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# Cutting Characteristics in the End Milling of Stainless Steel

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**Abstract**—A method is proposed for calculating the cutting characteristics in the end milling of stainless steel workpieces. The calculation is based on analysis of the parameters for the chip-formation zone and takes account of softening of the material under the action of the cutting temperature. The calculated tool life and the torque are approximated by polynomial equations, which may be used to calculate the constraints on milling and to optimize the machining conditions.

*Keywords:* stainless steel, milling, end mills, hard alloys, torque, tool wear, tool life, polynomial equations
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Stainless steel components are widely used in the aerospace industry and in manufacturing. Accordingly, it is important to increase the productivity and efficiency in machining such components. One approach is to use well-designed mills made of up-to-date materials in numerically controlled multicoordinate machine tools, in optimal conditions.

In the design of milling operations, we calculate the cutting conditions and the technological constraints on the power, the torque, and the tool life. For such calculations, we determine quantitative relations between the cutting characteristics and the controllable parameters. For example, for a long time, researchers focused on the calculation of the milling forces. Thus, the Weck–Teipel model of the cutting forces (1977) was noted in the review [1]. In this model, the cutting force takes the form $F = Ka_ph$, where $a_p$ is the axial cutting depth; $h$ is the thickness of the cut layer. The constant $K$ depends on the machined material and the cutting speed, and is determined experimentally. This approach was developed by Altintas, who proposed the equation $F = Ka_ph + K_ea_p$, where $K_e$ is a constant. Thus, when $h = 0$, the second term takes account of the influence of the cutting edge [2].

Tobias and Stepan proposed a nonlinear dependence of the force on the cut-layer thickness [1]: $F = Ka_ph^x$, where $x$ is an empirical parameter.

Faassen used models for the tangential and radial components of the cutting force [3]

$$\left.\begin{aligned} F_t &= K_ta_ph^x + K_{te}a_p; \\ F_r &= K_ra_ph^x + K_{re}a_p, \end{aligned}\right\} \quad (1)$$

where $K_t$, $K_{te}$, $K_r$, $K_{re}$, and the exponent $x$ are determined experimentally.

A development of this approach is the calculation of the cutting forces on the basis of the unit force, as outlined in detail in the handbook [4]; this method is widely employed by non-Russian tool manufacturers. In this approach, for any cutting process such as milling, the tangential component of the cutting force is determined as follows

$$F_c = bhK_cK_f = bh^{(1-m)}k_{c11}K_f, \quad (2)$$

where $b$ and $h$ are the width and thickness of the cut layer; $K_c$ is the unit cutting force; $K_f$ is a correction factor; $k_{c11}$ is the unit force per unit area of the cut; and $m$ is an exponent.

For numerous materials, values of $K_c$ and $m$ may be found in [4].

In the Russian literature, power laws are used to calculate the tangential force $P_z$ and cutting speed $v$ in milling

$$\left.\begin{aligned} P_z &= \frac{C_pt^xS_z^yB^uz^pK_p}{d^qn^w}; \\ v &= \frac{C_vd^{q_v}K_v}{T^{m_v}t^{x_v}S_z^{y_v}B^{u_v}z^{p_v}}. \end{aligned}\right\} \quad (3)$$

Here $C_p$ and $C_v$ are constants; $K_p$ and $K_v$ are correction factors; $T$ is the tool life; $t$ is the cutting depth; $S_z$ is the supply per tooth; $B$ is the milling width; $z$ is the number of mill teeth; $d$ is the mill diameter; and $n$ is the spindle speed. In general, the exponents are fractions.

A deficiency of Eqs. (1)–(3) is that they represent experimental results for specific machining conditions. Changes in the machining conditions are taken into account by means of correction factors. Mathematically, this implies the proportionality of nonlinear equations; considerable errors may result.

In addition, in order to obtain Eq. (3), numerous very laborious monofactorial or multifactorial experiments must be conducted, and the influence of six variables must be taken into account. On account of the considerable experimental difficulties, literature sources lack equations similar to Eq. (3)—in particular, equations for the cutting characteristics in the machining of current structural materials by hard-alloy mills.

A literature review indicates the need to develop analytical methods of calculating the cutting forces, temperature, wear, tool life, and other characteristics. In the present work, we outline a method by which the basic cutting characteristics may be calculated, without additional experiments, for the milling of stainless steel components. An approximate method is proposed for the derivation of polynomial equations with high precision on the basis of the calculation results obtained.

## CALCULATION OF THE CUTTING CHARACTERISTICS

The methods developed for calculating the cutting parameters have been outlined in a number of papers. For example, for the turning of structural steel by composite cutters and for the superprecise machining of nonferrous metal and alloy surfaces by diamond cutters, methods were presented in [5, 6]. On that basis, cutting characteristics have been developed for a one-piece hard-alloy end mill in the machining of slots and channels in aluminum-alloy workpieces [7, 8]. In the present work, the basic principles of those methods are analyzed and extended to the machining of stainless steel components by a hard-alloy end mill.

In the calculation of the cutting characteristics by the proposed method, it is possible to take account of the mechanical characteristics of the tool and workpiece and their softening under the action of the cutting temperature. An innovation is that the wear rate of the rear tooth surface is first calculated and then its wear and life are determined.

The calculation of the cut thickness and cutting forces in end milling was considered in detail in [7, 8]. In Fig. 1, we show the cutting edge of the mill teeth in simplified form. It consists of three section: the helical edge *1–2*, with inclination $\omega_0$ to the mill axis at the cylindrical section; the radial edge *2–3* with radius $r$; and the end section *3–4*, at the auxiliary plane angle $\varphi_1$. The radial edge *2–3* is divided into several portions, each of which is at a radius $R_i$ relative to the mill axis. With horizontal supply, the end section has no influence on the cutting forces. In kinematic terms, milling consists of mill rotation at speed $n$ and the auxiliary supply motion $D_s$ (Fig. 1).

In the coordinate system $XYZ$, with its origin at point *2*, the $X$ axis runs along the mill axis (not shown in Fig. 1); the $Y$ axis runs along the radius; and the $Z$ axis is aligned with the cutting speed.

At the helical edge *1–2* and for each portion of the radial edge *2–3*, we determine the resultant chip-forming forces $R_c$ and $R_{ci}$ on the basis of the tangential force in the shear plane. Thus, for helical edge *1–2*, the chip-forming force is inclined at an angle $\omega$ to the cutting speed and is

$$R_c = \frac{\tau_p ab}{\sin\beta\cos(\beta+\omega)}, \tag{4}$$

where $\tau_p$ is the tangential stress in the shear plane; $\beta$ is the mean shear angle; $a$ and $b$ are the cut-layer thickness and width.

We employ the following results for 12X18H10T stainless steel.

1. The relation between the tangential stress and the strength: $\tau_p = 0.9\sigma_B$ (MPa).

2. The relation between the hardness and the strength: $HB = \sigma_B/0.345$.

3. The softening under the action of the temperature $T_d$ in the shear plane: $\sigma_B = 657 - 0.41T_d$.

4. The decrease in the elastic modulus under the action of the temperature in the shear plane: $E = 200 - 0.077T_d$ (GPa).

The chip-forming force has tangential and radial components (not shown in Fig. 1):

$$R_{cz} = R_c\sin\omega;\ R_{cy} = R_c\cos\omega.$$

The tangential and normal components of the force at the tool's front surface are also determined from geometric considerations

$$F_1 = R_c\sin(\omega+\psi);\ P_n = R_c\cos(\omega+\psi),$$

where $\gamma$ is the tool's mean rake angle. The contact length of the chip with the front surface is assumed to be $l_1 = 2a/\sin\beta$.

The maximum contact pressure at the cutting edge may be expressed in terms of the normal force at the front surface and the contact area, as follows

$$\sigma_{max} = \frac{P_n(n_1+1)}{l_1 b}. \tag{5}$$

Here $n_1$ is the exponent in the contact-pressure formula $\sigma_p = \sigma_{max} = (1-m)^{n_1}$, where $m$ is the relative distance from the cutting edge to the contact point along the tool's front surface; $l_1$ is the contact length of the chip. We assume that $n_1 = 1$. In other words, we assume a triangular distribution of the normal contact pressure at the front surface. On the basis of the calculated values of the normal pressure, we determine the resultant force $P_m$ at the edge (rounding radius $\rho$) and

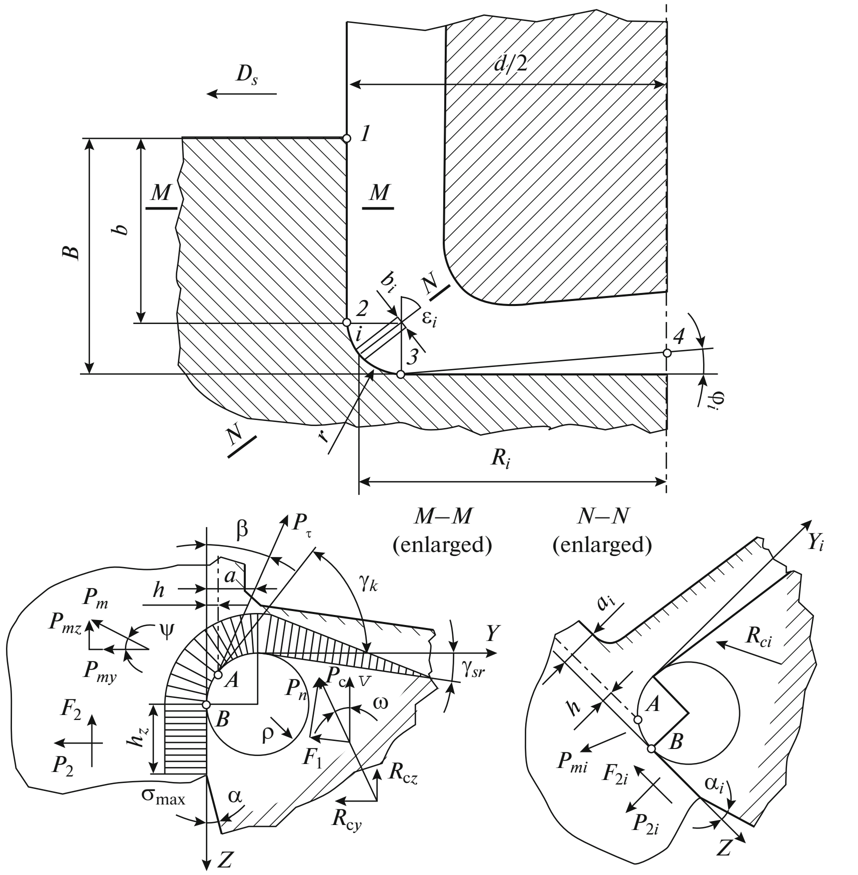


**Fig. 1.** Calculating the cutting forces in milling.

the normal force $P_2$ and tangential force $F_2$ at the tool's rear surface

$$\left.\begin{aligned} P_m &= \sigma_{\max} ABb; \\ P_2 &= \sigma_{\max} h_z b; \\ F_2 &= P_2 f_{\text{tr}}. \end{aligned}\right\} \tag{6}$$

Here $f_{\text{tr}}$ is the frictional coefficient; $AB$ is the arc length over the edge; $b$ is the cut-layer width; $h_z$ is the wear.

The frictional coefficient at the rear surface is assumed equal to the molecular component: $f_{\text{tr}} = \tau_0/HB + \beta_0$. (The approximation of $\tau_0$ and $\beta_0$ as a function of the temperature is outlined in [6].) The total contact length at the rear surface is $l_2 = AB + h_z$.

The primary (tangential) component of the cutting force is determined by summation over the corresponding directions of the forces at the front surface, the rounding arc at the edge, and the rear surface

$$P_{z1-2} = R_{\text{cz}} + P_{mz} + F_2. \tag{7}$$

Analogously, Eqs. (4)–(7) are used to calculate the primary component of the cutting force over the sections at the radial edge *2–3*.

Then, we may calculate the total torque on the mill tooth

$$M = \frac{P_{z1-2} d}{2000} + \sum_{i=1}^{k} \frac{P_{zi} R_i}{1000}, \tag{8}$$

where $d$ is the mill diameter; $R_i$ is the radius of the section at radial edge *2–3*; $P_{z1-2}$ is the tangential component of the force at helical edge *1–2*; $P_{zi}$ is the tangential component of the force at edge *2–3*; $k$ is the number of sections at edge *2–3*.

If there are several teeth at the contact arc, the corresponding forces must be included in the sum in Eq. (8).

The thermophysical cutting parameters are calculated by the method in [9]. At each cutting edge of the mill tooth, the following quantities are determined: the intensities $q_d$, $q_{1t}$, and $q_{2t}$ of the heat fluxes to the shear plane and at the front ($T_1$) and rear surfaces, respectively, and the temperature in the shear plane ($T_d$) and at the front ($T_1$) and rear ($T_2$) surfaces and the mean cutting temperature

$$T_{\text{cu}} = \frac{T_1 l_1 + T_2 l_2}{l_1 + l_2} + \Delta T,$$

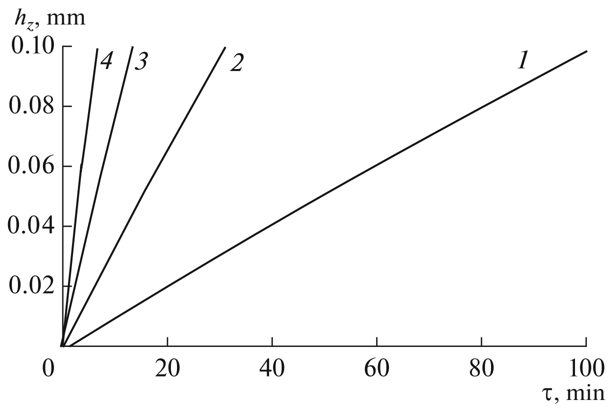


**Fig. 2.** Dependence of the wear $h_z$ at the rear surface of the mill tooth on the time $\tau$ when the spindle speed $n$ = 1000 (*1*), 1500 (*2*), 2000 (*3*), and 2500 rpm (*4*).

where $\Delta T$ is the correction for the action of the heat source of the preceding mill tooth at the contact arc.

Note that the cutting temperature stabilizes within ten contact cycles of the mill tooth and the workpieces—in other words, practically instantaneously.

By analogy with the wear model adopted by Pronikov, in which the basic factors are the contact pressure, the frictional speed, and the hardness of the worn material, while the quantitative influence of the cutting speed on the contact pressure and temperature is taken into account, we consider the relation of the wear rate at the tool's rear surface with a generalized parameter characterizing the cutting process.

The generalized parameter chosen is the ratio of the cutting speed (frictional speed) to the hardness of the worn surface as a function of the cutting temperature: $x = v/HV(T_{cu})$. Here $v$ is the cutting speed, m/s; and $HV$ is the Vickers hardness or microhardness, MPa.

The temperature dependence of the hardness is adopted in the following forms:

—for VK8 hard alloy, $HV = 12976.89 - 9.2\theta$;

—for VK6M hard alloy, $HV = 13448.1 - 8.7\theta$;

—for R10 fine-grain hard alloy, $HV = 17\,500 - 10\theta$;

—for VK6–TiN hard alloy (with a wear-resistant coating), $HV = 24\,495.2 - 22.7\theta$.

The cutting temperature is calculated from the formula

$$\theta = \frac{l_1^2 M_1}{\lambda_p (l_1 + l_2)} \frac{0.142\dfrac{\sqrt{w}}{\lambda}\sqrt{\dfrac{K_l l_1}{v}} q_{1t} + (1 + c) T_d}{M_1 \dfrac{l_1}{\lambda_p} + 0.148\dfrac{\sqrt{w}}{\lambda}\sqrt{\dfrac{K_l l_1}{v}}}.$$

Here $\lambda_p$ is the thermal conductivity of the hard alloy; $\lambda$, $w$ are the thermal conductivity and thermal diffusivity of the machined material; $K_l$ is the chip shrinkage; the coefficient $c$ takes account of the heating of the chip surface; the coefficient $M_1$ takes account of the influence of discontinuous machining on the cutting temperature.

For contemporary tool materials and different groups of machined materials, we establish the relation between the wear rate and the generalized parameter in the form

$$I_{nt} = 1.03 \times 10^7 (v/HV)^{2.47}, \quad (9)$$

where the tool hardness is a function of the contact temperature.

The cutting period is calculated as the sum of the time increments in each iteration and $\Delta_t$ (min): $t_{0,i+1} = t_{0,i} + \Delta t$. Then the corresponding wear increment, found from the wear rate in Eq. (9), is $\Delta_{hz} = \Delta_t I_{nt,i}$, while the total wear is $h_{z,i+1} = t_{z,i} + \Delta_{hz}$ (mm). The tool life corresponds to the cutting period such that the wear reaches the maximum permissible value $h_{z\max}$

$$\left.\begin{aligned} T &= t_{0,i+1}; \\ h_{z,i+1} &= h_{z\max}. \end{aligned}\right\} \quad (10)$$

The maximum permissible wear at the rear surface of the mill tooth is assumed to be 0.1 mm.

The formulas for the cutting forces, torque, temperature, wear rate, wear, and mill life are incorporated in the Milling program and algorithm. The cut thickness is assumed to be the mean thickness at the contact arc of the mill tooth.

In the analysis, we consider a one-piece hard-alloy end mill with the following parameters: $d$ = 16 mm; $z$ = 2; inclination of the edge to the axis $\omega_0$ = 55°; rounding radius at the tooth tip $r$ = 2 mm; rounding radius of edge $\rho$ = 0.01 mm. The tool materials are VK8, VK6M, R10, and VK6–TiN hard alloys.

As an example, we show the calculated time dependence of the wear $h_z$ at the mill tooth's rear surface in Fig. 2 for the milling of a slot by a VK6M alloy end mill in a 12X18H10T stainless steel workpiece, at different spindle speeds. The milling width here (the distance along the axis) is $B$ = 10 mm; the supply per tooth $S_z$ = 0.08 mm. In Fig. 3, we show the dependence of the mill life $T$ on the supply $S_z$ at spindle speed $n$ = 1500 rpm.

## POLYNOMIAL EQUATIONS FOR THE MILL LIFE AND CUTTING TORQUE

Multifactorial approximation is based on polynomial equations, within the framework of a general function approximating the experimental value at point $i$ of factorial space

$$y_i = \eta(\mathbf{x}_i) = \sum_{j=1}^{k} b_j f_{ij}(\mathbf{x}_i);\ i = 1, 2\ldots, N$$

or in matrix form

$$y = \mathbf{B}^T \cdot \mathbf{f}(\mathbf{x}),$$

where $N$ is the total number of points; $k$ is the number of terms in the model; $\mathbf{x}_i$ is the column matrix of input variables; $f_i(\mathbf{x}_i)$ denotes the functions (polynomials); $b_j$ are unknown coefficients; $\mathbf{B}$ is the coefficient matrix.

We calculate the coefficients of the polynomial models by means of stochastic approximation, which is essentially a larger-scale generalization of the least-squares method. (The application of stochastic approximation to metal-cutting formulas has been analyzed in detail elsewhere.)

The stochastic approximation algorithm includes procedures in which the coefficient matrix is refined in each iteration at each experimental point. The cycle continues until the mean error of the approximation is less than the specified value. The general procedure for changing the coefficient matrix in the stochastic approximation algorithm is as follows

$$\mathbf{B}_r = \mathbf{B}_{r-1} + g_r \cdot \mathbf{f}(\mathbf{x}_i) \cdot \left[ y_{ei} - \mathbf{B}_{r-1}^T \cdot \mathbf{f}(\mathbf{x}_i) \right], \quad (11)$$

where $y_{ei}$ is the initial value of the function at point $i$ of factor space; $g_1, \ldots, g_r$ is a sequence of positive numbers tending to zero; $r$ is the number of iterations.

By stochastic approximation, we may find a new sequence of unknown coefficients constituting the matrix $\mathbf{B}$ of the polynomial model by refining the model in each iteration, without formulating and solving the systems of equations required in the least-squares method. The number of coefficients in matrix $\mathbf{B}$ corresponds to the number of terms in the model specified by the matrix $\mathbf{f}$ of polynomial functions for the set of values of the factors $\mathbf{x}_i$ at each experimental point. The program calls for the input of positive numbers $g_r$ and $d_d$ and also interacts with a text file of input data containing $N$ rows of sequential numbers: the values of the factors and the corresponding initial value of the function in each row. The coefficient matrix $\mathbf{B}$ is refined by means of the data in each row of the initial file, in accordance with Eq. (11). After all of the $N$ rows of the file have been used, the mean error of the approximation is calculated and compared with its preceding value. The difference is consistent with the specified number $d_d$.

On the basis of Eq. (11), the polynomial equations may be classified as adaptive and modified by adding or removing terms (factors). Thus, in the development of equations for the tool life, the polynomial model is progressively complicated: from a linear model to a third-order model.

The third-order polynomial model for five variables includes 45 terms and may be written in general form as follows

$$y = \log T = b_1 x_1 + b_2 x_2 + \ldots + b_6 x_6 + \ldots + b_{44} x_6 x_4^2 + b_{45} x_6 x_5^2, \quad (12)$$

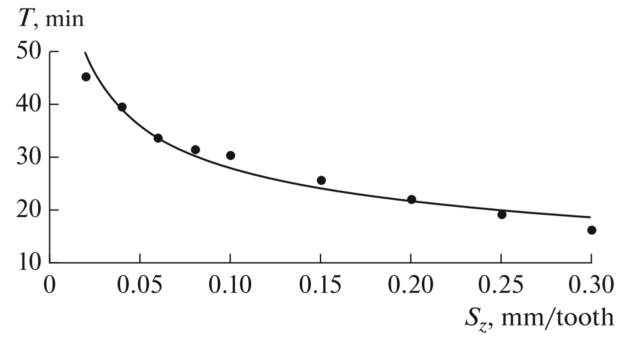


**Fig. 3.** Dependence of the mill life $T$ on the supply $S_z$.

where $T$ is the tool life, min; $x_1 = 1$ is a dummy variable.

The other variables $x_2$, ..., $x_6$ are included in Eq. (12) in coded (dimensionless) form, in accordance with the general procedure

$$x_i = C_{od}(x_{in}, x_{\max}, x_{\min}) = \frac{2(\log x_{in} - \log x_{\max})}{\log x_{\max} - \log x_{\min}} + 1, \quad (13)$$

where $x_{in}$ is the natural value of $x_i$; $x_{\max}$, $x_{\min}$ are the maximum and minimum values.

In accordance with the procedure in Eq. (13), the relation between the coded and natural variables in Eq. (12) is as follows

$$\begin{aligned} x_1 &= 1; \\ x_2 &= C_{od}(d; 40; 4); \\ x_3 &= C_{od}(v; 200; 25) - \text{for VK8, VK6M}; \\ x_3 &= C_{od}(v; 250; 50) - \text{for VK6–TiN, R10}; \\ x_4 &= C_{od}(t; 16; 2); \\ x_5 &= C_{od}(S_z; 0.3; 0.02); \\ x_6 &= C_{od}(B; 20; 2.5). \end{aligned} \quad (14)$$

Here $d$ is the mill diameter, mm; $v$ is the cutting speed, m/min; $t$ is the milling depth (perpendicular to the mill axis), mm; $S_z$ is the supply, mm/tooth; $B$ is the width, mm.

As a preliminary, a grid of combinations of the five variables at five levels of each is formed, in accordance with the procedure in Eq. (14). In all, it consists of $n = 5^5 = 3125$ points within the minimum and maximum values. From these points, we exclude those that are unfeasible, by means of the condition $t > d$. In other words, the milling depth must not be greater than the diameter of the end mill. For the remaining $N = 2500$ points corresponding to possible combinations of the variables, the tool life is calculated from Eq. (10) and the torque from Eq. (8). Thus, we formulate the initial databases for approximation by polynomial equations. Points with very low tool-life values are also excluded from the initial database.

**Table 1.** Approximation of the mill life by polynomial equations

| Model | Number of terms, $k$ | Error, min | | Relation of calculated and initial values |
|---|---|---|---|---|
| | | $Q_{ksr}$ | $Q_{ar}$ | |
| Linear | 6 | 28.2 | 8.8 | $T_p = 1.11 T_i$ |
| Quadratic | 11 | 25.3 | 8.3 | $T_p = 1.09 T_i$ |
| Quadratic, with interactions | 21 | 6.8 | 2.7 | $T_p = 0.99 T_i$ |
| Third-order, with interactions | 45 | 5.4 | 2.4 | $T_p = 1.00 T_i$ |

The following polynomial models for the tool life are considered successively: a linear model; a quadratic model; a quadratic model with variable interactions; and a third-order model with variable interactions. Table 1 presents the results of the analysis. For each model, we present the number $k$ of terms; the mean square error $Q_{ksr}$; the mean error $Q_{ar}$; the relation of the $T$ value calculated from the polynomial equation with its initial value from the database. Note that the error decreases severalfold on passing from a linear model to a third-order model.

Table 2 presents polynomial functions constituting the third-order model (with variable interactions) for the tool life and also the coefficients corresponding to different hard alloys from Eq. (11).

In Fig. 4, as an example, we show the relation between the initial $T_i$ values in the database and the values $T_p$ given by the polynomial equation in Table 2 for VK6M alloy. The relation is practically linear; its characteristics and the error of the approximation are presented in Table 1. The number of points $N = 2450$.

Analogous results are obtained for the torque.

## ANALYSIS OF THE POLYNOMIAL EQUATIONS

In the analysis, we plot isolines in the $v$–$S_z$ coordinate plane for the model functions, by means of the standard MATLAB *contour* function. In Fig. 5, we plot the isolines corresponding to tool life $T = 30$, 90, and 150 min for the machining of a 12X18H10T stainless steel workpiece by a VK6M end mill. The calculation is based on Eq. (12), with the corresponding coefficients from Table 2 (mill diameter $d = 16$ mm; cutting depth $t = 16$ mm; milling width $B = 10$ mm).

We see that the cutting speed $v$ has a considerable influence on the mill life. The supply $S_z$ also affects the tool life, but to a lesser extent.

In Fig. 6, we plot the corresponding isolines for tool life $T = 90$ min when machining a 12X18H10T stainless steel workpiece by VK6M, R10, and VK6–TiN hard-alloy end mills. The results qualitatively confirm that fine-grain R10 alloy and coated VK6–TiN alloy permit considerable increase in the milling speed.

The equations derived here may be used in optimizing the milling parameters. Consider the milling of

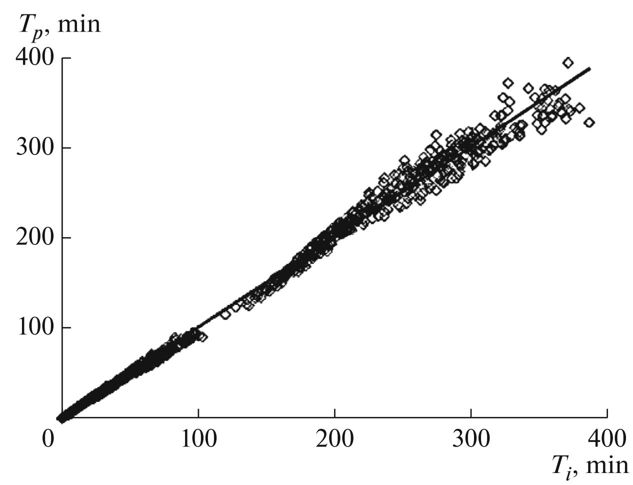


**Fig. 4.** Relation between the initial values of the mill life $T_i$ from the database and the calculated values $T_p$ from a third-order polynomial equation.

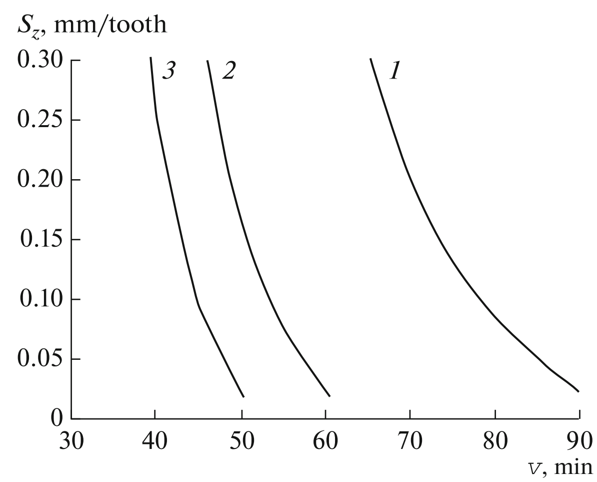


**Fig. 5.** Isolines corresponding to the life $T = 30$ (*1*), 90 (*2*), and 150 min (*3*) of a hard-alloy end mill in machining stainless steel workpieces.

**Table 2.** Polynomial functions and coefficients of polynomial equations for the function $y = \log T$

| Term | Polynomial function | Hard alloy | | |
|---|---|---|---|---|
| | | VK6M | VK6–TiN | R10 |
| | | coefficients | | |
| 1 | $x_1$ | 1.73834 | 1.62427 | 1.38102 |
| 2 | $x_2$ | 0.08277 | 0.19304 | 0.07807 |
| 3 | $x_3$ | –1.21845 | –1.09143 | –0.96703 |
| 4 | $x_4$ | –0.08779 | –0.17526 | –0.04954 |
| 5 | $x_5$ | –0.15862 | –0.35595 | –0.15543 |
| 6 | $x_6$ | –0.10059 | –0.21186 | –0.10091 |
| 7 | $x_2^2$ | –0.02212 | –0.04929 | 0.001 |
| 8 | $x_3^2$ | –0.00339 | 0.02081 | 0.06872 |
| 9 | $x_4^2$ | 0.00178 | 0.02216 | 0.04203 |
| 10 | $x_5^2$ | –0.06859 | –0.2218 | –0.09368 |
| 11 | $x_6^2$ | 0.00765 | 0.00781 | 0.02014 |
| 12 | $x_2x_3$ | 0.07677 | 0.23047 | 0.06536 |
| 13 | $x_2x_6$ | 0.0274 | 0.10192 | 0.00588 |
| 14 | $x_2x_4$ | 0.01557 | 0.0226 | –0.04664 |
| 15 | $x_2x_5$ | 0.06247 | 0.21063 | 0.07488 |
| 16 | $x_3x_4$ | –0.06179 | –0.18425 | –0.04889 |
| 17 | $x_3x_5$ | –0.09933 | –0.28791 | –0.10863 |
| 18 | $x_3x_6$ | –0.05605 | –0.16036 | –0.03569 |
| 19 | $x_4x_5$ | –0.04984 | –0.1787 | –0.06181 |
| 20 | $x_4x_6$ | –0.01812 | –0.07387 | 0.00229 |
| 21 | $x_6x_5$ | –0.03632 | –0.13694 | –0.02581 |
| 22 | $x_3^3$ | –0.13957 | –0.20502 | –0.18566 |
| 23 | $x_4^3$ | 0.00645 | 0.02351 | 0.01183 |
| 24 | $x_5^3$ | 0.00688 | –0.04892 | –0.07108 |
| 25 | $x_6^3$ | –0.00522 | –0.0151 | –0.0091 |
| 26 | $x_2x_3^2$ | 0.01636 | –0.02141 | 0.00229 |
| 27 | $x_2x_6^2$ | –0.00869 | –0.02022 | –0.00999 |
| 28 | $x_2x_4^2$ | –0.00013 | –0.05034 | –0.03757 |
| 29 | $x_2x_5^2$ | 0.01876 | 0.10171 | 0.05003 |
| 30 | $x_3x_2^2$ | –0.01142 | –0.03452 | –0.00525 |
| 31 | $x_3x_4^2$ | 0.0062 | 0.0138 | 0.0047 |
| 32 | $x_3x_5^2$ | –0.05114 | –0.17653 | –0.07842 |
| 33 | $x_3x_6^2$ | 0.00573 | 0.01029 | 0.00731 |
| 34 | $x_4x_2^2$ | –0.01371 | –0.00139 | 0.00264 |

**Table 2.** (Contd.)

| Term | Polynomial function | Hard alloy | | |
|---|---|---|---|---|
| | | VK6M | VK6–TiN | R10 |
| | | coefficients | | |
| 35 | $x_4x_3^2$ | –0.02118 | –0.02651 | –0.02294 |
| 36 | $x_4x_5^2$ | –0.00901 | –0.07936 | –0.04042 |
| 37 | $x_4x_6^2$ | 0.00834 | 0.01779 | 0.00697 |
| 38 | $x_5x_2^2$ | –0.00041 | –0.0026 | 0.00091 |
| 39 | $x_5x_3^2$ | –0.04934 | –0.08341 | –0.04994 |
| 40 | $x_5x_4^2$ | –0.00035 | –0.00736 | 0.00027 |
| 41 | $x_5x_6^2$ | 0.0014 | –0.00221 | 0.00333 |
| 42 | $x_6x_2^2$ | –0.00966 | –0.03472 | –0.00864 |
| 43 | $x_6x_3^2$ | –0.01682 | –0.0069 | –0.00912 |
| 44 | $x_6x_4^2$ | 0.0088 | 0.02135 | 0.00721 |
| 45 | $x_6x_5^2$ | –0.01412 | –0.06946 | –0.01127 |

The coded variables correspond to Eq. (14).

slot in a 12X18H10T stainless steel workpiece by an R10 alloy end mill, when the mill diameter $d = 16$ mm; the cutting depth $t = 16$ mm; and the milling width $B = 10$ mm. The goal of optimization is to minimize the time per operation.

The technological constrains are as follows.

—In terms of the tool life, $F_1 = T(v, S_z) - T_z$, where $T(v, S_z)$ is the life according to Eq. (12) with the coefficients in Table 2; and $T_z = 90$ min is the minimum life.

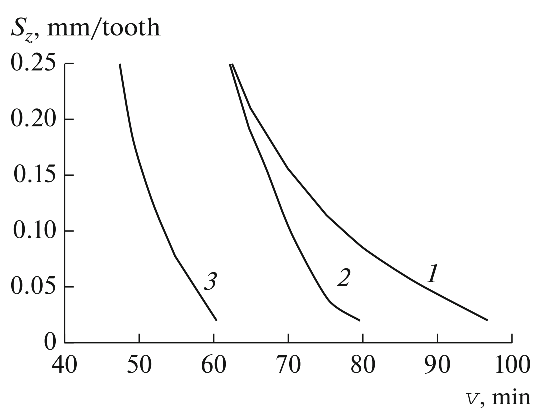


**Fig. 6.** Isolines corresponding to the life $T = 90$ min of VK6–TiN (*1*), R10 (*2*), and VK6M (*3*) hard-alloy end mills in machining stainless steel workpieces.

—In terms of the roughness of the machined surface, $F_2 = Ra_z - Ra(v, S_z)$, where $Ra_z = 3$ μm is the specified surface roughness and $Ra(v, S_z)$ is the roughness determined by the tool life and supply.

—In terms of the drive power in the machine tool, $F_3 = N_z - N(v, S_z)$, where $N_z = 7.5$ kW is the specified drive power and $N(v, S_z)$ is the power determined by the tool life and supply.

We calculate the roughness on the basis of a power law found in the literature

$$Ra = \left(\frac{S_z B^{n_{S2}}}{C_S d^{n_{S1}}}\right)^{1/n_{S3}},$$

where

$$C_S = 0.0045; n_{S1} = 0.902; n_{S2} = 0.339; n_{S3} = 0.618.$$

The power is related to the torque as follows

$$N(v, S) = \frac{M(v, S)n}{9554},$$

where $M(v, S)$ is the torque according to Eq. (12).

In Fig. 7, as an illustration, we show the isolines corresponding to the technological constraints in the $v$–$S_z$ coordinate plane.

The optimal point, corresponding to optimal parameter value, is found as the intersection of the corresponding isolines based on the technological constraints, in accordance with [6]. Thus, in Fig. 7,

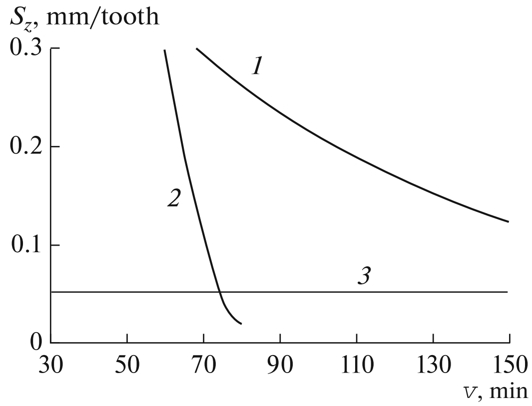


**Fig. 7.** Isolines corresponding to the technological constraints: (*1*) drive power $N = 7.5$ kW; (*2*) tool life $T = 90$ min; (*3*) surface roughness $Ra = 3$ µm.

the intersection of the isolines for the tool life and surface roughness is an optimal point.

This point may be found on the basis of the standard MATLAB *fsolve* function, which permits the solution of a system of nonlinear equations

$$[\mathbf{x}_o] = fsolve(@\,funvsp, [\mathbf{x}_n]).$$

Here $\mathbf{x}_o$ and $\mathbf{x}_{nn}$ are the vectors of the optimal and initial parameter values; *funvsp* is a user function consisting of the functions $F_1$ and $F_2$ describing the technological constraints.

The optimal parameter values are $[\mathbf{x}_o]$ = [74.4; 0.047]. In other words, the optimal cutting speed $v_o$ = 74.4 m/min; the optimal supply $S_{zo}$ = 0.047 mm/tooth.

## CONCLUSIONS

A method has been proposed for calculating the cutting characteristics in the end milling of stainless steel workpieces—specifically, the cutting forces, temperature, contact pressure, wear rate, wear, and tool life. The method eliminates the need for special experiments. In the method, the influence of softening of the workpiece and tool material under the action of the cutting temperature is taken into account. This method may be applied to other machining methods and conditions.

The tool life and the torque are approximated by polynomial equations

Polynomial models are recommended for calculation of optimization of the milling parameters.

The optimal parameter values are found as the intersection of isolines corresponding to the technological constraints on the tool life and surface roughness.

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