

STUDY REGARDING THE ECONOMIC OPTIMIZATION OF THE TOOL LIFE AND THE CUTTING SPEED AT DRILLING OF THE STAINLESS STEEL X2CrNiMo18-14-3

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Abstract: *In the specialized literature the cost of the machining process has been analyzed using a number of approaches and varying degrees of simplification to determine the optimum tool life and the tool speed. The accuracy of prediction is dependent on the degree of sophistication of the model. The purpose of this paper is the optimization of the cutting tool life and the cutting speed at the drilling of the stainless steels in terms of the minimum machining cost. A more comprehensive nonlinear programming model to minimize the total cost at the drilling of a stainless steel is developed in this paper. The optimum tool life and the associated tool speed are obtained by solving this model. The results can be taken into consideration in the educational studies and in the theoretical technical research. They can be implemented in the manufacturing activity.*

Keywords: *tool life, cutting speed, machining cost, drilling, stainless steel.*

1. Introduction

The stainless steels are used more and more in various key domains of the technique [4]. The problems related to the wear of the cutting tools and the tools life at the machining of the stainless steels are very important due to the chemical and mechanical characteristics of these steels [1, 9]. Over time the research have studied the causes which produce the cutting tool wear and the methods to improve the cutting tools durability, either by creating new types of materials for tools, either by the choice of tools geometric parameters and cutting regime [6, 8].

The purpose of this paper is the optimization of the cutting tool life and the cutting speed at the drilling of the stainless steels, in terms of the global indicator of the minimum machining cost.

In the specialized literature [5, 7] the cost of the machining process has been analyzed using a number of approaches and various degrees of simplification. The accuracy of the prediction of the cutting tool life and the cutting speed is dependent on the degree of sophistication of the cost model. Therefore, in this paper the total cost C of the drilling operation is considered as the sum of eight incremental costs C_i , $i = 1, \dots, 8$.

A more comprehensive nonlinear programming model to minimize the total cost at the drilling of a stainless steel is developed in this paper. By using the specialized software WinQSB, the optimum cutting tool life and the associated cutting tool speed are obtained by solving, the numerical model for the analyzed case study of the stainless steel X2CrNiMo18-14-3.

2. Determination of the cost of the drilling operation

The total cost C of a machining operation in a metal cutting process is presented in the specialized literature [5, 7] as the function:

$$C = \frac{c_1 \cdot l}{n \cdot f} \left(1 + \frac{c_2}{c_1 \cdot T} \right) \quad [\text{€}]. \quad (1)$$

where: c_1 is the wage of the worker, [€/min]; c_2 – tool operating expenses, [€]; T – cutting tool life, [min]; l – hole length, [mm]; n – rotational speed, [rot/min]; f – cutting feed, [mm/rot].

For a more accurate calculation of the cost of processing, other factors must be taken into account. In this manner, it is proposed the following relation for the total cost C of a

machining operation, as a sum of eight incremental costs:

$$C = \sum_{i=1}^8 C_i \quad [\text{€}]. \quad (2)$$

where: C_1 is the processing cost, [€]; C_2 – cost of the cutting tool change, [€]; C_3 – cost of the cutting tool grinding, [€]; C_4 – cost of the cutting tool depreciation, [€]; C_5 – cost of the machine tool depreciation, [€]; C_6 – cost of the cutter grinding machine depreciation, [€]; C_7 – cost of the electrical energy consumption of machine tool, [€]; C_8 – cost of the electrical energy consumption of grinding machine, [€].

The processing cost C_1 is given by the relation:

$$C_1 = c_1 \cdot (t_b + \sum t_n) \cdot (1 + q) \quad [\text{€}]. \quad (3)$$

where: c_1 is direct labour cost, [€/min]; t_b – machining time, [min]; $\sum t_n$ – sum of non-productive labour time (auxiliary and maintenance service), [min]; q – coefficient that takes into account the contributions of the economic and technical staff to processing achievement ($q = 0.5$ for a well organized production).

The cost of the cutting tool change C_2 is given by the relation:

$$C_2 = c_1 \cdot t_s \cdot \frac{t_b}{T} \quad [\text{€}]. \quad (4)$$

where: t_s is the tool change and resetting time consumption, [min]; t_b/T – number of tool changes within machining operation; T – cutting tool life, [min].

The cost of the cutting tool grinding C_3 is calculated by the relation:

$$C_3 = c_2 \cdot t_a \cdot \frac{t_b}{T} \quad [\text{€}]. \quad (5)$$

where: c_2 is the direct labour cost for the cutting tool grinding, [€/min]; t_a – the time consumption for the cutting tool grinding, [min].

The cost of the cutting tool depreciation C_4 is given by the relation:

$$C_4 = \frac{t_b}{T} \cdot \frac{C_s}{N_r} \quad [\text{€}]. \quad (6)$$

where: C_s is the initial cost of the new (unused) cutting tool, [€]; N_r – permissible number of cutting tool regrinds to out of use.

The cost of the machine tool depreciation C_5 is calculated by the relation:

$$C_5 = C_{mu} \cdot \frac{t_b + \sum t_n}{F_t} \quad [\text{€}]. \quad (7)$$

where: C_{mu} is the capital cost of the machine tool plus maintenance cost, [€]; F_t – the machine tool life, in min, given by the relation:

$$F_t = A \cdot z \cdot s \cdot h \cdot 60 \quad [\text{min}]. \quad (8)$$

where: A is the productive life of the machine tool, [years]; z – number of working days in an year; s – number of shifts in a day; h – working hours per shift.

The cost of the cutter grinding machine depreciation C_6 is given by the relation:

$$C_6 = \frac{C_{ma}}{F_{ta}} \cdot t_a \cdot \frac{t_b}{T} \quad [\text{€}]. \quad (9)$$

where: C_{ma} is the capital cost of the cutter grinding plus maintenance cost, [€]; F_{ta} – the cutter grinding machine life, given by relation (8), [min].

The cost of the electrical energy consumption of machine tool C_7 is calculated by the relation:

$$C_7 = P \cdot c_3 \cdot \frac{t_b}{60} \quad [\text{€}]. \quad (10)$$

where: c_3 is the cost of the electrical energy consumed, [€/kWh]; P – the power consumption of the machining process, [kW], which for drilling is given by:

$$P = \frac{M \cdot n}{9740 \cdot \eta} \quad [\text{kW}]. \quad (11)$$

where: M is the torsional moment, [Nm]; n – the rotation speed, [rot/min]; η – the efficiency.

The cost of the electrical energy consumption of grinding machine C_8 is given by the relation:

$$C_8 = P_a \cdot c_3 \cdot \frac{t_a}{60} \cdot \frac{t_b}{T} \quad [\text{€}]. \quad (12)$$

where: P_a is the power consumption of the cutter grinding machine, [kW].

The total cost of the drilling operation C is obtained by substituting the above eight incremental costs in equation (2). The obtained expression is the following:

$$\begin{aligned}
 C = & t_b \cdot \left(c_1 + c_1 \cdot q + \frac{C_{mu}}{F_t} \right) + \\
 & + \frac{t_b}{T} \cdot \left(c_1 \cdot t_s + c_2 \cdot t_a + \frac{C_s}{N_r} + \right. \\
 & + t_a \cdot \frac{C_{ma}}{F_{ta}} + P_a \cdot c_3 \cdot \frac{t_a}{60} \left. \right) + \quad [€]. \quad (13) \\
 & + P \cdot c_3 \cdot \frac{t_b}{60} + \\
 & + \left(c_1 + c_1 \cdot q + \frac{C_{mu}}{F_t} \right) \cdot \sum t_n
 \end{aligned}$$

3. Mathematical model to minimize the cost of the drilling operation

The machining time t_b can be written in the cost expression (13) as:

$$t_b = \frac{L}{n \cdot f} \cdot i \quad [\text{min}]. \quad (14)$$

where: L is the length of a hole (including the engagement and exceeding of the drill), [mm]; i – number of holes; f – the cutting feed, [mm/rot].

The rotational speed n is given by:

$$n = \frac{1000v}{\pi \cdot D} \quad [\text{rot/min}]. \quad (15)$$

where: D is the diameter of the hole, [mm]; v is the cutting speed, [m/min], given by the Taylor's relation at drilling:

$$v = \frac{C_v \cdot D^{x_v}}{T^m \cdot f^{y_v}} \quad [\text{m/min}]. \quad (16)$$

where: C_v is a constant determined experimentally, according to the couple workpiece material-tool and the cutting conditions; m – durability exponent of the spiral drill; x_v , y_v – polytropic exponents.

The proposed optimization mathematical model contains the optimization objective function and several restrictive relations:

$$\min C \quad (17)$$

$$f \leq C_f \cdot D^{0.6} \cdot k_s \quad (18)$$

$$f^{y_M} \cdot n \cdot v^{z_M} \leq \frac{9740\eta \cdot P}{C_M \cdot D^{x_M} \cdot c} \quad (19)$$

$$f^{y_F} \cdot v^{z_F} \leq \frac{F_{ma}}{D^{x_F} \cdot C_F \cdot c_m} \quad (20)$$

$$f^{y_F} \cdot v^{z_F} \leq \frac{2,465E \cdot I_{\min}}{C_F \cdot D^{x_F} \cdot l_c^2 \cdot c_f} \quad (21)$$

$$f_{\min} \leq f \leq f_{\max} \quad (22)$$

$$n_{\min} \leq n \leq n_{\max} \quad (23)$$

The objective function (17) of the above model is the total cost of machining operation C , given by the relation (13), which must be minimized.

The restrictive relation (18) of the cutting feed includes: C_f – a constant which depends on the processed material and on precision machining; k_s – a correction coefficient depending on the ratio l/D , where l is the length of the hole.

The restrictive relation (19) of the power consumption of the machining process includes: C_M – a constant; x_M , y_M , z_M – poly-tropic coefficients; c – safety coefficient, $c = 1.7$.

The restrictive relation (20) of the advance mechanism of the drilling machine includes: F_{ma} – the maximum allowed force of the advance mechanism; C_F – a constant; x_F , y_F , z_F – polytropic coefficients; c_m – safety coefficient, $c_m = 1.6$.

The restrictive relation (21) of the buckling resistance of the spiral drill includes: E – modulus of elasticity, [N/mm²]; I_{\min} – minimum moment of inertia, [mm⁴]; l_c – initial length in console of the spiral drill, [mm]; c_f – safety coefficient to buckling, $c_f = 1.8$.

The restrictive relations (22) and (23) of the drilling machine kinematics require that the two parameters f and n have values in the feed range and, respectively, the rotation range, developed by the drilling machine.

4. Case study for the drilling of the stainless steel X2CrNiMo18-14-3

The drilling operation of the studied stainless steel was performed using a machine tool GC₀ 32 DM3 drilling device and Rp5 high-speed steel spiral drills.

The constants $C_f = 0.031$ and $k_s = 0.9$ were chosen from the specialized literature (tab.6.10 and tab.6.11 in [10]). The values of the constants and polytropic coefficients for the drilling of the steel

X2CrNiMo18-14-3 were determined based on the experimental measurements: $C_F = 3570$, $x_F = 0.52$; $y_F = 0.46$, $z_F = -0.17$, $C_M = 28$, $x_M = 0.63$, $y_M = 0.57$, $z_M = -0.22$ from [3]; $C_v = 4.27$, $x_v = 0.55$, $y_v = 0.242$, $m = 0.137$ from [11].

The other values of the numeric model are: $L = 50$ mm; $i = 1$; $D = 16$ mm; $n = 246$ rot/min; $\eta = 0.8$; $P = 3.15$ kW; $F_{ma} = 960$ daN; $E = 2.1 \cdot 10^4$ daN/mm²; $I_{min} = 0.043 \cdot D^4 = 2818$ mm⁴; $l_c = 120$ mm.

From the relations (18)-(22) it is obtained $f \leq 0.14$ mm/rot. Because the used drilling machine ensures the feeds: 0.12; 0.20; 0.32; 0.50 mm/rot, it results that $f = 0.12$ mm/rot.

The resulted numerical optimization model for the stainless steel X2CrNiMo18-14-3 is resolved using the module *Nonlinear Programming* of the specialized software *WinQSB* [2].

The numerical model data are shown in Fig.1.

The command *Solve the problem* from the menu *Solve and Analyze* returns a table with the *Solution summary* (Fig.2), which contains: the optimum value of the tool life, $T_{oc} \cong 16.9$ min; the corresponding minimum value of the drilling cost, $C_{min} \cong 0.62$ €.

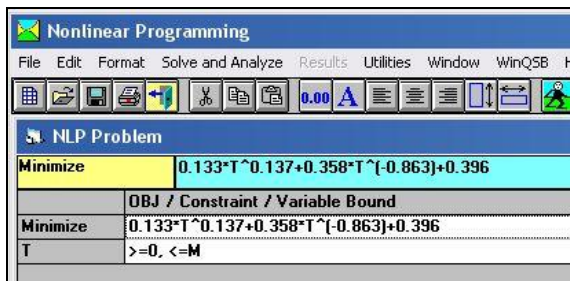


Figure 1: Numerical model data

04-05-2013	Decision Variable	Solution Value
1	T	16.9368
Minimized	Objective Function =	0.6231

Figure 2: Solution summary

The command *Objective Function Analysis* from the menu *Solve and Analyze* opens a dialog box, which is filled with values as in Fig. 3.

A click on the button *Table* returns the tabular analysis of the machining cost C depending on the tool life T , presented in Fig. 4, valid only for the studied steel. A click on the button *Graph* from the dialog box or the command *Show Objective Function Analysis-*

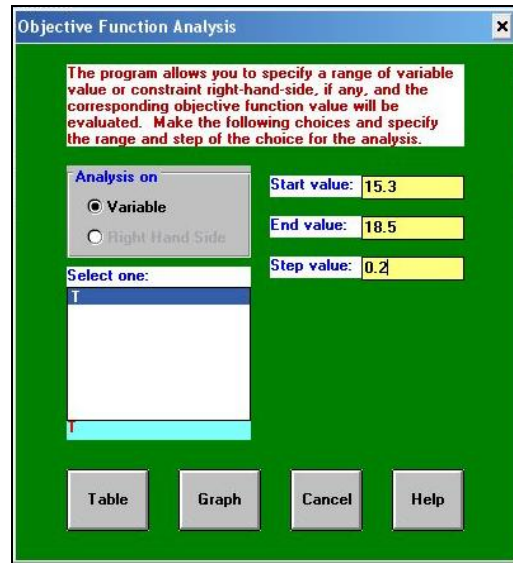


Figure 3: The dialog box *Objective Function Analysis*

04-05-2013	T	Objective Function
1	15.3000	0.6233
2	15.5000	0.6232
3	15.7000	0.6232
4	15.9000	0.6232
5	16.1000	0.6232
6	16.3000	0.6231
7	16.5000	0.6231
8	16.7000	0.6231
9	16.9000	0.6231
10	17.1000	0.6231
11	17.3000	0.6231
12	17.5000	0.6231
13	17.7000	0.6231
14	17.9000	0.6232
15	18.1000	0.6232
16	18.3000	0.6232
17	18.5000	0.6232

Figure 4: Tabular analysis of the machining cost depending on the tool life

Graph from the menu *Results* displays the graphical analysis of the machining cost C depending on the tool life T (Fig. 5).

The optimum cutting speed, v_{oc} , for minimum cost of the drilling operation is given by the relation (16):

$$v_{oc} = \frac{4.27 \cdot 16^{0.55}}{16.9^{0.137} \cdot 0.12^{0.242}} = 22.25 \text{ m/min}$$

5. Conclusions

The minimum cost can represent a global indicator for appreciation of the machinability. The optimum tool life to provide the minimum cost of the machining operation is derived from the new proposed cost model. The use of a more

comprehensive cost model allows greater accuracy in the prediction of the cost and getting the optimum tool life and the optimum cutting speed.

The presented results can be taken into consideration in the educational studies and in the theoretical technical research. They can be implemented in the manufacturing activity.

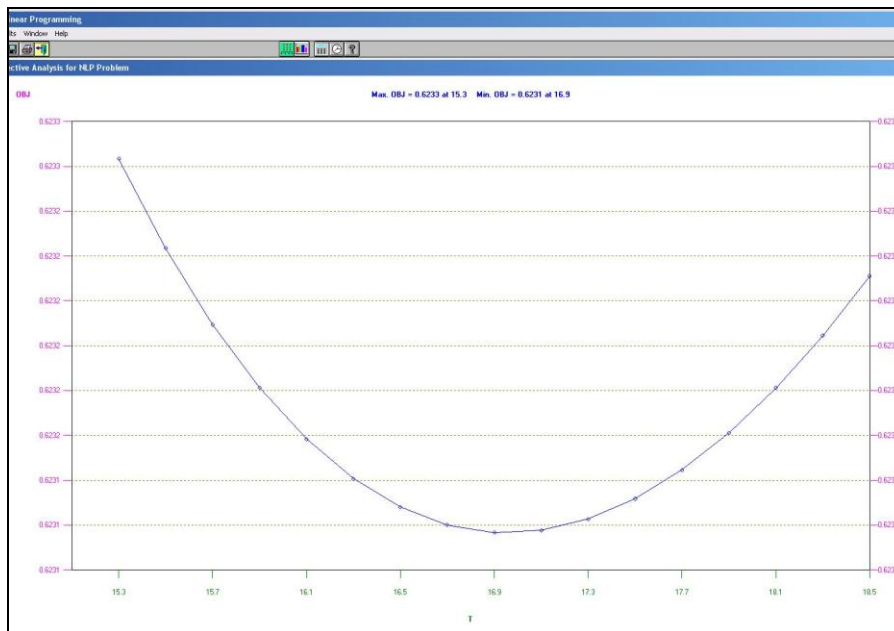


Figure 5: Graphical analysis of the machining cost depending on the tool life

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