of the productivity advantages reached on the CNC machines. The technological possibilities of existing grinding methods are considered. It was established that the most application was made by two kinds of gear grinding: the profile gear grinding (gear quality 3 to 6 to DIN 3961) and the worm wheel one (gear quality 4 to 7) [1]. The appearance of the CNC gear grinding machines allowed increasing the technological operations productivity by ensuring the self-sufficiency, autonomy and mobility of the grinding system with the software and with the minimum participation of the machine operator in the implementation of all stages of the grinding operation. The profile gear grinding compared with the worm wheel gear grinding ensures higher accuracy (DIN 3-6 instead of DIN 4-7), but yields less productivity. That is, you need to find reserves for further increase in productivity. One of these reserves is the use of the individual features of the grinding wheel, pre-machined workpieces of gears as well as disclosing the uncertainty coursed by influences derivable from lubricoolants, the grinding machine, etc. It is known, all elements of the grinding system must be adapted to each other to achieve the goal of the adaptive profile gear grinding. In order to use these reserves it is proposed to control the process by introducing appropriate adjustments on the basis of the process redesigning, monitoring and diagnosing with the help of corresponding computer subsystems built in an appropriate manner into the CNC structure [2].

The gear grinding stock measurement at the gear periphery on CNC machines allows to take into account the gear individual features when aligning the stock along the lateral sides of their tooth spaces, to ensure the individual removal of the stock, taking into account its value and actual location along the gear periphery. However, the gear grinding stock measurement consumes the auxiliary operation time, so there is a problem reducing this time by optimizing the number of measurements. The feature of the stock to be removed is its unplanned change in the gear periphery, which is influenced by the chosen method of aligning of the stock due to the correction in the gear angular position. It is known that the gear grinding stock determines the productivity of the operation; therefore, studies related to the stock determination which based on the results of its selective measurement in certain tooth spaces are relevant.

The gear grinding temperature is one of the factors limiting the productivity of the grinding operation. In the analysis of temperature field mathematical models during grinding, one of them was used with a phenomenological approach to determine the grinding temperature for a three-, two- and one-dimensional temperature field based on the Fourier partial differential heat conductivity equation under boundary conditions of the second kind. This approach was started in due time by well-known scientists-thermophysics H. S. Carslaw and J. C. Jaeger. The analysis of the relevant works showed that there are no acceptable solutions to the thermophysical problems for the purpose of gear grinding operation designing, monitoring and diagnosing.

To assess the productivity and for designing the grinding operation, a number of characteristic values are used, among which are: the volume of the material to be removed per unit time (the intensity of the grinding) Q_w (mm^3 /s), the total amount of removable material V_w (mm^3). In the literature, the first two indicators are additionally given to the unit of effective (further active) grinding wheel width and are indicated by: Q'_w in mm^3/(s·mm) and V'_w in mm^3/ mm. However, the literature does not describe the applied methods of determining the high-production modes of grinding on the basis of these indicators of grinding operation, there is no information on grinding diagnostics in real time. There is no mathematical dependence to determine the grinding intensity Q_w in mm^3/s for an arbitrary curvilinear profile, which differs from the rectangular profile for traditional rectangular grinding schemes. Parameters Q'_w and V'_w affect the grinding temperature and force as well as the grinding wheels wearing in different points of the grinding wheel profile, but the corresponding mathematical dependencies have not yet been installed. The analysis of literature has shown that the relationship between the Q'_w parameter and the thermal burns is still a formal one, because it is not related to the grinding temperature. Therefore, it is necessary to establish this relationship.

The urgency of monitoring and grinding diagnostics subsystems in gear grinding is due to the lack of deterministic relationships between the grinding system output (accuracy and quality of machining) parameters and the input control (grinding modes) ones. The output parameters, i.e. operation result, are determined after the end of the machining (control of the result), when there is no possibility of correction of the result, which creates a control problem by the grinding operation. Therefore, the control of the relevant grinding system state parameters, i.e. process parameters, may be useful to make the necessary corrections for obtaining the output parameters desired.

3 Profile grinding productivity on a CNC machine theoretical analysis

The methodology of scientific researches, which includes modeling, optimization and control in the grinding system, is given. These directions characterize the investigated grinding system as an object of control, which has input parameters $\boldsymbol{u}$, state parameters $\boldsymbol{x}$ and output parameters $\boldsymbol{y}$ [3].

The interconnections between these parameters are not deterministic ones; therefore the task of the research is to identify these parameters, based on ensuring the least number of grinding stock measurements that gives minimum measurements time. This requirement satisfies the representation of the grinding system in the form of an object of control in which it is necessary to provide the necessary output parameters at the highest machining efficiency with automated control of this object using the computer-aided design, monitoring, and grinding diagnosis subsystems [1, 2]. Monitoring and grinding diagnostics of the grinding system state partly compensate for the lack of adaptive control of the output parameters, which is impossible due to the lack of information about the output parameters which are available continuously. At the same time, the diagnostics of the grinding system state allows indirect characterization of its output parameters through deterministic-stochastic relations, in which the information is distributed from the input parameters through the state parameters to the output ones. Unlike the output parameters, information about the state parameters can occur continuously, providing the possibility of indirect adjustment of the output parameters and thus the solution of the problem.

The deterministic-stochastic nature of the profile gear grinding requires appropriate approaches and methods for solving the tasks; therefore, the theoretical-probabilistic approach is used in the work. In turn, the approach to dividing the information signal into elementary harmonic components is called the frequency approach in the work. According to this approach, any signal in the function of time can be transformed according to the Fourier algorithm into the corresponding dependence of the amplitudes and phases of the signal harmonic components from their frequency (direct Fourier transform) and back from the frequency dependence in the time one (inverse Fourier transformation). On the basis of these approaches (theoretical-probabilistic and frequency), methods of determining the gear grinding stock to be removed are developed, which allow determining the maximum value of the stock along the gear periphery. It has been established that the grinding stock includes constant z_0 and variable Δz parts, i.e. $z = z_0 + \Delta z$. In accordance with the theoretical-probabilistic approach, the variable part Δz of the stock is considered, assuming that it has a systematic (periodic) Δz_{sys} and random (aperiodic) Δz_{ran} components. Consequently, the structural formula for determining the stock $z(n)$ for gear grinding for both sides of the profile of the tooth space has the form

$$z(n) = z_0 + \Delta z(n) = z_0 + \Delta z_{sys}(n) + \Delta z_{ran}(n) , \qquad (1)$$

where n is the current number of the gear tooth space, $1 \le n \le N_{\max}$ ($N_{\max}$ is the number of gear teeth. The gear grinding stock distribution on the left and right sides of the tooth spaces as the serial number of the teeth changes has a sinusoidal nature of the change (Fig. 1). The stock instantaneous values are the sum of the constant, i.e. z_0^L or z_0^R , and the variable, i.e. $\Delta z^L(n)$ or $\Delta z^R(n)$, components of the stock. The instantaneous magnitude of the variable component of the stock in formula (1) can be positive and negative. In the first case, the instantaneous value of the corresponding stock on the right or left side of the tooth spaces is greater than its constant component, while in the second case is less than it.

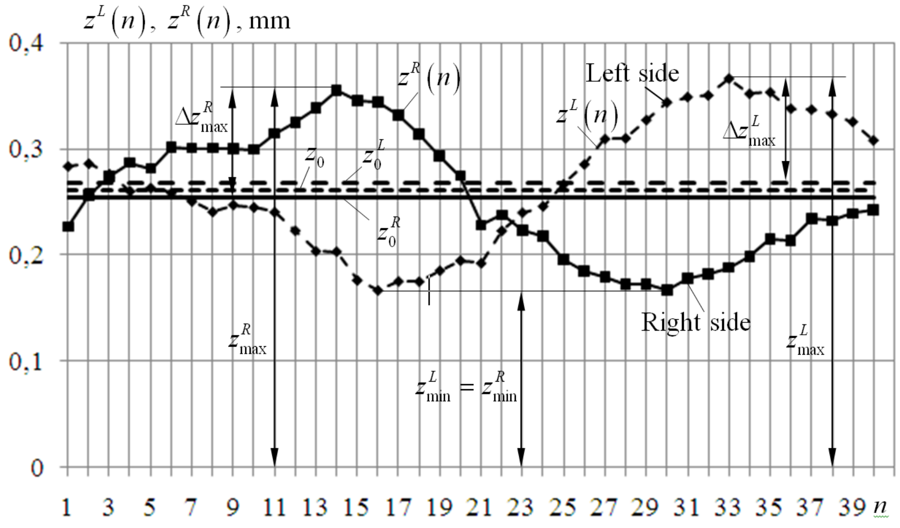

Fig. 1. Distribution of a stock to be removed on the right and left sides of the gear tooth spaces after aligning the stock minimum values.

Consequently,

$$z^L(n) = z_0^L + \Delta z^L(n) = z_0^L + \left[\Delta z_\beta^L(n) + \Delta z_\gamma^L(n)\right], \tag{2}$$

$$z^R(n) = z_0^R + \Delta z^R(n) = z_0^R + \left[\Delta z_\beta^R(n) + \Delta z_\gamma^R(n)\right], \tag{3}$$

where $\Delta z_\beta^L(n)$ and $\Delta z_\gamma^L(n)$ are systematic and random components of the variable part of the left-hand stock, mm; $\Delta z_\beta^R(n)$ and $\Delta z_\gamma^R(n)$ are systematic and random components of the variable part of the right-hand stock, mm.

In equations (2) and (3), the systematic component of the variable part of the stock can be replaced by the first harmonic of the corresponding Fourier series, that is,

$$\Delta z_\beta^L(n) = A_1^L \cos\ \omega_1 t\ + B_1^L \sin\ \omega_1 t\ , \tag{4}$$

$$\Delta z_\beta^R(n) = A_1^R \cos\ \omega_1 t\ + B_1^R \sin\ \omega_1 t\ ,$$

where A_1^L, B_1^L, A_1^R, B_1^R are Fourier coefficients; $\omega_1 t$ is observation interval at the central angle, $0 \le \omega_1 t \le 2\pi$.

The stochastic and deterministic models of the stock are developed, on the basis of which the algorithms for determining the maximum stock based on the results of its selective discrete measurements in certain gear tooth spaces are synthesized depending on the number of measurements performed. For up to four measurements it is made through the difference between one-sided stocks, that is, accumulated circumferential step and for more eight ones – through a one-sided stock and an accumulated circumferential step.

The maximum stock for the number of measurements $N \le 4$ is determined by the formula

$$z_{\max} = z_0 + \Delta z_{ran}\ , \tag{5}$$

where $\Delta z_{ran} = \varepsilon$, $\varepsilon = t_\gamma S_{\bar{x}}$, t_γ is confidence coefficient; $S_{\bar{x}} = \dfrac{s}{\sqrt{k}}$ is mean square deviation of the result, mm; $s = \dfrac{1}{\sqrt{k-1}}\sqrt{\sum_{n=1}^{k} (x_n - \bar{x})^2}$ is selective mean square deviation, mm. And $x_n = \Delta P(n) = z^L(n) - z^R(n)$, $\bar{x} = \Delta P_0 = \dfrac{1}{N}\sum_{n=1}^{N} \Delta P_n$ is deflection of the circumferential step and the mean deviation of the circumferential step, respectively.

The maximum stock for the number of measurements $N \ge 8$ found through an accumulated circumferential step is determined by the formula

$$z_{\max} = z_0 + \Delta z_{sys} + \Delta z_{ran} + c_0\ , \tag{6}$$

where $\Delta z_{sys} = A/2$ is a systematic component that is equal to half the amplitude of the sinusoid recovered by the least squares method at discrete values of the circumferential step; $\Delta z_{ran} = \varepsilon$ for a random component of the deflection of the circumferential step $\Delta P_\gamma(n)$. And $x_n = \Delta P_\gamma(n)$, $\bar{x} = \Delta P_0 = \dfrac{1}{N}\sum_{n=1}^{N} \Delta P_{\gamma n}$. The amplitude of the deflection of the circumferential step is counted upwards or downwards from the level of the constant component c_0 . And $c_0 = z_0^L - z_0^R$.

A large number of measurements lead to additional time expenditures for these measurements, especially for the gear with a large number of teeth. Therefore, reducing the number of measurements is a resource for increasing productivity at the CNC grinding machine setting stage. In turn, the reduction of the number of measurements is accompanied by loss of accuracy of the definition of the maximum allowance value. In this case, the grinding wheel is retracted to a certain distance for a non-predefined grinding, which is due to the maximum allowance value uncertainty. In this regard, the reduction in the number of measurements should be substantiated and investigated.

The theoretical preconditions for optimization of the operation of profile grinding on a CNC machine are developed and tested, according to which the optimization is performed with the help of developed evaluation functions. The first of which is the sum of squares of the difference of the stock extreme values, found by both the limited and maximum number of measurements; the second is the difference of the ordinal numbers of the tooth spaces with the maximum stock, which are found for both the limited and maximum number of measurements. Data on maximum ($z_{\max}^L$ and $z_{\max}^R$) and minimum ($z_{\min}^L = z_{\min}^R$) stocks are used to determine the dispersions D_1 ($z_{\max}^L$), D_2 ($z_{\max}^R$), and D_3 ($z_{\min}^L = z_{\min}^R$), respectively.

Dispersions D_1, D_2, D_3 represent the square of the difference of the corresponding stock, found on the maximum number of measurements for $N = N_{\max}$ (base version) and the same stock, found for a limited number of measurements at $N < N_{\max}$ (compared option version). Evaluation function, i.e. the sum of dispersions D_Σ is determined by the formula

$$D_\Sigma = \left(z^L_{\max}(N_{\max}) - z^L_{\max}(N)\right)^2 + \left(z^R_{\max}(N_{\max}) - z^R_{\max}(N)\right)^2 + \\ + \left(z_{\min}(N_{\max}) - z_{\min}(N)\right)^2 \qquad (7)$$

For example, D_Σ is defined for three gear wheels (GW1, GW2, and GW3) each of them have 29 teeth; the optimal number of measurements of the stock is 9 (Fig.2, *a*).

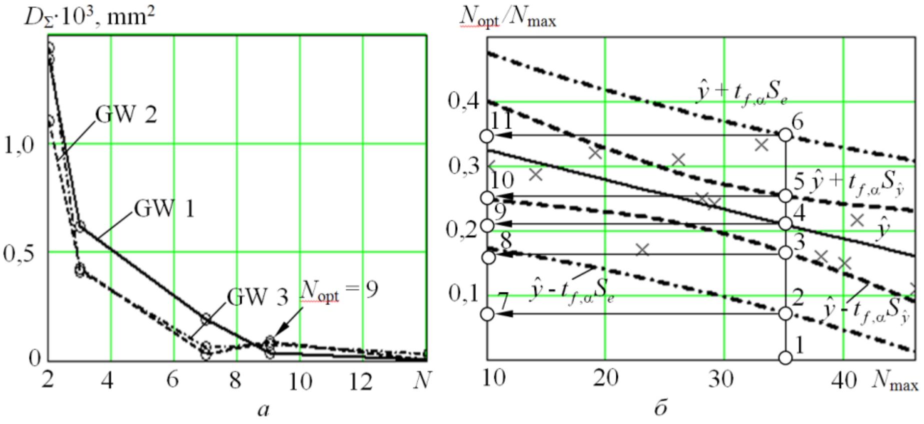

Fig. 2. Evaluation functions (*a*) and nomogram for determining the optimal number of measurements (*b*).

A nomogram based on the statistical processing of twenty gears has been developed to select the number of measurements of the stock (Fig.2, *b*) at the setting up stage of a CNC grinding machine equipped with a Renishaw company's measuring tactile system or a measuring system based on control of acoustic emission signal. Regression analysis has established the linear regression equation: $\hat{y} = 0.36834 - 0.00454N$ (solid line in Fig.2, *b*). Confidence intervals $\pm t_{f,\alpha}S_{\hat{y}}$ and $\pm t_{f,\alpha}S_e$ (Fig.2, *b*) to the regression line $\hat{y}$ depend on the following variables: $S_{\hat{y}}$ is standard deviation of regression value $\hat{y}$; S_e is standard deviation of forecast error; $t_{f,\alpha}$ is quantile of t - distribution with f degrees of freedom and at significance level α. For example, it is necessary to find the number of measurements of the allowance on the GW with the number of teeth $N_{\max} = 35$ (point 1 in Fig.2, *b*). Through point 1, the vertical is carried out to intersect with the lines of confidence intervals (points 2, 3, 5 and 6) and the regression line (point 4). Determine the ordinates N_{opt}/N_{max} of all points: for point 7 – 0.072; for point 8 – 0.167; for point 9 – 0.211; for point 10 – 0.254; for point 11 – 0.349. From here we find $N_{opt} = (N_{opt}/N_{max}) \cdot N_{max}$. We get for

N_{opt}: 2.52; 5.85; 7.37; 8.90; 12.22. Thus, the desired result with confidence intervals will be: 7.37 ± 1.53 and 7.37 ± 4.85.

For the grinding operation design, both the parameters of the grinding intensity (Q_w, Q'_w) and the grinding wheel life ones (V_w, V'_w) are used. In the analysis of the profile gear grinding scheme an analogy with the profile rectangular grinding scheme is found as for the volume of material removed per unit time. Consideration of this analogy allowed to formulate and prove the theorem about an equivalent rectangular profile, which at the same grinding depth creates the same cross section area $S_{i+1} = W_{a\ i+1}\ t_{i+1}$, where $W_{a\ i+1}$ is the active profile width, which is determined on the basis of the known geometric parameters of the profile grinding before ($W_{a\min\ i+1}$) and after ($W_{a\max\ i+1}$) the grinding wheel's profile installation for the next (i+1)-th working stroke. This area depends on the next grinding depth t_{i+1}. A method for determining the active width of an equivalent rectangular profile $W_{a\ i+1}$ for each (i+1)-th working stroke is developed, when the stroke is performed from the previous position of the involute profile $\sum_{k=1}^{i} t_k$ to the its current position $\sum_{k=1}^{i} t_k + t_{i+1}$, after which the stock to be removed value $\sum_{i+2}^{n} t_k$ remains.

According to the theorem on an equivalent rectangular profile the intensity of grinding or material removal rate (in mm^3/s) is determined by the formula

$$Q_{w(i+1)} = S_{i+1} V_f = t_{\text{i}+1} W_{a(i+1)} V_f \,, \tag{8}$$

where $S_{i+1} = W_{a\ i+1}\ t_{i+1}$ is the section cross area on (i+1)-th stroke, mm^2; V_f is axial feed, mm/s. Knowing the current intensity of the grinding $Q_{w(i+1)}$ (mm^3/s), i.e. during the (i+1)-th stroke, one can find the specific intensity per unit of active grinding wheel width $Q'_{w(i+1)}$ in mm^3/(s·mm) and the current amount of removable material $V'_{w(i+1)}$ in mm^3/mm, and regardless of the shape of the profile. These two parameters of the cutting material layer are known as specific material removal rate ($Q'_{w(i+1)}$) and specific material removal ($V'_{w(i+1)}$) [1]. With reference to the equation (8) we get for the spur gear:

$$Q'_{w(i+1)} = \frac{Q_{w(i+1)}}{W_{a(i+1)}} = t_{i+1} V_f \,; \quad V'_{w(i+1)} = \frac{Q_{w(i+1)}}{W_{a(i+1)}} \frac{B}{V_f} = B t_{i+1} \,. \tag{9}$$

The conducted theoretical and experimental analysis allowed formulating and proving the following theorem of the gear grinding stock extreme values aligning: the left and the right side gear grinding stocks which aligned by their minimum or maximum values do not depend on the location of the initial tooth space, from which the measurement of the stocks on two sides begins.

4 Automated design, monitoring and gear grinding diagnostics computer subsystems development

Theoretical preconditions for the development of built-in automated design, monitoring and profile gear grinding diagnostics subsystems are given [4, 5] to take into account the gear individual characteristics during the gear grinding operation on the CNC grinding machines. On the basis of the research carried out in the workflow, a system of five independent equations has been formed, which is transformed into a system of three equations for automated design, monitoring and grinding diagnostics subsystems development. Introducing the following notation

$$f(Q'_w, A_{num}, V_f) = 2\cdot 10^6 e_c \psi \frac{{Q'_w}^{0,75} {V_f}^{-0,25} \sin\alpha}{D^{0,25}\,\lambda} \sqrt{\frac{a}{\pi}}\ ,$$

we get

$$\begin{cases} Q'_w = t_v\ V_f \\ q = e_c \psi \dfrac{V_f t_v \sin\alpha}{\sqrt{D t_v}} \\ T_H = \dfrac{2q\sqrt{a\,\tau_н}}{\lambda\sqrt{\pi}} \\ \tau_н = \dfrac{\sqrt{D\ t_v}}{V_f} \\ V'_w = t_v\ B \end{cases} \Longrightarrow \begin{cases} T_H = f(Q'_w, A_{num}, V_f) \\ V'_w = \dfrac{Q'_w}{V_f} B \\ Q'_w = t_v\ V_f \end{cases} . \qquad (10)$$

where e_c is the specific grinding energy in J/mm^3; α is the profile angle in rad.

In accordance with equations (10), a block diagram of automated design, monitoring and gear grinding diagnostics computer subsystems is developed, which differs from the existing monitoring system on the CNC machine Höfler Rapid 1250 by the possibility of determining both the specific gear grinding work in J/mm^3 and the gear grinding temperature in °C.

Input parameters for the gear grinding system unit: part drawing data; material thermal diffusivity a in m^2/s; material thermal conductivity λ in W/(m·°C); heat partition factor ψ. Input parameters for the calculating device unit: a grinding depth t_v in mm; an axial feed V_f in mm/min; a gear width B in mm, the stock to be removed $\Delta z^L(n)$ and $\Delta z^R(n)$ in mm, *AE* signal in relative units, and grinding power in W.

The computer subsystem configuration may consist of both hardware and software or may be integrated to the CNC device on the basis of already existing software there. It may comprise a memory and a processor coupled to the memory, etc.

Conclusions

1. The paper gives theoretical bases for gear grinding operation automated design, monitoring, and grinding diagnostics computer subsystems to model the gear grinding stock and restore it on the basis of selective equidistant measurements of the stock and to define both the specific material removal rate and the specific material removal. The relationship between these parameters was established as well as that with the temperature of gear grinding.

2. The methods and the computer subsystems that implement them are provided to boost the productivity of the profile gear grinding operation on the CNC machines tools. For example, three such subsystems are considered based on the same generalized computer subsystem configuration: for automated design of gear grinding modes (first), for gear grinding process monitoring (second) and for the process diagnosis (third).

3. The disclosed methodology of gear grinding operation designing, monitoring, and diagnosing may be applicable to any grinding operation. This will help increase the productivity of the corresponding grinding operations in automated production on CNC machines.

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