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# THERMAL PROCESSES RESEARCH DEVELOPMENT IN MACHINE-BUILDING TECHNOLOGY

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The technique for determining the temperature in the surface layer of the workpiece with a blade tool is considered, taking into account the volume heat source in the cutting zone, on the basis of which it is proposed to calculate the processing errors caused by the thermal action on the cutting tool and the workpiece being machined. When determining the thermal impact on the cutting edge of the tool, heat flows acting on the front and back surfaces are taken into account. When determining the thermal effect on the workpiece, the heat fluxes acting on deformation of the material when removing the chips and the back surface of the cutting tool are taken into account. The temperature in the cutting zone is determined by the summation of the temperature in the surface layer resulting from the plastic deformations of the material in the cutting zone, the friction of the chips against the front surface of the cutting tool and the friction of the back surface of the cutting tool against the treated surface. The peculiarity of the proposed method is that the physical and mechanical properties of the processed and tool materials (thermal diffusivity, ultimate thermal conductivity, specific volume heat capacity), processing regimes (cutting speed, feed and cutting depth), dimensions of the workpiece and cutting tool, geometry of the cutting tool (front and rear corners, radius at the top of the cutter in the plan, radius of rounding of the cutting tool, main and auxiliary corners in the plan). The calculations take into account the change in the intensity of volumetric heat fluxes in the cutting zone along their height.

***Key words***: cutting machining; heat fluxes in the cutting zone; temperature in the cutting zone; the sin of processing; cutting tool; workpiece

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**Introduction.** Considering the question of studying thermal phenomena in the cutting zone, it is necessary to turn to the works of outstanding scientists in the field of engineering technology, who studied the effect of thermal phenomena on the accuracy of processing and the quality of the surface layer of the parts. This is primarily the professor A.N.Reznikov, A.D.Makarov, S.S.Silin, N.V.Talantov, M.F.Poletika, V.V.Maksarov [2, 3, 10], as well as foreign authors [8, 9, 11, etc.]. The scheme of the action of thermal sources in the work of A.N.Reznikov (Fig.1) [5] is most detailed, but the calculation of their influence on the processing error has not been adequately studied.

In the cutting zone, the following heat fluxes act:

$$Q_d = Q_{pd} + Q_{bf} - Q_b,$$

$$Q_s = Q_{ds} + Q_{ff} - Q_f,$$

$$Q_p = Q_f + Q_b,$$

where $Q_{pd}$ is the part of the heat of deformation flowing into the product; $Q_{bf}$ is the part of heat generated as a result of friction between the product and the cutter; $Q_b$ is the part of heat generated as a result of heat exchange at the contact surface of the cutting surface with the back surface of the tool; $Q_{ds}$ is the part of the heat of deformation that flows into the shavings; $Q_f$ is the part of heat generated as a result of heat exchange at the

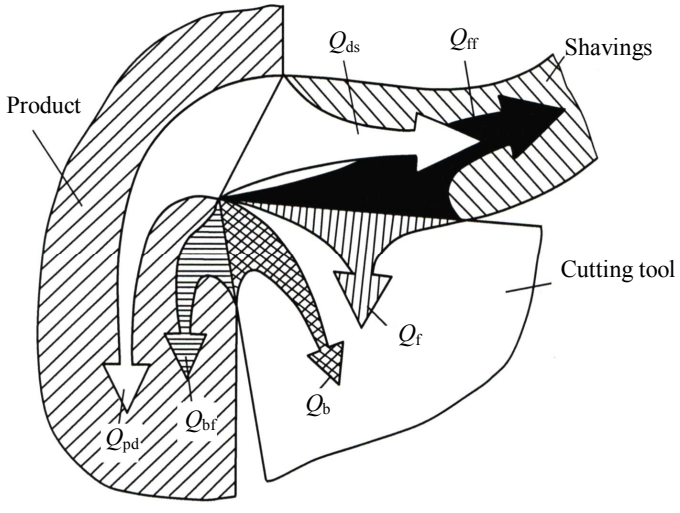



Fig.1. Amount of heat in the product $Q_d$, tool $Q_p$ and shavings $Q_s$

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contact surface of the tool's front surface with a chip; $Q_{ff}$ is the part of heat generated as a result of friction between the cutter and the shavings.

**Contents of the study.** Determination of the temperature in the surface layer from each volumetric heat source (Fig. 2) is related to the integration of the following expressions [1]:

$$\theta_1 = \frac{q_1 \exp(-p)}{2\sqrt{\pi\lambda c\rho v}} \int_{\Delta_1}^{\Delta_1+\Delta_2} \exp\left(p\frac{x_1}{x_2}\right) \frac{dx_1}{\sqrt{x-x_2}} \int_0^{a_1} \exp\left[-\frac{p\,\mathrm{ctg}\beta_1\, y_1}{\Delta_2} - \frac{v(y-y_1)^2}{4a(x-x_1)}\right] dy_1; \quad (1)$$

$$\theta_2 = \frac{q_2 \exp(-p)}{2\sqrt{\pi\lambda c\rho v}} \int_0^{\Delta_2} \exp\left(p\frac{x_2}{\Delta_2}\right) \frac{dx_1}{\sqrt{x-x_2}} \int_0^{h} \exp\left[-v\frac{(y-y_1)^2}{4a(x-x_2)}\right] dy_2; \quad (2)$$

$$\theta_3 = \frac{q_3 \exp(1+\frac{\Delta_2}{\Delta})}{2\sqrt{\pi\lambda c\rho v}} \int_{\Delta_2}^{\Delta_2+\Delta} \frac{dx_3}{\sqrt{x-x_2}} \int_0^{h_1} \exp\left[-\frac{v(y-y_3)^2}{4a(x-x_3)}\right] dy_3 - \frac{q_3 \exp\frac{1}{\Delta}}{2\sqrt{\pi\lambda c\rho v}} \int_{\Delta_2}^{\Delta_2+\Delta} \frac{x_3 dx_3}{\sqrt{x-x_3}} \int_0^{h_1} \exp\left[-\frac{v(y-y_3)^2}{4a(x-x_3)}\right] dy_3, \quad (3)$$

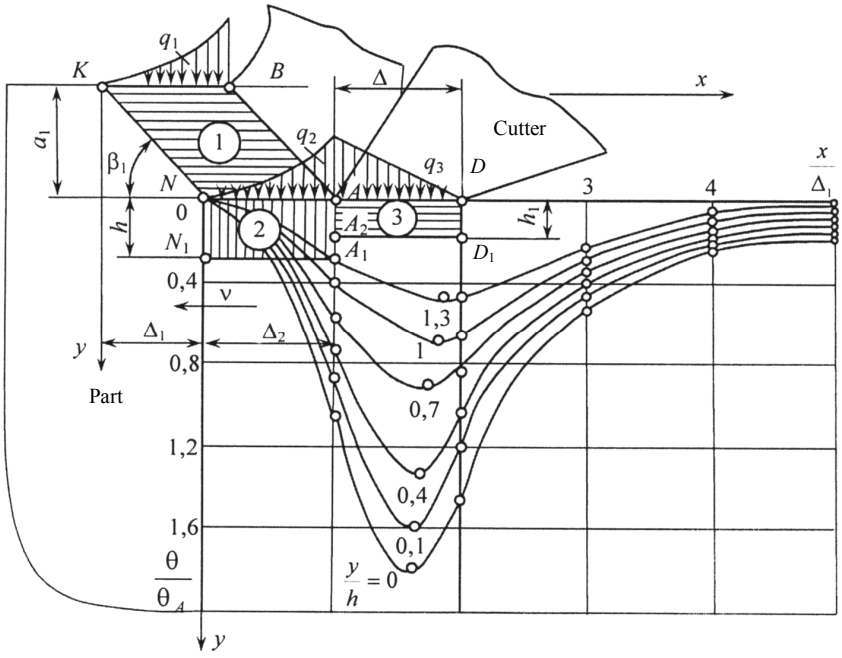



Fig.2. Scheme of volume heat sinks and temperature distribution action in the surface layer of the part during processing

where $\theta_1$, $\theta_2$, $\theta_3$ – temperature in the surface layer from the first, second and third heat sources, respectively; $v$ – cutting speed, m/s; $\lambda$ – thermal conductivity of the material of the workpiece, W/(m·K); $c\rho$ – specific volume heat capacity of the processed material, J/(m$^3$·K); $a$ – thermal diffusivity of the material of the processed workpiece, m$^2$/s; $a_1$ – hickness of the cut, m; $h$ – the size of the heat source $ANN_1A_1A$ along the $y$ axis, m; $h_1$ – he size of the heat source $DAA_2D_1D$ along the $y$ axis, m; $p = 5$ – constant, characterizing the distribution of heat dissipation; $\beta_1$ – slope angle of the conventional shear plane; $x_1$ and $y_1$ – coordinates of the linear source, m.

Studies by professors M.F.Poletika [4] and N.V.Talantov [7] allowed A.N.Reznikov and S.S.Silin to work out design schemes for heat fluxes in the product, tool and shavings [5, 6], and also determine the intensity of their heat release (Fig.2).

The intensity of heat release when cutting materials in the conditional tip of the cutting tool (point $A$ in Fig.2) is determined by the formula

$$q_A = \tau_p v \cos\beta_1,$$

where $q_A$ – is the heat dissipation rate at the conventional vertex of the tool (point $A$), J/(m·s); $\tau_p$ – treating material plastic slip resistance, Pa; $\beta_1$ – the slope angle of the conventional shear plane.

The heat release for the first, second and third heat sources (Fig.2) will be determined by the formulas:

$$q_1 = \frac{q_{AB} a_1 \frac{1}{\sin\beta_1}}{\int_0^{\Delta_2}\int_0^{h} \exp\left[-p\left(1-\frac{x_1 - y_1\,\mathrm{ctg}\beta_1}{\Delta_2}\right)\right] dy_1 dx_1};$$

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$$q_2 = \frac{q_{AB} a_1 \frac{1}{\sin\beta_1}}{\int_0^{\Delta_2}\int_0^{h} \exp\left[-p\left(1-\frac{x}{\Delta_2}\right)\right]\exp\left[-p\frac{y}{h}\right]dy_2 dx_2};$$

$$q_3 = \frac{p}{1-\exp(-p)}\frac{\tau_p v}{h_1}.$$

Based on the calculations using formulas (1)-(3) and processing of calculation results, a simplified formula was obtained for determining the temperature in the surface layer of the component [1]:

$$\left(\frac{\theta_m}{\theta_A}\right)_{ОБ} = R(БВ)^{m-n_y}\left(\frac{h}{a_1}\right)^n\left(\frac{h_1}{h}\right)^K\left(\frac{\Delta}{\Delta_1}\right)^P\left(\frac{y}{h}\right)^{m_y}\left(\frac{\Delta_1}{\Delta_2}\right)^U,$$

where $\theta_m$ – the temperature in the surface layer of the part at a certain depth from the surface, °C; $\theta_A$ – temperature in the conditional vertex of the cutting part of the tool (point A), °C; $y$ – the depth of the layer under consideration from the surface, m; $\rho_1$ – rounding radius of the cutting edge of the tool, m; $Б = va_i/a$; $h = a_1\left(\sqrt{\frac{1}{B^2}-1}-1\right)$ – the height of the volumetric heat source in the zone of the main plastic deformations (source 2), m; $h_1 = \Delta/\sqrt{2}$ – height of the volumetric heat source in the contact zone of the cutting tool with the treated surface (source 3), m; $\Delta = \arccos\left[1-a_2 B^{-b_2(1-\sin\gamma)^{-x}}\right] + \frac{a_2 B^{1-b_2(1-\sin\gamma)^{-x}}}{\sin\alpha(\cos\gamma + B\sin\gamma)}$ – length of heat source 3, м; $\gamma$ – cutting angle of the cutting tool, degree; $\Delta_1 = a_1/B$ – projection of the shear plane on the direction of displacement of the cutting tool, m; $B = 1/\mathrm{tg}\beta_1$; $\Delta_2 = a_1/B\sqrt{2(1+B^2)}+1$ – length of heat source 2, m; $R$, $m$, $n_y$, $k$, $p$, $m_y$, $u$, $a_2$, $x_2$, $b_2$ – epend on the properties of the processed and tool material (Tables 1, 2).

The cutting temperature at the conventional tip of the tool (point $A$, Fig. 2) is determined by the formula [6]

$$\theta_A = \frac{\tau_p}{c\rho B} erf\sqrt{\frac{БВ}{4}}.$$

Calculation can be used to determine the cutting speed during blade cutting and the optimum cutting speed corresponding to the optimum cutting temperature, at which the minimum wear of the cutting tool is observed. The latter phenomenon was discovered and substantiated by professor A.D.Makarov.

The optimum cutting speed is determined by the formula [6]

$$v_0 = \frac{k^2\lambda c\rho \sin^{0.2}\alpha\,\theta_0^2/\tau_\rho^2}{4a_1 c_0^2(\rho_1/a_1)^{2(n_0-0.1)}(1-0.45\sin\gamma)(b/b_1)^{0.8}}\times$$

$$\times\left[1+\sqrt{1+\frac{2.65\lambda_p\beta\varepsilon(a_1/b_1)^{0.3}c_0(\rho_1/a_1)^{2(n_0-0.1)}(1-0{,}45\sin\gamma)(b/b_1)^{0.8}\tau_\rho}{k^2\lambda c\rho\sin^{0.2}\alpha\theta_0}}\right]^2,$$

where $b$ – contact length of the cutting edge of the tool with the material being processed, m; $c_0$ and $k$ – quantities that depend on combinations of technological processing conditions; $\theta_0$ – optimum cutting temperature, °C.

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*Table 1*

**Values of coefficient and exponents**

| Quantities designhation | Change intervals $y/h$, $h_1/h$, $БВ$, $h/h_1$ и $\Delta/\Delta_1$ | | Quantities values | |
|---|---|---|---|---|
| $R$ | $\frac{y}{h}=0$ | $3.3\left(\frac{h_1}{h}\right)^{0.123}\left(\frac{h}{a_1}\right)^{x}\left(\frac{\Delta}{\Delta_1}\right)^{0.466}$ | $\frac{h}{a_1}\le 0.6$ | $\frac{h}{a_1}>0.6$ |
| | | | $x=0.07$ | $x=0.625$ |
| | | $БВ\le 30$ | $БВ>30$ | |
| | $0<\frac{y}{h}\le 3$ | $1.3(БВ)^{-0,259}$ | $3.2(БВ)^{-0.543}$ | |
| | $3<\frac{y}{h}\le 6$ | $0.78(БВ)^{-0.176}$ | $13.5(БВ)^{-1}$ | |
| | $6<\frac{y}{h}\le 9$ | $0.27$ | $70(БВ)^{-0.664}$ | |
| | $\frac{y}{h}>9$ | $БВ\le 20$ | $БВ>20$ | |
| | | $7(БВ)^{-1.072}$ | $0.62(БВ)^{-0.268}$ | |
| $m$ | $\frac{h_1}{h}\le 1$ | $0.195\left(\frac{\Delta}{\Delta_1}\right)^{0.7}$ | | |
| | $\frac{h_1}{h}>0.1$ | $\frac{h}{a_1}\le 0.8$ | $0.22\left(\frac{h}{a_1}\right)^{-0.306}$ | |
| | | $\frac{h}{a_1}>0.8$ | $0.2\left(\frac{h}{a_1}\right)^{-0.675}$ | |
| $n$ | $\frac{h_1}{h}\le 0.1$ | $\Delta/\Delta_1\le 0.5$ | $h/a_1\le 1$ | 0 |
| | | | $h/a_1>1$ | $0.0036(БВ)^{1.303}$ |
| | | $\Delta/\Delta_1>0.5$ | $h/a_1\le 8$ | $БВ\le 30$: $0.38(БВ)^{-0.73}$; $БВ>30$: 0 |
| | | | $h/a_1>8$ | $-0.036(БВ)$ |
| | $0.1<\frac{h_1}{h}\le 0.7$ | $h/a_1\le 0.5$ | $БВ\le 30$ | $БВ>30$ |
| | | | 0 | $-0.14$ |
| | | $h/a_1>0.5$ | $-0.025(БВ)^{0.74}$ | $-0.344$ |
| | $h/h>0.7$ | $-0.174$ | | $-0.0057(БВ)$ |
| $k$ | $БВ\le 5$ | $-0.052$ | | |
| | $5<БВ\le 30$ | $0.115(БВ)^{0.23}(h/a_1)^{0.15(БВ)^{0.364}}$ | | |
| | $БВ>30$ | $-0.2(h/a_1)^{0.8}$ | | |
| $p$ | $БВ\le 30$ | $0.07(БВ)^{0.48}$ | | |
| | $БВ>30$ | $0.36$ | | |
| $u$ | $\Delta_1/\Delta_2\le 0.5$ | $h_1/h<0.1$ | $1.24(БВ)^{-0.16}\left(\frac{h_1}{h}\frac{\Delta}{\Delta_1}\right)^{0.23}$ | |
| | | $h_1/h\ge 0.1$ | $(h/h_1)^{0.194}(h/a_1)^{0.3}$ | |
| | $\Delta_1/\Delta_2>0.5$ | $2.4(БВ)^{-0.158}\left(\frac{h_1}{h}\frac{\Delta}{\Delta_1}\right)^{0.061}$ | | |
| $n_y$ | $y/h=0$ | 0 | | |
| | $0<y/h\le 3$ | 0.22 | | |
| | $y/h>3$ | 1 | | |
| $m_y$ | $y/h=0$ | 0 | | |
| | $0<y/h\le 3$ | $-0.23$ | | |
| | $y/h>3$ | $-0.57(БВ)^{0,37}$ | | |

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It is established that at the optimum cutting temperature, not only the minimum wear of the cutting tool is provided, but also the most favorable quality parameters of the surface layer [1].

The results of the investigations made it possible, with a higher degree of accuracy, to perform calculations of processing errors due to the thermal action on the cutting tool and the workpiece being machined.

*Table 2*

**Coefficients values $a_2$, $x$ и $b_2$**

| Coefficient | $B \le 0.5$ | $0{,}5 < B \le 0.9$ | $B > 0.9$ |
|---|---|---|---|
| $a_2$ | 0.557 | 0.44 | 0.294 |
| $x$ | 0.75 | 0.53 | 0.445 |
| $b_2$ | 0.078 | 0.45 | 3.4 |

The accuracy of the part caused by the heating of the cutting tool during processing is determined by the formula

$$\Delta L_{\text{p}} = \frac{\beta_{\text{ст}}\theta_{\text{p}}}{2K}\left\{\left(1+2\sqrt{\frac{\alpha_1\alpha_{cm}\tau}{\pi\lambda_{cm}h}}\right)\sqrt{\frac{\lambda_{cm}h}{a_1}}\left[1-\exp\left(-L_{\text{p}}\sqrt{\frac{\alpha_1}{\lambda_{cm}h}}\right)\right]-\right.$$

$$-\frac{1}{\sqrt{\pi a_{cm}\tau}}\left[-\frac{\lambda_{cm}h}{\alpha_1}\exp\left(-L_{\text{p}}\sqrt{\frac{\alpha_1}{\lambda_{cm}h}}\right)\left(L_{\text{p}}\sqrt{\frac{\alpha_1}{\lambda_{cm}h}}+1\right)+\frac{\lambda_{cm}h}{\alpha_1}\right]-$$

$$-\left(1-2\sqrt{\frac{\alpha_1\alpha_{cm}\tau}{\pi\lambda_{cm}h}}\right)\sqrt{\frac{\lambda_{cm}h}{\alpha_1}}\left[1-\exp\left(-L_{\text{p}}\sqrt{\frac{\alpha_1}{\lambda_{cm}h}}\right)\right]-\frac{1}{\sqrt{\pi\lambda_{cm}h}}\times$$

$$\left.\times\left[-\frac{\lambda_{cm}h}{\alpha_1}\exp\left(L_{\text{p}}\sqrt{\frac{\alpha_1}{\lambda_{cm}h}}\right)\left(L_{\text{p}}\sqrt{\frac{\alpha_1}{\lambda_{cm}h}}-1\right)+\frac{\lambda_{cm}h}{\alpha_1}\right]\right\},$$

where $\beta_{\text{p}}$ – coefficient of temperature linear expansion of the tool holder material,1/°C; $L_{\text{p}}$ – the length of the cutter outset, m; $\theta_{\text{p}}$ – temperature in the cutting zone, °C; $K = \pi^2/2\beta\varepsilon$ – a value that takes into account the geometry of the tool with lack of free cutting; $\alpha_1$ – coefficient of heat transfer of the material of the tool holder into the environment, J/(m$^2$·s·°C); $a_{cm}$ и $\lambda_{cm}$ – coefficients of thermal diffusivity and thermal conductivity of the tool holder material, m/s$^2$, W/(m·K); $h$ – the ratio of the cross-section of the tool holder to its perimeter, m; $\tau$ – cutter working time, s; $\beta$ и $\varepsilon$ – angle of sharpening and angle at the top of the cutting part of the tool in plan, rad.

Value $\theta_{\text{p}}$ is determined by the formula [2]

$$\theta_{\text{p}} = \frac{2\theta_N\sqrt{a_{cm}\tau}}{H\left[-E_i\left(-\frac{\Delta^2}{16a_{cm}\tau}\right)\right]}\left\{\frac{H}{2\sqrt{a_{cm}\tau}}\left[-E_i\left(-\frac{H^2}{4\sqrt{a_{cm}\tau}}\right)\right]-\frac{\Delta}{4\sqrt{a_{cm}\tau}}\left[-E_i\left(-\frac{\Delta^2}{16a_{cm}\tau}\right)\right]+\right.$$

$$\left.+2\pi\left(erf\frac{H}{2\sqrt{a_{cm}\tau}}-erf\frac{\Delta}{4\sqrt{a_{cm}\tau}}\right)\right\},$$

where $H$ – the height of the tool holder; $E_i$ – an integral exponential function of Euler; $erf$ – the probability integral; $\theta_N$ – maximum temperature on the back surface of the tool, determined by the formula of S.S.Silin [6].

The temperature in the middle of the contact area of the cutting tool with the workpiece being machined is determined by the formula [5]

$$\theta_N = \theta_A\left(0.5+\frac{0.36\sin^{0.25}\alpha}{B^{1.25}\sqrt{БЕ}}+\frac{0.465B^{1.275}Б^{0.625}E^{0.55}\cos\alpha}{Г^{0.25}Д^{0.075}\sin^{0.275}\alpha erf\sqrt{\frac{БВ}{4}}}\right),$$

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where $E = \rho_1/a_1$ – dimensionless complex characterizing the effect on the process of processing of the geometric shape of the cutting edge of the tool; $Д = a_1/b_1$ – dimensionless complex characterizing the geometry of the cutter cross-section; $Г = (\lambda_р/\lambda_д)\beta\varepsilon$ – a dimensionless complex of the cutting process, which characterizes the effect of the geometry of the cutting part of the tool and the ratio of the thermal conductivity of the processed and tool $\lambda_р$ materials; β and ε – the angle of sharpening of the cutting edge of the tool and the angle at the top of the tool in the plan, radians.

The error in processing, due to the temperature of the workpiece being deformed, is determined by the formula:

$$\Delta R = \frac{C\beta_д\theta_{max}\,\mathrm{Fo}^m}{0.5R_н + 1}\left(\frac{l}{S_м}\right)^n\left(R_н - \left(\frac{R_в}{R_н}\right)^{0,5R_н} R_в\right),$$

where $\beta_д$ ($\beta_t$) – coefficient of temperature linear expansion of the material of the workpiece, 1/°C; $R_н$ и $R_в$ – external and internal radii of the surfaces to be treated, m; $S_м$ – feed of the cutting tool per minute, m; $l$ – is the length of the heat source moving along the surface being treated, m; $\mathrm{Fo} = a\tau/R_н$ – the Fourier criterion; τ – heating time, °C; $C$, $m$ и $n$ – quantities that depend on the values of the minute feed of the cutting tool and the Fourier criterion [1].

**Conclusion.** The calculated dependencies for determining the temperature in the cutting zone and the processing errors due to the thermal effect on the workpiece and cutting tool allow us to predict their value during the technological preparation of production on the basis of the assignment of cutting regimes and selection of the mark of the cutting part of the tool and its geometric parameters.

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