A Novel Method of Twist Drill Fluting Fulfilling Required Web Thickness and Rake Angle

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Abstract. As substitute of the meshing theory based fluting method, other analytical, machining movement simulation or empirical method are developed in last decades. Currently, a kind of flute prevails. It is ground by using 1V1/1A1 standard grinding wheel and should fulfill requirements of designated web thickness and radial rake angle. This paper presents a novel method by straightforwardly determining install position of the grinding wheel. Based on the relative movement with variables’ parameterization, equations to keep web thickness are firstly derived. Then, a family of flute cross-sectional curves is computed automatically with respect to grinding process parameters and wheel geometry. The calculation process is characterized by concise in principle and easy to use. Its validity is verified by good agreement between the results computed and manufactured example.

1. Introduction

Twist drill flute influences chip evacuation and cutting edge configuration. It also determines the flute parameters, i.e. the web thickness and radial rake angle. All these factors are essential to drill performance [1-2]. Originally, the flute profile was shaped by meshing method as in gear manufacturing. This process seems to be laborious [3], due to the complex surface of formed grinding wheel with excessive rigid in precision. It is not easily adapting to ever demanding of flute performance improvement [4]. As a large batch production tool, the grinding wheel is liable to be worn. The meshing theory based reconditioning is difficult and expensive, especially to grind the integrated carbide twist drills with diamond grinding wheels. Different kinds of practical and simplified drill fluting methods were developed [5-7].

Currently, a kind of twist drill flute prevails. It is ground by using 1V1/1A1 standard wheel and providing with specific web thickness and radial rake angle [8]. The former is dominating to drill stiffness and the later is influential to chip evacuation. There were a few papers in the literature dedicated to this topic. Some work solved this problem based on empirical design [9]. The wheel position should be assumed before matching a formed wheel profile by meshing method [10]. Graphic analysis and simulation in 2D/3D, using Boolean operations, are not easy to ensure the accuracy of the designed flute profiles [11-13]. Another paper handled it by numerical exploration with lengthy iterations [14]. Difficulty of the problem lies in fulfilling both web thickness and rake angle requirements simultaneously, since they are usually tangled up [15]. This paper presents a novel method to find a more effective solution.

It is evidenced in direct method of twist drill flute grounding [5], the profile is determined by installation angle, centre and eccentric distances between the wheel and drill blank axes. This peculiarity provides a break through to separate the perplexity mentioned above. Firstly, the web
thickness requirement can be achieved by setting a unique centre distance directly. Finally, the rake angle requirement is fulfilled by determining the eccentric distance. Using these mentioned two requirements as constraints, the problem can be simplified and solved by a linear search. The valid flute profiles with the same required web thickness and rake angle are calculated and illustrated.

Contents of the next sections are arranged as follows: strategy to fulfill the web thickness requirement alone by determining the centre distance between the wheel and drill blank is explained in section 2; mathematic modelling of the system and variables’ parameterization to calculate the flute profile and to determine the radial rake angle are deduced in section 3; one-dimensional exploration to determine the eccentric distance is described in section 4; precision comparison of example computed and that manufactured are illustrated in section 5; the influence of grinding process parameters and wheel profile parameters on flute geometry is discussed in section 6; concluding remarks are summarized in section 7.

2. Determining centre distance between drill blank and wheel fulfilling the required web thickness

Coordinate systems of the drill and grinding wheel and some nomenclatures are introduced as shown in Fig.1. The global coordinate system is \( \{O: X, Y, Z\} \). It is right-handed and originated at the end centre of the drill. The upward axis \( Z \) coincides with the drill axis. \( \{O_1: X_1, Y_1, Z_1\} \) is the moving system attached to the grinding wheel. Initially, axis \( X_1 \) coincides with axis \( X \) and axis \( Z_1 \) is skew to axis \( Z \) with distance \( A \), called as centre distance. At initial position, distance of the grinding wheel rear face to origin \( O_1 \) is \( T_1 \) called as eccentric distance. The grinding wheel rear face is parallel to the \( X_1O_1Y_1 \) plane and its axis \( Z_1 \) is inclining to \( Z \) axis with angle \( \beta \) named as installation angle. \( A, T_1 \) and \( \beta \) determine the wheel orientation fixed in the machining movement, called as grinding process parameters. The helical parameter \( P (P = L/2\pi, L \) is the lead) is also invariable.

In Fig.2, \( r_w \) is the radius of the inscribed circle in the flute cross-section. It is the half web thickness. Radial rake angle \( \gamma \) is an angle at the radius end. It is the intersecting angle of the radius and tangent of the flute cross-sectional profile at this point. Flute width \( \delta \) is the angle formed by line \( P_sO \) and line \( P_eO \) at the point \( O \). \( P_s \) is the start point and \( P_e \) is the terminal point of the flute profile. Flute width influences the chip evacuation capacity and the rigid of drill body.

1V1/1A1 grinding wheel are most widely used in the process of twist drill fluting. 1A1 wheel can be regarded as a specific 1V1 wheel with the inclined angle \( \lambda = 90^\circ \). In this section, a general mathematical model using 1V1 wheel is provided. In Fig.3, wheel profile is determined by four parameters: wheel radius \( r \), wheel width \( W \), fillet radius \( \rho \) and inclined angle \( \lambda \). The wheel’s 3D figure can be dispersed as slices with different radius. The sheet with the maximum radius is denoted as \( Q \). In Fig.4, The auxiliary coordinate system \( \{O_2: X_2, Y_2, Z_2\} \) is located on \( O_2 \) the centre of \( Q \). The axis \( X_2 \) coincides with axis \( X \) and axis \( Y_2, Z_2 \) is parallel to axis \( Y, Z \), respectively. In the conformal projection,
an arbitrary sheet on the wheel is an ellipse, projecting on $X_0Y_2$ plane. The outer profile of all these meshing ellipses, named as curve $S_1$ (with red colour in Fig.4), is the whole wheel’s projection. The coordinates of an arbitrary projection point on the $X_0Y_2$ plane is expressed as parametric (elliptical) equation,
\[
\begin{align*}
  x_2 &= (r - \rho + \rho \sin \varphi \cos \theta) \\
  y_2 &= (r - \rho + \rho \sin \varphi \cos \beta \sin \theta + \rho \cos \varphi \sin \beta)
\end{align*}
\]
where $\varphi$ is the circumferential angle of the sheet on the fillet radius. It determines the position of a sheet on the $Y_1O_1Z_1$ plane. In the $X_1O_1Y_1$ projection, $\theta$ is the central angle of the point on this round sheet (in Fig.3). The outer profile can be calculated by the envelope equation of planar curves[16],
\[
\frac{\partial x_2}{\partial \varphi} \times \frac{\partial y_2}{\partial \theta} - \frac{\partial y_2}{\partial \varphi} \times \frac{\partial x_2}{\partial \theta} = 0
\]
(2)
The partial derivatives are derived by Eq.(1). Then, Eq. (2) can be simplified below,
\[
\sin \theta = \frac{1}{\tan \varphi \cdot \tan \beta}
\]
(3)
For a given $\varphi$, there is a specific angle $\theta$ calculated by Eq. (3), called as envelope angle, corresponding to a sheet on the wheel. All these envelope points can be calculated by substitution of the envelope angle $\theta$ into Eq. (1). They form the outer profile of wheel projection, named as curve $S_1$. So Eq.(1) can express $S_1$ when $\theta$ satisfies Eq.(3). As the drill blank moves helically, the $S_1$ configuration remains unchanged and revolves around point $O$ with the installation angle.

A simplest condition is considered as shown in Fig.4. The wheel’s sheet $Q$ with the maximum radius is located at the drill blank upright direction. To keep half web thickness $r_w$, the centre distance $A$ should be given by:
\[
A = r + r_w
\]
(4)
should move along the curve $S_2$ equidistant to $S_1$. This conclusion reveals a breakthrough to solve the difficulty. After ensuring the web thickness, the way is paved to pursue the radial rake angle as another objective.

3. **Modelling the relative movement by using parameterized variables**

To achieve the objectives mentioned above, the first step is to model the relative motion of the grinding wheel. The wheel centre is assumed to be moving around the fixed drill blank along curve $S_2$ as an equidistant curve of $S_1$ (Fig. 4). It can be solved conveniently by using differential geometry [16]. The variable’s parameterization is effective in this procedure. All the expressions and derivations shown below are in accordance with this curriculum.

Considering relative motion, the wheel is assumed to be standstill. Accordingly, the centre distance $A$ and eccentric distance $T$ can be assumed. Coordinates of the drill blank axis are designated by $x_m$ and $y_m$, denoting relative position of the wheel and drill (Fig. 4), expressed in Eq. (5),

$$
\begin{align*}
    x_m &= -A \\
    y_m &= T_1 \sin \beta
\end{align*}
$$

(5)

A curve $S_2$ equidistant to the ellipse $S_1$ is drawn on the $XOY$ plane (Fig. 4). The distance is equal to the required half web thickness $r_w$. If the drill axis is adjusted to be located on the curve $S_2$ all the while, the half web thickness requirement for the drill after fluting is fulfilled. Coordinates $x_m$ and $y_m$ of the drill axis should fulfill the equation of the equidistant curve $S_2$. Equation of the curve $S_2$ with parameter $\phi$ (expressed in radian) should be determined at first as shown in Eq.(1), noted in terms of vectors.

$$
a(\phi) = (\alpha_x, \alpha_y, 0) = ((r - \rho \sin \phi) \cos \theta, (r - \rho \sin \phi) \cos \beta \sin \theta + \rho \cos \phi \sin \beta, 0)
$$

(6)

In order to derive the equidistance curve $S_2$, normal vector $n$ on an arbitrary point of $S_1$ is determined as shown in Eq.(7).

$$
n = \frac{(a' - a'')}{\|a'\|}
$$

(7)

where $a'$ and $a''$ is the first-order and second-order derivative of $a(\phi)$. According to the offset curve theory expounded in [17], parametric equation of the curve $S_2$ is given by Eq.(8).

$$
\hat{a}(\phi) = a(\phi) + r_n n
$$

(8)

The given value $x_m$ and $y_m$ should fulfil Eq.(5). It is expressed in Cartesian coordinates, as shown in Eq. (9).

$$
\begin{align*}
    x_m &= \alpha_x + r_n n_x \\
    y_m &= \alpha_y + r_n n_y
\end{align*}
$$

(9)

Substituting Eq.(5) into (9), expressions of the centre distance and eccentric distance are given by Eq. (10). That is the parameterized centre distance and eccentric distance.

$$
\begin{align*}
    A &= -(\alpha_x + r_n n_x) \\
    T_1 &= (\alpha_y + r_n n_y) / \sin \beta
\end{align*}
$$

(10)

where the coordinates of the normal vector $n$ can be calculated by substituting Eq.(6) into (7).

$$
\begin{align*}
    n_x &= -\alpha'_x / \sqrt{\alpha'^2_x + \alpha'^2_y} \\
    n_y &= \alpha'_y / \sqrt{\alpha'^2_x + \alpha'^2_y} \\
    \alpha'_x &= \rho \cos \phi \cos \theta - (r - \rho \sin \phi) \sin \theta / (\sin^2 \phi \tan \beta) \\
    \alpha'_y &= \rho \cos \phi \cos \beta \sin \theta + (r - \rho \sin \phi) \cos \theta / (\sin^2 \phi \tan \beta) - \rho \sin \phi \sin \beta
\end{align*}
$$

(12)

For an arbitrary parameter $\phi$, centre distance $A$ and eccentric distance equation $T_1$ are determined by Eq. (10). As shown in section 2, $A$ is defined in Eq. (4) as $(r + r_w)$. It has been witnessed as the very
solution of the first objective of the paper fulfilling the requirement of web thickness. The second objective is to fulfil the requirement of radial rake angle $\gamma_0$. Its solution is the contents of the section to follow.

4. Fulfilling the required radial rake angle $\gamma_0$

There are two steps to fulfil the requirement of radial rake angle $\gamma_0$: firstly, the radial rake angle calculation procedure is introduced and furthermore its exploration region is determined; secondly, one-dimensional exploration procedure by using golden section search [18] is synopsized; finally, optimal value is the required angle $\gamma_0$ with the corresponding eccentric distance $T_1$.

The radial rake angle is determined by numerical differentiation to calculate the curve tangent at the radius end by using B-Spline or software in MATLAB.

As preparatory work to explore the rake angle approaching the required value $\gamma_0$, the range of exploration is determined by a large number of examples calculating the radial rake angle with different parameters $\phi$. It manifests that the drill centre is located at lower right position of the curve $S_2$ according to the grinder configuration. It concludes that the parameter $\phi$ should be within the range $\phi \in [\pi/2 - \beta, \pi/2]$, corresponding to the point $B$ and point $A$ with inclined installation angle (Fig.4). As shown in Fig.5, the merit function $f(\phi)$ is expressed in square of $(\gamma(\phi) - \gamma_0)$ shown in Eq. (13).

$$\begin{align*}
\min f(\phi) &= (\gamma(\phi) - \gamma_0)^2, \quad \phi \in [\pi/2 - \beta, \pi/2] \\
(13)
\end{align*}$$

It is modelled and can be solved by one-dimensional numerical optimization with the well known method of golden section search.

![Fig.6 Machining locus](image)

![Fig.7 Samples of cross-sectional profile](image)

Table 1

Dimensions of the drill and grinding wheel

| Parameter                  | Value     |
|----------------------------|-----------|
| Diameter of the drill: $d$ (mm) | 7.988     |
| Helical parameter: $P$ (mm) | 6.918     |
| Wheel radius: $r$ (mm)      | 123.290/2 |
| Wheel width: $W$ (mm)       | 12.136    |
| Wheel fillet radius: $\rho$ (mm) | 0.13     |
| Wheel inclined angle: $\lambda$ (°) | 70       |
Table 2
Iterative data

| No. | $\phi$     | $f(\phi)$ |
|-----|------------|-----------|
| 1   | 0.399940   | 28.6162   |
| 2   | 0.647204   | 19.1794   |
| 3   | 0.799988   | 10.0857   |
| 10  | 0.926693   | 0.0347473 |
| 15  | 0.926327   | 0.00272582|
| 19  | 0.926354   | 1.18785e-5|
| 21  | 0.926355   | 4.74384e-5|

Table 3 Comparison of the calculated and measured data

| Sample | Designed | Measured | Errors |
|--------|----------|----------|--------|
| a      | Half web thickness: $r_w$ (mm) | 1.100 | 1.108 | 0.73% |
|        | Radial rake Angle: $\gamma$ (deg) | 5.00 | 4.89 | 2.20% |
| b      | Half web thickness: $r_w$ (mm) | 1.100 | 1.111 | 1.00% |
|        | Radial rake Angle: $\gamma$ (deg) | 15.00 | 15.16 | 1.10% |

5. Example
The centre distance $A$ and eccentric distance $T_1$ for an arbitrary parameter $\phi$ are determined according to Eq. (10). The corresponding flute profile is determined by using direct movement simulation method [5]. The machining locus is shown in Fig.6 and the manufactured flute cross-sectional profile is shown in Fig.7. There are two types of flute profile corresponding to variety curves mentioned above:
Fig. 8 Influence of wheel installation angle $\beta$ on flute profile

Fig. 9 Comparison of width angle of flute with the same core

Fig. 10 Comparison of width angle of flute with the same rake angle
Fig. 11 Influence of wheel geometry on flute profile

Type I. The whole cross-sectional curve is concave in Fig. 6(a). The flute profile is generated only by the wheel’s fillet radius.

Type II. This is a combination of both enveloped and non-enveloped curves in Fig. 6(b). The front section is the same as type I. The rear section is generated by the wheel’s rear face. It shows the front section is concave and the rear section is convex.

Dimensions of the drill and grinding wheel are listed in table 1. Iterative data are listed in table 2. Comparison of the calculated and measured data is listed in table 3. The results can be summarized as follows: The convergence precision achieves $\varepsilon = 10^{-4}$, after 21 times’ iteration. Errors of the web thickness and radial rake angle are no more than 2.2%, respectively.

6. Discussion

6.1 Evaluation of installation angle

According to Fig. 1, only three parameters ($A$, $T$, and $\beta$) determine the wheel position. A 1V1 grinding wheel is used in this example, with the parameters shown in Tab. 1.

The cross-sectional profiles of flute under different requirements of $\gamma=0^\circ, 5^\circ, 15^\circ$ and $r_w=1.1\text{mm}, 2.2\text{mm}$ are generated. As shown in Fig. 7(a), with the increase of $\beta$ from $40^\circ$ to $60^\circ$, the rear section of flute moves upward and the flute width $\delta$ decreases while the front section remain unchanged. Overcut appears in the rear section when the value of $\beta$ less than $50^\circ$ under the required $\gamma=15^\circ$ in Fig. 7(b). It causes the flute width $\delta$ drops quickly. In Fig. 7(a) ($\gamma=0^\circ$) and Fig. 7(c) ($\gamma=5^\circ$), the shape of flute profiles keeps concave, belonging to type I flute curve. But in Fig. 7(b) ($\gamma=15^\circ$), flute profiles are mostly type II and the concave section only appears in a limited range $\beta \in [50^\circ, 60^\circ]$. When the required web thickness increases, the flute becomes narrower. In comparison the profiles in Fig. 7(d) ($r_w=2.2\text{mm}$) with Fig. 7(c) ($r_w=1.1\text{mm}$), the curvature and the flute width of flute profile is smaller.
6.2 Evaluation of wheel geometry
As shown in Fig. 3, the wheel geometry is mainly described by four variable parameters: wheel radius \( r \), wheel width \( W \), fillet radius \( \rho \) and inclined angle \( \lambda \). When wheel radius \( r \) increases from \( \phi 40 \text{mm} \) to \( \phi 130 \text{mm} \), fulfilling the requirements \( r_w=1.1 \) and \( \gamma=15^\circ \), the flute width \( \delta \) only increase 5\% in Fig. 10(a). It indicates that the wheel radius \( r \) has a little effect to flute width \( \delta \). Some numerical examples at other different conditions show the similar results. It is convenient and applicable in practical operations. According to this conclusion, different wheel radius can be selected to grinding the same required flute profile. Furthermore, if the wheel outer surface has a slightly worn-out, it will cause the order of tens of micrometers modification and amendment of wheel radius. It hardly has much influence to the ground flute profiles.

As shown in Fig. 10(b), along with the increasing of fillet radius \( \rho \), flute width \( \delta \) increases slowly. In practice, the fillet radius \( \rho \) is normally selected no more than 5mm, considering the curvature of flute profiles restriction. So the fillet radius \( \rho \) has a slight effect on the flute too. Using the above calculation process, the wheel’s position will be self-adaptive to the different required web thickness and rake angle.

Fig. 10(c) and (d) show that width \( W \) and inclined angle \( \lambda \) just influences the flute width. The flute width increases with \( W \) increasing within the range \( W \in [1 \text{ mm}, 5 \text{ mm}] \) and all the generated flute curves are type II. When wheel width \( W \) is larger than 5mm, overcut occurs on the rear section by the wheel rear face. In this time, the illustrated flute curves coincide and the flute geometry will not be affected any more. Similarly, when the inclined angle \( \lambda \) is larger than 70°, overcut occurs on the rear section too. This is a guidance to select wheel. If the required flute profile is type II, a large value of wheel width or inclined angle should be selected; in the contrast, a small width or inclined angle wheel is advantageous to form type I flute curve. Further information using different wheel with complex shapes will be explored by the proposed modelling method. It is the basic work for developing a flute curve pattern system with distinguish and recognition to orient the experimental exploration for drill performance improvement.

7. Concluding remarks
A novel method of twist drill fluting by using 1V1/1A1 wheel fulfilling required web thickness and radial rake angle is studied. The most effective conception in solving the difficulty is separating these requirements into independent parts. Considering the machining process as relative motion of the drill blank with respect to the grinding wheel, centre of the drill is moving along a curve. It provides constraint to the wheel installation position fulfilling the web thickness requirement. The remaining requirement of rake angle is determined by one-dimensional exploration. It is worthy of mentioning that involved derivation and computation are simplified by using direct method for twist flute modelling. In the context, differential geometry is very helpful in clarifying the basic idea explanation and providing an accurate and easy method of computation.

Validity of the proposed method is demonstrated by accurate agreement of the computed example with that manufactured. The above mentioned system has been embedded in the operational software of our machine tool. The novel fluting method is fulfilled effectively.

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