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Authors' contributions

Hongyang Wang: Methodology, Conceptualization, Validation, Writing - Original Draft, Term, Data Curation. Xianli Liu: Funding acquisition, Writing - Review & Editing. Caixu Yue: Writing - Review & Editing. Shipeng Wang[1]: Writing - Review & Editing, Data Curation. Gaojun Zheng[1]: Writing - Review & Editing, Data Curation. Kaiwang Zhao[1]: Writing - Review & Editing, Data Curation.

Ethics approval

The content studied in this article belongs to the field of metal processing, does not involve humans and animals. This article strictly follows the accepted principles of ethical and professional conduct.

Consent to participate

My co-authors and I would like to opt in to In Review.

Consent for publication

I agree with the Copyright Transfer Statement.

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Abstract:

The flute plays an important role in the design process for tools. The complexity of the cutting edge is increasing continuously. Thus, it is difficult to grind flute precisely and efficiently. This paper presents a practical grinding method for the flute of tools. It solves the issue that how to grind the flute with the complex edge by standard wheels. It is summarized as follows: the curve of cutting edge and core are used as the designed parameters of the flute; We propose the fundamental conditions that the wheel doesn't interfere with designed parameters; We can find the posture and position of wheel in the curve frame easily, thus obtain wheel trajectory. Finally, using a taper end mill as an example, the results show a good agreement between the CAM data and the model data. This proves the effectiveness of this method.

Keywords:

The curve of cutting edge, Flute, Grinding trajectory

1. Introduction

Nowadays, the manufacturing industry is developing rapidly. The cutting tools are widely used, especially in aerospace, automotive, and mold. The flute is the key structure of tool. It directly affects the cutting performance and the tool life. For instance, the flute is strongly related to cutting forces, chip formation, and fracture. The core affects the rigidity of the end mill. Normally, the flute is generated by wheel rotating around the axis of the blank, which is a complex surface. The efficient and accurate method of CNC grinding for the flute has attracted considerable critical attention in the industry. Currently, the design methods of flute are classified into the direct method and the indirect method. The indirect method: The cross-sectional shape of flute is given, and the forming grinding wheel for machining the target flute is obtained by applying the envelope theory. The direct method: Flute is machined by managing the position of standard grinding wheel in the tool coordinate system.

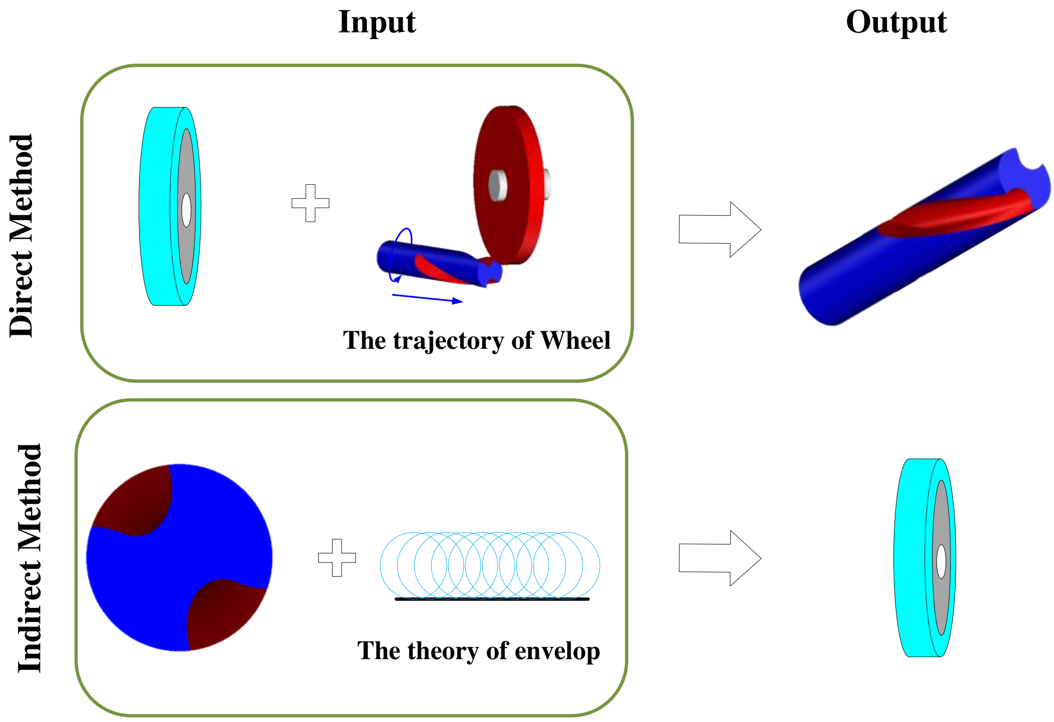


Fig.1 The method of grinding flute

The indirect method: Meshing theory is the basis of this method. Many researchers have explored the following two topics. How to describe the profile of flute by equations? How to find the shape of wheel? Ehmann et al. proposed a purely analytical approach, based on the common normal vectors at the points of contact must intersect the axis of wheel, to calculate the profile of wheel[1]. Li discussed the relationship between the interpolation methods and the precision of flute fitted curve[2]. Sometimes the profile of flute is generated by the combination of non-enveloped and enveloped curves. Meshing theory can't work smoothly. Then, the Boolean method was brought into the indirect method[3].In practice, the indirect method is decided that each flute must match a forming wheel. The profile of wheel must be accurate. So, these decrease the flexibility and efficiency of the indirect method.

The direct method: applies a known profile grinding wheel to grind the target flute. Zhang presented a direct method for calculating the profile of flute and the analytical expressions of flute were determined[4]. Nguyen analyzes the relationship between the singular point of wheel and flute[5]. Under knowing wheel, rake, and core conditions, Li developed an automatic search algorithm for finding the position of wheel[6]. Currently, precision manufacture poses higher demands on cutting tools, the profile of tool and complex cutting edge especially. However, the above articles don't consider the complex cutting edge in their models. It's hard to grind tools with complex cutting edge. such as a taper cylinder tool with constant helix. A method for grinding flute with complex edge by the edge of wheel has been reported[7], but the edge of wheel is worn easily. Chen demonstrated the grinding model for the rake face of the taper ball-endmill with a CBN spherical grinding wheel[8], but the spherical grinding wheel isn't a standard wheel. Thus, these methods aren't less prevalent. In the factory, most flutes were grinding by the standard wheel (Fig.3). It can be reshaped easily, because the profile of standard wheel is simple.

According to the discussion, this paper proposes a direct method for grinding flute by the standard wheel. Firstly, we build the model of cutting edge and the moving frame attached to edge. Then we established the model and equation of the core. After that, we presented a method for calculating the position of wheel. Finally, the effectiveness of the model is verified by a CAM example.

Nomenclature			
$O-XYZ$	global coordinate system	R_t	the radius of tool at Z=0
$O_w-X_wY_wZ_w$	coordinate system attached to wheel	R_c	the radius of core at Z=0
$P_i-\boldsymbol{T}_i\boldsymbol{B}_i\boldsymbol{N}_i$	moving frame attached to edge	G	the grinding point of wheel
γ	the rotation angle around $\boldsymbol{T}$	δ	the rotation angle around $\boldsymbol{N}$
μ	the angle between the normal vector of G_i and the axis of wheel		

2. The coordinate system and model

2.1 The cutting edge and the frame

In this paper, we take a taper end mill with constant helix angle as an example to explain this model. As shown in Fig.2, $O-XYZ$ is the global coordinate system, and the Z-axis coincides with the axis of the tool. In this system, the edge is expressed as

$$\begin{cases} x = R_{tool}(z)\cos\theta \\ y = R_{tool}(z)\sin\theta \\ z = z \end{cases} \tag{1}$$

where the angle θ is the circumferential angle of the projection of point in XOY plane. $R_{tool}(z)$ is the radius of tool, being a function of z. It is expressed as

$$R_{tool}(z) = R_t + z * \tan\varphi_t \tag{2}$$

where the angle φ_t is the taper of tool. R_t is the radius of tool at $z=0$. The helix angle of cutting edge[9]: the angle between the tangent of edge and the tangent of the generatrix that generates the tool rotating surface. Thus, the θ is given by

$$\theta = \theta_0 + \tan\beta \int_0^z \frac{1}{R_{tool}(z)} \sqrt{1 + \left(\frac{dR_{tool}(z)}{dz}\right)^2} \tag{3}$$

where β is the helix angle. The cutting edge with constant helix angle is given by

$$\begin{cases} x = R_{tool}(z) \cos\left(\theta_0 + \tan\beta \int_0^z \frac{1}{R_{tool}(z)} \sqrt{1 + \left(\frac{dR_{tool}(z)}{dz}\right)^2}\right) \\ y = R_{tool}(z) \sin\left(\theta_0 + \tan\beta \int_0^z \frac{1}{R_{tool}(z)} \sqrt{1 + \left(\frac{dR_{tool}(z)}{dz}\right)^2}\right) \\ z = z \end{cases} \tag{4}$$

The space curve frame is essential for this paper. It can describe the relative position conveniently. Take any point P_i on the cutting edge, we establish a frame $P_i - \boldsymbol{T}_i\boldsymbol{B}_i\boldsymbol{N}_i$ at this point. In global coordinate system, P_i is given by

$$P_i = [x_P, y_P, z_P] \tag{5}$$

The $\boldsymbol{T}_i$ is the tangent vector of the cutting edge at P_i point. The $\boldsymbol{N}_i$ is the normal vector of the tool rotating surface at P_i point. We define the binormal vector $\boldsymbol{B}_i$ as the vector product of $\boldsymbol{T}_i$ and $\boldsymbol{N}_i$.

$$\boldsymbol{B}_i = \boldsymbol{N}_i \times \boldsymbol{T}_i \tag{6}$$

$\boldsymbol{T}_i$, $\boldsymbol{B}_i$, $\boldsymbol{N}_i$ have unit length.

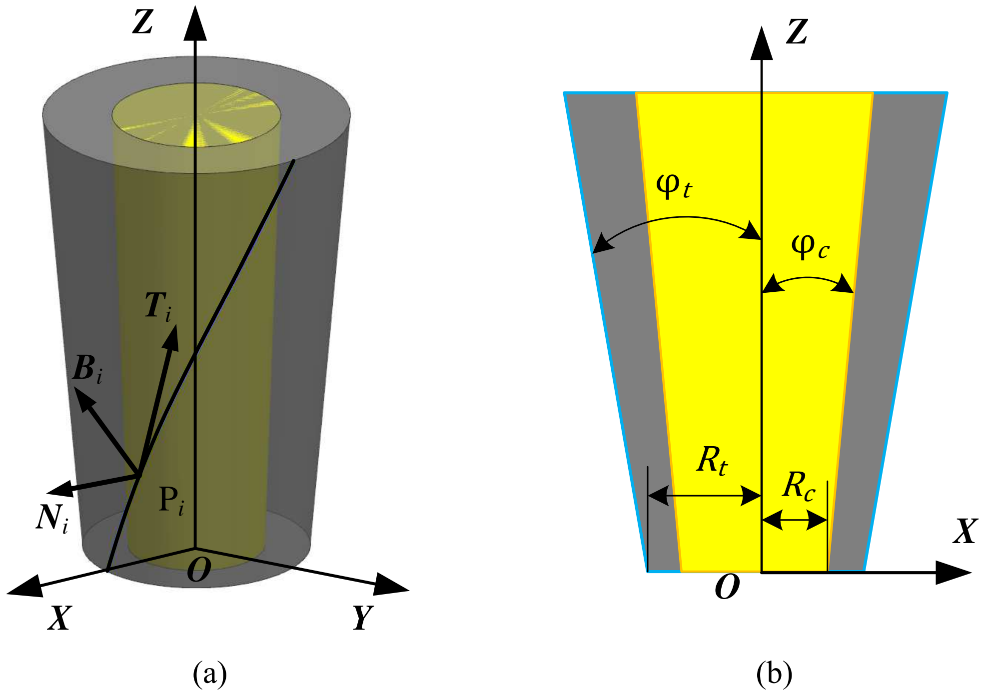


Fig.2 The cutting edge and the coordinate system

According to the relationship between the global coordinate system and the frame $\mathrm{P}_i - \boldsymbol{T}_i\boldsymbol{B}_i\boldsymbol{N}_i$, we can get the rotational matrix $\mathrm{M_R}$ and the translational matrix $\mathrm{M_M}$.

$$\mathbf{M_R} = [\boldsymbol{N}_i^{\mathrm{T}} \quad \boldsymbol{T}_i^{\mathrm{T}} \quad \boldsymbol{B}_i^{\mathrm{T}}] \tag{7}$$

$$\mathbf{M_M} = [\boldsymbol{x_P} \quad \mathbf{y}_{\boldsymbol{P}} \quad \mathbf{z}_{\boldsymbol{P}}]^{\mathrm{T}} \tag{8}$$

2.2 The model of core

Usually, the core also belongs to rotating surface that the generatrix is a line. For example, the cone surface and the cylinder surface. So, the surface of core is represented in global coordinate system by the equations

$$\begin{cases} z_{core} = z \\ x_{core} = R_{core}(z)\cos\theta \\ y_{core} = R_{core}(z)\sin\theta \end{cases} \tag{9}$$

where the angle θ is the circumferential angle of the projection of point in the XOY plane. $R_{core}(z)$ is the radius of core, being a function of z. It is expressed as

$$R_{core}(z) = R_c + z * \tan \varphi_c \tag{10}$$

where the angle φ_c is the taper of core. R_c is the radius of core at $z = 0$.

2.3 The coordinate system and model of wheel

As shown in Fig.3, $O_W - X_W Y_W Z_W$ is the coordinate system of wheel, and the Z-axis coincides with the axis of wheel. In this system, the surface of wheel is expressed as

$$\begin{cases} x_{wheel} = R_{wheel}(z)\, sin\, \theta \\ y_{wheel} = R_{wheel}(z)\, sin\, \theta \\ z_{wheel} = z \end{cases} \tag{11}$$

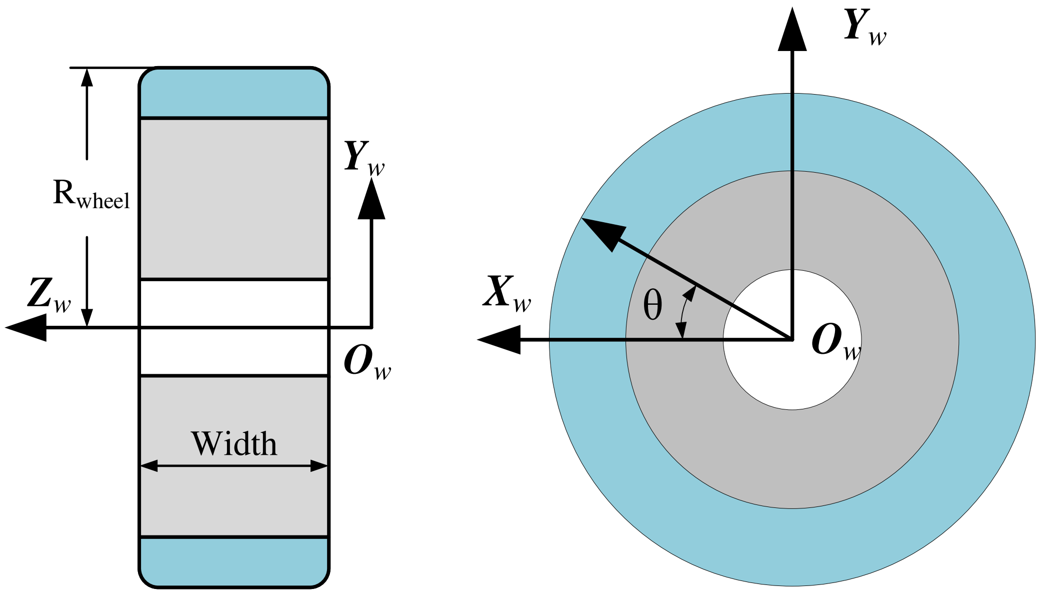


Fig.3 The coordinate system of wheel

where the angle θ is the circumferential angle of the projection of point in $X_W O_W Y_W$ plane. $R_{wheel}(z)$ is the radius of wheel, being a function of z.

3. Generation of the grinding path

We illustrate the method of calculating the grinding path. During the grinding process of flute, the motion of wheel is continuous. But the path must be discrete, when we calculate the path. So, the grinding path consisted of the position of wheel in order. The procedure of the method that calculates the position of wheel is as follows.

Step 1: Select any point on the round chamfer of wheel, we define this point as the grinding point G. G can be represented in the coordinate system of wheel by equation (Fig.4).

$$G = [x_G, y_G, z_G] \tag{12}$$

The angle μ is the angle between the normal vector of G and the axis of wheel, is a constant, and $0 \le \mu \le \frac{\pi}{2}$. The initial position of wheel is shown in Fig.4. This position must satisfy the following requirements:

a) The grinding point G must coincide with P_i that the origin of moving frame.

b) The normal vector of G and the binormal vector $\boldsymbol{B}_i$ are collinear.

c) The axis of wheel must be in the plane that the plane contains $\boldsymbol{B}_i$, P_i, and $\boldsymbol{T}_i$.

The rotational matrix M_{R1} and the translational matrix M_{M1} describe translation and rotation from $O_W - X_W Y_W Z_W$ to $P_i - \boldsymbol{T}_i \boldsymbol{B}_i \boldsymbol{N}_i$ and are represented by

$$M_{R1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\mu & \sin\mu \\ 0 & -\sin\mu & \cos\mu \end{bmatrix} \tag{13}$$

$$M_{M1} = \begin{bmatrix} x_G \\ y_G \\ z_G \end{bmatrix} \tag{14}$$

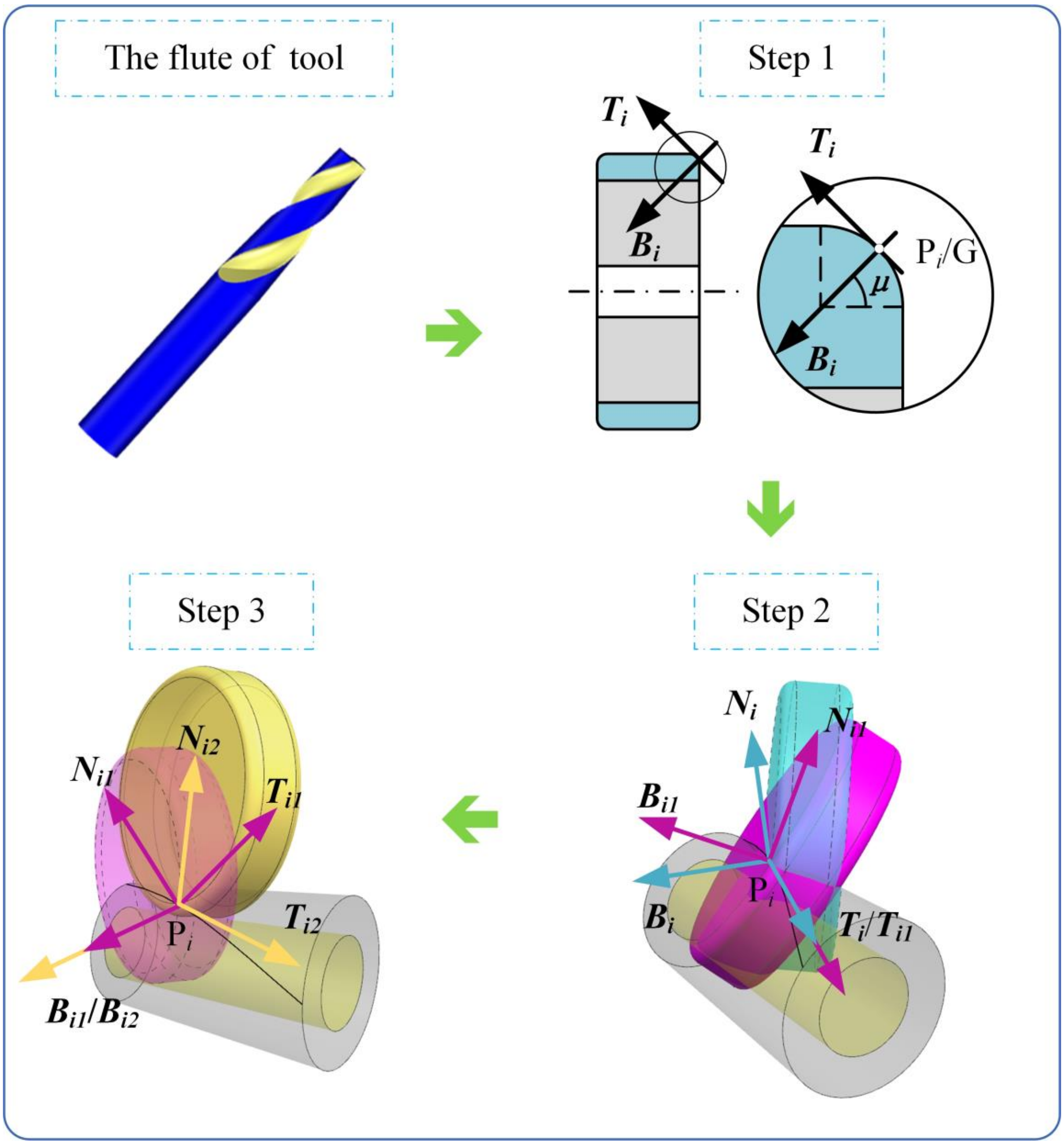


Fig.4 The calculation process of wheel position at P_i

Step 2: The moving frame $P_i - \boldsymbol{T}_i\boldsymbol{B}_i\boldsymbol{N}_i$ and wheel are rotating around $\boldsymbol{T}_i$, the rotational angle is γ. Normally, γ is set by users and affects rake angle. We obtain a new moving frame $P_i - \boldsymbol{T}_{i1}\boldsymbol{B}_{i1}\boldsymbol{N}_{i1}$. Like Step 1, we can get the rotational matrix M_{R2}, which is given by

$$\mathrm{M_{R2}} = \begin{bmatrix} \cos\gamma & 0 & -\sin\gamma \\ 0 & 1 & 0 \\ \sin\gamma & 0 & \cos\gamma \end{bmatrix} \tag{15}$$

Step 3: As is shown in Fig.4. The moving frame $P_i - \boldsymbol{T}_{i1}\boldsymbol{B}_{i1}\boldsymbol{N}_{i1}$ and wheel are rotated about $\boldsymbol{B}_{i1}$ with the rotational angle δ. The new moving frame is defined as $P_i - \boldsymbol{T}_{i2}\boldsymbol{B}_{i2}\boldsymbol{N}_{i2}$. At this position, the surface of wheel must be tangent to the surface of core theoretically. But the minimum value of distance between two surfaces must be within the manual setting error in practice. Similarly, the rotational matrix M_{R3} is represented as

$$\mathrm{M_{R3}} = \begin{bmatrix} \cos\delta & -\sin\delta & 0 \\ \sin\delta & \cos\delta & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{16}$$

This position of wheel (Fig.4) satisfies the design requirements. It is obvious that the surface of wheel in global coordinate system is represented by the equation

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathrm{M_R} \cdot \mathrm{M_{R2}} \cdot \mathrm{M_{R3}} \cdot \mathrm{M_{R1}} \cdot \left(\begin{bmatrix} x_{wheel} \\ y_{wheel} \\ z_{wheel} \end{bmatrix} + \mathrm{M_{M1}} \right) + \mathrm{M_M} \tag{17}$$

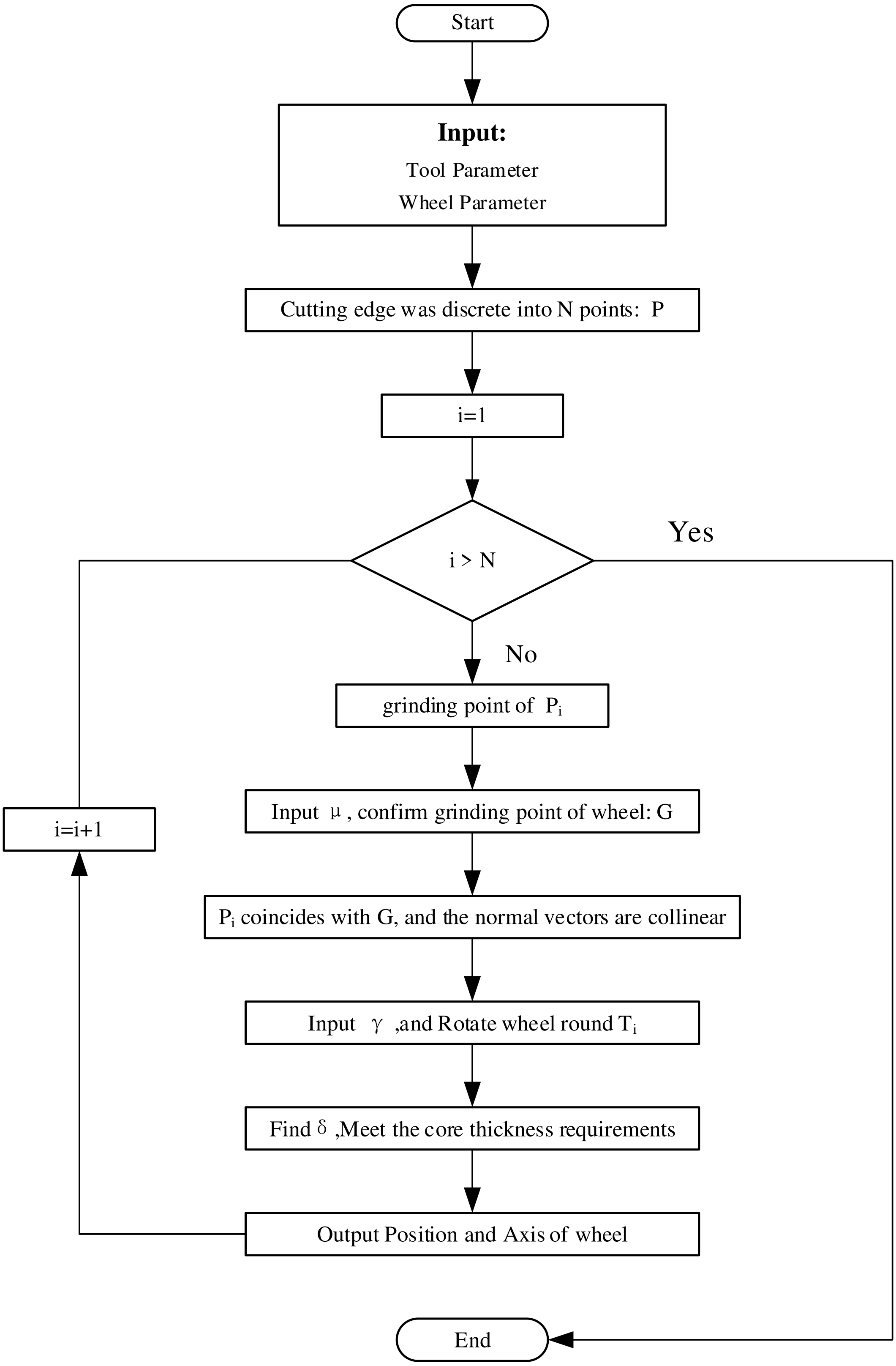


Fig.5 Principle of calculate the grinding path

4. Numerical example and verification

To illustrate the method, a CAM example of grinding flute was performed.

4.1 Parameters and calculation

A taper end mill is used in this example, Table 1 is the parameters of tool. The flute is ground by the standard wheel which type is 1L1, parameters are shown in Table 2.

Table 1 The parameters of tool

Radius of tool	Taper angle of tool	Helix angle	Number of teeth
5 mm	3°	30°	2
Length of edge	Radius of core	Taper angle of core	
30mm	1.5 mm	1°	

Table 2 The parameters of wheel

Diameter	R1	R2	Width	Tilt angle
100mm	0.1mm	0.1mm	10mm	10°

Now, we calculate the grinding path. The cutting edge is divided into discrete points which the distance of points is 0.05mm along the Z-axis. The error of core is $\pm 0.01mm$. The following is the grinding parameters.

$$\mu = 10°, \gamma = 10°$$

Then, we can calculate the positions and axis of wheel by the above data (Table 3).

Table 3 The Axis and Position of wheel

No	Axis of wheel			Position of wheel		
	X	Y	Z	X	Y	Z
1	-0.3078	-0.7335	0.606	29.8996	-33.6792	-28.3005
2	-0.3036	-0.7352	0.606	30.0978	-33.5048	-28.2505
3	-0.2993	-0.737	0.606	30.2949	-33.3292	-28.2005
4	-0.295	-0.7387	0.606	30.4908	-33.1526	-28.1505
5	-0.2907	-0.7404	0.606	30.6856	-32.975	-28.1005
6	-0.2864	-0.7421	0.606	30.8793	-32.7962	-28.0505
7	-0.2821	-0.7437	0.606	31.0719	-32.6165	-28.0005
8	-0.2777	-0.7454	0.606	31.2633	-32.4357	-27.9505
9	-0.2734	-0.747	0.606	31.4536	-32.2539	-27.9005
10	-0.2691	-0.7485	0.606	31.6427	-32.071	-27.8505

4.2 Result of CAM

In this paper, we have two ways to find the profile of flute (Fig.6). The first way: The intersections of plane z with the surface of wheel that wheel is located in the calculated positions are the profile of flute, where z is an arbitrary value. The profile of flute can be achieved by MATLAB's boundary algorithm (Fig.7). The second way: Import the positions of wheel into NUMROTO which is the center of competence for tool grinding. Then we can get the result of CAM by NUMROTO-3D (Fig.6). After that, we can export the profile of flute. Comparing two results of CAM, the line profile is within 0.06 mm. In Z=5 and Z=10 plane, the normal deviation along the profile of flute is shown in Fig.8. The error may come from discrete accuracy. It means the CAM is accurate.

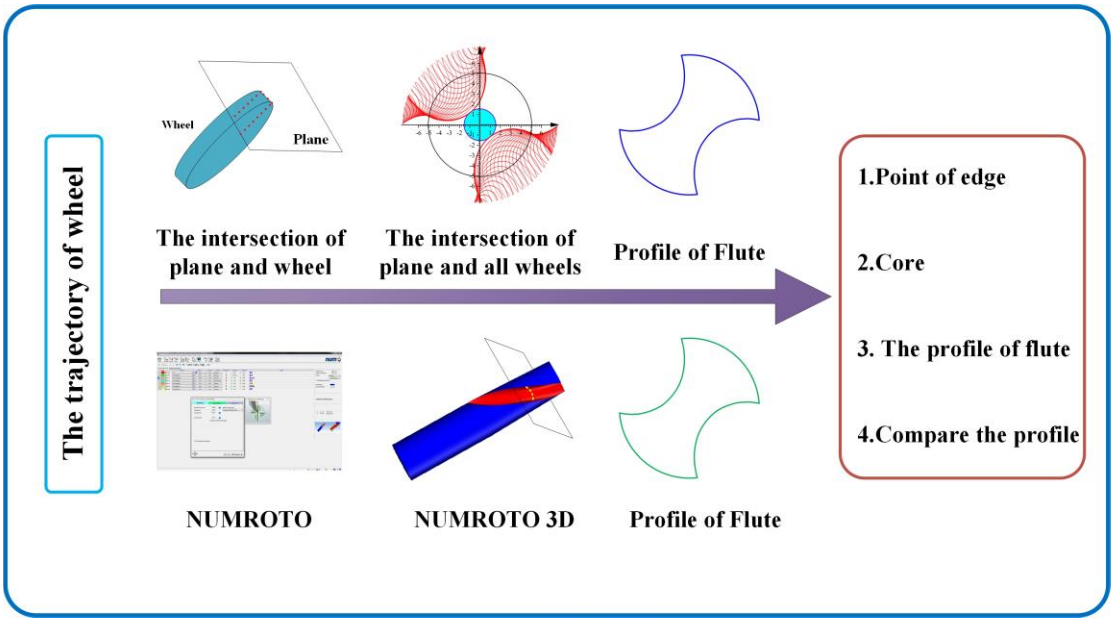
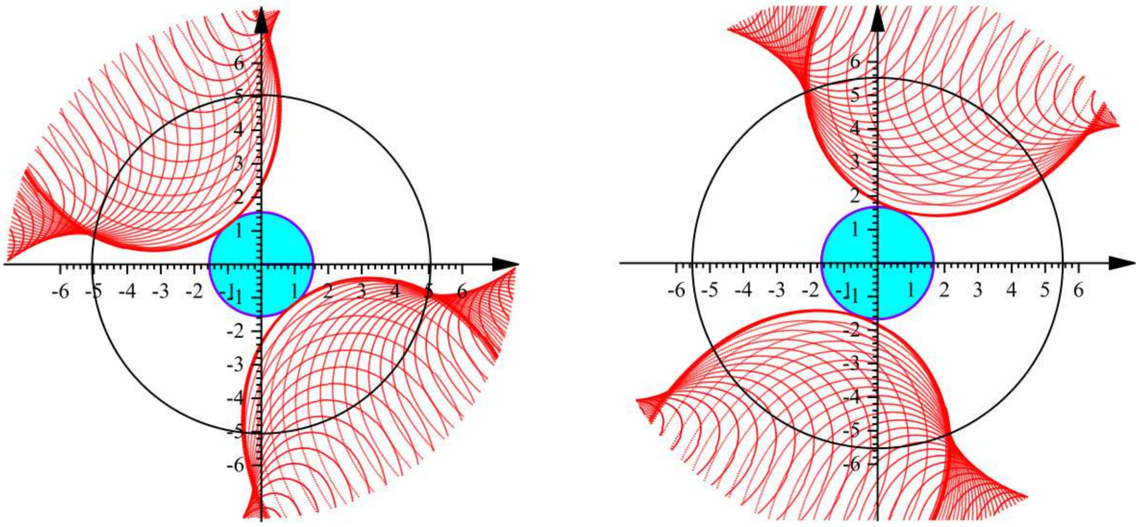


Fig.6 The process of calculate the profile of flute



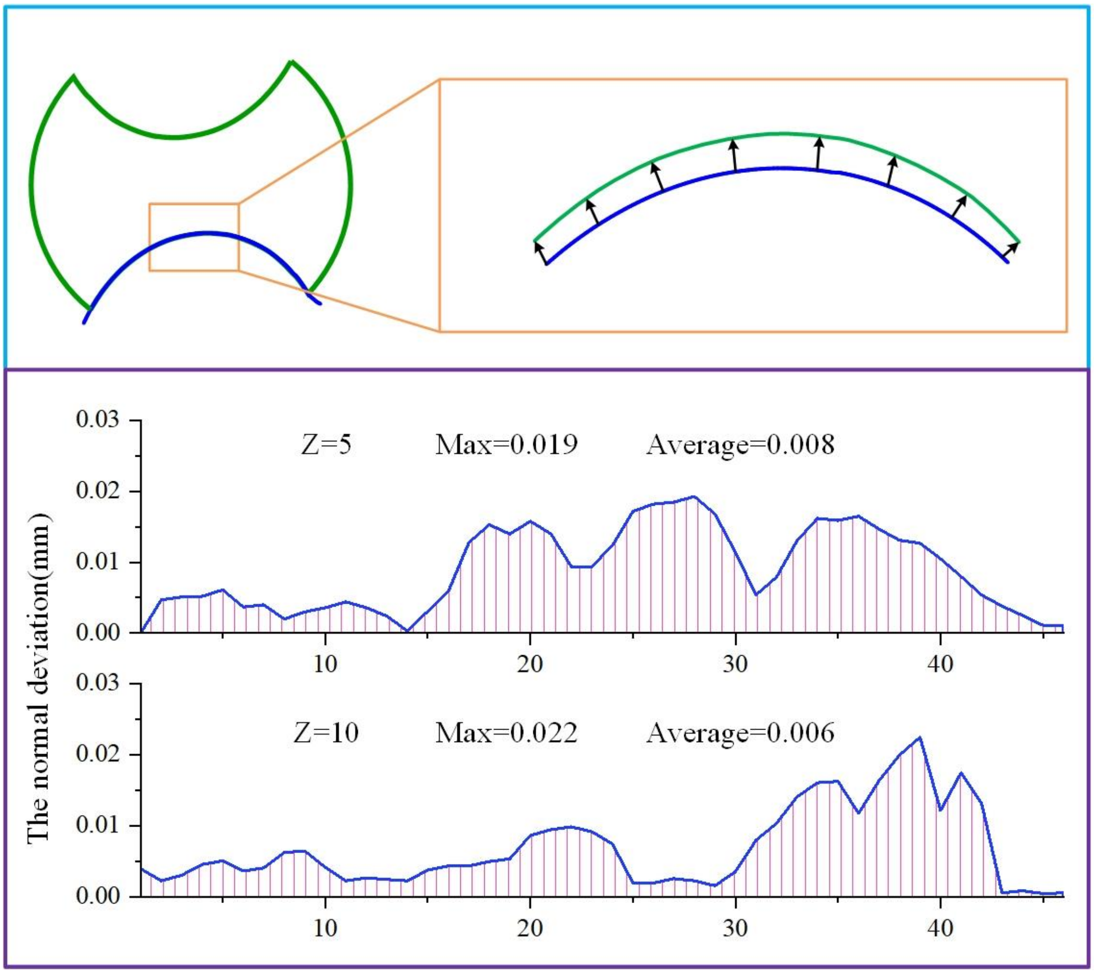
(a) Z_1=1 (b) Z_2=10

: The intersection of plane and wheel

: The intersection of plane and core

: The intersection of plane and tool

Fig.7 The profile of flute by CAM



: The profile by NUMROTO

: The profile by the intersection of the plane and all wheels

Fig.8 The normal deviation along the profile of flute

Based on the profile of flute, we can obtain the core and the cutting edge easily. The theoretical and simulated radius of core are shown in Table 4. All errors satisfy the manual setting error. Table 5 is the position of the edge. The maximum position is 0.004 mm within a reasonable range.

Table 4 The error of core by CAM

Z	The radius of core (mm)	The radius of core by CAM (mm)	Error (mm)
0	1.500	1.501	0.001
1	1.517	1.520	0.002
2	1.535	1.539	0.004
3	1.552	1.558	0.006
4	1.570	1.578	0.008
5	1.587	1.590	0.003
6	1.605	1.609	0.005
7	1.622	1.624	0.002
8	1.640	1.642	0.002
9	1.657	1.661	0.004
10	1.675	1.681	0.006

Table 5 The position of cutting edge

Z	Theoretical values		The value of simulation		Position
	X	Y	X	Y	
0	5.0000	0.0000	5.0000	-0.0018	0.0037
1	5.0190	0.5799	5.0192	0.5780	0.0038
2	4.9717	1.1581	4.9721	1.1563	0.0037
3	4.8593	1.7274	4.8599	1.7256	0.0038
4	4.6840	2.2805	4.6848	2.2787	0.0039
5	4.4485	2.8107	4.4494	2.8091	0.0037
6	4.1562	3.3120	4.1574	3.3105	0.0038
7	3.8113	3.7785	3.8126	3.7772	0.0037
8	3.4182	4.2053	3.4196	4.2041	0.0037
9	2.9818	4.5878	2.9834	4.5868	0.0038
10	2.5076	4.9221	2.5093	4.9213	0.0037

5. Conclusion

In this paper, a novel and practice method for grinding flute is presented. This method realizes design parameters of flute are ground by the standard wheel. A CAM example was performed to verify this method. The error of core satisfies the manual setting value. The position of edge is within a reasonable range. Under the same condition that the same wheel, the same cutting edge, and the same core, we can adjust the parameters μ and γ to find the target flute. By shifting the equation of the cutting edge curve, we can easily extend this method to the manufacturing models of tools and structures.

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