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Optimization of Cutting Processes

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Abstract—Known criteria for the optimization of cutting processes are appraised. A new criterion for determining the optimal conditions in metal cutting is proposed.

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The optimization of cutting processes is currently of great importance in metalworking so as to ensure high product quality while improving competitiveness.

Existing optimization methods may be divided into two broad categories: (1) conditional optimization; (2) unconditional optimization [1]. In conditional optimization, we search for a minimum or maximum value of the target function $f(x)$ with an n-dimensional argument, within specific constraints. Static optimization is based on the analysis of experimental data. Three basic methods of this type are known: (1) the Taguchi method; (2) factorial design; (3) the response-surface method. Besides static optimization, we may note numerical methods: linear programming, nonlinear programming, and dynamic programming.

Unconditional optimization determines a near-optimal solution on the basis of a heuristic algorithm. The basic idea is to convert the conditional optimization into a sequence of unconditional-optimization problems. The problem of finding the local minimum of function $\Phi(X)$ defined for a set D in n-dimensional arithmetic space is reduced to a sequence of auxiliary problems in which we find the local minimum of the function $\Phi(X) + P(\alpha, X)$ defined throughout n-dimensional arithmetic space. Here $P(\alpha, X)$ is a function that increases close to the boundary of permissible D values, at a rate that depends on the scalar parameter α. The solution of the auxiliary unconditional-optimization problem with sufficiently large α is adopted as the approximate solution of the initial conditional-optimization problem. The best-known methods of successive unconditional optimization are the penalty-function method and the barrier-function method. A classification of optimization methods is presented in Fig. 1 [1].

The cutting process is characterized by a wealth of interdependent factors that affect both the path and outcome of the process. As a rule, conditional optimization is used for cutting processes, so as to increase the product quality while reducing its cost. Effective optimization requires high quality of all the stages in selecting the optimal cutting conditions: satisfactory physical and mathematical models of the actual process; and the use of up-to-date optimization procedures. In machining, physical and mathematical mod-

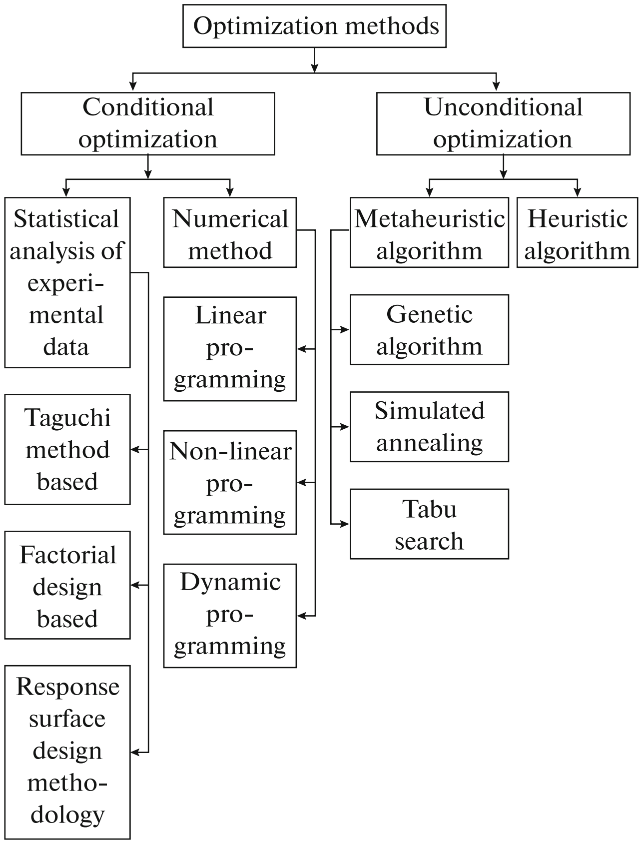

Fig. 1. Classification of optimization methods.

els of the process are of the greatest importance. In optimizing the cutting process, the first priority is to improve the models employed.

Research on the optimization of cutting has been undertaken by Igumnov, Tinn, Tyugu, Jacobs, Jacob, and many others. A whole series of optimization methods has been developed. Each one has proved useful in some way. Accordingly, the optimization criteria for the cutting conditions may be developed into three basic groups: (1) economic criteria; (2) quality criteria; (3) energy criteria. The first group includes the minimum machining cost; the minimum cost of the technological operations; the minimum costs in margin removal, with maximum productivity; and the maximum tool life. The second group includes maximum dimensional precision and surface quality of the product. The third group focuses on minimum energy costs.

In optimization of the cutting zone with respect to energy resources, it is expedient to use the thermodynamic characteristic Ψ, which is the ratio of the power N (W) consumed in cutting (the rate of mechanical energy dissipation) and the mean absolute cutting temperature T (°C)

$$\Psi = \frac{N}{T} = \frac{P_z v}{T}, \qquad (1)$$

where P_z is a component of the cutting force, N.

In physical terms, Ψ is the rate of entropy production [2]. It is characterized by the energy consumed in shear and deformation of the machined material. Its value is largely determined by the properties of that material. This ratio may be different for different cutting conditions, the cutter geometry, and other factors but note that the thermodynamic system is self-organizing and tends to dynamic equilibrium. The equilibrium conditions may be assumed to correspond to optimal conditions.

An analogous characteristic is $\Psi_{\Re}$, which reflects the deformation processes only in the shear zone [2]

$$\Psi_{\Re} = \frac{N_{\Re}}{T_{\Re}} = \frac{\mathrm{P}_{\Re} v_{\Re}}{T_{\Re}}.$$

Here $P_{\Re}$ is the force required to deform the material in the conditional shear plane, N; $N_{\Re}$ is the power consumed in shear, W; $v_{\Re}$ is the shear rate in the margin, m/s; $T_{\Re}$ is the temperature in the conditional shear plane, °C.

The optimal (recommended) cutting speed is then as follows [2]

$$v_0 \approx v\left(\frac{H}{H_0}\right)^3, \qquad (2)$$

where v is the actual cutting speed at a given time; H_0 is the relative (unit) machinability recommended as optimal by the previously selected optimization method; H is the actual relative (unit) machinability at the given time [2]

$$H = \frac{N}{T}\frac{T_{\Re}}{N_{\Re}} = \frac{\Psi}{\Psi_{\Re}} = f(z).$$

The first approximation in Eq. (2) permits determination of the direction (increase or decrease) and magnitude of the required correction in the cutting speed.

The cutting temperature is a very informative cutting parameter. For example, increase in the productivity on the basis of the maximum permissible cutting temperature in terms of several cutting parameters—the tool wear, the workpiece hardness, the axial cutting force, and the torque—was proposed in [3]. These parameters may be determined from known values or measured directly in the course of machining. Thus, the maximum cutting temperature may be adopted as a control parameter in preventing catastrophic tool wear. The main benefit of this approach is that it is simple, since it permits the recovery of a large number of cutting parameters on the basis of the minimum number of primary sensors. Despite its advantages, this characteristic requires laborious calculations and may give ambiguous results in some cases.

The methods proposed in [4–6] share the following assumptions: that the parameter adopted in optimization must adequately reflect the development of the process; permit ongoing efficiency assessment of the cutting conditions; and employ the minimum feasible quantity of input information. Some of the most informative parameters characterizing the cutting conditions are the cutting temperature and cutting force. They are relatively easy to measure. Theoretical research has shown that the cutting conditions (the cutting temperature, supply, and cutting depth) do not have the same effect on the cutting temperature and cutting force. The empirical formulas for these variables are as follows [7]

$$\begin{aligned} T &= f_1(v,s,t) = K_T v^{x_T} s^{y_T} t^{z_T}; \\ P_z &= f_2(v,s,t) = K_P v^{x_P} s^{y_P} t^{z_P}, \end{aligned},$$

where s is the supply, mm/turn; t is the cutting depth, mm; K_T, K_P are general coefficients characterizing the machining conditions; and x_T, y_T, z_T, x_P, y_P, z_P are exponents characterizing the rate of increase in the cutting temperature and cutting force with increase in v, s, t.

Comparison of the cutting force and cutting temperature is used in the familiar approach to estimating the rate of entropy production Ψ in Eq. (1) [2]. Because Ψ is dimensional, difficulties arise in optimization. In the present work, we propose optimization on the basis not of the temperature but of the temperature gradient—for example, along the shear plane or in the supply direction. It characterizes the heat flux from the cutting zone and reflects the proportion of energy that is not effectively utilized.

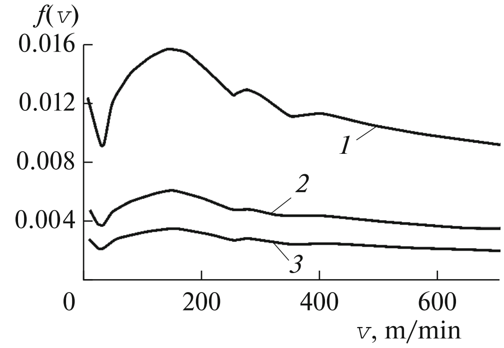

Fig. 2. Dependence of ξ on the cutting speed: (*1*) $s = 0.25$, $t = 2$; (*2*) $s = 0.5$, $t = 3$; (*3*) $s = 0.75$, $t = 5$.

In this case, it is expedient to write Eq. (1) in the form

$$\xi = f(v) = \frac{\mathrm{grad}(T)}{N} = \frac{\varepsilon\lambda T}{sN} = \frac{\varepsilon\lambda T}{sP_z v}, \qquad (3)$$

where λ is the thermal diffusivity of the machined material; ε is a dimensional conversion factor.

It follows from Eq. (3) that the proposed characteristic is dimensionless and takes account of the supply and thermophysical properties of the machined material. Like any other characteristic employed in the optimization of cutting, it must have an extremum (in particular, a minimum) corresponding to the maximum effective utilization of the energy introduced in the cutting zone

$$J = \min_{s,v} \xi(s, v). \qquad (4)$$

To verify the behavior of the target function in Eq. (4), we investigate its dependence on the cutting speed. The range of cutting speed may be divided in two: (1) $0 < v \le 300$ m/min; (2) $300 < v \le 700$ m/min. The first part corresponds to experimental determination of the cutting temperature and cutting force in the turning of a smooth steel 45 shaft [7]. The second corresponds to simulation using models of the cutting temperature and the cutting force [8, 9]

$$T = 572.35 v^{0.297} s^{0.219} t^{0.06} \lambda^{-1.09} \omega^{0.766} \varphi^{0.376}, {}^\circ\mathrm{C};$$

$$P_z = 2000 v^{0.01} s^{0.95} t^{0.3}, \mathrm{N},$$

where ω is the thermal diffusivity of the tool, m^2/s; φ is the primary plane angle, deg.

It is evident from the results (Fig. 2) that the proposed characteristic has extrema, whose position is in good agreement with some familiar characteristics used in the optimization of cutting. In particular, the optimal cutting speed in terms of maximum wear resistance of the tool is 36 m/min and corresponds to the first minimum of ξ (for the semifinal turning of a smooth steel 45 shaft) [10]. The optimal cutting speed in terms of minimum surface roughness is 250 m/min and corresponds to the second minimum of ξ (for the final turning of a smooth steel 45 shaft) [11].

In comparison with other characteristics used in the optimization of cutting, ξ has the following benefits: it requires few initial parameters; and it is dimensionless.

CONCLUSIONS

(1) Despite the many known characteristics used in optimization, none reflects all the factors that have a significant influence on the cutting process.

(2) When using the proposed characteristic ξ, the properties of the machined material and the supply may be taken into account as the control signal.

(3) If the value of the target function is established on the basis of mathematical modeling (for example, by means of a neural network) and is compared with ongoing diagnostics of the cutting process, there is great potential for selecting satisfactory control signals.

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