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Pre-hole diameter optimization in high speed drilling considering machining cost

Monia Ben Meftah¹ · Maher Baili² · Bassem Gassara¹ · Gilles Dessein² · Wassila Bouzid Saï¹

Abstract

In this paper, a new methodology of tool diameter optimization in high-speed peck drilling cycle G83 is investigated in order to predict the pre-drill diameters and cutting speed which lead to the minimum cutting cost. In this aim, a pre-drill diameter modeling is proposed. The cycle time is calculated based on a feed rate modeling which depends on the kinematic performance of the machine. To reach higher precision of the predicted results, an optimization algorithm is developed taking into consideration the technological and machine constraints (machine power, spindle speed, and feed rate). An experimental study is carried out to validate the feed rate modeling and to calculate the value of the specific cutting force of studied material. To demonstrate the procedure, an illustrative example of AISI 4140 workpiece material is discussed in detail. The obtained results show that the economical process of drilling in peck drilling cycle G83 is obtained with the minimum number of pre-drill diameter.

Keywords High speed drilling · Pre-drill diameter · Peck drilling cycle G83 · Machining time · Machining cost · Optimization

Nomenclature

T_m	Total machining time [min]	t_u	The time during which the tool is in contact with the work piece [min]
t_c	Time of drilling cycle [min]	T	The tool life [min]
t_r	Time of tool movements at the work feed rate [min]	t_{chns}	The spindle change time per operation [min]
t_{tch}	Time of tool change [min/tool]	t_{sch}	The spindle change time [min]
t_{chnt}	Time of tool change per piece [min]	T_s	The spindle life [min]
t_a	Auxiliary time related to the operator [min]	t_{ld}	The time of unloading a drill tool and loading another one [min]
		t_{rp}	The time of movement at rapid feed rate [min]
		t_{VF}	The time of movement at work feed rate [min]
		t_{EF}	The total temporization time [min]
		V_m	Maximum feed rate [mm min ⁻¹]
		V_f	The feed rate [mm min ⁻¹]
		V_c	The cutting speed [m min ⁻¹]
		$V_{c_{jc}}$	The corrected cutting speed [m min ⁻¹]
		f	The feed [mm/rev]
		f_{jc}	The corrected feed [mm/rev]
		D	The hole diameter [mm]
		l	The hole depth [mm]
		l'	The total hole depth [mm]
		δ	Point angle [°]
		P	The size of first peck drilling cycle [mm]
		Q	The size of following peck drilling cycle [mm]
		Q_f	The last peck drilling [mm]
		n	The number of peck drilling

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n_p	The number of pre-holes
A_m	Maximum acceleration [m s^{-2}]
A	Acceleration of work [m s^{-2}]
J_m	Maximum jerk [m s^{-3}]
J	Jerk of work [m s^{-3}]
C	The total machining cost [\\$]
C_a	The auxiliary cost [\\$]
C_t	The tool cost per operation [\\$]
C_0	Machine and operator costs [$\text{\$ min}^{-1}$]
C_1	The cost of tool [\\$]
C_2	The spindle cost [\\$]
C_m	The machining cost [\\$]
C_s	The spindle cost per operation [\\$]

1 Introduction

The drilling operation is one of the most important operations in the mechanical production, and many researchers have dealt with the optimization of machining parameters in conventional drilling without pre-hole. However, the total material to be removed to achieve the final hole size is limited by various constraints such as available tool capacity and machine power. Thus, it is crucial to make some pre-hole drilling. In fact, there are a few works on the optimization of drilling operation with pre-hole reported in the literature.

Starting with the works in drilling operation without pre-drill, Kim and Dornfeld [1] have presented a model to estimate and minimize the cost of drilling operation based on a drilling burr control chart and Bayesian statistics, in which the cost of a drilling operation consists of the cost of drilling (hole making) and the cost of deburring. Kim and Ramulu [2] have optimized the drilling process of graphite/bismaleimide-titanium alloy (Gr/Bi-Ti) stacks in terms of machining cost and hole quality used a multiple objective linear program. Iacob et al. [3] have optimized the cutting tool life and the associated cutting speed in the drilling of the stainless steels to minimize the machining cost. Herein, a nonlinear programming model is developed. In the case of drilling operation with pre-drill, Shunmugam et al. [4] have presented an optimization approach of the parameters in drilling with pre-hole (cutting speed, pre-drill diameter) which leads to the minimum production cost considering technological and machine constraints. This model was developed for the case of drilling in conventional machining. The selection of pre-drill diameters is arbitrary. Debongnie [5] has proposed a pre-drill diameter as the one third of the final diameter. Recently, Guiotoko et al. [6] have presented a hole drilling process with pre-drill. This process depends on the final diameter and the selected hole tolerance.

In deep hole drilling, the cutting is carried out at the bottom of the hole so the evacuation of chips from the hole and the discharge of heat at the cutting edge becomes difficult. In this

respect, a peck drilling cycle (G83) is used to break and evacuate the chips by the regular retraction movement to a level above the work piece. The movements of retraction tend to increase the cycle time. So, a precise estimation of the machining time becomes necessary. Othmani et al. [7] have presented a model of cutting parameter optimization in NC milling without considering the variation of the feed rate, particularly in peck drilling cycle. But in high speed machining, particularly in drilling, the programmed feed rate is not always reached. The feed rate profile depends on tool path geometry and kinematical parameters of the machine [8, 9]. This leads to an underestimation of machine time.

In this paper, a methodology of pre-drill diameter optimization in high-speed peck drilling cycle G83 is developed. This methodology based on a pre-drill diameter model which is developed in Section 2. Then, a machining time model is presented in Section 3, in which a feed rate modeling is developed. Section 4 gives a machining cost model. In Section 5, a methodology of pre-drill diameters optimization is proposed. Section 6 shows an experimental study and validation. Finally, Section 7 draws the results and discussions.

The peck drilling cycle G83 is used when a deep hole is being machined [10]; initially the tool moves at rapid feed rate from the A (safe position) to the B (approach plane) (Fig. 1). Then, the tool moves incrementally, and after each incremental distance, the tool retracts to the approach plane. After, it moves for the next incremental distance at rapid feed rate, until L_{ij} depth is reached (C position).

2 Pre-drill diameter modeling

2.1 The known recommendations and limitations

In drilling operation, the final hole diameter is obtained by drilling with one or more drills. The number of pre-drill diameter depends on technological constraints, such as final hole size, workpiece material, and tool geometry.

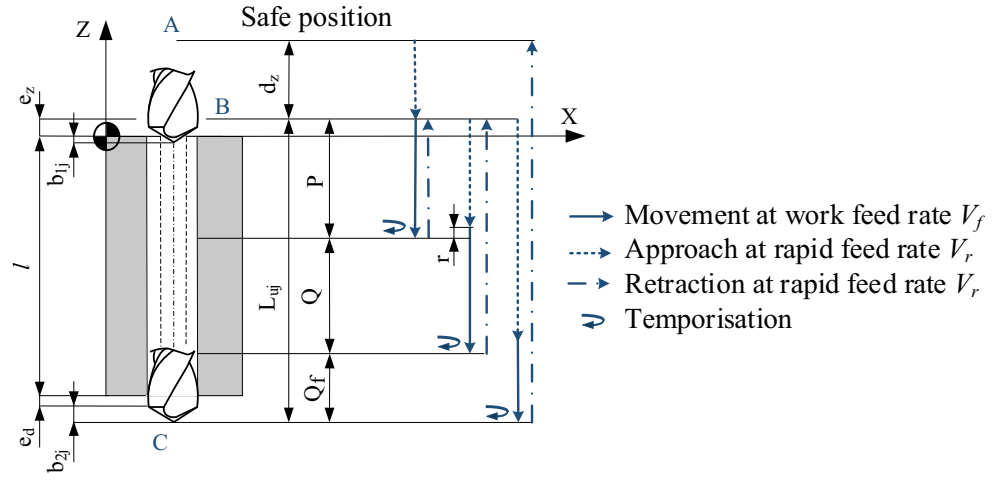
The maximum diameter drilled without pilot drill for the AISI 4140 alloy steel is fixed equal to 20 mm [6].

Debongnie [5] has proposed a pre-drill diameter as the one third of the final diameter. In this study, the limitation of pre-drill diameter proposed is given by:

$$D_{j+1} \geq \frac{D_j}{3} \quad (1)$$

The pre-hole diameter is also limited by the geometry of the drill; the drill web thickness W_j must be smaller than the pre-hole diameter [11] (Fig. 2). The W_j is in the range of 8–12% of the drill diameter [12]; this limitation is respected in the precedent condition.

Fig. 1 Peck drill cycle G83
(drilling through hole with a pre-drill)



2.2 The model developed in this work

The pre-drill diameters $D_{j'}$ (j' from 1 to n_p) are calculated from the final diameter D to the first pre-drill diameter. The using equations are detailed as follows:

$$\begin{cases} \text{If } (D_{j'+1} \leq D_m) & \text{so } D_j = 0 \\ \text{else } D_{j'+1} = D_{j'} - d_{j'} & \end{cases} \quad (2)$$

$$\text{With : } d_{j'} = \text{Int} \left(\frac{100m}{D_{j'}} \right) \quad (3)$$

The value of D_m is given by:

$$\begin{cases} D_m = D_{1m} & \text{If } (D_{1m} < 20) \\ D_m = 20 & \text{If not} \end{cases} \quad (4)$$

D_{1m} is calculated as follows:

$$D_{1m} = x(3 + m) \quad (5)$$

where m is a coefficient which depends on tool, workpiece material, and machine specifications (power), x is a constant equal to 3, and D_{1m} is the maximum hole diameter which can be machined without pre-hole. It depends on the coefficient m .

The methodology used for the determination of the different sizes of pre-drill $D_{j'}$ ($j' = 1$ to n_p) to obtain the final hole diameter is presented in Fig. 3.

In the following paper, we design the pre-drill diameter by D_j with j from 1 to $n_p + 1$ is given by: $j = n_p - j' + 2$. So, the drilling process starts with D_1 to the final diameter D_{n_p+1} (D).

3 One-hole machining time modeling

The total machining time T_m for drilling one hole at a final diameter D_{n_p+1} with n_p pre-drill diameters D_j (j from 1 to n_p) is calculated as the sum of each machining time T_{mj} for drilling a diameter D_j , as follows:

$$T_m = \sum_{j=1}^{n_p+1} T_{mj} \quad (6)$$

The machining time for drilling a diameter D_j can be composed of six parts as in the expression below:

$$T_{mj} = t_{c_j} + t_{r_j} + t_{l_{d_j}} + t_{chnt_j} + t_{chns_j} + \frac{t_a}{n_p + 1} \quad (7)$$

where:

- t_{c_j} is the drilling cycle time (min),
- t_{r_j} is the time of the approach and retract movement using a rapid feed rate (min),

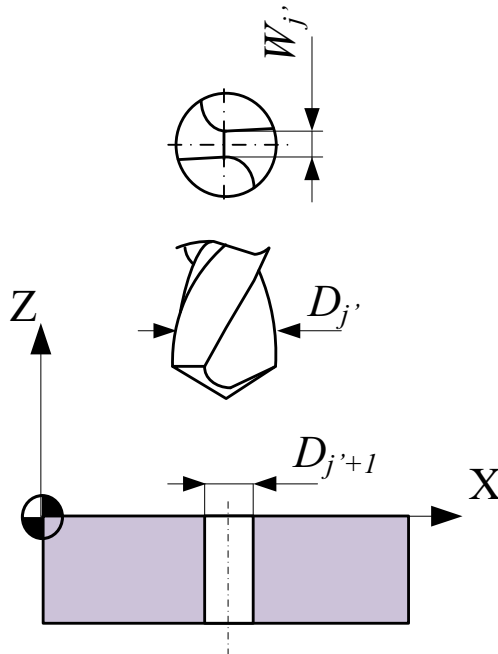
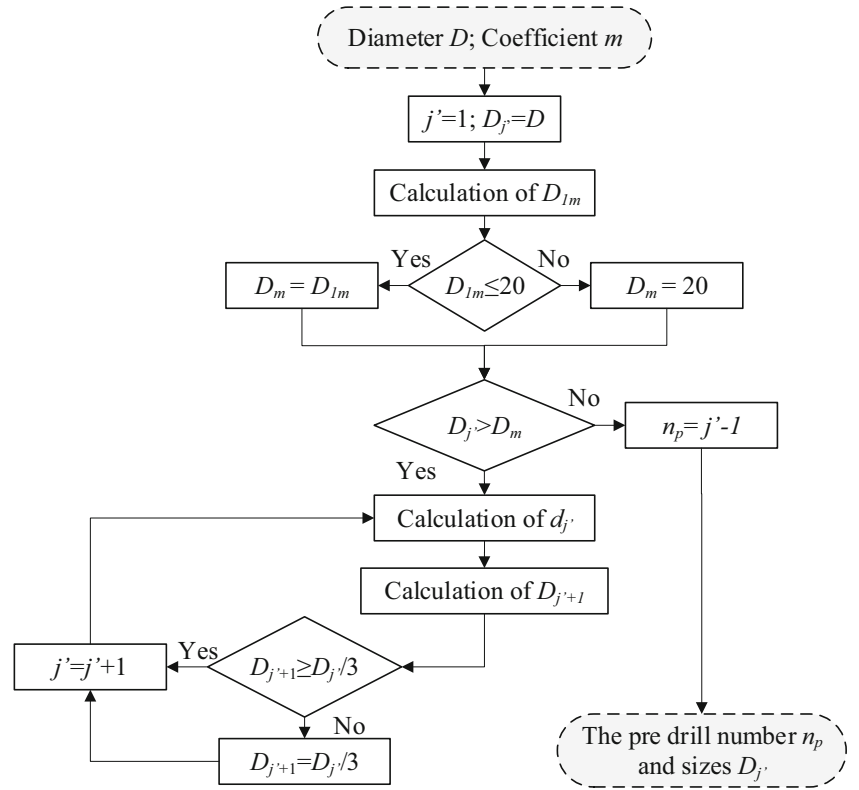


Fig. 2 Drilling with a pre-drill

Fig. 3 Algorithm 1 for pre-drill number and size calculation



- t_{ldj} is the time of unloading a drill tool and loading another one, it depends on the characteristics of tool change magazine (min),
- t_{chnj} is the tool change time when the tool life is reached (min),
- t_{chnsj} is the spindle change time (min),
- t_a is the non-productive time according to the workpiece and the machine preparation (min).

3.1 Drilling cycle time t_{cj}

In high speed drilling, the cycle time depends on the cutting parameters, the tool path geometry, and the kinematic characteristics of the machine.

3.1.1 Cutting parameters of peck drilling cycle G83

In drilling, the feed f_j depends on the drill diameter D_j and the material to be removed [13]. It is calculated as follows:

$$f_j = k_f D_j^{n_f} \quad (8)$$

where k_f is a constant which depends on the work/piece material and n_f is a constant which depends on the tool material.

For deep holes ($l_j' \geq 3D_j$), the feed and the cutting speed used for short drilling are reduced by two correction

coefficients, respectively, β_1 and β_2 [13], so:

$$f_{jc} = \beta_1 f_j \quad (9)$$

$$V_{jc} = \beta_2 V_c \quad (10)$$

β_1 and β_2 are the correction coefficients which depend on hole depth l_j' to diameter D_j ratio [13]. Based on the coefficient values, of both β_1 and β_2 proposed by Dietrich et al. [13], the equations of these coefficients are determined as follows:

$$\beta_1 = 0.012 \left(\frac{l_j'}{D_j} \right)^2 - 0.195 \frac{l_j'}{D_j} + 1.378 \quad (11)$$

$$\beta_2 = 0.008 \left(\frac{l_j'}{D_j} \right)^2 - 0.120 \frac{l_j'}{D_j} + 1.245 \quad (12)$$

Total hole depth is given by:

$$l_j = l + \frac{D_j - D_{j-1}}{2 \tan(\delta/2)} \quad (13)$$

3.1.2 Tool path geometry of deep hole drilling cycle G83

The drilling cycle (Fig. 1) is formed by $3n_j$ linear blocks which are n_j steps at rapid feed rate, n_j blocks with work feed, and n_j retraction block at rapid feed rate.

P_j , Q_j , and Q_{fj} are, respectively, the length of the first incremental distance (mm), the following incremental distance (mm), and the last incremental distance (mm).

The total number n_j of incremental distance and the last incremental distance are given by:

$$\begin{cases} n_j = \text{Int} \frac{L_{uj}-P_j}{Q_j} + 2 & \text{and } Q_{fj} = L_{uj}-P_j-(n_j-2)Q_j & \text{if } \frac{L_{uj}-P_j}{Q_j} \text{ decimal} \\ n_j = \frac{L_{uj}-P_j}{Q_j} + 1 & \text{and } Q_{fj} = 0 & \text{if not} \end{cases} \quad (14)$$

where L_{uj} is expressed as:

$$L_{uj} = l + e_z + e_d + b_{2j} \quad (15)$$

$$\text{with } b_{2j} = \frac{D_j}{2 \tan(\delta/2)}$$

where l is the depth of the hole, e_z is the approach distance, e_d is the breakthrough distance, and δ is the drill point angle.

The first and the following incremental distances, respectively, P_j and Q_j , depend on the diameter D_j [5]:

$$Q_j = P_j = k_1 D_j \quad (16)$$

where K_1 is a constant depending on the ability to evacuate chips without blocking into the flute which depends on the tool (geometry, Material) and the work piece material; the recommended value is equal to 1 [5].

3.1.3 Feed rate and drilling cycle time modeling t_{cj}

Based on the work of Pessoles et al. [8], an analytical study for calculating the feed rate evolution (Fig. 4) according to dynamic performance of machine is detailed.

The model is composed of seven steps (Fig. 4).

Step 1: $\forall t \in [t_0, t_1]$

$$\begin{cases} J(t) = J_m \\ A(t) = J_m(t-t_0) \\ V_f(t) = \frac{1}{2} J_m(t-t_0)^2 + V_{f0} \\ Z(t) = \frac{1}{6} J_m(t-t_0)^3 + V_{f0}(t-t_0) + Z_0 \end{cases} \quad (17)$$

Step 2: $\forall t \in [t_1, t_2]$

$$\begin{cases} J(t) = 0 \\ A(t) = A_m = J_m(t_1-t_0) \\ V_f(t) = A_m(t-t_1) + V_{f1} \\ Z(t) = \frac{1}{2} A_m(t-t_1)^2 + V_{f1}(t-t_1) + Z_1 \end{cases} \quad (18)$$

Step 3: $\forall t \in [t_2, t_3]$

$$\begin{cases} J(t) = -J_m \\ A(t) = -J_m(t-t_2) + J_m(t_1-t_0) \\ V_f(t) = -\frac{1}{2} J_m(t-t_2)^2 \\ \quad + J_m(t_1-t_0)(t-t_2) + V_{f2} \\ Z(t) = -\frac{1}{6} J_m(t-t_2)^3 + \frac{J_m}{2}(t_1-t_0) \\ \quad (t-t_2)^2 + V_{f2}(t-t_2) + Z_2 \end{cases} \quad (19)$$

Step 4: $\forall t \in [t_3, t_4]$

$$\begin{cases} J(t) = 0 \\ A(t) = 0 \\ V_f(t) = V_m \\ Z(t) = V_m(t-t_3) + Z_3 \end{cases} \quad (20)$$

Step 5: $\forall t \in [t_4, t_5]$

$$\begin{cases} J(t) = -J_m \\ A(t) = -J_m(t-t_4) \\ V_f(t) = -\frac{1}{2} J_m(t-t_4)^2 + V_m \\ Z(t) = -\frac{1}{6} J_m(t-t_4)^3 + V_m(t-t_4) + Z_4 \end{cases} \quad (21)$$

Step 6: $\forall t \in [t_5, t_6]$

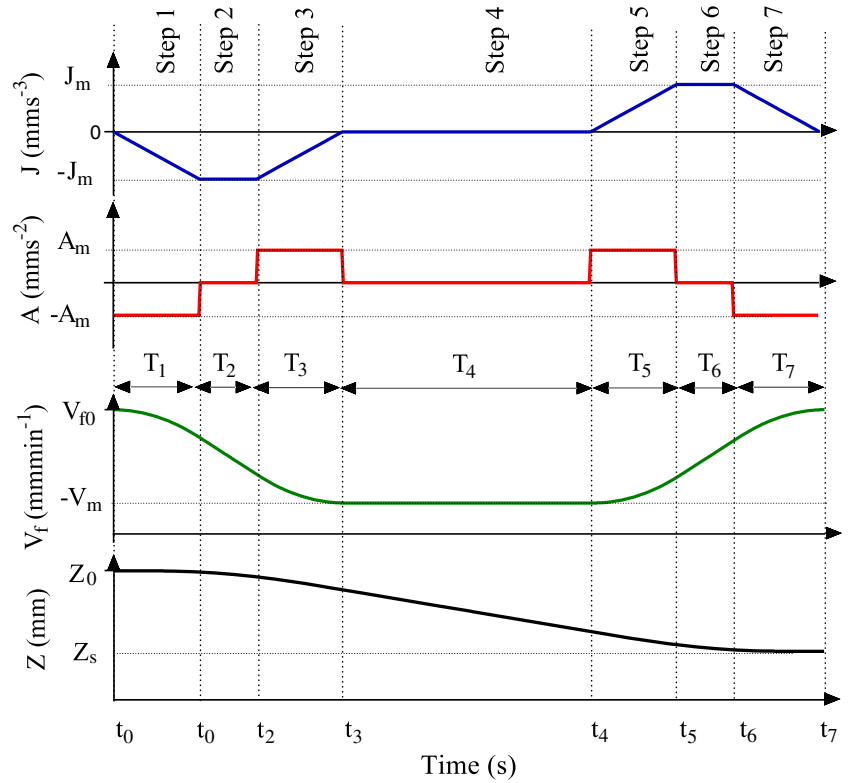
$$\begin{cases} J(t) = 0 \\ A(t) = -A_m \\ V_f(t) = -J_m(t_5-t_4)(t-t_5) + V_{f5} \\ Z(t) = -\frac{1}{2} J_m(t_5-t_4)(t-t_5)^2 \\ \quad + V_{f5}(t-t_5) + Z_5 \end{cases} \quad (22)$$

Step 7: $\forall t \in [t_6, t_7]$

$$\begin{cases} J(t) = J_m \\ A(t) = J_m(t-t_6) - J_m(t_5-t_4) \\ V_f(t) = \frac{1}{2} J_m(t-t_6) - J_m(t_5-t_4)(t-t_6) + V_{f6} \\ Z(t) = \frac{1}{6} J_m(t-t_6)^3 - \frac{1}{2} J_m(t_5-t_4)(t-t_6)^2 + V_{f6}(t-t_6) + Z_6 \end{cases} \quad (23)$$

where J_m is the maximum jerk, A_m is the maximum acceleration, V_m is the maximum feed rate, V_{f0} is the input feed rate,

Fig. 4 Kinematic profiles for constant jerk



V_{fs} is the output feed rate, Z_0 is the input position, and t_0 is the initial time. The feed rate V_{fk} , the position Z_k , and the time t_k (k from 0 to 6) are calculated in terms of the initial input and the duration of each step $T_{k+1} = t_{k+1} - t_k$ ($k=0$ à 6).

Depending on kinematic parameters (jerk, programmed feed rate, and the input and output feed rate) and path geometry (path length), some steps of the feed rate curve may disappear. In fact, the programmed feed rate is not always reached, and it will be limited by the length of the block L from which the fourth profile area disappears. Moreover, the disappearance of the second and the sixth steps is related to the low values of the jerk by keeping a sufficient length to reach the maximum feed rate. Pessoles et al. [8] have studied the different cases.

The duration of each step T_k can be calculated by using MATLAB software.

The cycle time t_{cj} for peck drilling cycle is determined as follows:

$$t_{c_j} = t_{ar_j} + t_{VF_j} + t_{re_j} + t_{EF_j} \quad (24)$$

where:

t_{EF_j} is the total temporization time which depends on the number of the incremental distance:

$$t_{EF_j} = (n_j - 1)EF \quad (25)$$

t_{ar_j} is the total time for approach movement with fast feed

$$\text{rate: } t_{ar_j} = \sum_{i=0}^{n_j-1} \sum_{k=1}^7 T_{k_{3i+1}}$$

t_{VF_j} is the total time for the movement with programmed

$$\text{feed rate: } t_{VF_j} = \sum_{i=0}^{n_j-1} \sum_{k=1}^7 T_{k_{2i+1}}$$

t_{re_j} is the total time for the retraction movement with fast

$$\text{feed rate: } t_{re_j} = \sum_{i=1}^{n_j} \sum_{k=1}^7 T_{k_{3i}}$$

The time t_{u_j} during which the tool is in contact with the work piece is calculated as follows:

$$t_{u_j} = t_{VF_j} - t_{ap_j} \quad (26)$$

where t_{ap_j} is the time of approach and the breakthrough movement with programmed feed rate; it is calculated using feed rate modeling by summing the time during the approach movement which corresponds to the first approach distance e_z , the following approach distance r , and the breakthrough distance e_d (Fig. 1).

3.2 Time of the approach and retract rapid movement t_r

In the approach and retract movement, the tool path is represented by a linear contour (MA) (Fig. 5). where X_M , Y_M , and Z_M are the point M coordinates and X_A , Y_A , and Z_A are the

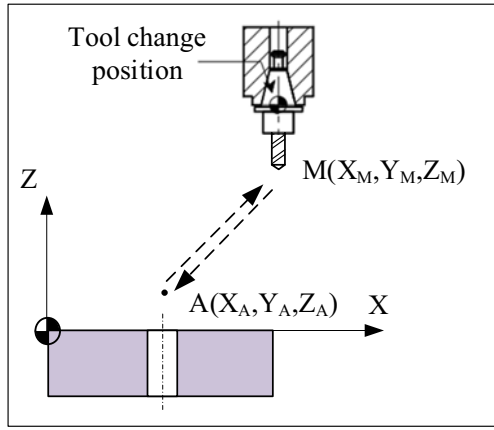


Fig. 5 Rapid movement

point A coordinates. The time is calculated by using the feed rate modeling with the rapid feed rate V_r . The distance value of the linear contour (MA) is given by:

$$MA = \sqrt{(X_M - X_A)^2 + (Y_M - Y_A)^2 + (Z_M - Z_A)^2} \quad (27)$$

The time of the approach and retract rapid movement t_r is calculated as follows:

$$t_{r_j} = 2 \sum_{k=1}^7 T_k \quad (28)$$

3.3 Tool change time t_{chntj}

The tool change time per hole t_{chntj} is calculated in relation to tool life:

$$t_{chntj} = t_{tch_j} \frac{t_{uj}}{T_j} \quad (29)$$

where t_{tch_j} is the drill change time (min/tool), t_{uj} is the time during which the tool is in contact with the work piece (min), and T_j is the tool life (min) calculated according to the model of Shunmugam et al. [4]:

$$T_j = C V_{c_j}^n f_{c_j}^x D_j^y \left(\frac{D_j - D_{j-1}}{2} \right)^z \quad (30)$$

C , n , x , y , z are the tool life coefficients which depend on the tool and work piece material, whose values, in the case of drilling the AISI 4340 with carbide drill, are shown in Table 1.

Table 1 Taylor's coefficients [4, 14]

Coefficient	C	n	x	y	Z
Direct drilling	6.988	-2.165	-2.5	2	0
Drilling with pre-hole	69.88	-2.165	-2.5	2	-1

3.4 Spindle change time t_{chnsj}

The Spindle change time t_{chnsj} for drilling one hole at a diameter D_j is calculated in relation to the tool life:

$$t_{chnt_j} = t_{sch} \frac{t_{uj}}{T_s} \quad (31)$$

where t_{sch} is the spindle change time (min/spindle) and T_s is the spindle life (min). T_s varies from 5000 and 10,000 h [15].

4 Total one-hole machining cost modeling

The total machining cost C for drilling one hole at a final diameter D_{np+1} with n_p pre-drills diameters D_j (j from 1 to n_p) is calculated as the sum of each machining cost C_j for drilling a diameter D_j , and it is expressed as follows:

$$C = \sum_{j=1}^{n_p+1} C_j \quad (32)$$

The machining cost for drilling a diameter D_j can be composed of four parts as in the below expression:

$$C_j = \frac{C_a}{n_{p+1}} + C_{t_j} + C_{s_j} + C_{m_j} \quad (33)$$

where:

C_a is the auxiliary cost (\$), it is attached to the machine and workpiece preparation.

- C_{t_j} is the tool cost (\$), calculated by:

$$C_{t_j} = (C_{1_j} + C_0 t_{tch_j}) \frac{t_{uj}}{T_j} \quad (34)$$

Where C_{1_j} is the price of the tool (\$), C_0 is the machine cost (\$ min⁻¹),

- C_{s_j} is the spindle cost per piece (\$), it is given by:

$$C_{s_j} = (C_2 + C_0 t_{sch}) \frac{t_{uj}}{T_s} \quad (35)$$

With C_2 is the spindle cost (\$),

- C_{m_j} is the machining cost related to the machine cost, it is given by:

$$C_{m_j} = C_0 (t_{c_j} + t_{r_j} + t_{d_j}) \quad (36)$$

5 Optimization of pre-drill diameters

5.1 Constraints

The cutting parameters values are limited by the machine tool constraints such as spindle speed, feed rate and power.

5.1.1 Spindle speed and feed rate

The feed f_{jc} and the cutting speed V_{cjc} are limited by the admissible spindle speed of the machine N_{ad} and the maximum axes feed rate V_{max} as follows:

$$V_{cjc} \leq V_{cadj} = \frac{\pi D_j}{1000} N_{ad} \quad (37)$$

$$V_{cjc} \leq V_{cmj} = \frac{\pi D_j}{1000 f_{jc}} V_{max} \quad (38)$$

5.1.2 Machine power

The cutting power P_{cj} should not exceed the maximum value of the available machine power transmitted to the cutting tool P_{cmax} :

$$P_{cj} \leq P_{cmax} = \frac{\eta}{c_s} P_M \quad (39)$$

η is the machine efficiency, P_M is the nominal motor power, and c_s is the safety coefficient which equal to 1.7 [3].

In drilling with a pilot hole, the value of cutting power is given by:

$$P_{cj} = \frac{K_{cj} f_{jc} V_{cjc}}{240} (D_j - D_{j-1}) \quad (40)$$

In direct drilling, the value of D_{j-1} is equal to zero.

With K_{cj} is the specific force which is defined as in the model:

$$K_{cj} = A f_{jc}^{n_1} V_{cjc}^{n_2} \quad (41)$$

A , n_1 , and n_2 are constant.

So:

$$P_{cj} = \frac{A f_{jc}^{n_1+1} V_{cjc}^{n_2+1}}{240} (D_j - D_{j-1}) \quad (42)$$

and:

$$P_{cjmax} = \frac{A f_{jc}^{n_1+1} V_{cjcmax}^{n_2+1}}{240} (D_j - D_{j-1}) = \frac{\eta}{c_s} P_M \quad (43)$$

The maximum speed V_{cjmax} is given by:

$$V_{cjmax} = \sqrt[n_2+1]{\frac{240 P_M \eta}{A f_{jc}^{n_1+1} (D_j - D_{j-1}) c_s}} \quad (44)$$

5.2 Optimization

The objective of the optimization is to determine the drill sizes and the cutting speed V_{cej} for each tool which lead to the minimum machining cost. In this study, the proposed method is based on the model of the pre-drill diameter, and it is defined in two steps. In the first step, for different coefficient m (from $m_0 = 1$ to $m_{max} = 6$), the pre-hole diameters D_j ($j = 1$ to n_p) are predicted from the Algorithm 1 (Fig. 3). Then, for each diameters D_j , the economical cutting speed V_{cej} are determined. Afterwards, the used cutting speed V_{cj} are predicted as following:

$$V_{cj} = \min (V_{cej}, V_{cadj}, V_{cmj}, V_{cmaxj}) \quad (45)$$

For each drill diameter D_j , the cutting cost C_j is calculated according to the value of the selected cutting speed V_{cj} . The total cutting cost C for each coefficient m is determined as the

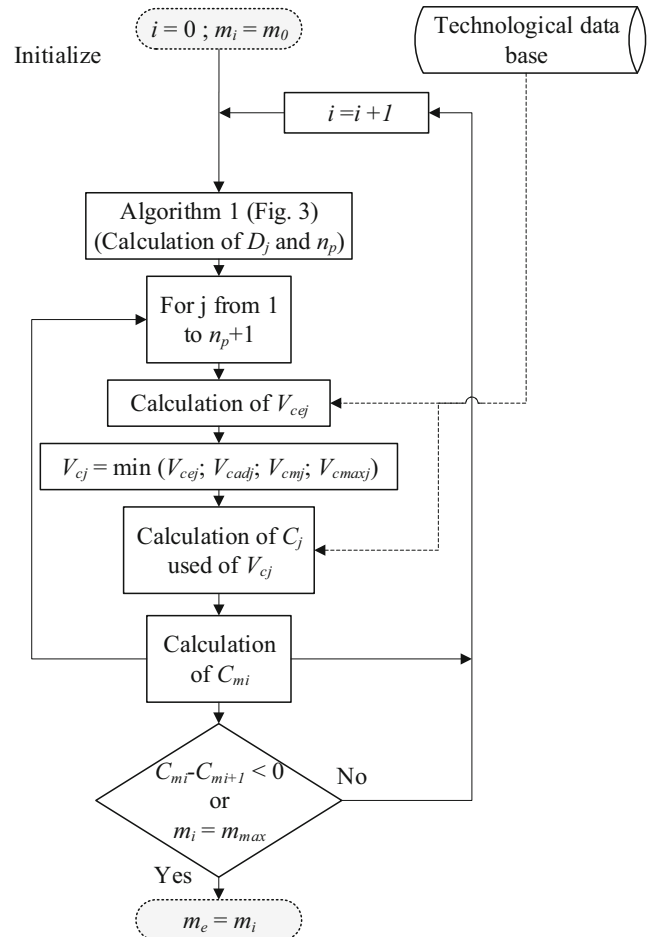


Fig. 6 Algorithm 2 of searching for optimum pre-drill diameters

Table 2 Machine characteristics

Huron Kx10		
Spindle:	Maximum power:	20 kW
	Spindle speed:	100 à 24,000 rev/min
	The machine efficiency (η)	0.9
Axis capacity:	Maximum fast speed XY:	30 m/min
	Maximum fast speed Z:	18 m/min
	Maximum acceleration:	3 m/s ²
	Jerk maxi:	50 m/s ³

Table 3 Work piece and tool characteristics

Work piece	Work piece material	AISI 4140 alloy steel
	Hole final diameter (mm)	16
	The length of the hole, l (mm)	56
Tool	Tool drill material	Carbide drill
	The drill point angle, δ	140°

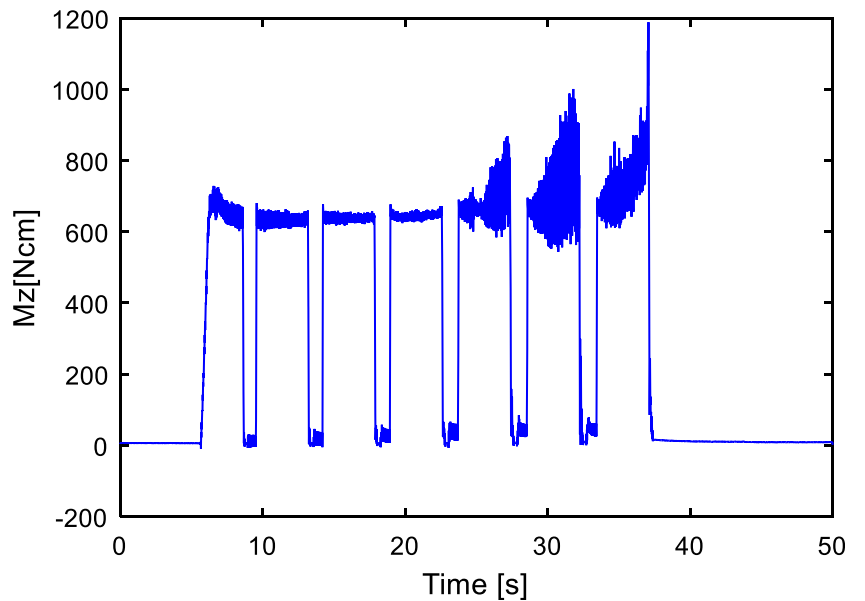
sum of the cutting cost C_j . In the second step, the used coefficient m that leads to the minimum cutting cost is predicted. Figure 6 depicts the algorithm of the described procedure.

6 Experimental study and validation

In order to validate the feed rate models and examining the torque and thrust force generated during cycle drilling operation, an experimental study was carried on a high speed machine (Table 2). AISI 4140 steel workpiece of 100-mm diameter with a length of 60 mm is used. The drill tool is a carbide drill Guhring type.

The drilling thrust force was measured by a Kistler cutting force dynamometer (type 9272).

Fig. 7 Variation of the torque M_z ($V_c = 55.82$ m/min; $f = 0.118$ mm/rev; $D_1 = 10$ mm; $D_2 = 16$ mm; $P = Q = 8$ mm; $l = 56$ mm)



6.1 Work piece and tool characteristics

The work piece and tool characteristics are shown in Table 3.

6.2 Drilling forces

An examination of the cutting torque M_z (Fig. 7) indicates that when drilling deep holes, the torque M_z increases as drilling progresses deeper into the work piece. This increase is due to margin rubbing and the chips rubbing with the wall of the drilled hole; it is also caused by the chip thickening [16]. In our study, the safety coefficient c_s takes into account this increase in the prediction of the available machining power.

Tables 4 and 5 show the measured torque M_{zj} and the specific cutting force K_{cj} that is calculated by:

$$K_{cj} = 8 \frac{M_{zj}}{(D_j^2 - D_{j-1}^2) f_{jc}} \quad (46)$$

The equations of the specific cutting force were obtained through the ANOVA regression analysis using the results shown in Tables 4 and 5, and it is expressed as follows:

– For direct drilling:

$$K_{cj} = 1379.648 f_{jc}^{-0.4} V_{cjc}^{-0.03} \quad (47)$$

– For drilling with a pilot hole:

$$K_{cj} = 878.77 f_{jc}^{-0.563} V_{cjc}^{-0.004} \quad (48)$$

Table 4 Experimental torque M_z (direct drilling)

Test	K_1	D_j (mm)	D_{j-1} (mm)	Q (mm)	V_{cjc} (m/min)	f_{jc} (mm/tr)	M_z (Nm)	K_c (N/mm ²)
1	1.25	8	0	10	79.70	0.05	1.640	4270.80
2	0.5	10	0	5	49.43	0.06	3.120	3902.50
3	1	10	0	10	65.91	0.06	2.598	3247.50
4	1.25	16	0	20	93.30	0.12	10.817	2914.06

Table 5 Experimental results (drilling with a pre-drill)

Test	K_1	D_j (mm)	D_{j-1} (mm)	Q (mm)	V_{cjc} (m/min)	f_{jc} (mm/tr)	M_z (Nm)	K_c (N/mm ²)
5	1.25	12	8	15	86.48	0.08	2.939	2986.78
6	1	13	10	13	70.70	0.10	2.561	2886.44
7	1	16	13	16	74.61	0.12	3.783	2649.15
8	1.25	16	12	20	93.18	0.12	4.677	2477.22
9	0.5	16	10	8	55.82	0.118	6.627	2880.17

6.3 Cycle time and feed rate

Figure 8 shows the experimental and theoretical feed rate evolution for deep hole cycle G83. It presents a good correlation between experimental and theoretical results.

7 Results and discussion

7.1 Numerical data for the illustrative example

The numerical parameters and the tool cost used in the application example are shown in Tables 6 and 7 respectively.

7.2 Pre-hole number in relation to m coefficient

Figure 9a and b give the number and the size of several pre-hole drill diameters D_j to obtain a final hole diameter respectively in the case of a coefficient m equal to 2 and 5. They show that the number of pre-drill increases with the small number of coefficient m . For example, in the drilling of the final diameter D equal to 25 mm, the use of a coefficient m equal to 2 may be preceded by drilling of two pre-drill ($D_1 = 6$ mm, $D_2 = 17$ mm); however, the use of a coefficient m equal to 5 leads to only one pre-drill ($D_1 = 8$ mm).

Fig. 8 Feed rate variation during a peck drill cycle G83 ($V_c = 55.822$ m/min; $l = 56$ mm; $f = 0.118$ mm/rev; $D_2 = 16$ mm, $D_1 = 10$ mm, $P = Q = 8$ mm, $V_r = 18,000$ mm/min; $t_c = 32.64$ s)

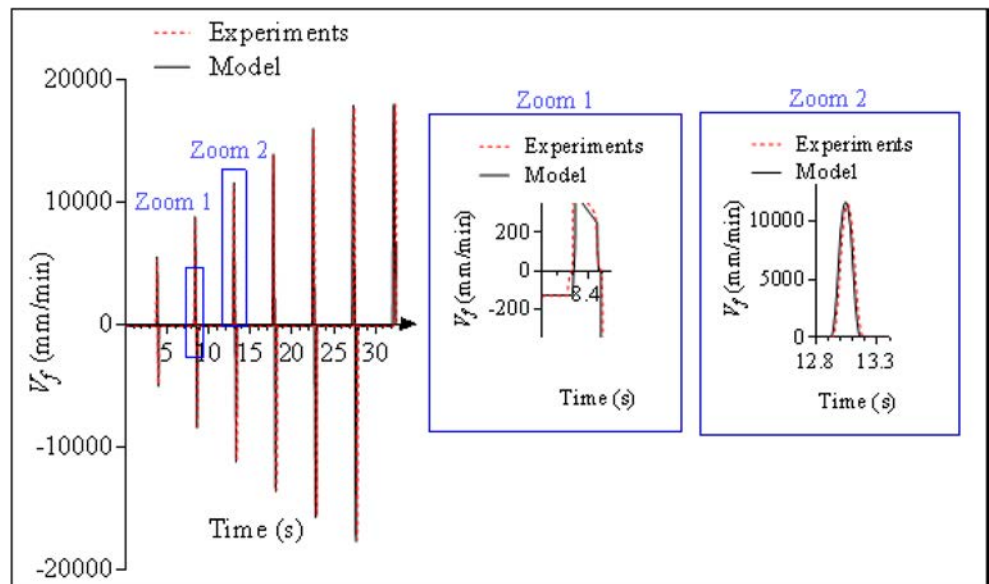


Table 6 Numerical parameters

Tool change time, t_{tch} (min/tool)	5
The time of unloading and loading tool, t_{ldj} (s)	10
The spindle change time, t_{sch} (min/spindle)	60
The non-productive time, t_a (min)	1
The spindle life, T_s (h)	10,000
The non-productive time related to the auxiliary, t_a (min)	1
The overhead cost, C_0 ($\$ \text{min}^{-1}$)	2
The auxiliary cost, C_a ($\$$),	1
The spindle cost, C_s ($\$$)	24,000
Coefficient, K_1	1
The length of the hole, l (mm)	56
The constant, k_f	0.025
The constant, n_f	0.76
The safety coefficient, c_s	1.7

Table 7 Tool cost C_1

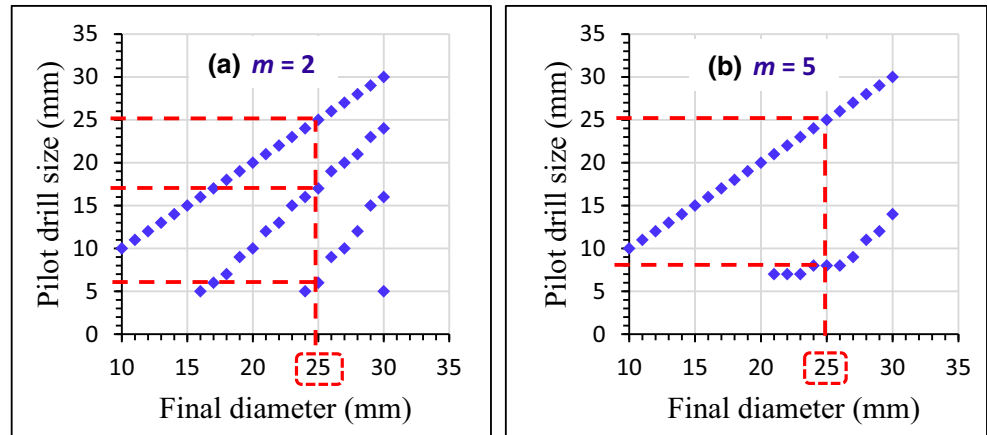
Tool length	Tool cost, C_1 ($\$$)
$\leq 3D_j$	$C_1 = 0.5(0.464D_j^2 - 5.980D_j + 36.860)$
$> 3D_j$ and $\leq 5D_j$	$C_1 = 0.5(0.867D_j^2 - 11.280D_j + 69.300)$
$> 5D_j$ and $\leq 12D_j$	$C_1 = 0.5(1.388D_j^2 - 17.950D_j + 110.600)$

7.3 Total cost and time of one-hole drilling

7.3.1 Drilling without pre-hole

Figures 10 and 11 present respectively the time and the cost evolution with cutting speed for different values of the drill diameter in the case of drilling without pre-hole. So, we can determine the optimal V_{co} and economical V_{ce} value of cutting speed for each diameter. It can be concluded that during one-hole drilling with a single drill, the optimal and economical cutting speed decrease by increasing the value of the drill diameter.

Fig. 9 Pre-hole diameters according to final diameter: **a** $m = 2$; **b** $m = 5$



7.3.2 Drilling with pre-hole

In this section, the time evolution and cost evolution function of cutting speed under different drilling final hole sizes are presented (Figs. 12 and 13). The impact of the coefficient m on the machining time, machining cost, and cutting speed selection in drilling of the final diameter D_{np+1} can be determined. For each diameter D_{np+1} , the machining time and cost increase with the increase of coefficient m , and it is due to the impact of the increase of the width of cut d on the tool life. However, the optimal cutting speed V_{co} and the economical cutting speed V_{ce} decrease with the increase of the coefficient m .

7.4 Pre-hole diameter optimization

The results predicted using the developed model are listed in Table 8. The economical values of cutting parameters such as feed and speed are obtained considering the machine constraints. These results permit, firstly, to determine the economic value of the coefficient m (size of the pilot drill) then the economical speed used for drilling such pilot hole. For example, in the case of drilling of a 22-mm diameter hole, the minimal machining cost is obtained when drilling a pre-hole of 1- mm diameter with a cutting speed of 71.32 m/min and a final diameter with a cutting speed of 50 m/min. In our illustrative example, the machining regimes are always covered by the data of the machine tool used.

Clearly, Fig. 14 provides a sufficient approximation to the true optimal coefficient m that leads to the minimal machining cost. It is noted that, although the satisfaction of drill tool life with the multiplication of pre-drill number, the minimum machining cost is obtained with the minimum tool number by reason of the significant increase of the machine cost in peck drilling cycle.

Fig. 10 Cutting time variation with the cutting speed for different diameter D ($d=D$; without pre-hole)

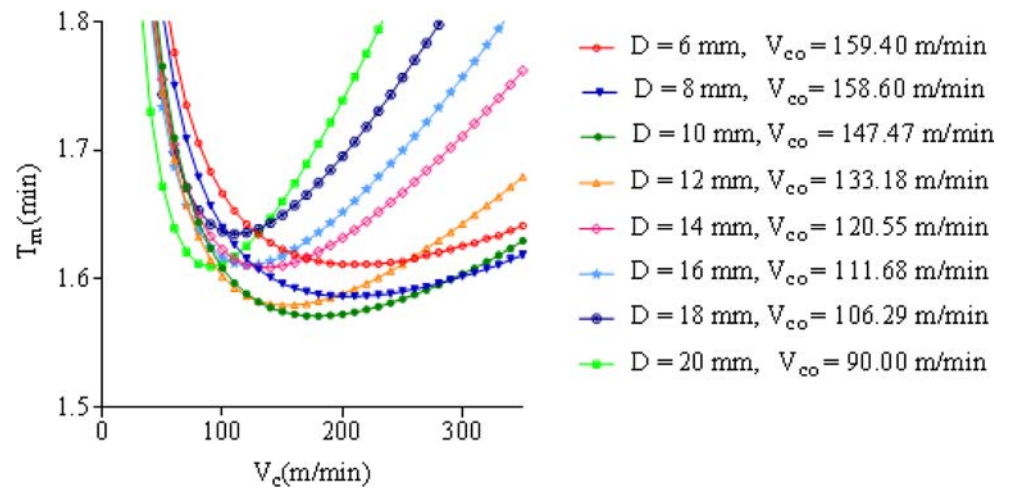


Fig. 11 Total cutting cost variation with the cutting speed for different diameters D ($d=D$; without pre-hole)

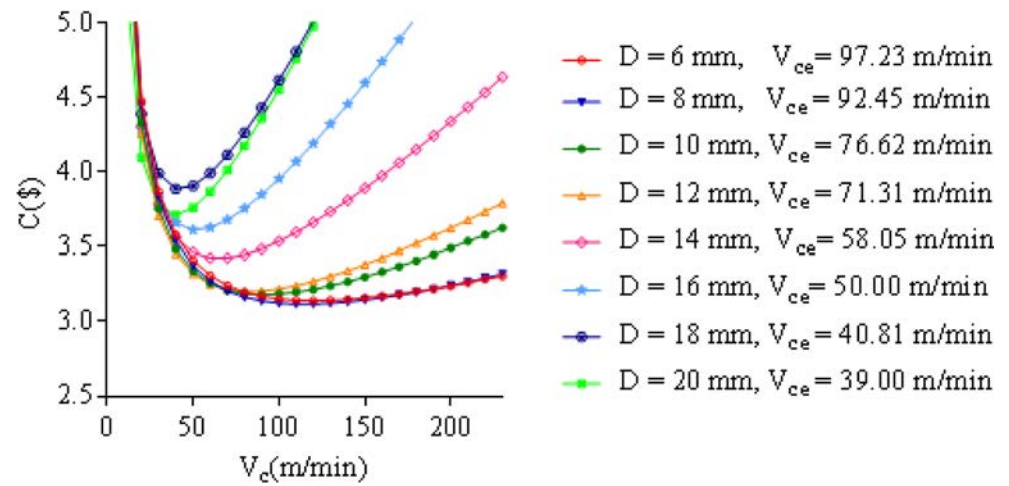


Fig. 12 Cutting time and cost variation for drilling the final diameter D_{np+1} ($D_{np+1} = 22$ mm)

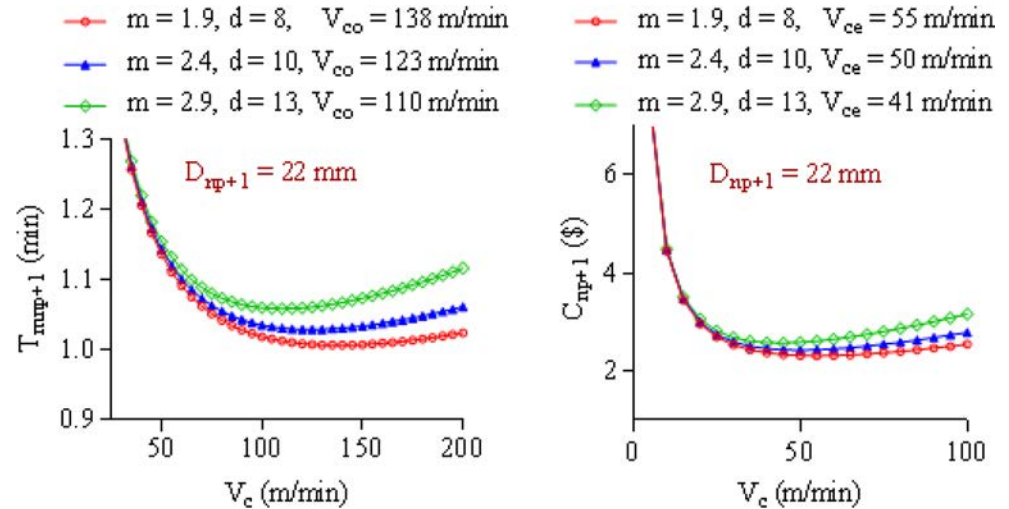


Fig. 13 Cutting time and cost variation for drilling the final diameter D_{np+1} ($D_{np+1} = 30$ mm)

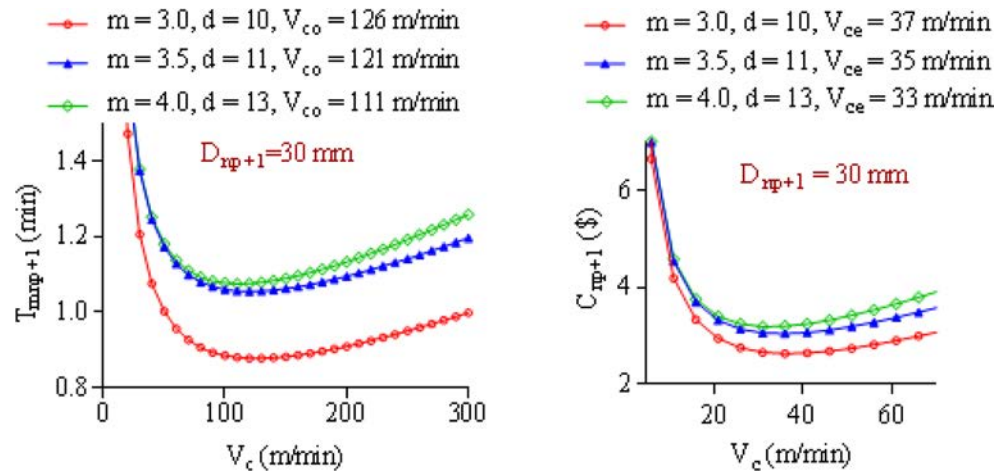
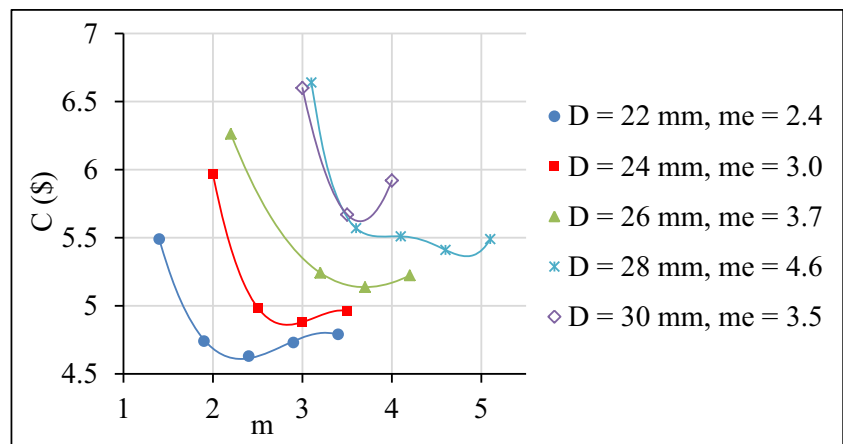


Table 8 Calculated values using developed models (the italicized values are the economical data)

D_{np+1} (mm)	m	d_j (mm)	D_j (mm)	V_{cej} (m/min)	f_{jc} (mm/rev)	V_{cmaxj} (m/min)	V_{cadj} (m/min)	V_{cj} (m/min)	C_j (\$)	C (\$)
22	1.9	14	14	58.04	0.145	504.54	791.68	58.04	2.42	4.74
		8	22	55	0.261	666.22	1244.07	55	2.32	
	2.4	12	12	<i>71.31</i>	<i>0.119</i>	<i>668.47</i>	<i>678.58</i>	<i>71.31</i>	<i>2.20</i>	4.63
		10	22	50	0.261	532.50	1244.07	50	2.43	
	2.9	9	9	80.80	0.082	1129.13	508.93	80.80	2.14	4.73
13		22	44	0.261	409.18	1244.07	44	2.58		
30	3	6	6	98.03	0.056	2169.95	339.29	98.03	1.80	6.60
		14	20	46	0.243	392.10	1130.97	46	2.15	
	10	30	37	0.331	480.17	1696.46	37	2.63		
		19	19	<i>41</i>	<i>0.234</i>	<i>274.01</i>	<i>1074.42</i>	<i>41</i>	<i>2.62</i>	5.67
	3.5	11	30	35	0.331	436.36	1696.46	35	3.04	
		4	17	17	44.01	0.184	356.01	961.32	44.01	2.74
	13		30	33	0.331	368.98	1696.46	33	3.18	

Fig. 14 Total cost variation with the coefficient m



8 Conclusion

In this paper, a model of pre-drill diameter optimization in high-speed peck drilling cycle G83 is proposed. The developed algorithm of optimization provides a precise estimation of pre-drill diameter that leads to the minimum machining cost. It based on a pre-hole diameter model taking into account the geometric constraints of pre-drill. The cycle time is calculated used a feed rate model which is validated by an experimental study.

The pre-hole optimization is reached in two steps. In the first step, the economical cutting speed for each drilling diameter is determined considering the limitations and machine tool constraints, and in the second step, the optimal pre-drill diameter that leads to the minimal cutting cost are predicted. The results of this paper have shown that the economical process in peck drilling cycle G83 is obtained with the minimum number of pre-drill diameters, and it is due to the fact of the high cost of the machine.

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