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Mathematical simulation and optimization of cutting mode in turning of workpieces made of nickel-based heat-resistant alloy

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Abstract. A predictive simulation technique of optimal cutting modes in the turning of workpieces made of nickel-based heat-resistant alloys, different from the well-known ones, is proposed. The impact of various factors on the cutting process with the purpose of determining optimal parameters of machining in concordance with certain effectiveness criteria is analyzed in the paper. A mathematical model of optimization, algorithms and computer programmes, visual graphical forms reflecting dependences of the effectiveness criteria – productivity, net cost, and tool life on parameters of the technological process - have been worked out. A nonlinear model for multidimensional functions, "solution of the equation with multiple unknowns", "a coordinate descent method" and heuristic algorithms are accepted to solve the problem of optimization of cutting mode parameters. Research shows that in machining of workpieces made from heat-resistant alloy AISI N07263, the highest possible productivity will be achieved with the following parameters: cutting speed v = 22.1 m/min., feed rate s=0.26 mm/rev; tool life T = 18 min.; net cost – 2.45 $ per hour.

1. Introduction

Up-to-date machinery production is impossible without data support of production planning and engineering. Parameters of the manufacturing process should be calculated as well as optimized in order to increase effectiveness and competitiveness.

One of the ways of productivity enhancement refers to the application of intensive operating modes. Meanwhile the relevance of these operating modes should be confirmed by a physical experiment or simulation modelling.

2. Materials and methods

Nickel-based heat-resistant alloys such as AISI N07263 are widely used in manufacturing of components of machines and devices operating at high temperatures of approximately 700 - 950°C. The peculiarity of such alloys is concerned with their complex chemical composition, which defines a specific character of their properties and characteristics.

One of the versions of chemical composition of alloy AISI N07263 is presented in Table 1.

Table 1. Chemical composition of the alloy AISI N07263

C (%)	Si (%)	Mn (%)	Cr (%)	Ti (%)	Al (%)	W (%)	Mo (%)	Fe (%)	P (%)	S (%)	(Al+T) (%)	Amount of γ-phase (%)
0.07	0.5	0.4	14.5	2.75	1.8	6.0	3.2	1.03	0.015	0.007	4.56	22

The alloy possesses high specific strength, corrosion resistance, low plasticity and heat conductivity, a tendency to sticking and strain that determines the increased labour intensity and specific features of its machining. Research conducted by many authors [1, 2, 3] has shown that cutting modes and resistance data of tools in machining of heat-resistant alloys do not always correspond to optimum values and require examination of this issue in detail.

The objective of the present research is to define the cutting mode parameters optimizing the values of certain effectiveness criteria such as productivity, net cost, and tool life at different options of initial technological parameters. The research method involves mathematical simulation and optimization of the cutting mode of heat-resistant alloy workpieces; development of computer software; use of numerical computation for solving the optimization problem in machining workpieces made of heat-resistant alloys AISI N07263. The research method also includes experimental check of the obtained research results.

3. Development of Mathematical Model

The mathematical model of the optimization has been developed including the following component:

- development of the information model;
- formalized presentation of input, output and internal parameters;
- setting the type and the variation range of running variables;
- choice and justification of optimization criteria;
- mathematical descriptions of the objective function;
- definition of the constraint system;

The information model defines a set of initial parameters: cutting modes, the work material, tool geometry, and the processing type on the basis of which a mathematical model for solving a specific problem is constructed.

Mathematical models and optimization algorithms reflect the interrelation of cutting mode parameters with such quality criteria as productivity, net cost and etc. [4, 5, 10]. A formalized presentation of input and output information with a visual display of the research results is carried out by means of software in Delphi environment [6].

Output data include calculation data of P, T, C criteria; tables of dependences P = f (v), T = f(v), C = f (v); characteristic curves; optimal values of parameters. Dependences of criteria P, T, C on the parameters of cutting modes are calculated according to formulas worked out by Makarov A.D. [7] and represented as follows:

$$P = \frac{\pi \cdot D \cdot n \cdot t \cdot s}{1 + \dfrac{\tau_{ch}}{T}} \quad , \tag{1}$$

where:
D – diameter of a workpiece (mm);
n – speed of rotation (number of revolutions per minute) (r/min);
s – feed rate (mm/rev);
τ_{ch} – tool change rate of a cutting tool (min);
T – cutting tool life (min).

The cutting tool life is determined according to the following dependence:

$$T = \frac{C_v \cdot k_v}{v \cdot t^x \cdot s^y} \ , \tag{2}$$

where:
v – cutting speed (m/min);
C_v – constant value for defining a group of the work material;
k_V – coefficient, depending on properties of materials being machined and a cutting tool, its geometry, wear as well as lubricating-cooling fluid;
x, y – exponent quantities, depending on the tool properties and the cutting conditions.

Putting (2) into (1) and taking the change of allowance value z at constant t for a disturbance effect, let us obtain the objective function:

$$P = \frac{\pi \cdot D \cdot n \cdot t \cdot s}{1 + \dfrac{v \cdot \tau_{ch} \cdot t^x \cdot s^y}{C_v \cdot k_v}} \tag{3}$$

Net cost of manufacturing a workpiece is defined in accordance with the following formula:

$$A = t_m(\alpha_s + \alpha_m) + \frac{t_{ch}}{Q}(\alpha_s + \alpha_m) + \frac{e}{Q} \quad \text{[\$/piece]}, \tag{4}$$

where:
t_m – machining time of a workpiece (min);
t_{ch} – tool change time over a period of its tool life (min);
a_s - salary of a machine worker per minute, (kopeck);
a_m - operating costs of a machine tool (equipment) for a minute of its operation, (kopeck);
e - operating costs of a cutting tool during its tool life, (kopeck);
Q – quantity of the machined workpieces during tool life value (pieces).
Q=f (v, s, t, T).

Criteria of surface roughness dependence on the cutting mode are presented as follows:

$$Rz = \frac{\sqrt[0.4]{\left(8.25 \quad r^{0.15} \big/ t^{0.3} \quad \sin\varphi^{0.4}\right)^2}}{v \quad 8 \quad r} \ , \tag{5}$$

where:
r – nose radius (mm);
v – cutting speed (m/min);
t – depth of cut (mm);
φ – principal edge angle in the plan (grade).

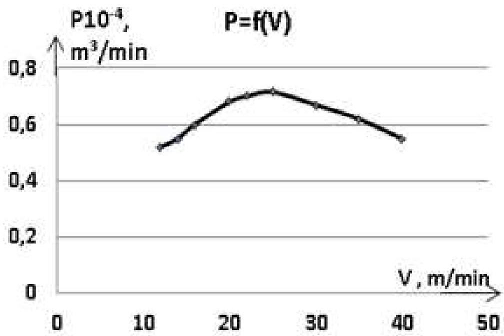
Figure 1 shows characteristic curves reflecting the influence of cutting speed v on basic characteristics of the cutting process.

Analysis of characteristic curves, introduced in Figure 1, demonstrates that there are extreme values – net cost minimum (C) and productivity maximum (P) in a wide range of variation of cutting speed v. In such case, the impact of cutting speed v on these results is not uniquely defined. Cutting speed v significantly differs with regard to the extreme values – C_{min} and P_{max}. Consequently, it is necessary to examine a variation interval of cutting speed within the range from $v_{c\ min}$ to $v_{p\ max}$ for optimization of the cutting mode.

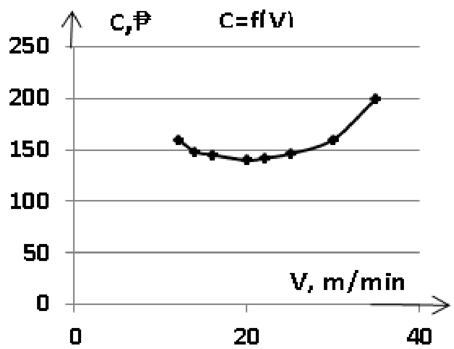
The mathematical models under study are represented in view of the set of multiparameter nonlinear dependences and functions. These functions are stored on a database and used for the optimization model formation and as well as the presentation in a required format. A nonlinear model for multidimensional functions, “solution of the equation with multiple unknowns”, “a coordinate descent method” and heuristic algorithms are accepted to solve the problem of optimization of cutting mode parameters [8, 9]. Allowed values of parameters are considered as limitations. Optimization is performed owing to the variation of these parameters within the given limited ranges. The optimal solution is presented in view of the adjusted values of the parameters at which the objective function assumes extreme value F_{min} (or F_{max}) for the specified criterion of effectiveness.

V m/min	P m³/min	T min	C ₽
12	0,52	50	160
14	0,55	60	148
6	0,6	42	145
20	0,68	20	140
22	0,7	14	142
25	0,71	9	146
30	0,67	5	160
35	0,62	3	200
40	0,55	2	250

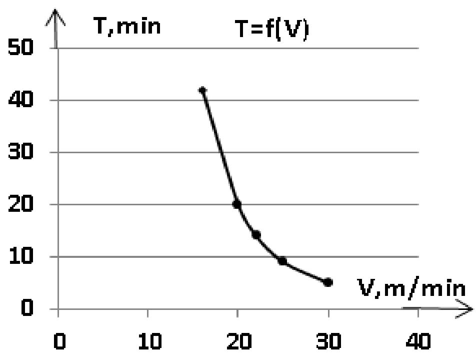
a



b



c



d

Figure 1. The influence of cutting speed *v* on basic characteristics of the cutting process in turning workpieces made from alloy AISI N07263 at *s* = 0.26 mm/rev.
a – influence of cutting speed V on productivity P, cutting tool life T (m/min), net cost C;
b - influence of cutting speed V on productivity P; **c** – influence of cutting speed V on net cost C;
d – influence of cutting speed V on cutting tool life T.

4. Research results

Calculations are performed and dependences of productivity, net cost and tool life on cutting speed v and feed rate s are determined. Optimal parameters for various cutting modes for specified effectiveness criteria are defined including restrictions to the variation range of data under research. Thus, in machining of workpieces made from heat-resistant alloy AISI N07263, the highest possible productivity will be achieved at the following parameters: cutting speed $v = 22.1$ m/min., feed rate s=0.26 mm/rev; tool life $T=18$ min.; net cost - 142 roubles per hour. Cutting speed v has changed in a range of 10-40 m/min. the feed rate has changed in a range of 0.14-0.4 mm/rev.

5. Conclusion

The influence of mechanical properties of heat-resistant alloy AISI N07263 on characteristics of the turning process mode was analyzed in the present paper. For the purpose of reducing labour intensity and expensive full level test, forecasting effort was carried out by means of an electronic computing machine and mathematical simulation of the cutting process with the following verification in a view of the experiment in laboratory and working conditions.

The authors have developed the graphical interface of computational modeling for the optimization of parameters of the cutting process in turning, which allows one to predict the cutting modes in accordance with the given optimization criteria on basis of the particular range of initial parameters.

The current model can be applied for other processing types: milling, drilling and etc. with some amendments and modifications determined by the characteristics of the processing type.

With reference to the present research, the guidelines for optimizing the cutting process of heat-resistant alloys AISI N07263, taking into consideration the restrictions imposed on the parameters of cutting systems in conformity with the appropriate effectiveness criteria, have been worked out.

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