Mathematical simulation and optimization of cutting modes in turning of titanium alloy workpieces

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Abstract. A predictive modeling technique of optimal cutting modes in machining of workpieces made of titanium alloys, different from the well-known ones, is offered. The influence of various factors on the process of cutting for the purpose of defining optimal parameters of machining in accordance with certain effectiveness criteria is examined in the present paper. Mathematical models of optimization, algorithms and computer programmes, visual graphical forms presenting dependences of effectiveness criteria on the master schedule parameters have been worked out. Verification of mathematical models in laboratory and working conditions has been carried out.

1. Introduction

Modern machinery production is impossible without data support. Cutting parameters should be optimized for the purpose of increasing effectiveness as well as competitiveness.

One of the ways of increasing effectiveness of manufacturing is the application of optimal cutting modes obtained by simulation modeling. The relevance of these cutting modes should be confirmed by a physical experiment. The investigation of cutting process requires considering a great number of factors, taking into account the impact of cutting modes and geometry of a cutting tool on productivity and net cost of machining. From the position of optimization and manufacture intensification, simulation modeling is more multipurpose and less labour-consuming in comparison with the physical experiment.

Titanium alloys refer to the material groups, which are widely used in engineering. Titanium alloys have a wide application in airspace and chemical industry, shipbuilding, etc. [1]. Titanium alloy BT9 (Ti-6Al-3Mo) is applied in manufacturing of parts working at high temperatures (approximately 500 ^{0}C), on heavy loading, in aggressive environment, etc. It possesses high specific strength and corrosion resistance, low plasticity and heat conductivity, propensity to sticking and strain or work-hardening that causes the increased labour intensity of its machining. Research conducted by many authors [2-6], has presented that cutting modes and geometry of cutting tools in machining of titanium alloys do not always correspond to optimum values.

2. Problem Statement

The research objective is to define the cutting mode parameters and geometry of turning cutters optimizing basic indexes of the production process effectiveness: productivity, net cost, cutting tool life, roughness of the machined surface. Difficult -to-machining titanium alloy BT9 (Ti6Al3Mo) has been selected as a work material. The input data of other work materials can be included into a database for optimization if necessary.

The research method involves mathematical simulation, development of computer software, use of computational methods for solving the optimization task of machining of workpieces made of titanium alloy BT9 as well as the experimental test aiming to the identification of obtained results in working conditions.

3. Development of Mathematical Model

Mathematical models and optimization algorithms reflecting the interrelation of cutting mode parameters with such quality criteria as productivity (P), net cost (C), cutting tool life (T) and roughness of the machined surface (Rz) have been developed.

Dependences of criteria P, T, C, Rz on the parameters of cutting modes are accepted according to formulas (1) and (2) [4] and presented as follows:

$$Rz = \frac{\sqrt[0.4]{(8.25 \quad r^{0.15} / t^{0.3} \quad \sin\varphi^{0.4})^2}}{V \quad 8 \quad r} \qquad [\mu m], \qquad (1)$$

Where:
r – nose radius at the top of a turning cutter, mm; v – cutting speed, m/s; t – cutting depth, mm; φ – cutting edge angle on the plan, degrees [º].

$$P = \frac{\pi \quad D \quad n \quad t \quad s}{1 + \frac{\tau_{cm}}{T}} \times 10^{-6} \qquad [m^3/min], \qquad (2)$$

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

$$T = \frac{C_v \quad k_v}{v \quad t^x \quad s^y} \qquad [min], \qquad (3)$$

Where:
Cv - coefficient, depending on a group of work and cutting tool materials; k_V – coefficient, depending on strength and chemical composition of work and cutting tool materials, geometry of a cutting tool, use of cutting lubricant; x, y – exponent quantities, depending on the grade of work and cutting tool materials and cutting conditions.

The following function for P is obtained by putting (3) into (2) and taking the change of allowance value *z* at constant *t* for a disturbance effect.

$$P = \frac{\pi \quad D \quad n \quad t \quad s}{1 + \frac{v \quad \tau_{cm} \quad t^x \quad s^y}{C_v \quad k_v}} \qquad [m^3/min], \qquad (4)$$

The net cost of manufacturing of a workpiece (a reference area of machining of a workpiece equals 0.1 m^2) is defined using the following formula:

$$C = t_m(\alpha_s + \alpha_m) + \frac{t_{ch}}{Q}(\alpha_s + \alpha_m) + \frac{e}{Q} \quad [\$/piece], \qquad (5)$$

Where:
t_m – cutting (machine-tool) time for machining of a workpiece with a reference area equal to 0.1 m^2 (min,); t_{ch} – tool change time over a period of its tool life (min); a_s - salary of a machine worker per minute, dollar ($); a_m - operating costs of a machine tool (equipment) for a minute of its operation, dollar ($); e - operating

costs of a cutting tool during its tool life, dollar ($); Q – quantity of the machined workpieces during tool life value (pieces). $Q = f(v, s, t, T)$.

The mathematical models under consideration are presented as the set of multiparameter nonlinear functions. These functions are stored on a database and used for the formation of the optimization model as well as the presentation of functions in a required format.

A ‘coordinate descent method’ for multidimensional functions is used to determine the optimum value of effectiveness criteria. Allowed values of initial parameters are considered as limitations. Optimization is performed due to variations of initial parameters in the given limited ranges.

The optimal solution is represented in view of the adjusted values of parameters when the objective function takes extreme value *F*min (or *F*max) for a specific effectiveness criterion.

Software for the problems to be solved has been developed in Delphi environment [5]. A formalized

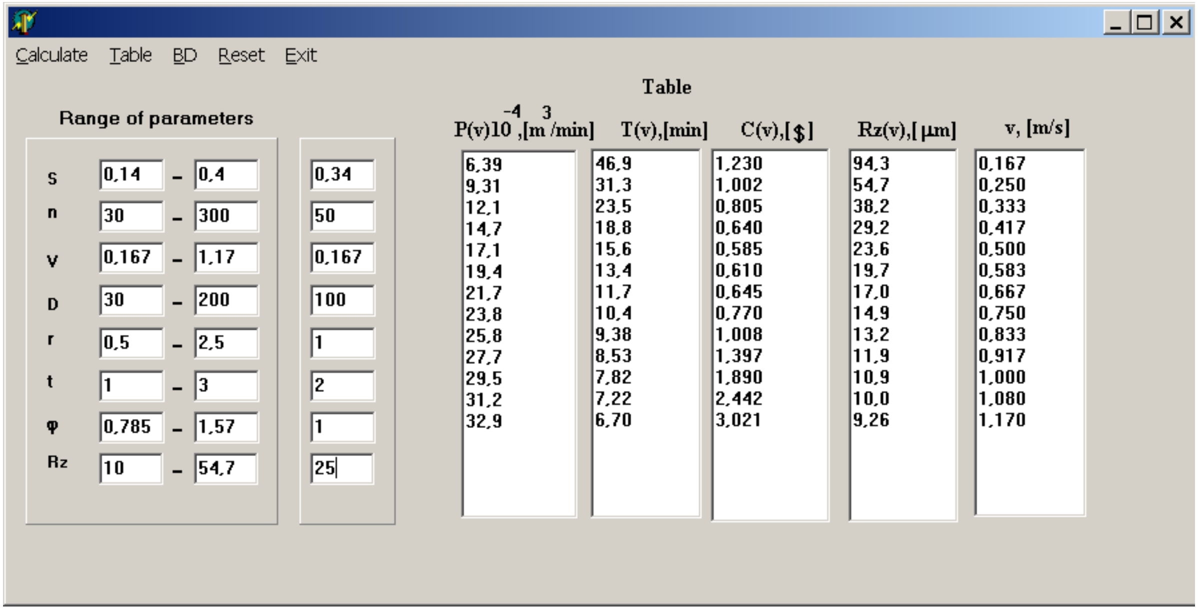

Figure 1. Dynamic pattern of dependences *P = f(v), T = f(v), C = f(v), Rz = f(v,)* at *s* = 0.34 mm/rev, *t* = 1 mm

presentation of the initial and output information and a range of variation of cutting mode parameters are represented in Figure 1.

The output data include the calculation data of criteria *P*, *T*, *C*, *Rz*, depicted in the form of dependences *P=f(v), T=f(v), C=f(v), Rz=f(v)*. A graphic presentation of the output data is shown in Figure 2.

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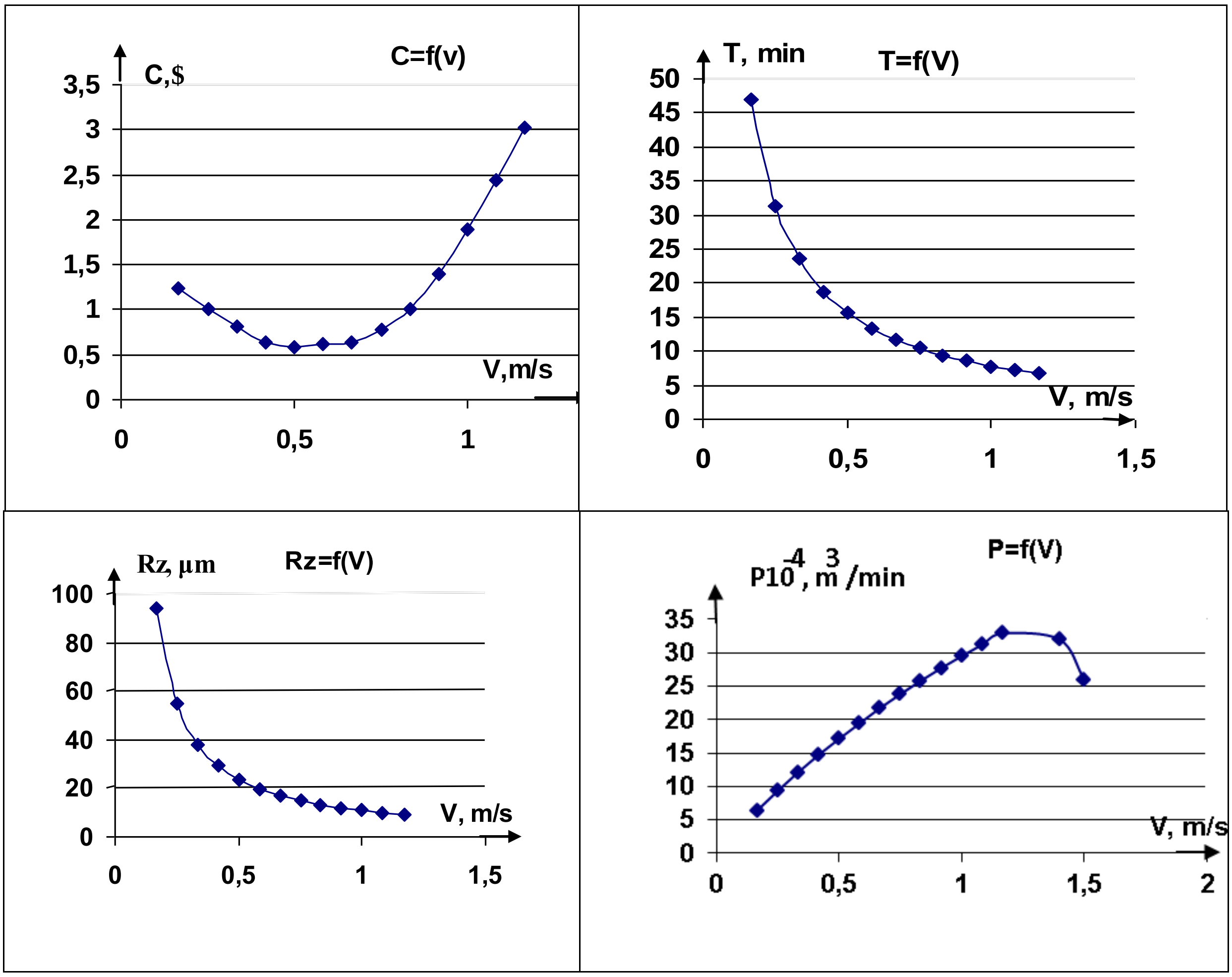

Figure 2. Influence of the cutting speed v on principle characteristics of the cutting process in turning of workpieces made of titanium alloy BT9 at feed rate *s* = 0.34 mm/rev, depth of cut *t* = 1 mm.

Calculation data (results) are performed for feed rate s=0.34mm/rev. A unit of measurement P on the graph is presented in m^3. Data for other values s within the given range of feed rate is calculated in a similar way according to the relevant technique. Corresponding to the graphs it is possible to define current values of criteria P, T, C, and Rz when the cutting speed v is changed in limits from 0.17 to 1.5 m/s.

A ‘coordinate descent method’ is used to determine the optimum value of the effectiveness criterion *P*, *T*, *C*, *Rz*. A calculation of minimum net cost *C* = *f (s, n, v, D, r, t)* of machining of the workpiece made of titanium alloy BT9 is demonstrated in Figure 3.

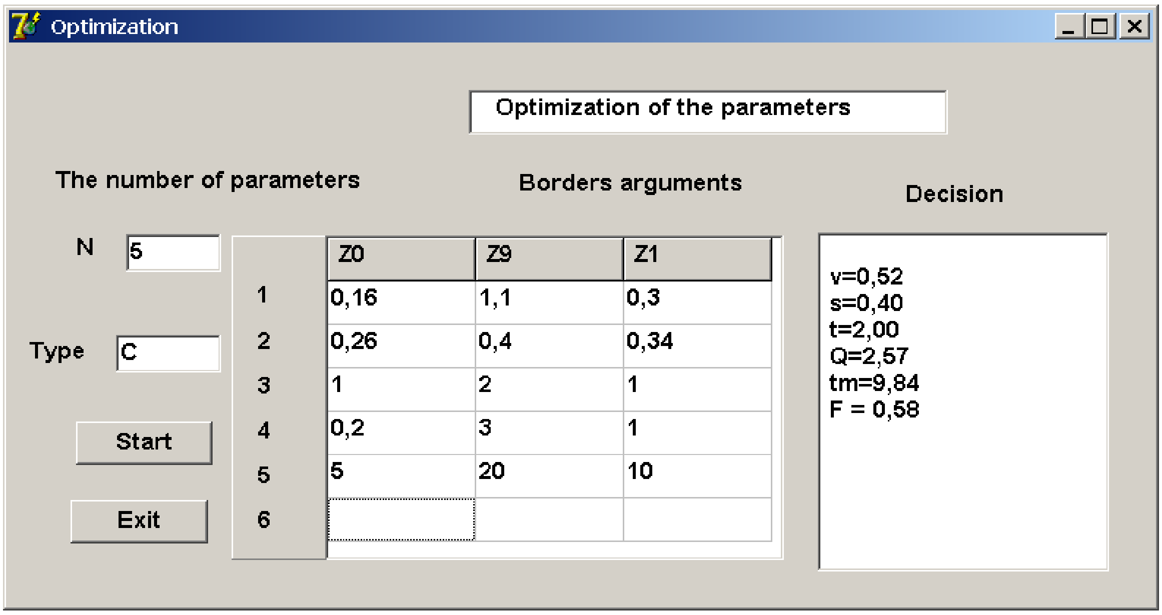

Figure 3. Optimization of cutting mode parameters for net cost $C = f(s, n, v, D, r, t)$.

4. Research results

Mathematical models, numerical methods and graphical interface offer the possibility to determine optimal cutting modes in accordance with the specified effectiveness criteria on the basis of initial parameters and the variation of their values in the given range.

Research is conducted and graphical dependences on cutting speed v and feed rates are plotted for the following criteria: effectiveness, productivity, cutting tool life, net cost, and roughness of the machined surface. It is possible to define optimization parameters for various cutting modes using graphical characteristics. Thus, in machining of the workpiece made of titanium alloy BT9 at depth of cut t=1 mm the minimum net cost C = $ 0.585 will be obtained under the following parameters: productivity $P = 17.1 \cdot 10^{-4}$ m^3/min, cutting tool life T = 15.6 min, cutting speed v = 0.5 m/s, feed rate s = 0.34 mm/rev, depth of cut t = 1 mm.

Experimental research was carried out in laboratory and plant conditions on the lathe machine (model 16K20). Cutting speed v was being changed in a range of 0.17…1.17 m/s, feed rate s was being varied in a range of 0.14…0.4 mm/rev.

Straight-turning tools with indexable inserts made of cemented carbide BK8 (WC-8Co) were used as a cutting tool. The conducted experimental research showed the correlation of the theoretical (Figure 1…3) and practical results (Table 1). The criterion of tool deterioration of wear-land h_f was 0.3 mm.

Table 1. Experimental data

№ exp.	Cutting speed V, [m/s]	Cutting tool life T [min]	Productivity P×10^{-4}, [m^2/min] when t=1 mm	Quantity of machined parts, [pieces]	Machining time, t_m [min]	Net cost, $ [dollar]
1	0.19	40	39.5	2.44	19.75	1.18
2	0.46	18.8	94.5	2.6	9.62	0.6
3	0.66	6.8	134	1.07	7.7	0.628
4	0.9	1.6	183.5	0.284	6.48	1.245
5	1.11	0.8	220	0.139	5.35	2.33

5. Conclusion

The calculation of cutting mode parameters has been carried out by means of mathematical simulation with the subsequent verification in the form of experiment under plant conditions for the purpose of decreasing labour input and reducing high cost of actual test.

The graphical interface of computational modeling for optimization of cutting process parameters for turning of the hard-to-machine titanium alloy has been developed. It allows setting optimal cutting modes based on the range variation of initial parameters.

Guidelines for the cutting process optimization taking into account the restrictions imposed on parameters of the cutting mode in conformity with the specified effectiveness criteria have been worked out on the basis of the present research.

References

[1] Semeniuta V and Krzhenizkii I 2002 *Titanium* **1** 62–65
[2] Vereshhaka A, Anikeev A, Dacheva A 2010 *Mechanical engineering technology* **3** 17–22
[3] Kozlov V and Li X 2015 *Applied Mechanics and Materials: Scientific Journal* **756** 126–131
[4] Makarov A 1976 *Moscow: Mechanical engineering* 278
[5] *Information on Embarcadero Delphi XE2 Lite* http://www.embarcadero.com/
[6] Kirsanov S and Babaev A 2014 *IOP Conference Series: Mater. Science and Engineer.* **661(1)** 1–5