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SIMULATION OF THE CONTACT TEMPERATURE IN THE CYLINDRICAL PLUNGE GRINDING PROCESS

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Abstract

The intensifying of the manufacturing process and increasing the efficiency of production planning of parts are the first-priority task in modern manufacturing. The use of various methods for controlling the cutting force and temperature in cutting zone under cylindrical infeed grinding and studying its impact on the quality and accuracy of parts machining can improve machining efficiency. The peculiarity of the work is to the proposal to consider a fast-moving source like a heat source in the plunge grinding process. Based on the Peclet analysis, the further development of the method for calculating the allowance removed at each workpiece revolution by optimizing the cylindrical plunge grinding cycle parameters has been justified. The methodology for determining the optimal parameters of a cylindrical plunge grinding cycle, which based on a simulation of the dynamics of such a process represented by a three-mass model of a 3M151 circular grinding machine has been used in research. The practical value of the study lies in studying the ways of improving the grinding performance of the parts by intensifying cutting modes and optimizing the structure of machining cycles.

Keywords: thermophysics of the grinding process, contact zone of the grinding wheel and the workpiece, grinding process dynamics, surface quality, defective layer

1. INTRODUCTION

Among the main and priority tasks for the modern competitive manufacturing enterprises, the active search for optimal technological solutions in the field of intensification of technological processes is highlighted [1, 2]. Priority is given to improving the efficiency of manufacturing critical and expensive parts, which require abrasive processing methods. Such parts are subject to high requirements in terms of roughness, dimensional accuracy, etc. These requirements are fulfilled by machining these parts using universal and special grinding machines with the use of special tooling and fixture. At the same time, it is necessary to note the sharply increased requirements for technical and economic indicators of grinding operations, especially in automated and robotic production. Thus, in the context multiproduct manufacture, should be taken into account the quality criteria [3, 4] and energy efficiency [5, 6], equipment [7, 8] and tooling [9, 10] capabilities, processing modes [11, 12], the design and technical parameters of the parts [13-15], the properties of materials and coatings [16-20].

The performance and cost of cylindrical plunge grinding operations for parts are largely determined by the selected parameters of the grinding cycle and the method of managing this cycle. Besides, grinding parts, the optimal machining cycle can be determined by the minimum machine time, as defined by the speed of the cross-infeed traverse and the amount of allowance. Increasing the cross-traverse leads to an increase in the cutting force components, which triggers an increase in the elastic strain of the elements of the technological system "workpiece-grinding wheel-grinding machine".

A large influence on the accuracy and quality of the ground surface is exerted by the temperature in the contact zone of the workpiece and the grinding wheel. The depth of the defective layer on the surface of the workpiece directly depends on the temperature in the contact zone, which in turn is determined by the cutting conditions.

Thus, the search for optimal cutting conditions, providing, on the one hand, maximum productivity, and, on the other hand, the minimum depth of the defective layer, is an urgent task.

2. LITERATURE REVIEW

Two basic approaches have been applied in the study of the thermal physics of grinding when the workpiece heating sources are primarily considered: the surface area of contact of the grinding wheel with the workpiece [21-24]; the total thermal effect in the case of single abrasive grains cutting [25-30].

The thermophysics of the grinding process is also reflected in the research citations [31, 32, 33].

In article [34] was shown to the development of a mathematical model of the combined grinding process. Based on the main provisions of the theory of abrasive processing, authors [34] dependencies are developed to calculate the probability of removal of the material at any point in the contact zone taking into account several simultaneous processes of formation. The complexity of the physical processes of surface formation connected with a large number of technological factors, with the help of which the parameters of this process can be changed, is shown [34]. The model takes into account the peculiarities of the stochastic nature of the abrasive processing process and the interaction of additional physical processes and technological factors. In paper [35] authors were proposed a model is based on the probabilistic approach and it allows calculating the value of the bond layer removed with erosive discharges and predict the state of the technological system at any moment. In paper [36] by authors was proposed improvement the contact performance properties, by submitting presentation of optimization of flat grinding of titanium parts by following two parameters: the relative bearing length of the profile and the relative bearing part of the parts' surface that allow assessing the quality of the surface at the micro- and macro-scale. The Bogutsky, V. and all shown that during the grinding of complex profile blades of metal cutting tools from tool steels, unfavorable thermodynamic conditions are created in the cutting zone and, as a result, grinding burns and cracks occur on the surface of the polished workpiece [37]. The method of calculating the profile of the discontinuous surface of the grinding wheel presented in the article makes it possible to determine its geometric parameters taking into account the wear resistance of the grinding wheel and the heat stress of the process of treatment [37]. In paper [38] a vitrified bond CBN point grinding wheel with coarse grinding area slope angle θ was presented. The theory of grinding heat generation and distribution and infrared temperature measurements were submitted. The effects of different grinding parameters were generalized. In the paper [39], the authors emphasized that a massive amount of heat is generated during the high-efficiency grinding process, which leads to a serious burnout problem that limits the increase of the material removal rate. An oscillating heat pipe grinding wheel that is a combination of a grinding wheel and OHPs was proposed by Qian, N. and all. The results of researches on temperature variations during flat peripheral grinding are presented in Smirnov's V.A. and Repko's A.V. paper [40]. In the article, a nonlinear two-dimensional thermophysical grinding model is suggested. The researchers claim that the proposed thermophysical model makes it possible to predict with high accuracy the temperature variations during grinding by the wheel periphery [41]. In paper [42] the result of the investigation of thermal processes in the course of magnetorheological polishing has been carried out. Physical and mathematical description of heat transfer from a treated surface to a polishing tool is given with consideration of the specifics conditions [42]. An analytical estimate of the thermal state of a magnetorheological abrasive tool and a treated workpiece surface is given [42]. A procedure to calculate the temperature in grinding massive, thin, and wedge-shaped parts with account taken of the geometric and thermophysical parameters of the tool and the treated part, and also of cutting regimes has been presented by Dement and other [43]. In the paper, a relationship between the temperature in the grinding zone and the regimes of treatment which makes it possible to control the quality of the surface layer of massive, thin, and wedge-shaped plates from hard-to-machine steels has been estimated [43]. In scientific works [44, 45], the surface being processed is presented as a set of adiabatic rods, which allows the authors to solve the problem of heat balance and improve the surface quality according to the temperature criterion. In the present work, the continuous surface area of the grinding wheel with the surface being machined is taken as the heating source of the workpiece. This approach is quite fully developed in paper [23]. However, the main difference between the present work is the representation of the heat source not in the form of a plane that moves along the surface of the half-space, but in the form of a fast-moving one. The possibility of such a substitution is proved by the Peclet criterion analysis [26] (1):

$$\mathrm{P_e} = \frac{\mathrm{V_z} \cdot L}{a} \le 8 \div 10 , \qquad (1)$$

where L – the heat source size in the direction of its movement; a – thermal diffusivity of the workpiece material.

Application of the concept of “fast-moving heat source” made it possible to obtain the dependence $T(\tau, x)$ [46] by integration over time, i.e. taking into account the surface of the workpiece in the heat source and outside it. This, in turn, made it possible to take into account the different heat transfer from the surface of the workpiece when it is in the contact zone and outside it. In the present paper, when optimizing the parameters of the cylindrical plunge grinding cycle, the allowance for the workpiece removed at each turn is calculated based on the formulas obtained in research [46], in which the so-called “generalized static characteristic of the grinding process” is used (2):

$$\mathrm{K}_{gr} = \frac{C_p}{j + C_p} , \qquad (2)$$

where C_p – grinding process rigidity; j – rigidity of the system “workpiece – abrasive wheel – metal-cutting machine”.

The rigidity j is determined experimentally, as shown in research [46]. And C_p is determined based on the experimental formula for calculating P_z from the grinding conditions with the transition to P_y – the radial component of the grinding force and its linearization concerning the grinding depth h., i.e. getting dependency (3)

$$P_y = C_p \cdot h\,. \tag{3}$$

3. METHODS FOR SOLVING THE PROBLEM OF THE OPTIMAL PARAMETERS DETERMINING OF A CYLINDRICAL PLUNGE GRINDING CYCLE

The methodology for determining the optimal parameters of a cylindrical plunge grinding cycle (CPGC) is based on a simulation of the dynamics of a CPGC represented by a three-mass model of a 3M151 circular grinding machine. Based on it, formulas for calculating the allowance taken during grinding at each phase of the cycle using the experimental dependence of the grinding force Pz on the grinding conditions (processes, wheel characteristics, dressing conditions) and the generalized static CPGC characteristic are obtained.

The amount of allowance necessary for removal, i.e. the value of the workpiece defective surface layer is determined based on the analytically obtained dependence $T(\tau, x)$ for a fast-moving heat source with programming the integration limits over time. This takes into account the differing intensity of heat transfer from the workpiece in the contact zone with the grinding wheel and outside contact zone.

The heating of the grinded workpiece $T(\tau, x)$, as a function of x – the distance from the surface in the radial direction and τ – the time counted from the moment the workpiece surface enters the contact zone with the grinding wheel [46] is calculated by the formula (4):

$$\begin{aligned}
T(\tau,\mathrm{x}) = \frac{q\cdot\sqrt{a}}{\lambda\cdot\sqrt{\pi}} \int_{0}^{if\,(\tau<\tau_1,\tau,\tau_1)} & \frac{\exp\left(-\dfrac{\mathrm{x}^2}{4\cdot a\cdot(\tau-t)}\right)}{\sqrt{\tau-t}} \cdot \\
& \cdot\left[1-\frac{\mathrm{if}\left[\tau\le\tau_1,\alpha_1,\alpha\left(1-\dfrac{\tau}{\tau_2}\right)\right]}{\lambda}\cdot\right. \\
& \cdot\sqrt{\pi\cdot a(\tau-t)}\cdot \\
& \cdot\left[1-\mathrm{erf}\left[\frac{x}{\sqrt{4\cdot a\cdot(\tau-t)}}+ \right.\right. \\
& \left.\left. +\frac{\mathrm{if}\left[\tau\le\tau_1,\alpha_1,\alpha\left(1-\dfrac{\tau}{\tau_2}\right)\right]}{\lambda}\cdot\sqrt{a\cdot(\tau-t)}\right]\right], \\
& \cdot\exp\left[\left[\frac{x}{\sqrt{4\cdot a\cdot(\tau-t)}}+ \right.\right. \\
& \left.\left.\left. +\frac{if\left[\tau\le\tau_1,\alpha_1,\alpha\left(1-\dfrac{\tau}{\tau_2}\right)\right]}{\lambda}\cdot\sqrt{a\cdot(\tau-t)}\right]^2\right]\right]\mathrm{dt}
\end{aligned}$$

(4)where $q=\frac{P_z\cdot V_\kappa}{L\cdot B}\cdot\beta$ - heat flux density, $\frac{J}{sm^2\cdot\sec}$; P_z – peripheral grinding force, N; V_κ – grinding wheel peripheral speed, m/sec; a – thermal diffusivity, mm^2/sec; λ – heat conduction coefficient, $\frac{J}{mm\cdot\sec\cdot\deg}$; τ – temperature observation time; $(\tau-t)$ – heat propagation time from the moment t of the occurrence of the heat pulse to τ – observation time; τ_1 – heating source action time, sec; τ_2 – the time of workpiece processing, sec; α_1 – heat transfer coefficient in the heat source, $\frac{J}{mm^2\cdot\sec\cdot\deg}$; α – heat transfer coefficient outside the heat source; “if” – conditional operator, with the help of which the solution of the problem of determination $\mathrm{T}(\tau,\mathrm{x})$ in the heat source and outside it is programmed.

The grinding circumferential force P_z is calculated from the experimental dependence [46]:

$$P_z = 2{,}254\frac{\sigma_t^{0{,}342}\cdot H^{0{,}258}\cdot V_p^{0{,}945}\cdot B}{Z^{0{,}051}\cdot S^{0{,}073}\cdot S_{pr}^{\;0{,}073}\cdot t_{pr}^{\;0{,}026}}\text{, N} \tag{5}$$

where σ_t – tensile strength of the workpiece material at a temperature of 600°C; H – the meter readings “Звук – 202” (natural frequency kHz, GOST 25961-83); Z – grain size; V_p – infeed rate, mm/min; S – the peripheral speed of workpiece rotation, m/min; S_{pr} – the longitudinal speed with the impregnated diamond tool, mm/min; t_{pr} – the depth of dressing, mm.

The arc length contact L is calculated by the formula [28, 31]:

$$L=\sqrt{D_e\cdot h}\,, \qquad (6)$$

where $D_e=\frac{D_w}{1+\frac{D_w}{d_z}}$ - the effective grinding wheel diameter, mm; D_w – grinding wheel diameter, mm; d_z – workpiece diameter; h – grinding depth (lateral feed per workpiece revolution), mm.

The fraction of heat generated during grinding entering the workpiece is taken into account by the input coefficient β [23, 46]:

$$\beta=\frac{1}{1+h\sqrt{\frac{4\cdot V_z\cdot 10^3}{60\cdot L\cdot a\cdot \pi}}}\,, \qquad (7)$$

Period of applicability of the heat source τ_1, and the workpiece processing time τ_2 are calculated by (8):

$$\tau_1=\frac{L\cdot 60}{V_z\cdot 100}\,; \qquad \tau_2=\frac{\pi\cdot d_z\cdot 60}{V_z\cdot 100}\,. \qquad (8)$$

To calculate the number of revolutions in the phases of roughing and finishing grinding, it is necessary to use the following formulas for calculating the removed allowance for the workpiece radius [46]:

i. for grinding on rough feed S_{10}

$$\prod=\sum_{i=1}^{n_2}\left[S_{10}\left(1-K_{gr}^{i}\right)\right]; \qquad (9)$$

ii. for grinding in fine feed S_0

$$\prod{}_1=\sum_{i=1}^{n_1}\left[S_0\left(1-K_{gr}^{i}\right)+S_{10}\cdot K_{gr}^{i}\right]. \qquad (10)$$

In these formulas, n_1 and n_2 are the numbers of revolutions of the workpiece during the finishing and rough grinding phases, respectively.

The calculation of the maximum workpiece revolutions number necessary to remove the allowance **П** for the CPGC operation with the removal of the defective layer formed by grinding with rough feed S_{10} is as follows:

i – selectable S_{10};

ii – the depth of the defective layer H_d is calculated;

iii – from (10), find the selection n_1 so that the allowance **П**$_1$ removed at the final feed S_0 is equal to H_d;

iv – the allowance for the rough feed of the previous finishing feed will be equal to **П**–**П**$_1$ and n_2, which is necessary for its removal could be found using (9);

v – the total minimum number of revolutions $n=n_1+n_2$ and determines the optimum grinding operation.

4. RESULTS AND DISCUSSION

The study of the CPGC operation as applied to grind a cylindrical surface ∅100$f7$ $\begin{pmatrix}-0{,}036\\-0{,}071\end{pmatrix}$ along the axis B = *40* mm long was performed. In the research, the optimal two-stage CPGC with peripheral workpiece rotation speeds S = *35* m / min and feed S = *100* m / min are compared in terms of productivity.

The optimal CPGC is the cycle that providing the part heating no higher than T_{lim} = *490 °C* and the minimum number of workpiece rotations.

To calculate the force P_z according to formula (5), we assume that grinding is performed with a wheel 24A16HCM1K. Therefore, for the hardness of the circle CM1, the readings of the «Звук-202» device are H = 1.38.

Hardened steel 40X is grinded and therefore σ_B=22 kgf / mm2, the grain size of the selected wheel is z = 16. Dressing process: S_{pr}=150 mm/min, t_{pr} = 0.01 mm. The values of the coefficients are α_1=0, α_2=0,017; $\frac{J}{mm^2\cdot\sec\cdot\deg}$, which corresponds to the cooling of the workpiece by water-based irrigation liquid [26].

The heat transfer in the contact zone, taken into account by the coefficient α, is extremely small since the cooling fluid practically does not enter the contact zone and therefore α_1 can be taken equal to zero.

The values of a and λ for steel 40X are as follows [28]: a=6,7 mm^2/sec; λ=0,0339 $\frac{J}{mm\cdot\sec\cdot\deg}$. Thus, there is all the data for calculating $T(\tau, x)$, which means that for calculating the value of the defective layer of the workpiece, i.e. layer heated above 490 °C. Changing V_p in formula (4) and sorting out the value of x, we can find its value x_i such that the maximum value of $T(\tau,\ x_i)$ is equal to 490 °C (Fig. 1).

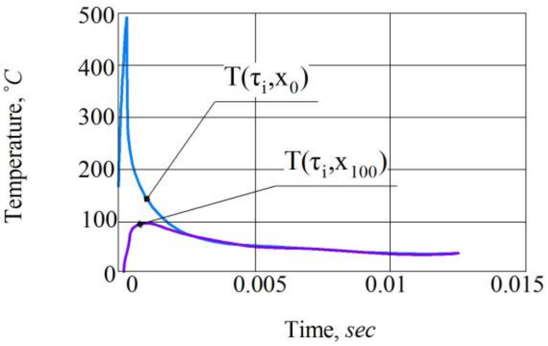


Fig. 1. Results of determination of x_i value, for which value of function $T(\tau, x)$ will be maximum ($T_{\max}$=490°C)

Figure 2*a* shows a fragment of the MathCAD program for determining the speed V_p, denoted as

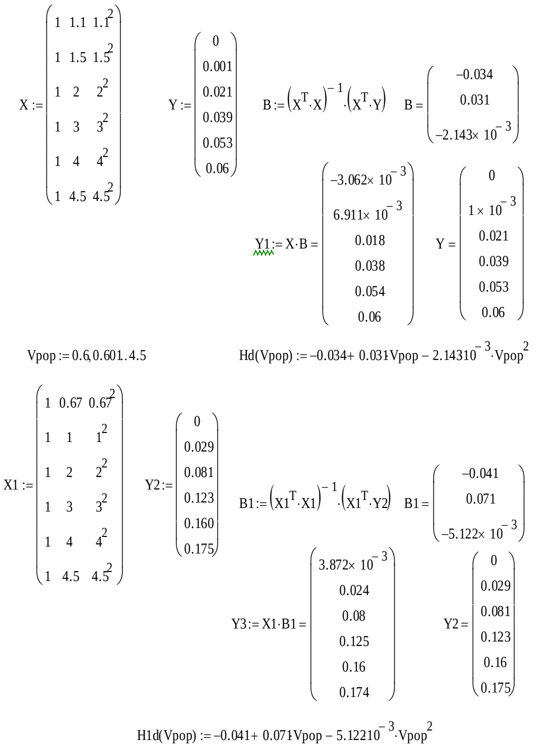
V_{pop}, that provides the maximum temperature on the surface $T_{max} = 490^o$ C.

So for $S = 100$ mm/min the vector of discrete values $V_p = (1.1,\ 1.5,\ 2,\ 3,\ 4,\ 4.5)^T$ have been received respectively the vector of the defective layer depth H_d, i.e., the layer heated above 490 °C, $H_p = (0,\ 0.001,\ 0.021,\ 0.039,\ 0.053,\ 0.06)^T$.

The dependence $H_d(V_p)$ is approximated by a polynomial of the 2^d degree, as is done when planning experiments and it is denoted as $H_d(V_{pop})$ on Fig. 2*a*.

The vector V_p is represented by the matrix **X** of the experimental conditions, and the vector H_p is represented by the vector H_d of the experimental results, and by the formula $\mathbf{B}=(\mathbf{X}^{\mathbf{T}}\cdot\mathbf{X})^{-1}\cdot(\mathbf{X}^{\mathbf{T}}\cdot\mathbf{Y})$, compute the coefficients of the polynomial of the second degree. The vector **Y** is compared with the vector **Y**1 – calculated by the model of H_p values. It can be seen from this comparison that the obtained model equation describes the $H_d(V_p)$ dependence well. The dependence $H_p(V_p)$ was obtained at $S = 35$ m/min and it is denoted as $H1_d(V_{pop})$ in the Fig. 2*a*. The resulting dependence is the polynomial $H_{1d}(V_p)$. The graphical comparison (Fig. 2*b)* of dependences $H_d(V_p)$ and $H_{1d}(V_p)$ shows that the depth of the defective layer at $S = 100$ m/min is significantly less than at $S = 35$ m/min when V_p varies in the range of its possible values on the 3M151 grinding machine.

Since in the formulas (9) and (10), the allowance is a function of S_0, S_{10}, it is necessary to have formulas for calculating the depth of the defective layer H_d as a function of the transverse feed per revolution.



$$X := \begin{pmatrix} 1 & 1.1 & 1.1^2 \\ 1 & 1.5 & 1.5^2 \\ 1 & 2 & 2^2 \\ 1 & 3 & 3^2 \\ 1 & 4 & 4^2 \\ 1 & 4.5 & 4.5^2 \end{pmatrix} \quad Y := \begin{pmatrix} 0 \\ 0.001 \\ 0.021 \\ 0.039 \\ 0.053 \\ 0.06 \end{pmatrix} \quad B := \left(X^T \cdot X\right)^{-1} \cdot \left(X^T \cdot Y\right) \quad B = \begin{pmatrix} -0.034 \\ 0.031 \\ -2.143\times 10^{-3} \end{pmatrix}$$

$$Y1 := X \cdot B = \begin{pmatrix} -3.062\times 10^{-3} \\ 6.911\times 10^{-3} \\ 0.018 \\ 0.038 \\ 0.054 \\ 0.06 \end{pmatrix} \quad Y = \begin{pmatrix} 0 \\ 1\times 10^{-3} \\ 0.021 \\ 0.039 \\ 0.053 \\ 0.06 \end{pmatrix}$$

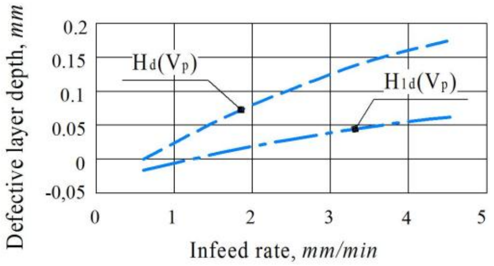
$$Vpop := 0.6, 0.601 .. 4.5 \qquad Hd(Vpop) := -0.034 + 0.031 \cdot Vpop - 2.143 10^{-3} \cdot Vpop^2$$

$$X1 := \begin{pmatrix} 1 & 0.67 & 0.67^2 \\ 1 & 1 & 1^2 \\ 1 & 2 & 2^2 \\ 1 & 3 & 3^2 \\ 1 & 4 & 4^2 \\ 1 & 4.5 & 4.5^2 \end{pmatrix} \quad Y2 := \begin{pmatrix} 0 \\ 0.029 \\ 0.081 \\ 0.123 \\ 0.160 \\ 0.175 \end{pmatrix} \quad B1 := \left(X1^T \cdot X1\right)^{-1} \cdot \left(X1^T \cdot Y2\right) \quad B1 = \begin{pmatrix} -0.041 \\ 0.071 \\ -5.122\times 10^{-3} \end{pmatrix}$$

$$Y3 := X1 \cdot B1 = \begin{pmatrix} 3.872\times 10^{-3} \\ 0.024 \\ 0.08 \\ 0.125 \\ 0.16 \\ 0.174 \end{pmatrix} \quad Y2 = \begin{pmatrix} 0 \\ 0.029 \\ 0.081 \\ 0.123 \\ 0.16 \\ 0.175 \end{pmatrix}$$

$$H1d(Vpop) := -0.041 + 0.071 \cdot Vpop - 5.122 10^{-3} \cdot Vpop^2$$

a

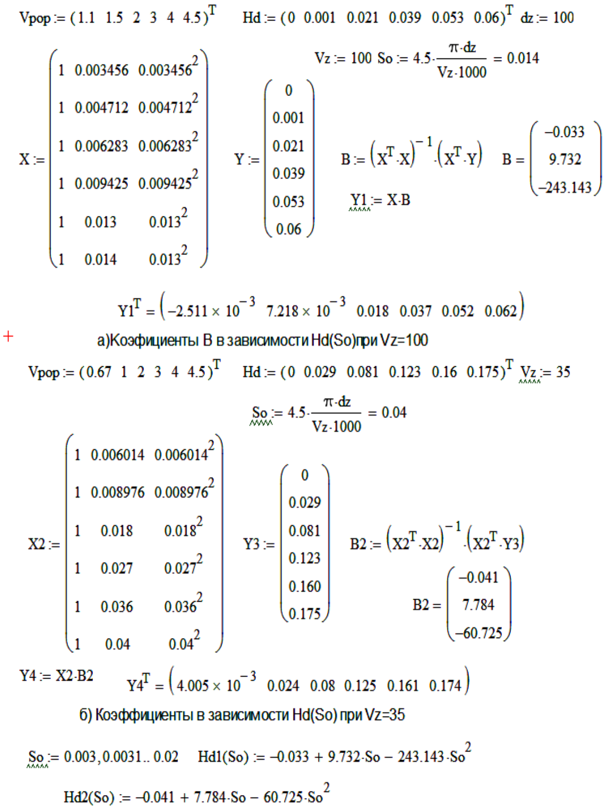


b

Fig. 2. Modelling of the dependence of the defective layer depth on indeed rate: *a* – the procedure for obtaining $H_d(V_p)$ and $H_{1d}(V_p)$ in MathCAD; *b* – the approximation of the dependences $H_d(V_p)$ and $H_{1d}(V_p)$ for *S*=35 m/min and *S*=100 m/min respectively

For this, the transition to V_{pop} vectors was made $S_0 = V_p \cdot \dfrac{\pi \cdot d_z}{V \cdot 100}$, and then, similarly to the $H_d(V_p)$ dependences, the $H_{d1}(S_0)$ dependences were obtained for $S = 100$ m/min and $H_{d2}(S_0)$ for $S = 35$ m/min. All necessary calculation results are shown in Fig. 3*a*.

It can be seen from Fig. 3,*b* that $H_{d1}(S_0)$ and $H_{d2}(S_0)$ there is minimal difference between each other, however, given that the workpiece revolution time at $S = 100$ m/min is almost three times less than the revolution time of it at $S = 35$ m/min, we should expect the performance of a two-stage plunge grinding cycle with optimal combinations of S_0 and S_{01} will be significantly higher at $S = 100$ m/min than at $S = 35$ m/min.



$$Vpop := (1.1\ \ 1.5\ \ 2\ \ 3\ \ 4\ \ 4.5)^T \quad Hd := (0\ \ 0.001\ \ 0.021\ \ 0.039\ \ 0.053\ \ 0.06)^T \quad dz := 100$$

$$Vz := 100 \quad So := 4.5 \cdot \frac{\pi \cdot dz}{Vz \cdot 1000} = 0.014$$

$$X := \begin{pmatrix} 1 & 0.003456 & 0.003456^2 \\ 1 & 0.004712 & 0.004712^2 \\ 1 & 0.006283 & 0.006283^2 \\ 1 & 0.009425 & 0.009425^2 \\ 1 & 0.013 & 0.013^2 \\ 1 & 0.014 & 0.013^2 \end{pmatrix} \quad Y := \begin{pmatrix} 0 \\ 0.001 \\ 0.021 \\ 0.039 \\ 0.053 \\ 0.06 \end{pmatrix} \quad B := \left(X^T \cdot X\right)^{-1} \cdot \left(X^T \cdot Y\right) \quad B = \begin{pmatrix} -0.033 \\ 9.732 \\ -243.143 \end{pmatrix}$$

$$Y1 := X \cdot B$$

$$Y1^T = \left(-2.511\times 10^{-3}\ \ 7.218\times 10^{-3}\ \ 0.018\ \ 0.037\ \ 0.052\ \ 0.062\right)$$

а)Коэфициенты В в зависимости Hd(So)при Vz=100

$$Vpop := (0.67\ \ 1\ \ 2\ \ 3\ \ 4\ \ 4.5)^T \quad Hd := (0\ \ 0.029\ \ 0.081\ \ 0.123\ \ 0.16\ \ 0.175)^T \quad Vz := 35$$

$$So := 4.5 \cdot \frac{\pi \cdot dz}{Vz \cdot 1000} = 0.04$$

$$X2 := \begin{pmatrix} 1 & 0.006014 & 0.006014^2 \\ 1 & 0.008976 & 0.008976^2 \\ 1 & 0.018 & 0.018^2 \\ 1 & 0.027 & 0.027^2 \\ 1 & 0.036 & 0.036^2 \\ 1 & 0.04 & 0.04^2 \end{pmatrix} \quad Y3 := \begin{pmatrix} 0 \\ 0.029 \\ 0.081 \\ 0.123 \\ 0.160 \\ 0.175 \end{pmatrix} \quad B2 := \left(X2^T \cdot X2\right)^{-1} \cdot \left(X2^T \cdot Y3\right) \quad B2 = \begin{pmatrix} -0.041 \\ 7.784 \\ -60.725 \end{pmatrix}$$

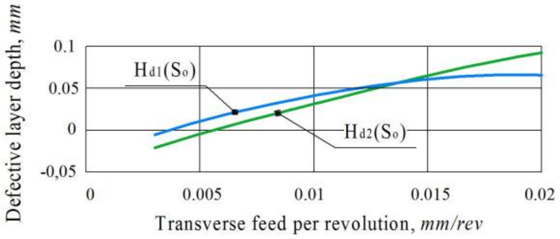
$$Y4 := X2 \cdot B2 \qquad Y4^T = \left(4.005\times 10^{-3}\ \ 0.024\ \ 0.08\ \ 0.125\ \ 0.161\ \ 0.174\right)$$

б) Коэффициенты в зависимости Hd(So) при Vz=35

$$So := 0.003, 0.0031 .. 0.02 \qquad Hd1(So) := -0.033 + 9.732 \cdot So - 243.143 \cdot So^2$$

$$Hd2(So) := -0.041 + 7.784 \cdot So - 60.725 \cdot So^2$$

a



b

Fig. 3. Modelling of the dependence of the defective layer depth on indeed rate: *a* – the procedure for obtaining $H_{d1}(S_o)$ and $H_{2d}(S_o)$ in MathCAD; *b* – the approximation of the dependences $H_{d1}(S_o)$ and $H_{2d}(S_o)$ for *S*=35 m/min and *S*=100 m/min respectively

Assuming that $P_y \cong 2{,}5P_z$ and going to (5) from V_p to h by the formula $V_p=\frac{h\cdot 1000\cdot S}{\pi\cdot d}$, the radial component of the grinding force

$$P_y=1{,}306\cdot 10^3\,\frac{\sigma_t^{0{,}342}\cdot H^{0{,}258}\cdot S^{0{,}872}\cdot B}{Z^{0{,}051}\cdot S_{\text{Pr}}^{0{,}073}\cdot t_{\text{Pr}}^{0{,}026}\cdot d^{0{,}945}}\cdot h^{0{,}945}.\quad(11)$$

Dependence (11) should be linearized concerning h, i.e. replace $h^{0{,}945}$ with $C\cdot h$, which is performed by the least-squares method in the range of variation of $h=(0{,}001-0{,}02)$ mm and $C=1{,}262$ obtained.

Besides, it should be noted that in the model of the CPGC dynamic on the 3M151 grinding machine [46], the grinding depth has a dimension of meters, the equation (11) is converted to:

$$P_y=1{,}306\cdot 10^3\,\frac{\sigma_t^{0{,}342}\cdot H^{0{,}258}\cdot S^{0{,}872}\cdot B}{Z^{0{,}051}\cdot S_{\text{Pr}}^{0{,}073}\cdot t_{\text{Pr}}^{0{,}026}\cdot d_z^{\;0{,}945}}\cdot 1{,}262\cdot 1000\cdot h$$

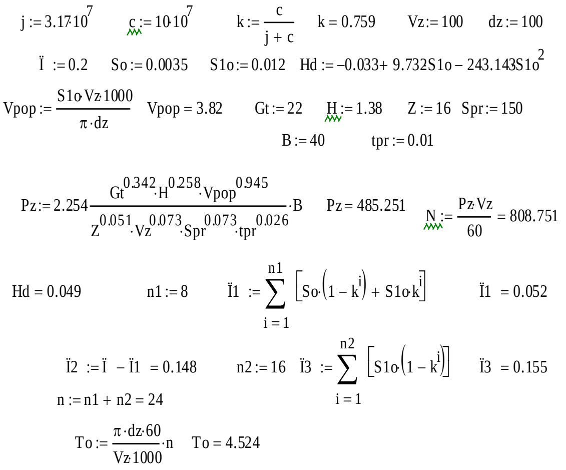
Consequently

$$C_P=1{,}642\cdot 10^6\,\frac{\sigma_t^{0{,}342}\cdot H^{0{,}258}\cdot S^{0{,}872}\cdot B}{Z^{0{,}051}\cdot S_{\text{Pr}}^{0{,}073}\cdot t_{\text{Pr}}^{0{,}026}\cdot d_z^{\;0{,}945}}\quad(12)$$

and for $S=100$ m/min and the other parameters of equation (11) adopted above, it was obtained that $C_p=9{,}999\cdot 10^7$ N/m, and for $S=35$ m/min – $C_p=4\cdot 10^7$ N/m.

The rigidity j necessary for calculating K_{gr} was obtained experimentally [46] and is equal to $3.17\cdot 10^7$ N/m. Consequently: K_{gr} = 0.759 for $S=100$ m/min and $K_{\text{ш}}$ = 0.557 for $S=35$ m/min.

In Fig. 4 shows the calculation n_1 and n_2 when S designated as $V_Z=100$ m/min. The allowance **П** according to its calculation and analytical definition [47] is 0.2 mm per radius. The final feed per revolution S_O is defined and equal to 0.0035 mm. The calculation formula is obtained (Fig. 3*a*) $H_d=-0.033+9.732\cdot S_{10}-43.143\cdot S_{10}^2$.



$j := 3.17\cdot 10^7$ $c := 10\cdot 10^7$ $k := \frac{c}{j+c}$ $k = 0.759$ $Vz := 100$ $dz := 100$

$Ï := 0.2$ $So := 0.0035$ $S1o := 0.012$ $Hd := -0.033 + 9.732\cdot S1o - 243.143\cdot S1o^2$

$Vpop := \frac{S1o\cdot Vz\cdot 1000}{\pi\cdot dz}$ $Vpop = 3.82$ $Gt := 22$ $H := 1.38$ $Z := 16$ $Spr := 150$

$B := 40$ $tpr := 0.01$

$Pz := 2.254\,\frac{Gt^{0.342}\cdot H^{0.258}\cdot Vpop^{0.945}}{Z^{0.051}\cdot Vz^{0.073}\cdot Spr^{0.073}\cdot tpr^{0.026}}\cdot B$ $Pz = 485.251$ $N := \frac{Pz\cdot Vz}{60} = 808.751$

$Hd = 0.049$ $n1 := 8$ $Ï1 := \sum_{i=1}^{n1}\left[So\cdot\left(1-k^i\right)+S1o\cdot k^i\right]$ $Ï1 = 0.052$

$Ï2 := Ï - Ï1 = 0.148$ $n2 := 16$ $Ï3 := \sum_{i=1}^{n2}\left[S1o\cdot\left(1-k^i\right)\right]$ $Ï3 = 0.155$

$n := n1 + n2 = 24$

$To := \frac{\pi\cdot dz\cdot 60}{Vz\cdot 1000}\cdot n$ $To = 4.524$

Fig. 4. The choice of the optimal value of the roughing feed S_{10} for the CPGC at $S=V_z$=100 m/min

In Fig. 4, the calculation is given for $S_{10}=0.012$ mm, which corresponds to the third step of selection S_{10} according to the Tab. 1.

Table 1. Selection of the optimal value S_{10} when $S=V_z$=100 m/min m/min

No step selection	S_{10}, mm	V_p, mm/min	H_d, mm	n_1	n_2	n	P_z, N	N, W
1	0.007	2.23	0.023	5	28	33	291	485
2	0.01	3.183	0.041	7	19	26	408	680
3	0.012	3.82	0.05	8	16	24	485	808
4	0.013	4.138	0.055	8	14	22	523	872

The optimal value S_{10} corresponds to the third step of its appointment. The fourth step $S_{10}=0.013$ provides higher productivity, but the power N consumed by the drive rotates the workpiece equal to 872 W more than the nominal, which is unacceptable.

Thus, setting $V_p=3.82$ mm/min, $S=100$ m/min when implementing a two-stage plunge grinding cycle with a restriction on heating the part no higher than 490° C, the main grinding time – $T_0=4.572$ s.

A similar search for optimal conditions for plunge grinding is performed for $S=V_z=35$ m/min and its results are summarized in the Tab. 2.

Table 2. Selection of the optimal value S_{10} when $S=V_z$=35 m/min

No step selec-tion	S_{10}, mm	V_p, mm/min	H_d, mm	n_1	n_2	n	P_z, N	N, W
1	0.01	1.114	0.031	5	18	24	163.5	95
2	0.015	1.671	0.062	9	11	20	239.8	139.9
3	0.02	2.228	0.09	12	7	19	314.8	183.6
4	0.025	2.785	0.116	16	5	21	388.7	226

From table 2 it is seen that the optimal grinding conditions with $S = V_z = 35$ m/min correspond to $S_{10} = 0.02$ mm/rev or $V_p = 2.228$ mm/min. Thus grinding with a high speed of the workpiece rotation $S = 100$ m/min compared to grinding with the recommended $S = 35$ m/min [48] provides a performance 2 times higher with the restriction on heating the part no more than 490° C.

The high speed of the workpiece rotation during CPGS not only provides an increase in processing productivity while limiting its maximum permissible heating temperature polished surface $T_{\max}$ but also a lower feed per revolution at this temperature (see the values in the first row of the second columns of the matrices X and X_2 in Fig. 3).

So at V_z=100 m/min $T_{\max}$ = 490^{o}C is provided at S_0=0.0035 mm, and at V_z=35 m/min the same temperature will be reached if S_0=0.006 mm.

It is known that it is precisely the reduction in feed per revolution (grinding depth), which is achieved, for example, in the sparking-out phase during CPGS, which ensures the smallest surface roughness.

Therefore, CPGS with a high speed of the workpiece rotation is preferable when compared with grinding at a lower speed of the workpiece rotation and for achieving a small surface roughness. CPGS with less feed per revolution also forms less out of roundness of the cylindric surface of the part.

In the preceding studies, the processing of a cylindric surface along an axis length of 40 mm was analyzed, while grinding wheels with a height of 80 mm were used on the 3M151 grinding machine. This limitation of the surface length in 40 millimeters is due to the rotation drive power for the workpiece revolution, the nominal value of which for a 3M151 grinding machine is 850 W. For grinding with a high speed of the workpiece revolution, for example, equal to 100 m/min, a surface length of 80 mm requires an increase in drive power by about two times.

CONCLUSIONS

Mathematical modelling for calculating the optimal cutting conditions during cylindrical plunge grinding with a view to minimizing the depth of the defective layer formed by the temperature in the contact zone of the grinding wheel and the workpiece was carried out. Modelling results show next:

1. The high speed of the workpiece rotation provides a smaller depth of the defective layer depending on the size of the cross-feed motion V_p.
2. The use of the plunge grinding cycle with a high peripheral speed of the workpiece rotation *S*, for example, equal to 100 m/min, allows reducing the main operation time by 2 times with defect-free processing, according to the temperature criteria.
3. All indicators of the machining quality using CPGS both physical and mechanical and geometric (roughness, out-of-roundness) are achieved at higher productivity if grinding is carried out at a high speed of the workpiece rotation.

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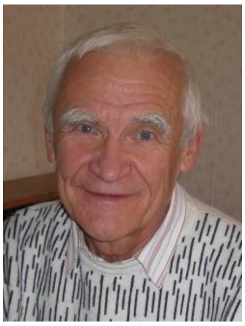

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