Tool life and cutting speed for the maximum productivity at the drilling of the stainless steel X22CrMoV12-1

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Abstract. Two addressed issues in the research regarding the cutting machinability, establishing of the optimum cutting processing conditions and the optimum cutting regime, do not yet have sufficient data for solving. For this reason, in the paper it is proposed the optimization of the tool life and the cutting speed at the drilling of a certain stainless steel in terms of the maximum productivity. For this purpose, a nonlinear programming mathematical model to maximize the productivity at the drilling of the steel is developed in the paper. The optimum cutting tool life and the associated cutting tool speed are obtained by solving the numerical mathematical model. Using this proposed model allows increasing the accuracy in the prediction of the productivity for the drilling of a certain stainless steel and getting the optimum tool life and the optimum cutting speed for the maximum productivity. The results presented in this paper can be used in the production activity, in order to increase the productivity of the stainless steels machining. Also new research directions for the specialists in this interested field may come off from this paper.

1. Introduction
The stainless steels are used more and more in various key domains of the technique [1]. The processing of these steels is determined by their specific physical-chemical characteristics and by their technological properties [2, 3]. The research in the last decade regarding the cutting machinability of the stainless steels have highlighted the insufficiency of the data for establishing of the optimum cutting processing conditions and the optimum cutting regime [4, 5]. Therefore the purpose of this paper is the optimization of the tool life and the cutting speed at the drilling of a stainless steel, in terms of the global indicator of the maximum productivity.

For maximize the productivity at the drilling of the steel, a nonlinear programming mathematical model is developed in this paper. The cutting tool life is the optimum solution of this model. The cutting tool speed is obtained on the basis of this value of the tool life. The numerical model, developed for the analyzed case study of the stainless steel X15CrNiSi20-12 (DIN 17243, EN 95), is resolved using the specialized software WinQSB. The variation (numerical and graphical) of the productivity depending on the cutting tool life is also presented in this paper, valid only for the studied steel. Thus the results of the analytical solving of the model are confirmed.
2. **Determination of the productivity of the drilling operation**

The time technical norm $N_t$ of a machining operation in a metal cutting process is presented in the specialized technical literature [6] as the function:

$$N_t = t_b + t_{aux} + t_{dt} + t_{do} + t_{on} + \frac{t_{pi}}{n_l} \text{ [min/piece]}$$  \hspace{1cm} (1)

where:
- $N_t$ is time norm on piece (or operation or phase), [min/piece];
- $t_b$ – machining time, [min/piece];
- $t_{aux}$ – auxiliary time, [min/piece];
- $t_{dt}$ – technical maintenance time, [min/ piece];
- $t_{do}$ – organizational maintenance time, [min/ piece];
- $t_{on}$ – rest and natural necessities time, [min/ piece];
- $t_{pi}$ – preparation-closing time on the lot, [min];
- $n_l$ – batch of parts that are continuously processed, to the same machine tool.

The machining time $t_b$ for the drilling operation can be written as:

$$t_b = \frac{L}{n \cdot f} \text{ [min]}$$  \hspace{1cm} (2)

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 the relation:

$$n = \frac{1000 \cdot v}{\pi \cdot D} \text{ [rot/min]}$$  \hspace{1cm} (3)

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

$$v = \frac{C_v \cdot D^{x_v} \cdot T^{y_v}}{T^{m} \cdot f^{1-y_v}} \text{ [m/min]}$$  \hspace{1cm} (4)

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

Substituting for $v$ from (4) in (3), and then for $n$ from (3) in (2), the expression of the machining time $t_b$ becomes:

$$t_b = \frac{L \cdot T^m \cdot D^{1-x_v} \cdot i}{318 C_v \cdot f^{1-y_v}} \text{ [min]}$$  \hspace{1cm} (5)

The auxiliary time $t_{aux}$ is chosen from normative tables.

The technical maintenance time $t_{dt}$ is calculated by the relation [6]:

$$t_{dt} = \frac{(t_s + t_a) \cdot t_b}{T} \text{ [min/piece]}$$  \hspace{1cm} (6)

where:
- $t_s$ is the consumed time for the tool changing and adjustment remaking, [min];
- $t_a$ – the consumed time for the drill sharpening, [min].

The organizational maintenance time $t_{do}$ is given by the relation [6]:

$$t_{do} = \frac{k_2}{100} (t_b + t_{aux}) \text{ [min/piece]}$$  \hspace{1cm} (8)

where $k_2$ is a constant chosen from normative tables.

The obtained expression of the time technical norm for drilling operation is the following:
Finally, the relation of the productivity for the drilling operation can be written as:

\[ t_{on} = \frac{k_2}{100} \left( t_b + t_{aux} \right) \text{ [min/piece]} \]  

(10)

3. Mathematical Model to Maximize the Productivity of the Drilling Operation

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

\[
\begin{align*}
\text{max } P \\
\begin{cases}
f & \leq C_f \cdot D^{0.6} \cdot k_s \quad (12) \\
f^\gamma_u \cdot n^\gamma_u & \leq \frac{9740 \gamma \cdot P_m}{C_m \cdot D^{\gamma_u} \cdot c} \quad (13) \\
f^\gamma_r \cdot v^\gamma_r & \leq \frac{F_{ma}}{D^{\gamma_r} \cdot C_F \cdot c_{ua}} \quad (14) \\
f^\gamma_f \cdot v^\gamma_f & \leq \frac{2.465E \cdot I_{min}}{C_F \cdot D^{\gamma_f} \cdot l_c^2 \cdot c_f} \quad (15) \\
f_{min} & \leq f \leq f_{max} \\
n_{min} & \leq n \leq n_{max} 
\end{cases}
\end{align*}
\]

(11) (12) (13) (14) (15) (16) (17)

The objective function (11) of the model is the productivity of the processing operation, \( P \), given by the relation (10), which must be maximized. The restrictive relation (12) of the cutting feed includes: \( C_f \) – a constant which depends on 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, [mm]; \( D \) is the hole diameter, [mm]. The restrictive relation (13) of the power consumption of the machining process includes: \( C_{F} \) – a constant; \( \gamma_u, \gamma_r, \gamma_f \) – polytropic coefficients; \( c \) – safety coefficient, \( c = 1.7 \) in [6].

The restrictive relation (14) 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; \( c_{ma} \) – safety coefficient, \( c_{ma} = 1.6 \) in [6].

The restrictive relation (15) 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 (16) and (17) 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 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 (table 6.10 and table 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: \( L = 50 \text{ mm} \); \( i = 1 \); \( D = 16 \text{ mm} \); \( ts = 0.5 \text{ min} \); \( ta = 2 \text{ min} \); \( k_1 = 1 \); \( k_2 = 4 \) in [6]; \( \tau_1 = 1.48 \text{ min} \); \( \tau_1 = 15 \text{ min} \); \( n = 246 \text{ rot/min} \); \( \eta = 0.8 \); \( P_m = 3.15 \text{ kW} \); \( F_m = 960 \text{ daN} \); \( I_{\min} = 0.043 \cdot D^3 = 2818 \text{ mm}^4 \); \( E = 2.1 \cdot 10^4 \text{ daN/mm}^2 \); \( l_c = 120 \text{ mm} \).

From the relations (12)-(16) it is obtained \( f \leq 0.24 \text{ mm/rot} \). Because the used drilling machine ensures the feeds: 0.12; 0.20; 0.32; 0.50 mm/rot, it results that \( f = 0.20 \text{ mm/rot} \).

Finally, the resulted numerical optimization model is a nonlinear programming model without restrictions:

\[
\begin{align*}
[p_{\text{max}}] = \frac{60}{0.684 \cdot T^{0.164} + 1.628 \cdot T^{-0.836} + 1.704} & \quad (18)
\end{align*}
\]

The objective function \( P \) of the above model (18) is a nonlinear function, poynomial type, of a real variable, \( T \). The model is resolved using the module Nonlinear Programming of the specialized software WinQSB [10].

For this purpose, first the command New Problem, from the main menu File, opens the dialog box NLP Problem Specification, which is filled as shown in figure 1.

**Figure 1.** The dialog box NLP Problem Specification.

A click on the OK button opens the workspace window NLP Problem. The numerical model data are inserted in a table, as shown in figure 2. The command Solve the problem, from the main menu Solve and Analyze, returns the table Solution summary (figure 3), which contains: the optimum value of the tool life, \( T_{\text{op}} \approx 12 \text{ min} \); the corresponding maximum value of the drilling productivity, \( P_{\text{max}} \approx 20 \text{ pieces/h} \).

**Figure 2.** Numerical model data.

**Figure 3.** Solution summary.
The command *Objective Function Analysis*, from the main menu *Solve And Analyze*, returns the tabular analysis (figure 4) and the graphical analysis (figure 5) of the machining productivity $P$ depending on the tool life $T$, valid only for the studied steel X15CrNiSi20-12.

**Figure 4.** Tabular analysis of the machining productivity depending on the tool life.

**Figure 5.** Graphical analysis of the machining productivity depending on the tool life.
The optimum cutting speed, \(v_{\text{op}}\), is calculated based on the optimum value of the tool life \(T_{\text{op}}\):

\[
v_{\text{op}} = \frac{C_v \cdot D^x}{T_{\text{op}}^m \cdot f^y} = \frac{4.227 \cdot 16^{0.39}}{12.11^{0.164} \cdot 0.20^{0.272}} = 12.83 \text{ m/min}
\] (19)

The optimum rotational speed, \(n_{\text{op}}\), corresponding to the optimum cutting speed, \(v_{\text{op}}\), is determined with the relation (3):

\[
v_{\text{op}} = \frac{C_v \cdot D^x}{T_{\text{op}}^m \cdot f^y} = \frac{4.227 \cdot 16^{0.39}}{12.11^{0.164} \cdot 0.20^{0.272}} = 12.83 \text{ m/min}
\] (20)

5. Conclusions
The maximum productivity of a machining operation is ensured by the optimum cutting tool life, which is derived from the proposed mathematical model in this paper. Using this model allows increasing the accuracy in the prediction of the productivity for the drilling of a certain stainless steel and getting the optimum tool life and the associated optimum cutting speed. The maximum productivity can represent a global indicator for appreciation of the machinability.

The results presented in this paper can be used in the production activity, in order to increase the productivity of the stainless steels machining. Also new research directions for the specialists in this interested field may come off from this paper.

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