International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. VII, No. 2 / 2015

MODEL FOR ECONOMIC OPTIMIZATION OF THE TOOL LIFE AND THE CUTTING SPEED AT DRILLING OF THE STEEL X15CrNiSi20-12

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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.
Key words: tool life, cutting speed, machining cost, drilling, stainless steel.

1. INTRODUCTION

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]. 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 [2,3]. 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 [4, 5] 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 Ci, i=(1...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 X15CrNiSi20-12.

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 [1, 5] as the function:

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

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:

$$C = \sum_{i=1}^{8} C_i \quad [€] \tag{2}$$

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, [€]. In detail, each of these incremental costs is given below:

$$C_1 = c_1 \cdot \left(t_b + \sum t_n\right) \cdot (1+q) \quad [€] \qquad (3)$$

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).

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

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].

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

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].

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

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.

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

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:

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

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 hour per shift.

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

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

$$C_7 = P_m \cdot c_3 \cdot \frac{t_b}{60} \quad [€] \qquad (10)$$

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

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

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

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

where: P_a is the power consumption of the cutter grinding machine, [kW].
The obtained expression of the total cost of the drilling operation is the following:

$$\begin{gathered} C = t_b \cdot \left(c_1 + c_1 \cdot q + \frac{C_{mu}}{F_t}\right) + \frac{t_b}{T} \\ \left(c_1 \cdot t_s + c_2 \cdot t_a + \frac{C_s}{N_r} + t_a \cdot \frac{C_{ma}}{F_{ta}} + P_a \cdot c_3 \cdot \frac{t_a}{60}\right) + \\ + P \cdot c_3 \cdot \frac{t_b}{60} + \left(c_1 + c_1 \cdot q + \frac{C_{mu}}{F_t}\right) \cdot \Sigma t_n \end{gathered} \qquad (13)$$

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:

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

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:

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

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

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

where: C_v is a constant determined experimentally, according to the couple workpiece material-tool and the cutting conditions; m_v – 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:

$$\begin{cases} \min\ C & (17) \\ f \le C_f \cdot D^{0,6} \cdot k_s & (18) \\ f^{y_M} \cdot n \cdot v^{z_M} \le \dfrac{9740\eta \cdot P_m}{C_M \cdot D^{x_M} \cdot c} & (19) \\ f^{y_F} \cdot v^{z_F} \le \dfrac{F_{ma}}{D^{x_F} \cdot C_F \cdot c_m} & (20) \\ f^{y_F} \cdot v^{z_F} \le \dfrac{2{,}465 E \cdot I_{\min}}{C_F \cdot D^{x_F} \cdot l_c^2 \cdot c_f} & (21) \\ f_{\min} \le f \le f_{\max} & (22) \\ n_{\min} \le n \le n_{\max} & (23) \end{cases}$$

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 [6] 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 – polytropic coefficients; c – safety coefficient, c =1.7 in [6].
The restrictive relation (20) of the advance mechanism of the drilling machine expresses the condition that the axial component of the cutting force to be lower than the maximum force allowed; it 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 in [6].
The restrictive relation (21) of the buckling resistance of the spiral drill includes: E – modulus of elasticity, [N/mm^2]; $I_{\min}$ – minimum moment of inertia, [mm^4]; l_c – initial length in console of the spiral drill, [mm]; c_f – safety coefficient to buckling, c_f = 1.8 in [6].
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 X15CrNiSi20-12

The drilling operation of the studied stainless steel X15CrNiSi20-12 (DIN 17243, EN 95) was performed using a machine tool GC_0 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 [6]). The values of the constants and polytropic coefficients for the drilling of the steel X15CrNiSi20-12 were determined based on the experimental measurements: C_F = 2316, x_F = 1.06, y_F = 0.4, z_F = -0.42 in [7]; C_M = 0.72, x_M = 1.84, y_M = 0.34, z_M = -0.35 in [8]; C_v = 4.227, x_v = 0.39, y_v = 0.272, m_v = 0.164 in [9].
The other values of the numeric model are: $c_1 = c_2$ = 0.12 €/min; t_a = 2 min; t_s = 0.5 min; C_s = 1.9 €; N_r = 40; l_c = 120 mm; P_a = 3 kW; C_{mu} = 41000 €; C_{ma} = 3200 €; F_t = 1440000 min; F_{ta} = 720000 min; c_3 = 0.38 €/kWh; L = 50 mm; i = 1; D = 16 mm; n = 246 rot/min; η = 0.8; P_m = 3.15 kW; F_{ma} = 960 daN; $I_{\min} = 0.043 \cdot D^4 = 2818\,mm^4$; $E = 2.1 \cdot 10^4$ daN/mm^2.
From the relations (18)-(22) it is obtained $f \le 0{,}24$ mm/rot. Because the used drilling machine ensures the feeds: 0.12; 0.20; 0.32; 0.50 mm/rot, it results that f = 0.20 mm/rot.
Finally, the resulted numerical optimization model is the following nonlinear programming model, with the objective function C, one real variable, T, without restrictions:

$$\begin{cases} [\min]\ C = 0.143 \cdot T^{0.164} + \dfrac{0.402}{T^{0.836}} + 0.77758 \\ T \ge 0 \end{cases} \qquad (24)$$

The above model is resolved using the module *Nonlinear Programming* of the specialized software *WinQSB* [10]. The table with input data is shown in Fig. 1. The command *Solve the problem* returns the table with *Solution summary* (Fig. 2), which contains: the optimum value of the tool life, $T_{oe} \cong 14.3$ min; the corresponding minimum value of the drilling cost, $C_{\min} \cong 1.04$ €.

	OBJ / Constraint / Variable Bound
Minimize	0.143*T^0.164+0.402*T^(-0.836)+0.77758
T	>=0, <=M

Fig. 1. Numerical model data

02-01-2015	Decision Variable	Solution Value
1	T	14.3049
Minimized	Objective Function =	1.0423

Fig. 2. Solution summary

The command *Objective Function Analysis* returns the tabular analyze (Fig. 3) and the graphical analyze (Fig. 4) of the machining operation C depending on the tool life T, valid only for this steel.

02-01-2015	T	Objective Function
1	11.3000	1.0434
2	12.3000	1.0427
3	13.3000	1.0424
4	14.3000	1.0423
5	15.3000	1.0424
6	16.3000	1.0426
7	17.3000	1.0429

Fig. 3. Tabular analysis of the machining cost depending on the tool life

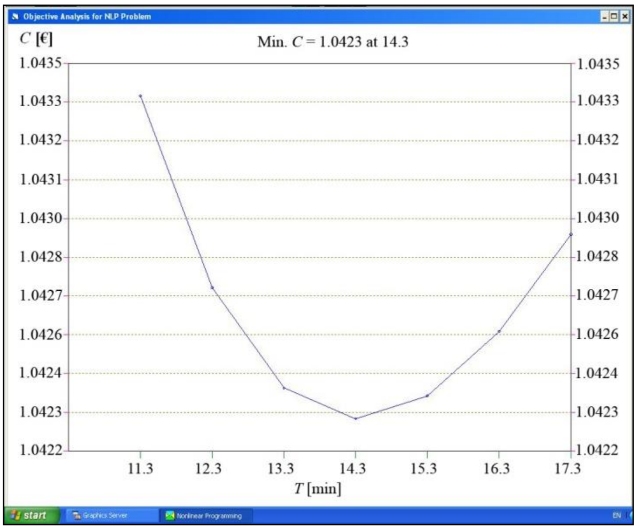

Fig. 4. Graphical analysis of the machining cost depending on the tool life

The optimum cutting speed, v_{oe}, is calculated with the relation (16), based on the optimum value of the tool life T_{oe}:

$$v_{oe} = \frac{C_v \cdot D^{x_v}}{T_{oe}^{m_v} \cdot f^{y_v}} = \frac{4.227 \cdot 16^{0.39}}{14.3^{0.164} \cdot 0.20^{0.272}} = 12.48 \text{ m/min} \quad (25)$$

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 machining cost and getting the optimum tool life and, respectively, the optimum cutting speed.

The presented results can be taken into consideration in the educational studies for pedagogical purposes and in the theoretical technical research. Also, the results can be implemented in the manufacturing activity.

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Received: July 12, 2015 / Accepted: December 10, 2015 / Paper available online: December 20, 2015 © International Journal of Modern Manufacturing Technologies.