A New Method of Modeling Flank and Fillet Rake Surfaces of Fillet End-mills

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ABSTRACT

A New Method of Modeling Flank and Fillet Rake Surfaces of Fillet End-mills

Hanshi Chen

Carbide end mill, as one of the most commonly used cutting tool in aluminum, titanium and steel machining industry, is of crucial importance in the industry regarding to the machining efficiency and quality. For fillet end-mill, because of its complexity geometry in flank and fillet parts, a free-form geometry model is needed for further analysis and optimization. Many research works have been conducted on building geometric model based on grinding tool path. In this thesis, a parametric and easy controlled method is proposed for design and modeling of the fillet flank and the fillet rake surface. First, the end and side clearance surface need to be established according to geometric parameters and constraints; Secondly, the fillet cutting edge is designed to achieve the machining requirement of the corner radius geometry, which is critical for the modeling of the fillet flank and the fillet rake surface face; Then, the surface of the fillet flank is supported by splines which derived from the customized two-dimensional corner. And a rake angle based method is applied for modeling of the fillet rake surface. A detailed discussion on parametric variables of this method is provided for a more accurate surface. Together with flutes and gashes, the solid model of the fillet end-mill can be modeled using Boolean operations. All the modeling process is carried out with a VB automatic program for fast and customized

modeling in CATIA. In order to examine the geometry of this model, machining simulation is conducted in a finite element analysis software compared with the original model which based on grinding tool path.

ACKNOWLEDGEMENTS

I hereby would like to thank my supervisor, Dr. Chevy Chen, for his kind guidance and patient instructions through all this work. It really improves me quite a lot going through all this research, I would not accomplish thesis without him.

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CHAPTER 1 INTRODUCTION

1.1 Fillet End-mill

End mill cutter plays a major role in machining cutters and is widely used in the metal cutting industry. With the rapid development of manufacturing, the increasing categories of work material and the complexity of component geometry, requirements for end mills in many aspects also improves. Currently, several categories of end mill exist in the industry, like flat, ball, fillet and chamfer as shown in Figure 1.1. They can also be divided by number of flutes, by helix angle and by material. Even though the solid end mills are gradually replaced by inserted cutting tool which is more cost-effective, they still have their unique advantage in many manufacturing areas.

Fillet end-mill, also known as bull nose end mill, is a flat end mill with a corner radius which

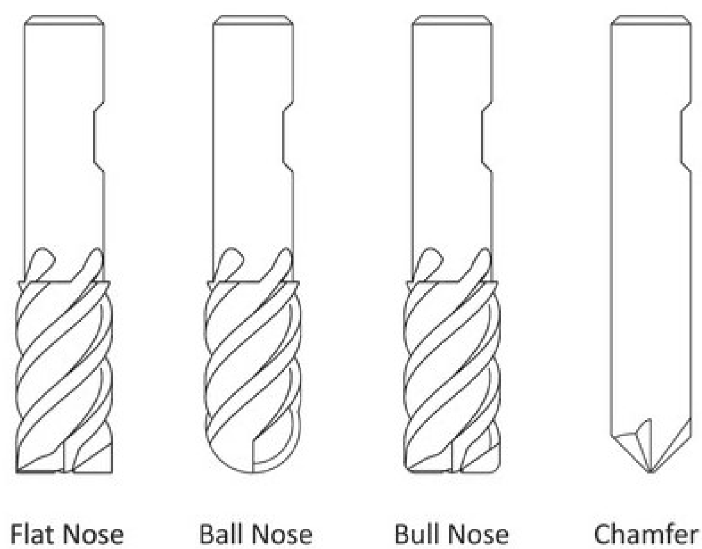

Figure 1.1 Different types of end mills

provides longer tool life. Different machining operations can be performed by fillet end-mill, such as peripheral end milling, milling slots and keyways, open and closed pockets. Especially, they are used between two perpendicular surfaces with radius connection.

For the traditional flat bottom end mill, the weakest point is the sharp corner which could cause chipping or crumbling of cutting edges easily as shown in Figure 1.2. However, because of

Figure 1.2 Chipping of the fillet edge on a flat-end mill

the geometry design of corner radius, the fillet end-mill with radius fillet cutting edge can improve the strength of the cutter dramatically at the intersect part between end teeth and side teeth which is more durable.

However, only when the fillet feature is well designed, the cutter can achieve prospected performance and contribute to machining process. Poor fillet design could also results damage at the radius edge which may lead to total cutter failure. So the design of the fillet in the modeling of fillet end-mill is of primary importance in this thesis. A model of fillet end-mill in CATIA is shown in Figure 1.3.

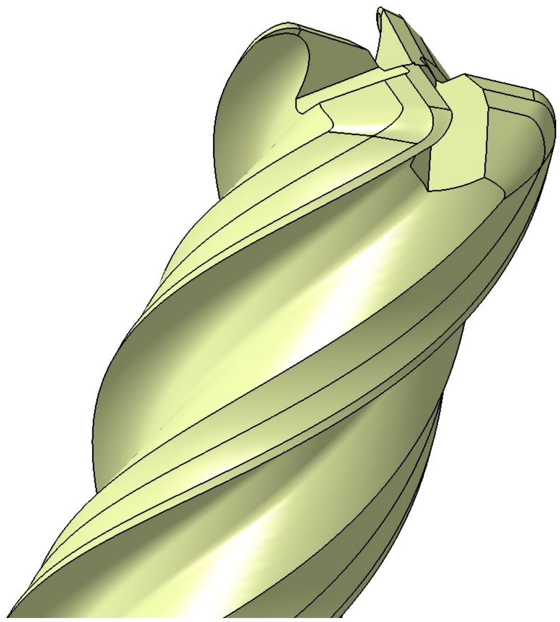

Figure 1.3 3D model of fillet end-mill

1.2 Feature-based Design

A product model can be built by using (design) features; this is known as design by features or feature based modelling. Features can be seen as package of information which contains different forms and attributes of a part, this information can be used to explain the design, part manufacture or assemblies which they are related to [1]. The modeling of feature-based design is defined as parametric models which indicating associated parameters (such as geometric parameters, positional parameters etc). Part dimensions, constraints and relations among parts and dimensions can be determined according to the design of the feature. With the techniques of computer-aided design, feature-based design can be easily accomplished.

Feature-based design not only can gather the information for application in the design part, but also considers related factors of manufacturing process in the early design stage. For fillet end-mill design, on one hand, key parameters of the cutter should be established in the design, like shank diameter, rake angle, relief angle; on the other hand, the manufacturability of the designed feature should also be considered. For example, flanks, gashes and flutes of end mills are manufactured on grinding machine. If one of the designed features is not machinable on the grinding machine and needs further manufacturing process, this feature may not be acceptable.

1.3 Parametric Modeling

Now, one of the core techniques of CAD is parametric part modeling. Since the functions of parametric modeling in major commercial CAD software are introduced, parametric models can be easily built and modified in the design process. The parametric representation of features provides a powerful way to change features with respect to their dimensions. [1] Compared with traditional modeling method which all the parameters are not associated, dimensions and constraints are specified with relations. With the parametric modeling on CAD software, the time of design and the error caused by traditional method can be greatly reduced.

Even though there is not a commercialized CAD system specializing in the modeling for the cutting tool which is under further research and development, modeling system of cutting tool begins to present with integration, networking and customization. In the design of the fillet end mill, by implementing the parametric modeling with VB programming in CATIA, the model of the fillet end mill can be built by defining major parameters and constraints which is available for further analysis and optimization.

1.4 Literature Review

Many academic articles have proposed models of generalized end mills. Xu and Zhao [2] proposed an accurate parametric model based on geometric parameters and relative positioning between the end mill and the grinding wheel. Pham and Ko [3] present a flat-end mill model using a five-axis CNC grinding machine. Given wheel profile and position parameters, the profile of the helical groove is calculated accurately. Kim et al. [4] use simulation method with Boolean operations to derive the machined shape of an end mill. The required geometry of a grinding wheel and cutter location data can be obtained according to dimensional parameters of the end mill. Yi et al. [5] provides a new integrated system to design the ball end mill. Cutting characteristics of different ball end mills which are successfully fabricated are investigated. Tandon and Khan [6] offers a simple method to generate a high-quality model of the flat end mill. The parametric equation of each surface is demonstrated, including the fluted shank and the end surface. FEA simulation is conducted to analyze the cutting force, von mises stress and translational displacement. Tsai and Hsieh [7] published an article about an analysis method which integrates design, manufacturing and simulation to build a model for design and NC manufacturing of the ball end mill. Helical edge curve and helical groove cross-section equation are also presented in this article. Hosseini et al. [8] proposed a method of modeling serrated cutting edges geometrically as a B-spline curve which could predict cutting forces and examine the inaccuracy by simulation.

With regard to rake and relief surface, two papers are reviewed. Zhao et al. [9] describe a precise and smooth rake face of an end mill in Solid Works. The mathematical equation of the rake face is derived from the fillet of grinding wheel motion which is verified by comparing with the discrete entity of rake face with Boolean operation. Zhao et al. [10] presented a mathematical model of the relief surface curve which is verified on a five-axis CNC grinding machine. With the model of a cup wheel edge, the coordinates of grinding point and other necessary data, the NC code can be generated for 3D simulation and actual machining with good product.

1.5 Objective of Thesis

As the flute is the major feature in majority of end mills and has a great influence on the performance of machining, most researches about end mill modeling focus on the flute modeling and use the method of combining the grinding wheel path with relative position of end mill. While the flank and the fillet rake surfaces are not that popular, even though the fillet rake surface is an essential feature of fillet end-mill. In the industry of cutting tool design and manufacturing, big companies like WALTER and SAACKE, the method of modeling end mill in the grinding software is not open to users which make it difficult to design new customized flank and fillet rake surfaces. Thus, an approach of design and modeling flank and fillet rake is proposed in this thesis.

An unequal helical 4-flute fillet end-mill is set as the example for parametric modeling. The geometry of end and side clearance face is built first as the basis of fillet part. Then the fillet flank and fillet rake surfaces are designed and modeled with several variables for customized modeling. With the model built from previous research, the model of solid fillet end-mill can be generated using Boolean operations.

Because it is time consuming to build this model in 3D software, a program is developed in VB 6.0 for automatic modeling. An interface is created for modifying variables to build different fillet end-mill.

At last, a finite-element analysis simulation is conducted for this model compared with model based on the grinding wheel path. The results are shown in figures and chart to illustrate difference between these two models.

1.6 Thesis Outline

This thesis consists of five chapters. Chapter 1 introduces the basic knowledge about the fillet end-mill, feature-based design and parametric modeling, followed by literatures reviewed about this topic. Chapter 2 describes the orthogonal model first, and the modeling of fillet cutting edge is proposed based on flute profile. Then the determination of two-dimensional corner is presented and the modeling method of fillet flank is provided. Chapter 3 shows an approach to build a rake angle based model of fillet rake surface, and the actual rake angle of several fillet rake surfaces with different guide sets are measured to illustrated accuracy of this model. Chapter 4 shows simulation of proposed model in a FEA software compared with grinding wheel path based model to verify the geometry of the model. Chapter 5 concludes the modeling method of flank and fillet rake surfaces and the future work.

CHAPTER 2 DESIGN AND MODELING OF FILLET FLANK

2.1 Introduction of the Orthogonal Model

There are various shapes of cutting tools in the machining industry. As each of them has their unique way to remove material, the complexity of the geometry of different cutting tools differs. However, a simplified cutting model can be adopted to explain the basic geometry of most cutting operation which is called orthogonal model. The geometry for most cutting operation is three-dimensional, however, the orthogonal model displays the cutting process in two-dimensional way which can eliminate many independent variables so that the basic knowledge of cutting tool is simplified.

By definition, the wedge-shaped tool is applied in this model and the cutting edge of the tool is perpendicular to the direction of the motion between the workpiece and tool which indicates the cutting speed. The failure of the material only happens at the cutting edge which separates the chip from the parent material.

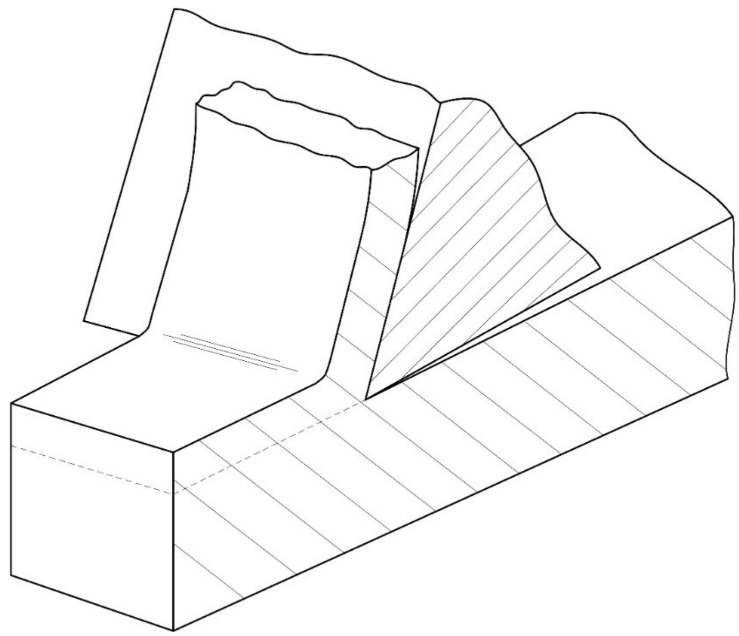

Figure 2.1 Orthogonal Model

In Figure 2.1 , a basic three-dimensional cutting model is shown. In this model, a section view is displayed which is perpendicular to the cutting edge. As the tool processes into the workpiece, the chip is separated by shear deformation along the shear plane. Along the shear plane, the consuming of energy leads to the plastic deformation of material.

Figure 2.2 shows the section view of the orthogonal model with several major variables. Two surfaces intersect to form the cutting edge which is projected into a point. The surface which the chip shears along is known as the rake face. The surface facing the machined workpiece surface is called tool flank, or known as the relief face. And the tool in orthogonal plane has two important angels, the rake angle and the clearance angle. The rake angle is measured from the normal of the cutting speed along the orthogonal plane to the rake face. The rake angle can vary from the positive direction to the negative direction. The rake angle shown in Figure 2.2 is positive, as the wedge angle increases, the rake angle goes from the positive to zero then to the negative. Negative rake angle means stronger cutting edge which is more suitable for rough machining. The clearance angle is the angle between flank face and the cutting speed projects on the orthogonal plane which gives a clearance room between the flank face and the newly machined surface. Even though the clearance angle doesn't remove any material in the machining process, this angle has major influence on the quality of machined surface and affects significantly on the rate of tool wear.

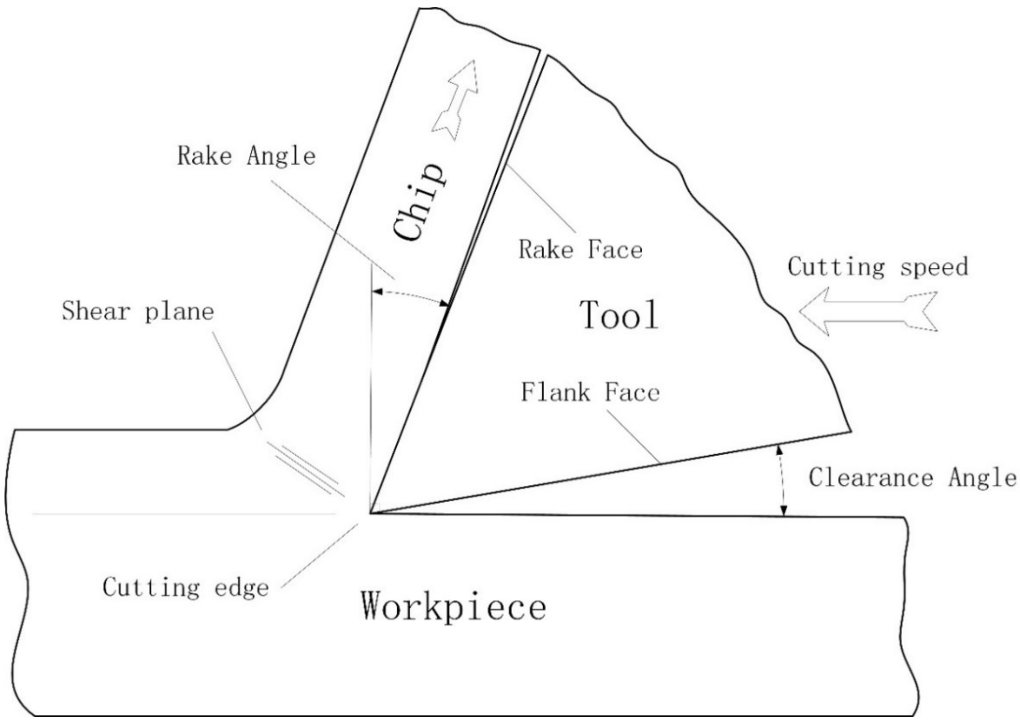

Figure 2.2 Section view of the orthogonal model

2.2 Design of Fillet Cutting Edge

2.2.1 Introduction of the Geometry of Fillet End-mill

There are different sizes, and shapes of fillet end-mills being used in the industry for different machining purposes. The major feature of end mills is the number of flutes. The end mill with two spiral flutes provides large room for chip flow, so they are usually recommended for rough milling with fast metal-removal rates. While the end mill with four flutes provides a fine finish for the workpiece after roughing machining. Four-flute end mill is one of the end mills commonly used in the industry, so in this thesis, a four-flute fillet end-mill is selected for design and modeling.

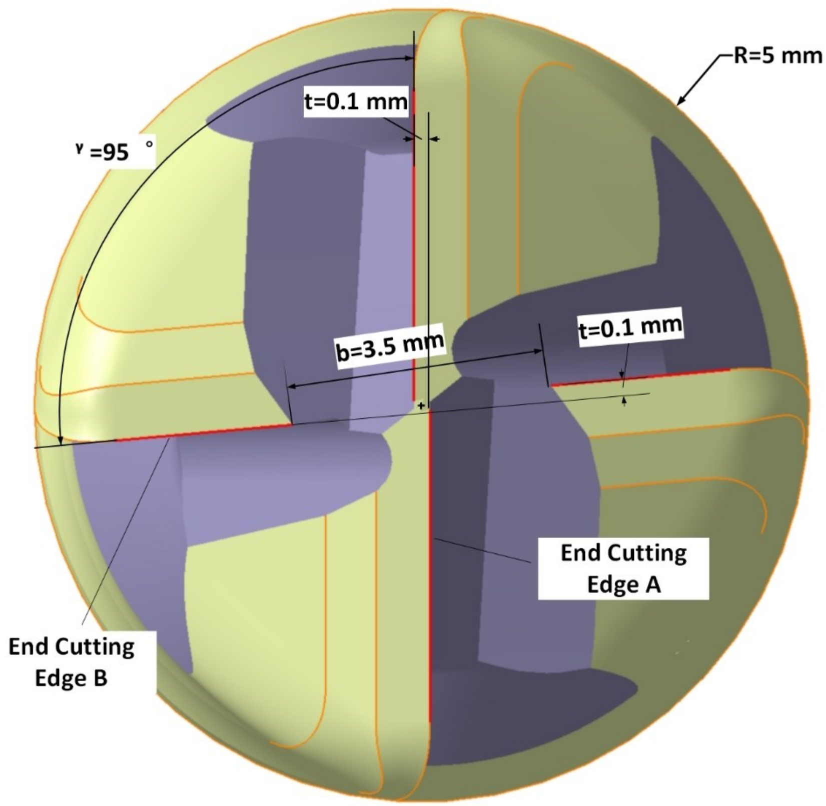

Figure 2.3 Geometric parameters on bottom view

End mills have cutting teeth both on the end side and the periphery. The cutting edge of tooth on the end is called end edge, while those on the periphery tooth is side edge. In a four-flute end mill, the angle between two neighboring end edges is flute angle. One of the two opposite end teeth meets at the end of cutter, merging together as cutting lips across the bottom which eliminates the material in the center area. Other two opposite teeth do not exceed the center, but are separated by gash. The geometry of end tooth could both remove the central material and give room to chip flow.

Side teeth are the extension of end teeth to the periphery part which are based on a certain helix line around the shank. But some end mills have side teeth which are

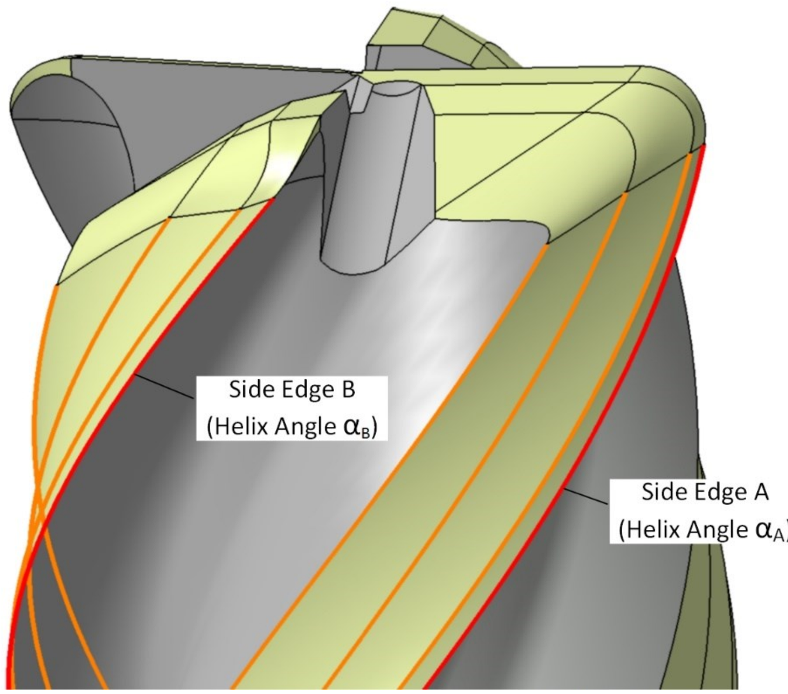

Figure 2.4 Geometric display of side teeth

straight or not constant with the same helix angle. The length of the cut is measured by the length of side teeth. Machining operations mainly conducted by side teeth are peripheral end milling, open and closed pockets. Both end teeth and side teeth are separated by the features of flutes and gashes.

The feature which makes the fillet end-mill different is the radius corner. As mentioned in the introduction, the radius corner is the key element to the fillet end-mill. Geometrically, the radius corner is a section of cutting edge connected with the end edge and the side edge with rake face and clearance face. The fillet radius of every fillet end-mill is the only parameter it has to form the fillet feature. So a method of the fillet design and modeling is described in this chapter and

Chapter 3.

In Table 2-1, Table 2-2 and Table 2-3, parameters of the example fillet end-mill are shown. All the variables discussed below about this cutter are listed in these tables.

Table 2-1 General parameters of fillet end-mill

Parameters	Definition	Value
R	Cutter radius	5 mm
L_{cut}	Length of cut	25 mm
L	Overall Length	75 mm
r	Fillet radius	1 mm

Table 2-2 Parameters of end teeth

Parameters	Definition	Value
b	Distance between inner start points of cutting edge B	3.5 mm
γ	Flute angle	95°
θ	Concavity angle of end edge	2°
c	Parallel distance between two cutting edge B	0.1 mm
σ_{er}	Rake angle of end edges	5°
b_{e1} b_{e2} b_{e3}	Clearance width of end tooth	0.7 mm 1.4 mm 4 mm
β_{e1} β_{e2} β_{e3}	Clearance angle of end tooth	8° 25° 30°

Table 2-3 Parameters of side teeth

Parameters	Definition	Value
α_A	Helix angle of side edge A	38°
α_B	Helix angle of side edge B	40°
σ_{sr}	Rake angle of side edges	6°
b_{s1} b_{s2} b_{s3}	Clearance width of side tooth	0.35 mm 1.4 mm 4 mm
β_{s1} β_{s2} β_{s3}	Clearance angle of side tooth	11° 25° 30°

2.2.2 Boolean Operations

Boolean operation is one of the most difficult modeling functions in CAD technique. However, they provide a powerful way to build complex models. Boolean can present different operations between two solids or between solid and surface, like union, trim, intersection. For the modeling of the fillet end-mill, this is the key operation for the final model.

In order to generate each feature according to the available parameters, each feature can be presented in certain defined surface. Like the process of manufacturing a fillet end-mill in a grinding machine, every feature is trimmed with Boolean operations in sequence from a solid cylinder which considered as the toolbar. So, only by modifying the parametric designed features, the model of the fillet end-mill can be generated parametrically.

The method of modeling flank and fillet rake surfaces is demonstrated below. A complete parametric model of fillet end-mill will be generated after Boolean operations between the parametric surfaces of flank and fillet rake and the previous model.

2.2.3 Fillet Cutting Edge Based on Flute Profile

As a critical feature of the fillet end-mill, the design of radius corner has a great impact on the performance of the cutter. After corner machining with a fillet end-mill, the intersection of finished surface should be a 1/4 arc with the same radius of fillet corner which is tangent with two planes machined by the end edge and the side edge as shown in Figure 2.5.

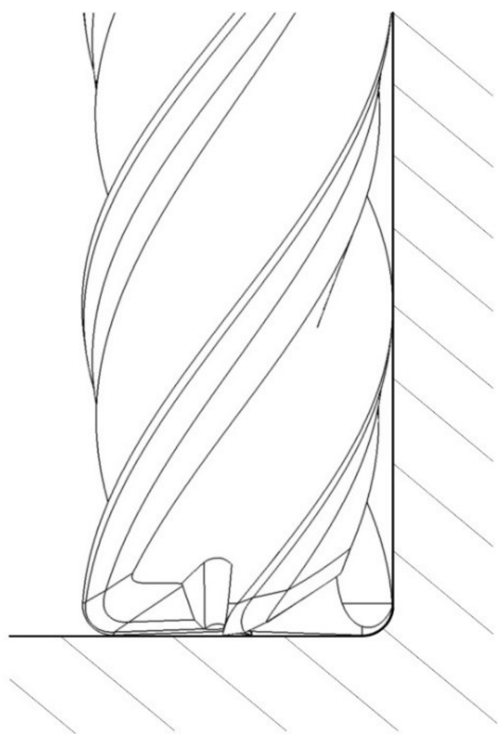

Figure 2.5 Corner machining with fillet end-mill

However, the only parameter which defines the fillet is the corner radius. So the method to model the clearance face and rake face of the fillet varies from person to person. And since the modeling of clearance face and rake face is based on the fillet cutting edge which is the foundation of designing these two, the geometric shape of fillet cutting edge is of the most importance.

In the industry of cutting tool manufacturing, fillet end-mills are machined in a grinding machine with a cornered toolbar as shown in Figure 2.6. The radius of the corner equals to the radius of the fillet of the end mill. The first process of manufacturing is grinding flutes, while the fillet cutting edge is formed in this process.

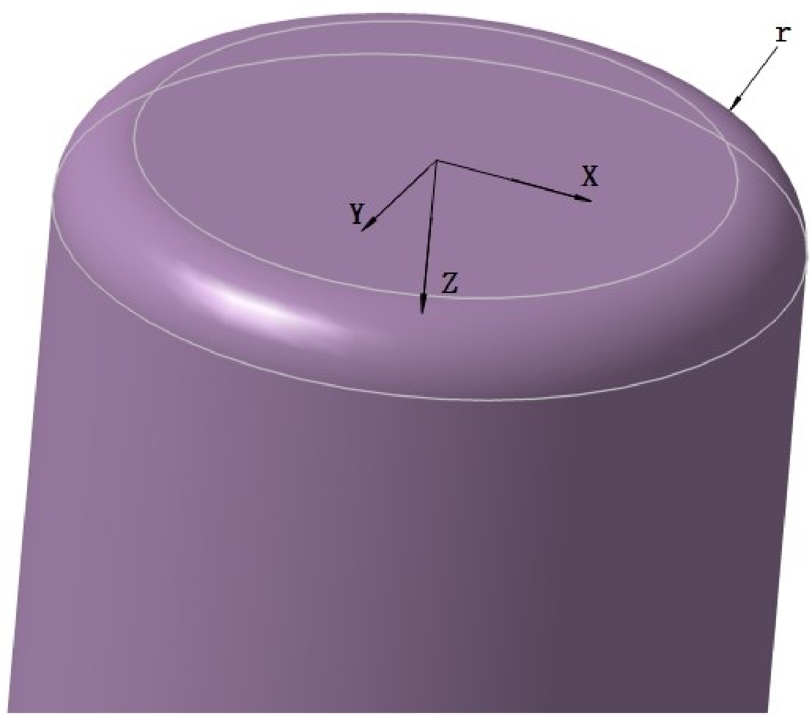

Figure 2.6 The toolbar with cornered bottom

Geometrically, the fillet cutting edge is the intersection curve between the cornered toolbar and the flute surface. However, in order to derive the parametric equation of the fillet cutting edge, a modeling method is proposed below.

The flute profile shown in Figure 2.7 indicates the grinding wheel path on X-Y plane. The modeling of the flute surface has been discussed in many previous researches which is by sweeping along the helix of the side cutting edge. Only a portion of flute profile intersects the corner of toolbar which is within the projection section of the corner on X-Y plane as indicated in Figure 2.7 as a red curve. Ten evenly distributed points on the intersection profile is defined as the profile points for further modeling.

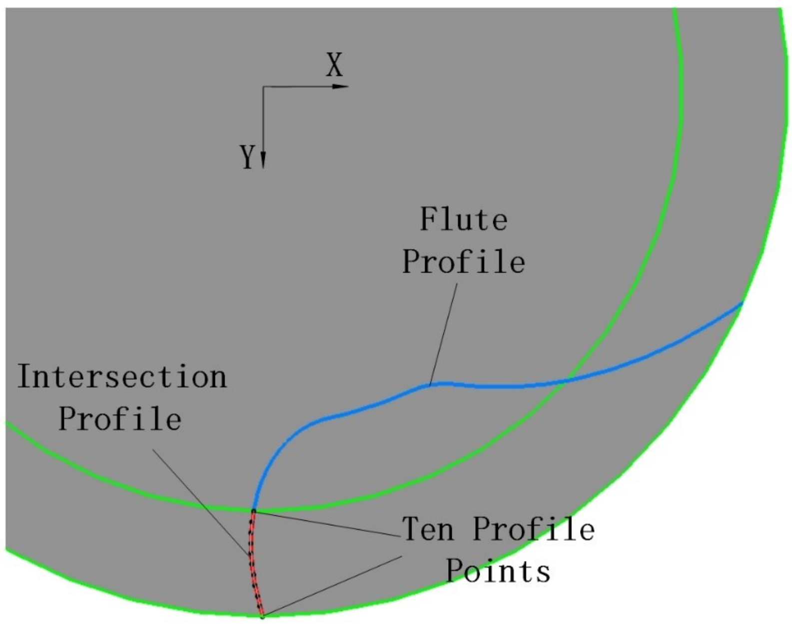

Figure 2.7 Building profile points on flute profile

As mentioned above, the flute surface is modeled by sweeping the flute profile along the helix of the side cutting edge. The paths of these ten profile points on the flute surface are also ten helixes where the starting point of each helix is each one of these then profile points. However, the radius of each helix is defined by the distance between the profile point and the z-axis which is also the axis of the end mill. Given the coordinates of each profile point defined as [a, b, 0], the radius of the helix is

$$r_H = \sqrt{a^2 + b^2} \qquad \text{Eq. 2.1}$$

And the profile point is the start point of the helix, as shown in Figure 2.8, the angle between x-axis and the radius direction of the profile point is derived

$$\phi = \arctan\frac{b}{a} \qquad \text{Eq. 2.2}$$

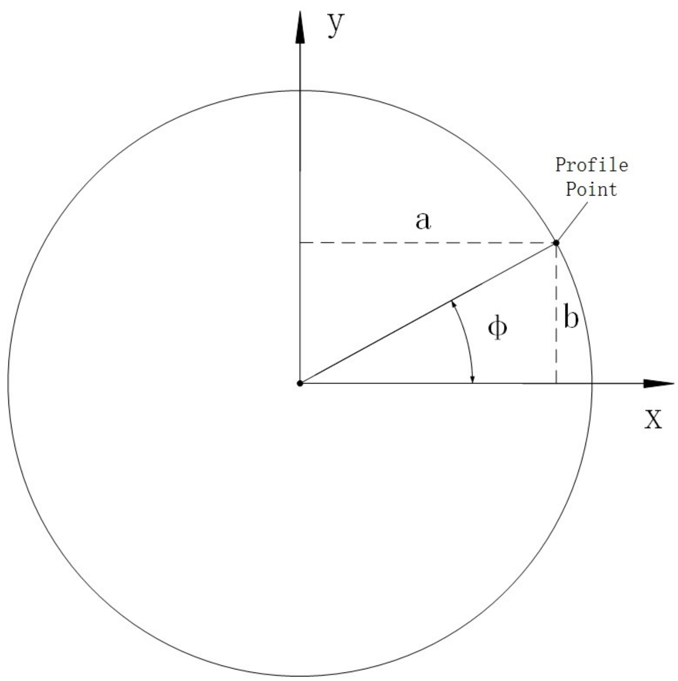

Figure 2.8 Profile Point on grinding wheel path

Assigning d as the coordinate along z-axis, the parametric equation of the helix can be derived,

$$P_h(d) = \begin{cases} \sqrt{a^2+b^2}\cdot\cos(\arctan\frac{b}{a}+\frac{\tan\beta\cdot d}{\sqrt{a^2+b^2}}) \\ \sqrt{a^2+b^2}\cdot\sin(\arctan\frac{b}{a}+\frac{\tan\beta\cdot d}{\sqrt{a^2+b^2}}) \\ d \end{cases} \qquad \text{Eq. 2.3}$$

$$d \in [-\infty, 0]$$

where β is the helix angle of the side cutting edge, d is the coordinate on z axis of this helix.

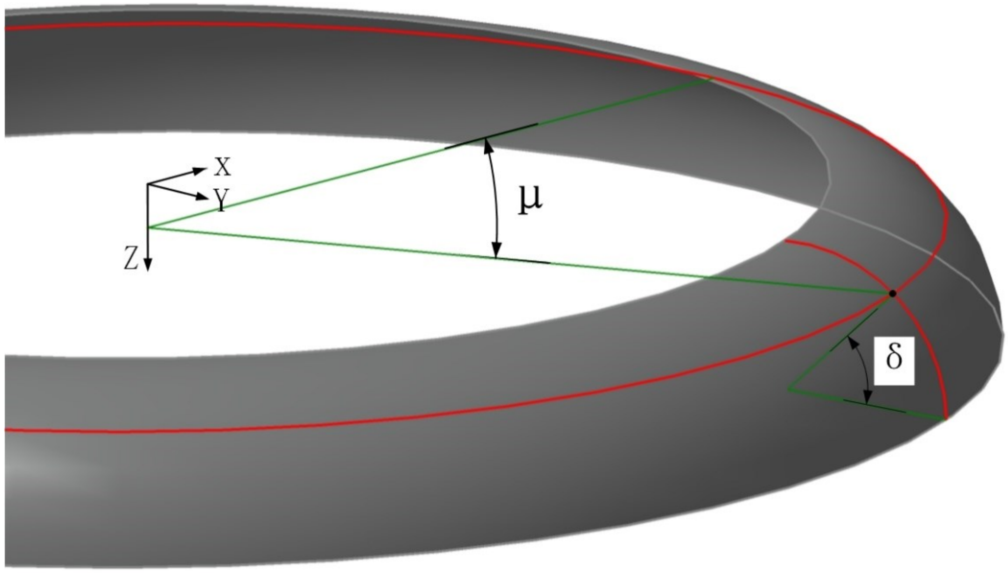

Figure 2.9 Corner surface defined by two parameters

Any point on the corner surface can be defined as the intersection of a circle and an arc as shown in Figure 2.9. Then the parametric equation of the corner surface can be derived with two angles, μ and δ which define the circle and arc,

$$P_{corner}(\mu,\delta)=\begin{cases}(R-r+r\cdot\cos\delta)\cdot\cos\mu\\(R-r+r\cdot\cos\delta)\cdot\sin\mu\\r-r\cdot\sin\delta\end{cases} \quad \text{Eq. 2.4}$$

$$\mu\in[0,2\pi]$$

$$\delta\in[0,\frac{\pi}{2}]$$

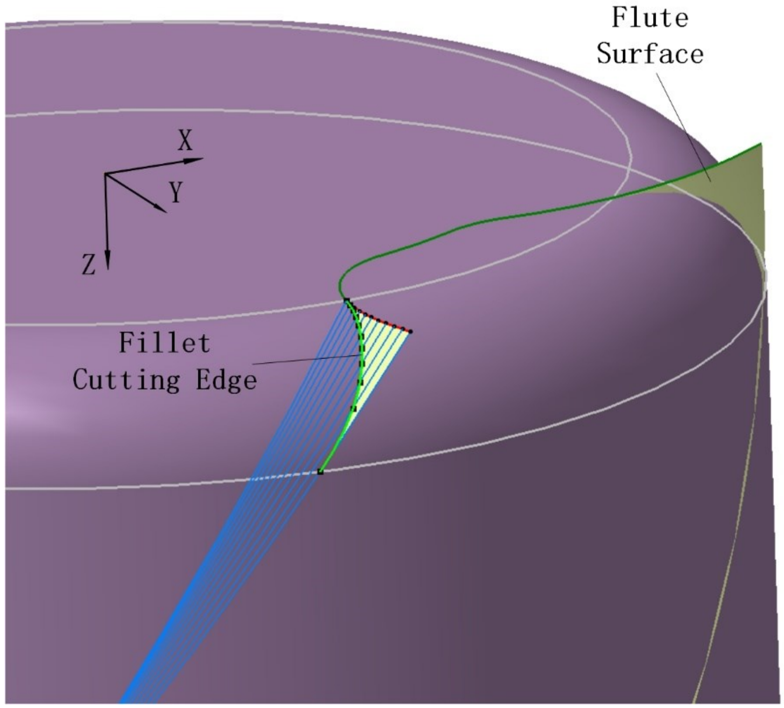

Figure 2.10 Modeling of the fillet cutting edge with intersection points

With these two parametric equations, the coordinates of intersection point on the fillet cutting edge can be calculated by solving

$$P_h(d) = P_{corner}(\mu, \delta) \qquad \text{Eq. 2.5}$$

which is

$$\begin{cases} \sqrt{a^2+b^2}\cdot\cos(\arctan\dfrac{b}{a}+\dfrac{\tan\beta\cdot d}{\sqrt{a^2+b^2}}) = (R-r+r\cdot\cos\delta)\cdot\cos\mu \\ \sqrt{a^2+b^2}\cdot\sin(\arctan\dfrac{b}{a}+\dfrac{\tan\beta\cdot d}{\sqrt{a^2+b^2}}) = (R-r+r\cdot\cos\delta)\cdot\sin\mu \\ d = r - r\cdot\sin\delta \end{cases}$$

After all ten intersection points being created, the fillet cutting edge can be modeled by a spline which is defined by ten intersection points shown in Figure 2.10. Thus, with this method of modeling, four fillet cutting edges are generated on the corner surface displayed in Figure 2.11.

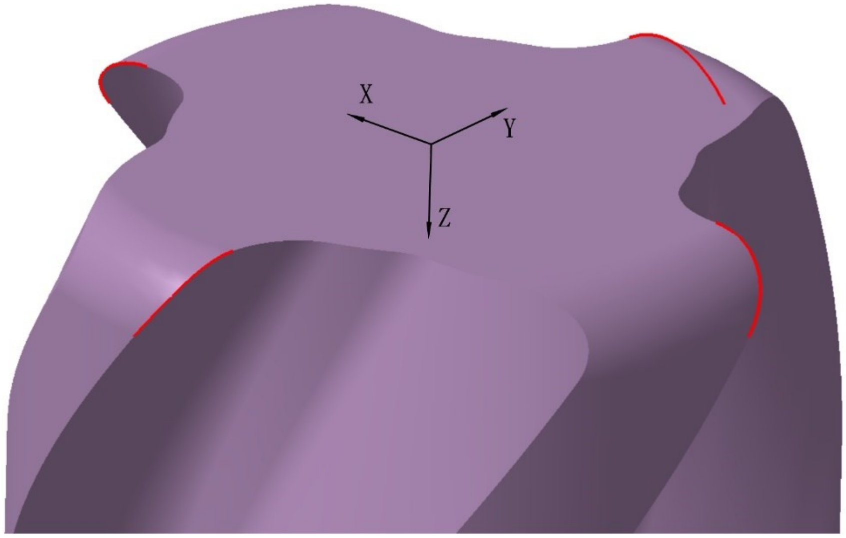

Figure 2.11 Modeling of four fillet cutting edges

2.2.4 Modeling of the End and Side Clearance Surfaces

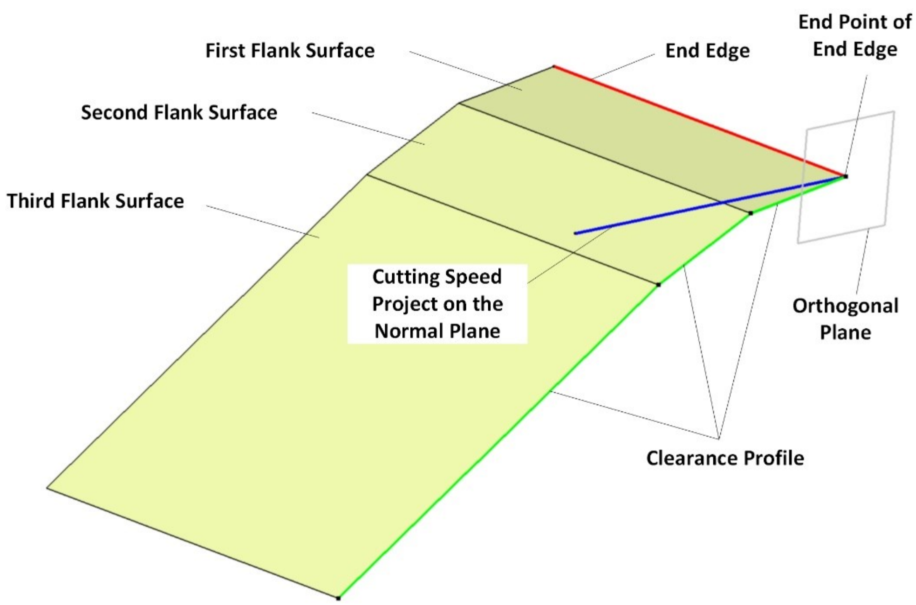

Figure 2.12 Model of the end clearance surface

As discussed in the first topic of Chapter 2, the orthogonal model of cutting is adopted in the modeling of end and side clearance surface. In the end clearance surface, the end cutting edge can be built according to the parameters given from Table 2-2. And the end point was chosen to build the orthogonal plane which is normal to cutting edge. This plane is the orthogonal plane at which the clearance profile is defined. With defined clearance angle and width, the clearance profile is generated in the orthogonal plane in Figure 2.13. Because the clearance angle and the clearance width are constant along the end cutting edge, the function of swept surface in 3D modeling software can be adopted to form the clearance surface. The model of end clearance surface can be generated by sweeping clearance profile along the end cutting edge which is shown in Figure 2.12.

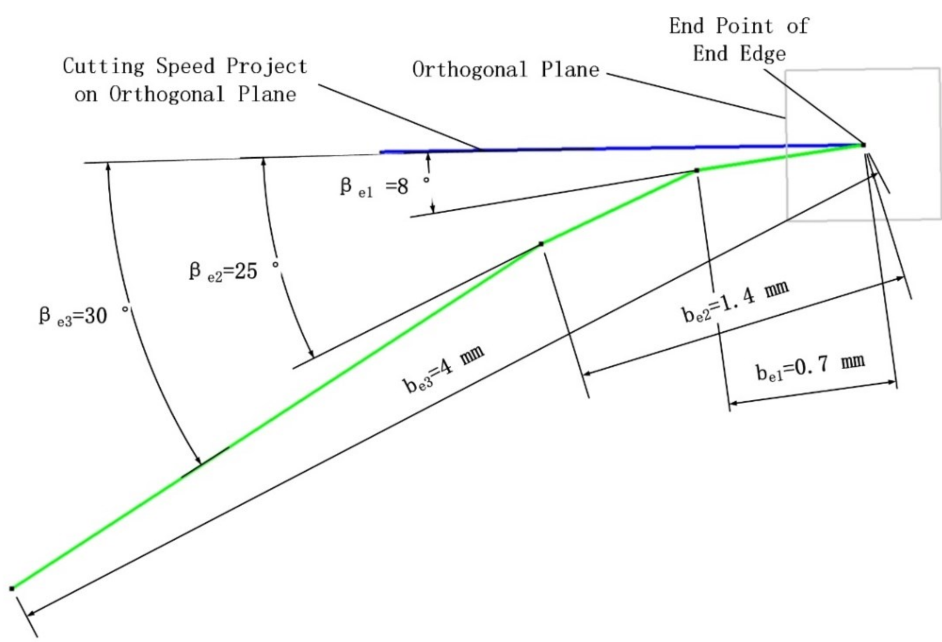

Figure 2.13 Clearance profile of the end clearance surface

As for the side clearance surface, a helix is built first according to the parameters related to the side edge with the desired helix angle. The end point of the helix on the end side of cutter is extracted as the start point for further modeling. The cutting speed of this point is perpendicular with the direction of the radius between the axis of the cutter and this point. Then the side clearance profile is defined on the plane which is perpendicular with the axis of the cutter and also through the start point. Since the helix is a curve around the axis of cutter with certain pitch angle, side clearance surface can be built with the modeling feature of sweep along pulling direction, when side clearance profile as the profile, helix as guide curve, with pulling direction of the axis of the cutter as shown in Figure 2.14.

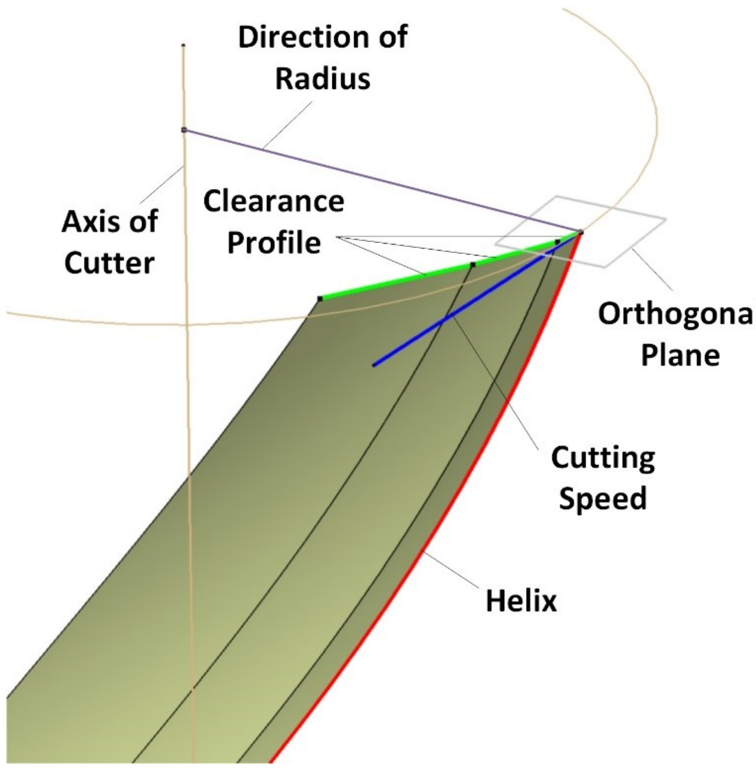

Figure 2.14 Modeling of the side clearance surface

2.3 Modeling of Fillet Flank

2.3.1 Design of Three Clearance Edges

Fillet flank, the connecting section where the end flank and the side flank merge, could be considered as the clearance of the fillet cutting edge. Geometrically, the fillet flank together with the end clearance face and side clearance face form the flank surface. Three clearance surfaces are commonly seen in most high performance end mills. Here, a method of modeling by creating three variables to build the fillet flank in 3D modeling software is demonstrated below.

The fillet flank on tooth A is selected to illustrate this method. A fillet flank consists of three

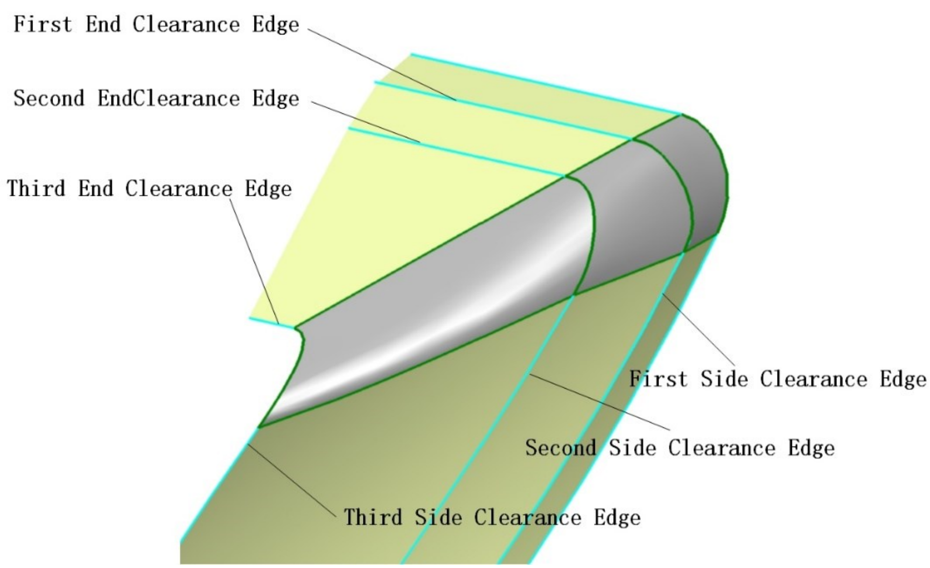

Figure 2.15 Three clearance edges of end and side flank

segment which is primary, secondary and tertiary clearance. Three clearance edges of the end and side flank are displayed in Figure 2.15. Each clearance surface is constructed between two curves which here called clearance edge. While the primary clearance is between the fillet cutting edge and the first clearance edge, secondary clearance between first clearance edge and second clearance edge, tertiary clearance between second clearance edge and third clearance edge. By building up these clearance edges, the three clearance surfaces can be formed.

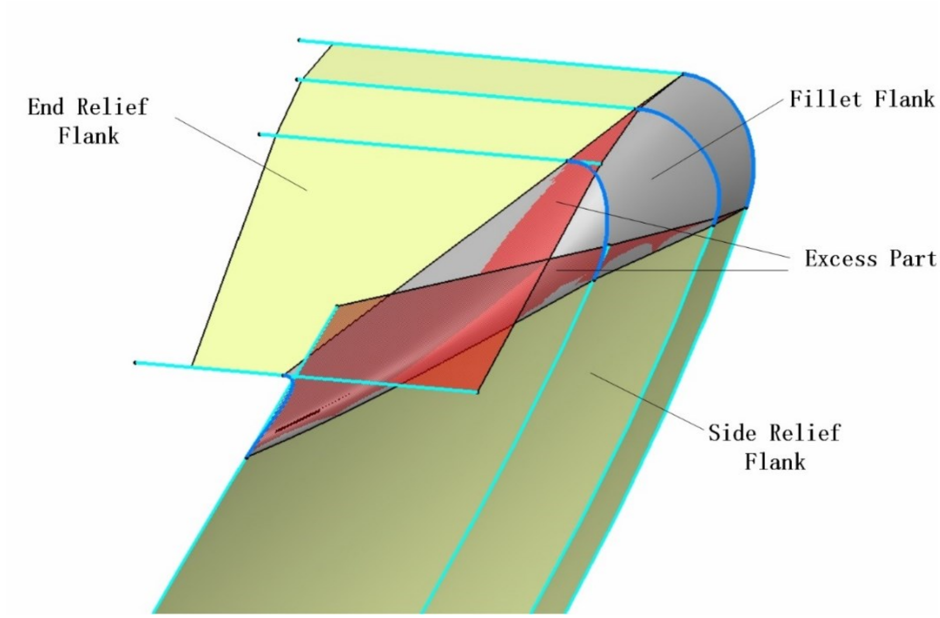

Figure 2.16 Intersection between the end and side flank

Due to the end relief flank and side relief flank are modeled by sweeping the clearance profile, there would be intersection between them if the width of tertiary clearance is too large. So the excess part should be trimmed and replaced by fillet flank as shown in Figure 2.16. As discussed above, the fillet flank is framed by determining three clearance edges and fillet cutting edge as boundaries to separate three clearance surfaces. To define the clearance edge of fillet, two end points on the end and side clearance edge should be determined. A method based on 2D corner is proposed to achieve this purpose.

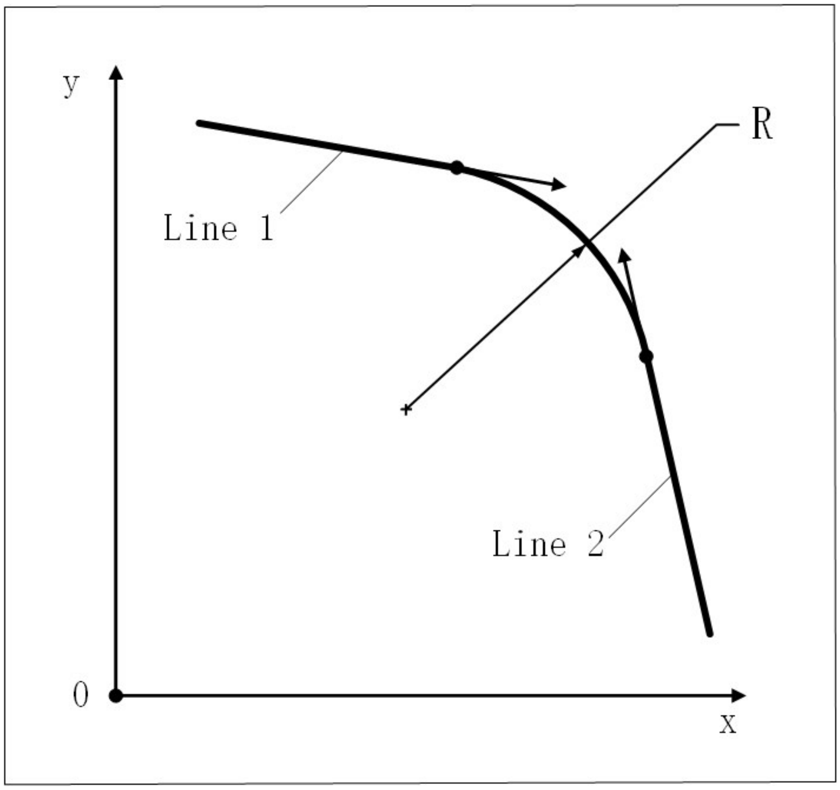

Figure 2.17 Two-dimensional corner

It is known that a two-dimensional corner can be defined by two unparallel lines with a designated value of radius. The connecting points are therefore generated at the end of corner at which tangent continuity is achieved. A 2D corner is demonstrated in Figure 2.17. The derivation of the parametric equation of 2D corner is illustrated below.

Define the parametric equations of two random lines as

$$P_{l1}(t) = \begin{cases} t \\ k_1 t + d_1 \end{cases} \qquad \text{Eq. 2.6}$$

$$P_{l2}(t) = \begin{cases} t \\ k_2 t + d_2 \end{cases} \qquad \text{Eq. 2.7}$$

$$t \in (-\infty, \infty)$$

where t is the coordinate on x axis of these two lines, d_1 and d_2 are the coordinates of the intersection points with y axis.

Then the center of corner (x_c, y_c) can be derived by solving

$$\begin{cases} \sqrt{(x_c-t)^2+(y_c-k_1t-d_1)^2}=R^2 \\ \sqrt{(x_c-t)^2+(y_c-k_2t-d_2)^2}=R^2 \end{cases}$$

which is

$$\begin{cases} x_c=\dfrac{2t\pm\sqrt{4t^2-4\left[(k_1+2k_2)^2t^2+2(k_1+2k_2-\frac{1}{2})(d_1+d_2)t+(d_1+d_2)^2-\mathrm{R}^2\right]}}{2} \\ y_c=2(k_1+k_2)t+2(d_1+d_2) \end{cases} \quad \text{Eq. 2.8}$$

where there are 4 different answers because there are 4 centers generated. The one which is needed can be chosen geometrically.

The parametric equation of corner is

$$P_{co}(\theta)=\begin{cases} x_{co}=R\cdot\cos(\theta)+x_c \\ y_{co}=R\cdot\sin(\theta)+y_c \end{cases} \quad \text{Eq. 2.9}$$

then, the two connecting points can be generated when the corner intersects with two lines,

$$\begin{cases} P_{co}(\theta)=P_{l1}(t) \\ P_{co}(\theta)=P_{l2}(t) \end{cases} \quad \text{Eq. 2.10}$$

After solving the equations above, the parametric coordinates of two connecting points can be derived.

When the concept of 2D corner is applied in the modeling of the fillet clearance edge, a projection plane is needed to define the radius R of the corner. The component of the two curves which is parallel to the projection plane can be treated as the tangent vectors of two lines in the two-dimensional corner. Then a corner can be generated in the projection plane with a required radius between two lines.

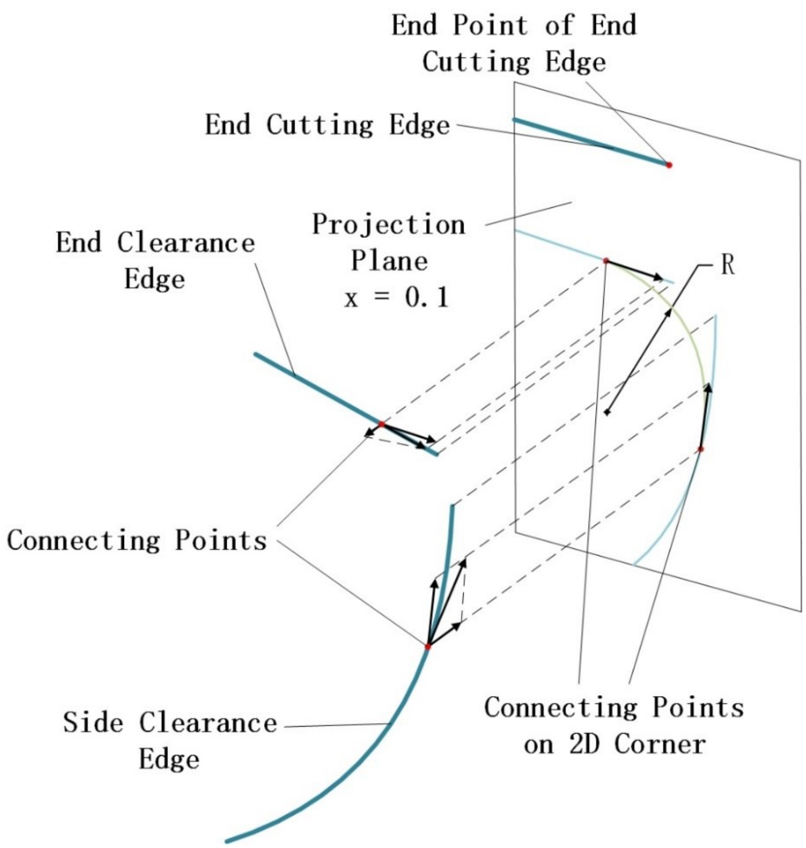

Figure 2.18 Determination of connecting points based on 2D corner

Take the first fillet clearance edge on one of tooth A as an example as shown in Figure 2.18. The projection plane is defined as the plane which the end cutting edge passes and is perpendicular to the speed direction of the end point of the end cutting edge. The projection plane is $x = 0.1$. After transformation from the end cutting edge, the parametric equation of the first end clearance edge is

$$P_{ecA}(a) = \begin{cases} -\dfrac{c}{2} + e_x \\ a \cdot \cos(\theta) + R - r + e_y \\ a \cdot \sin(\theta) + e_z \end{cases} \qquad \text{Eq. 2.11}$$

$$a \in (-R + r, 0)$$

where e_x, e_y, e_z are three transformation constants along X, Y and Z axis, t is the parameter of a length. And the tangent vector of the first end clearance edge is

$$P_{ecA}'(a) = \begin{cases} 0 \\ \cos(\theta) \\ \sin(\theta) \end{cases}$$

As the first end clearance edge is parallel to the projection plane, the projected line of the tangent vector on the plane is

$$P_{ecAp}(a') = \begin{cases} 0.1 \\ a' \\ \tan(\theta) \cdot a' \end{cases} \qquad \text{Eq. 2.12}$$

$$\mathrm{a}' \in (-\infty, +\infty)$$

where a′ is the parameter of a length.

For the first side clearance edge,

$$P_{scA}(t) = \begin{cases} -R' \cdot \cos(\phi)\sin(t) - R' \cdot \sin(\phi)\cos(t) \\ -R' \cdot \sin(\phi)\cos(t) + R' \cdot \cos(\phi)\cos(t) \\ \dfrac{R' \cdot t}{\tan \alpha_A} - r \end{cases} \qquad \text{Eq. 2.13}$$

$$\mathrm{t} \in \left(-\frac{L_{cut}}{\cos \beta \cdot R}, 0\right)$$

where ϕ is a certain rotation angle, t is the parameter of an angle. And the tangent vector of the first side clearance edge is

$$P_{scA}'(t) = \begin{cases} R' \cdot \sin(\phi)\cos(t) + R' \cdot \cos(\phi)\sin(t) \\ R' \cdot \sin(\phi)\sin(t) - R' \cdot \cos(\phi)\sin(t) \\ \dfrac{R'}{\tan \alpha_A} \end{cases}$$

$$\mathrm{t} \in \left(-\frac{L_{cut}}{\cos \beta \cdot R}, 0\right)$$

After transformation with projection matrix, the projected lines on the projection plane can also be derived

$$P_{scAp}(t') = \begin{cases} 0.1 \\ R' \cdot \sin(\phi)\sin(t') - R' \cdot \cos(\phi)\sin(t') \\ \dfrac{R'}{\tan \alpha_A} \end{cases} \qquad \text{Eq. 2.14}$$

$$t' \in (-\infty, +\infty)$$

where t' is the parameter of a length

As it can be noticed that the projection of the first side clearance edge contains a variable t'. Because the first side clearance edge is technically a helix, as t changes, the tangent vector of this helix changes, which means the projection $P_{scAp}(t')$ presents a number of lines on the plane as t' changes. Therefore, more than one corner can be generated with a certain radius by modifying the variable t'.

However, with this method, not all connecting points on each corner are qualified for further modeling. As the variable t' increases, the connecting point between the corner and first side clearance edge moves along the projection line, but only when this connecting point on the projection plane lies on the projection of either the end or the side clearance edge which could be perceived as that this connecting point is the projection of a point on the clearance edge. With the demonstration of connecting points of 2D corner, the connecting points on fillet clearance edge can be derived.

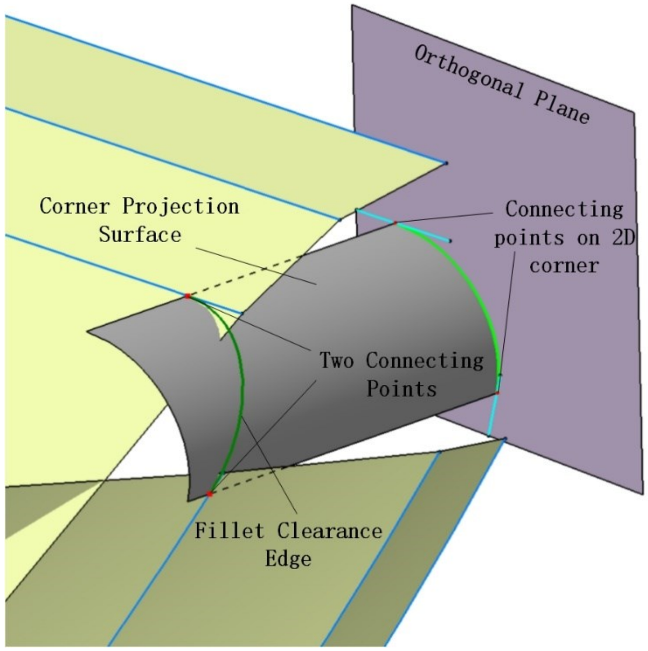

Figure 2.19 Modeling of fillet clearance edge

Then two connecting points are used to connect the end and side clearance edges. A surface swept from the 2D corner. A B-spline is built which connects the end and side clearance edge at the connecting points with curvature continuity. And a projection surface is built by sweeping the 2D corner along the normal direction of the orthogonal plane. In most CAD software, like CATIA, an optimized solution “spline” can be generated for modeling this curve. By defining two curves and starting points of them, and supported by the corner projection surface, the spline which presents fillet clearance edge can be generated. With this method illustrated above, three fillet clearance edges can be modeled by only defining three radiuses as shown in Figure 2.20.

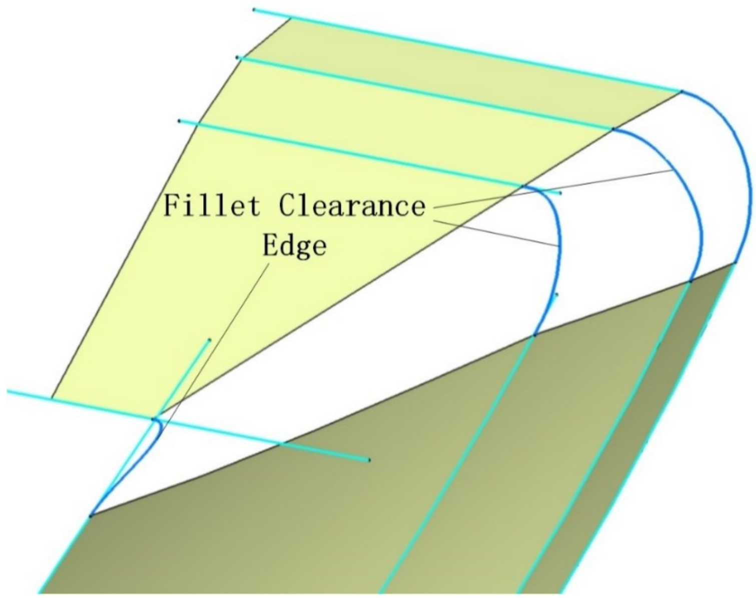

Figure 2.20 Fillet clearance edges based on 2D corner

2.3.2 Modeling of the Fillet Flank

The fillet flank can be divided into three segments by clearance edges. Each fillet clearance edge has two end points which also lies on the end clearance face and side clearance face. Connect neighboring end points on the end and side clearance surface as the intersect curve between the fillet flank and the end or side flank. Together with clearance edges, a closed boundary can be formed. As shown in Figure 2.21, each fillet flank segment can be built with the function “fill” with the closed boundary in CATIA.

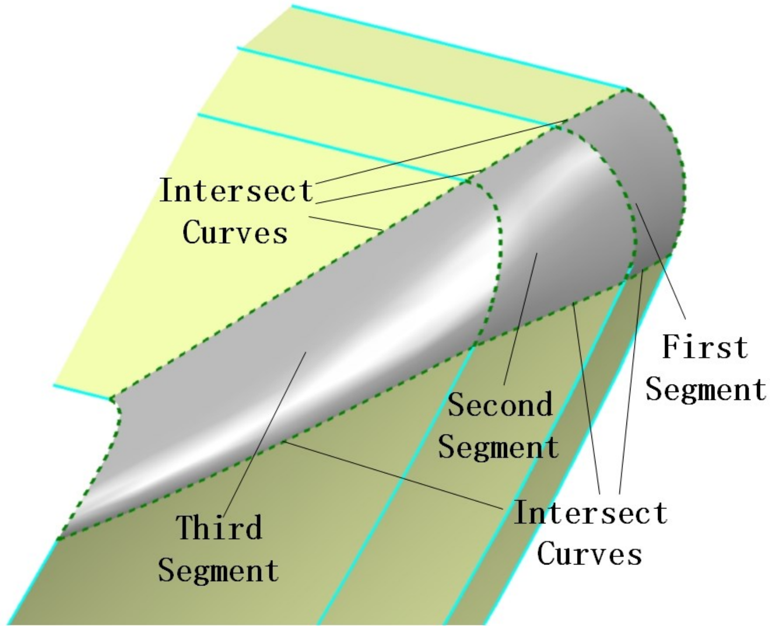

Figure 2.21 Model of fillet clearance surface

Thus, the fillet flank of a fillet end-mill with three relief faces can be defined and modeled. The radiuses of first, second and third 3D corner are defined as R_1', R_2', R_3'. As the three clearance angles of the end and side relief surface increases ($\beta_{e3} > \beta_{e2} > \beta_{e1}$ and $\beta_{s3} > \beta_{s2} > \beta_{s1}$), the radiuses should be decreased ($R_1' > R_2' > R_3'$) correspondingly. However, the assigned values of three radiuses vary from one to another. For one fillet end-mill with fixed end and side relief, the shape of the fillet flank and the performance of the cutter are affected if given different values of radius.

When two sets of radius values are assigned for a fillet end-mill with the same end and side relief, two models of the fillet flank are quite different. (First fillet flank: $R_1' = 1mm,\quad R_2' = 0.8mm,$ $R_3' = 0.5mm$; Second fillet flank: $R_1' = 0.9mm,\quad R_2' = 0.6mm,\quad R_3' = 0.3mm$)

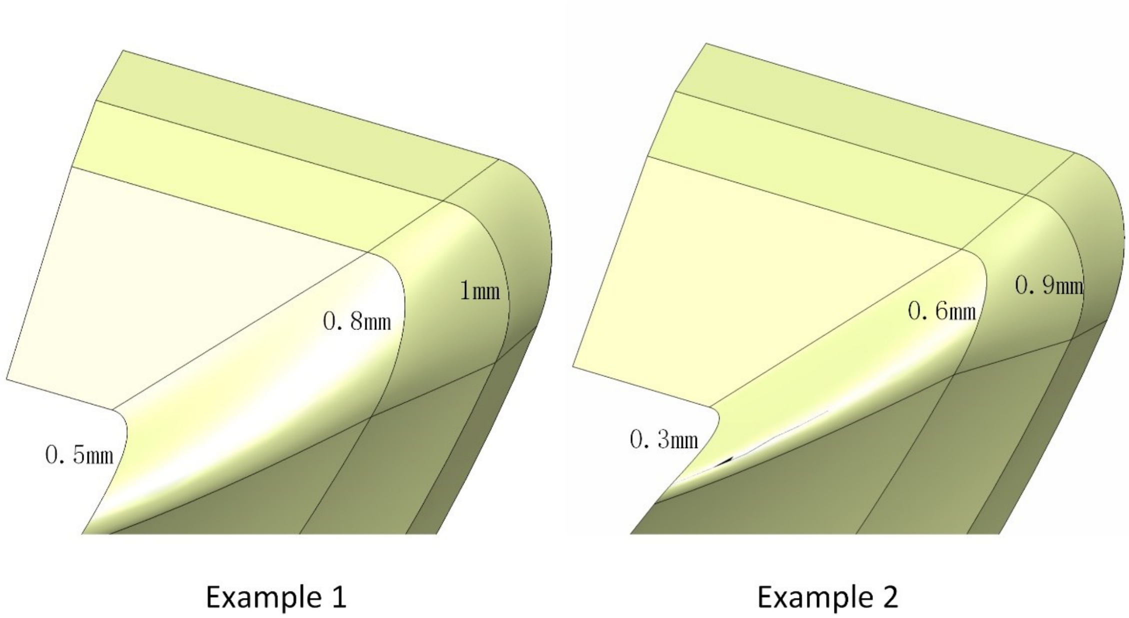

Figure 2.22 Shape of two fillet flank with different radius settings

The shapes with different radius settings are displayed in Figure 2.22. Compared with Example 1, less portion of the end and side clearance surface is taken over by fillet clearance surface in Example 2. Clearance edges constructed by smaller radius make the fillet flank of Example 2 thicker which strengthen the fillet and give a better machining finish of workpiece.

CHAPTER 3 DESIGN AND MODELING OF FILLET RAKE SURFACE

3.1 Introduction

Fillet rake surface is the rake face of fillet cutting edge which geometrically connects the end and side cutting edge. As discussed in Chapter 1, the radius corner is of most importance for a fillet end-mill, while the geometry of the fillet rake surface actually affect the cutting performance the most.

After a series of Boolean operations, the end and side rake face intersect at the fillet corner. The fillet rake surface is supposed to merge the end and side rake face with rake angle shift from the end rake angle to the side rake angle. Because the rake angle is the key factor for fillet rake surface, a rake angle based method is proposed below.

3.2 Design of Fillet Rake Surface

Since the fillet rake surface is a complex surface, a set of variables needs to be assigned to control the shape of fillet rake surface. Rake angle based modeling method is the method which uses the rake angle as the control variables to form the rake face. First, the modeling of a line defining the rake angle has to be established.

As is illustrated in Chapter 2 about the orthogonal model, this model is also adopted to define the rake angle of the fillet rake. And the fillet cutting edge has been modeled in Chapter 2. If the rake angle of a certain point on the cutting edge needs to be defined, several steps should be followed. First, assign the cutting speed direction of this point which is the radial speed along the axis of the cutter; Second, define the orthogonal plane of this point which is normal to the cutting edge, thus the cutting speed of this point on the orthogonal plane can be defined; Third, find the direction which is normal to the cutting speed on the orthogonal plane. Finally, the rake angle profile is built by defining the angle between itself and the normal direction in the orthogonal plane which is the rake angle as shown in Figure 3.1.

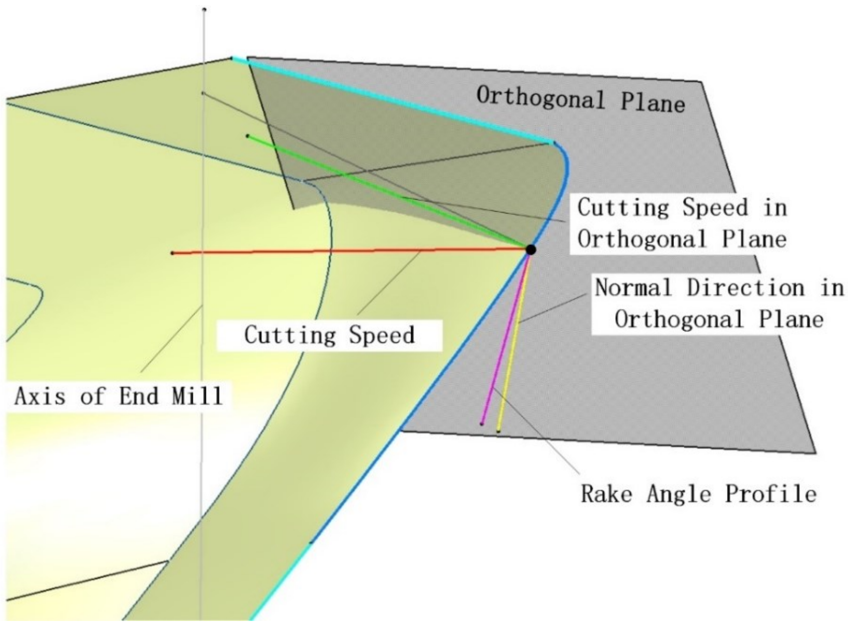

Figure 3.1 Modeling of the rake angle profile

As long as the rake angle of fillet rake surface can be defined, a surface modeling function in CATIA “Multi-sections Surface” can be adopted to model the rake face by assigning several guide profiles as section profiles. Each guide profile is defined with a certain rake angle and length. By modifying the rake angle of every guide profile, the tendency of the rake angle of rake face can be controlled.

Compared with the clearance surface, this method based on clearance angle is not applicable for modeling of the fillet flank. For most fillet flank, there are commonly two or three clearance faces. If the clearance angle is defined according to the orthogonal model, because of the changing curvature of fillet cutting edge and the complexity of the shape, the tendency of clearance angle does not present fillet flank reasonably which could not be used for modeling as shown in Figure 3.2.

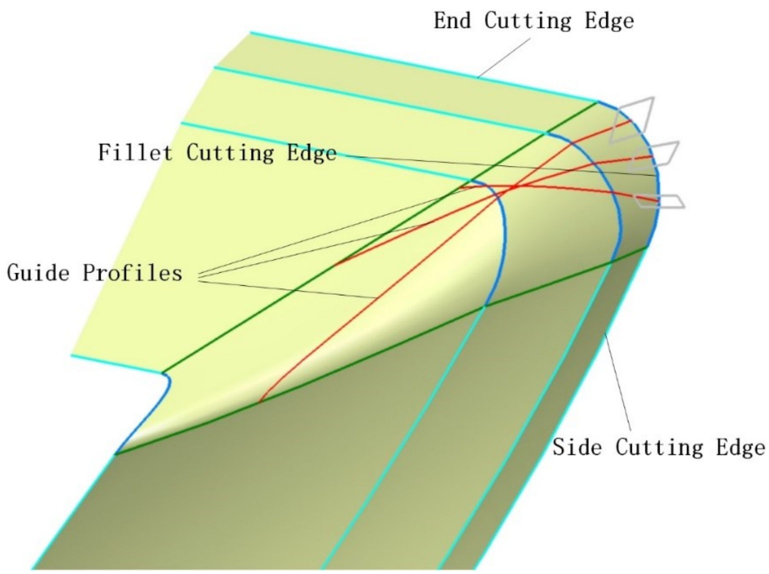

Figure 3.2 Three clearance angle profiles for fillet flank

As the size of fillet rake surface is rather small, and the length along the direction of the rake angle profile is acceptable for building the surface, this modeling method is a suitable for fillet rake surface. “Multi-sections Surface” could generate a surface by sweeping several sections along a spline which is the fillet cutting edge. The rake angle of fillet rake surface should start with rake angle of the end cutting edge and end with rake angle of the side cutting edge. In this example of this fillet end-mill, it’s $5°$ (end edge) and $6°$ (side edge). Of course, the rake angle of the fillet rake surface don’t need to be in the range between $5°$ and $6°$. It can increase to larger rake angle like $8°$, it can also decrease to $4°$. Normally, the rake angle of the fillet rake surface is positive in fillet end-mills. When the rake angle is larger, the tool can get sharper. However, the strength of tool is reduced and the cutting edge of fillet could be more easily to break.

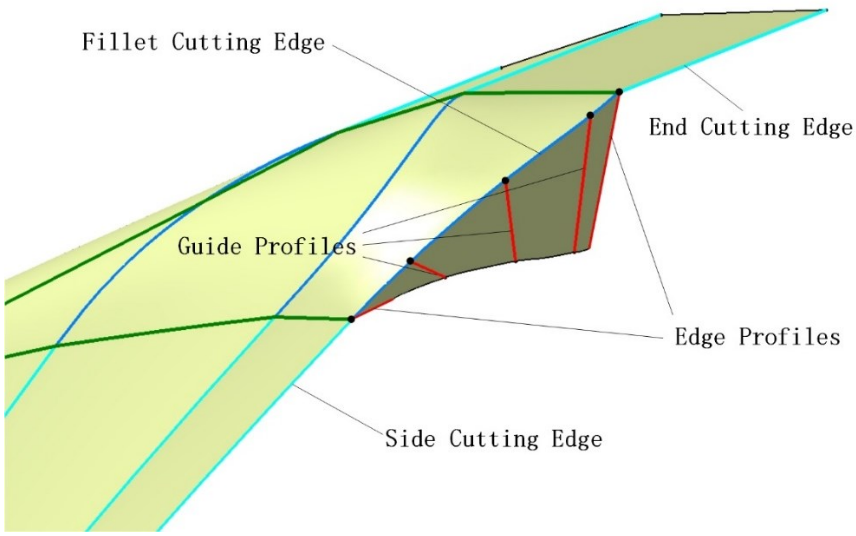

Figure 3.3 Distribution of guide profiles for modeling rake face

The guide profiles include two edge profiles which locate on the end points of the fillet cutting edge and several guide profiles in between. In order to make the variation of the surface evenly, guide profiles between edge profiles should be uniformly distributed on the cutting edge as illustrated in Figure 3.3. This is achieved by building section points of guide profiles along the fillet cutting edge by ratio of length. Also, the length of guide profiles should be considered. The length should be less than the limit which could cause intersection between neighboring profiles, as long as the surface expands enough to trim the previous model. In this fillet end-mill, all length of guide profiles is assigned of 0.7 mm.

3.3 Analysis of Different Guide Set

Even though the guide profiles can determine the approximate trend of rake angle, the change of the rake angle is still not linear as the variation of guide rake angles. The number of guide profiles has a great influence on the shape of rake face. So four groups of guide profile settings are examined to illustrate the difference by measuring the rake angle of ten evenly distributed points along the fillet cutting edge. These ten rake angles are also measured in the orthogonal plane. .

Table **3-1** shows the values of rake angle for four groups of guide profiles.

Table 3-1 Guiding rake angles for four groups of guide profiles

Number of Guide Profiles	Rake Angle of Each Guide Profile/ degree							
5	5	5.25	5.5	5.75	6			
6	5	5.2	5.4	5.6	5.8	6		
7	5	5.166	5.333	5.5	5.666	5.933	6	
8	5	5.143	5.286	5.429	5.571	5.714	5.857	6

The rake angle of the fillet is all organized linearly from $5°$ to $6°$ in four groups of guide profiles. The results of rake angles for each group are demonstrated in Table 3-2. In order to give a more intuitive demonstration, the change of the rake angle is shown in charts below.

Table 3-2 Measured results of rake angle for four groups of guide profiles

	Rake Angle (degree)			
Measuring Points	5 Guide Profiles	6 Guide Profiles	7 Guide Profiles	8 Guide Profile
0	5	5	5	5
1	5.782	5.651	5.421	5.293
2	5.354	5.225	5.158	5.199
3	5.234	5.262	5.288	5.256
4	5.509	5.395	5.444	5.424
5	5.539	5.567	5.522	5.520
6	5.779	5.641	5.642	5.601
7	5.812	5.793	5.727	5.689
8	5.587	5.838	5.902	5.893
9	5.272	5.434	5.569	5.687
10	6	6	6	6

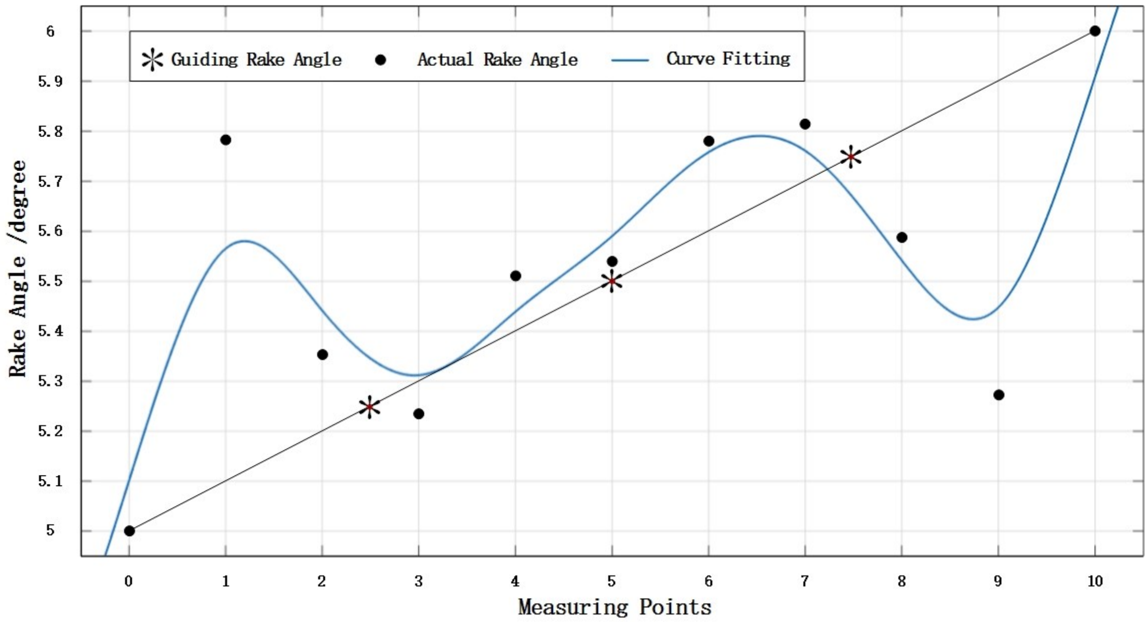

Figure 3.4 Curve fitting of actual rake angle with 5 guide profiles

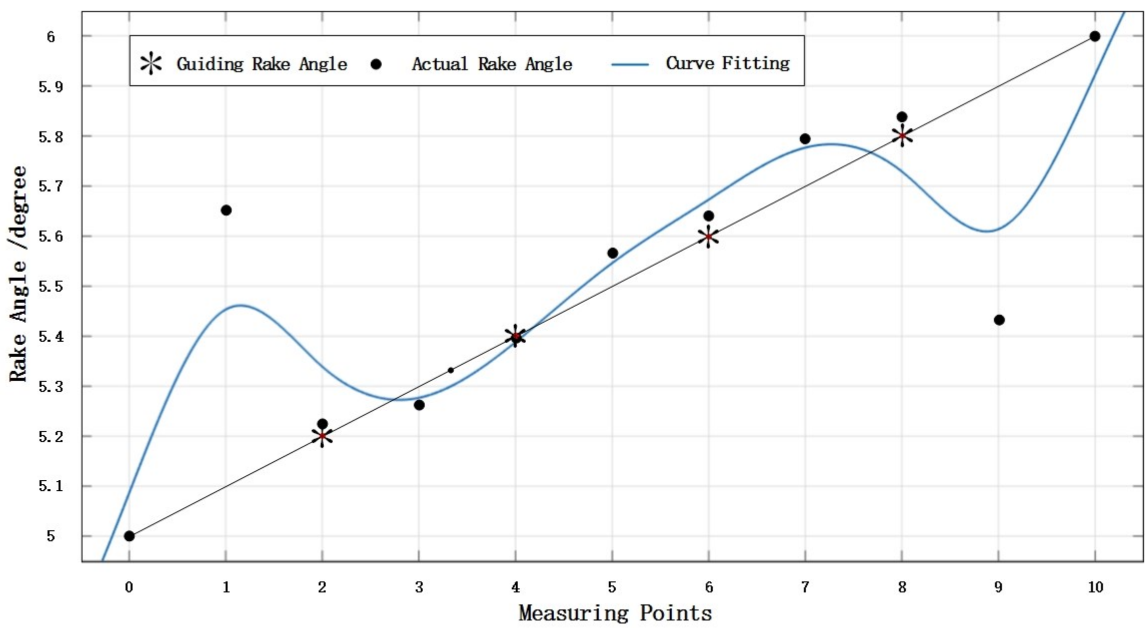

Figure 3.5 Curve fitting of actual rake angle with 6 guide profiles

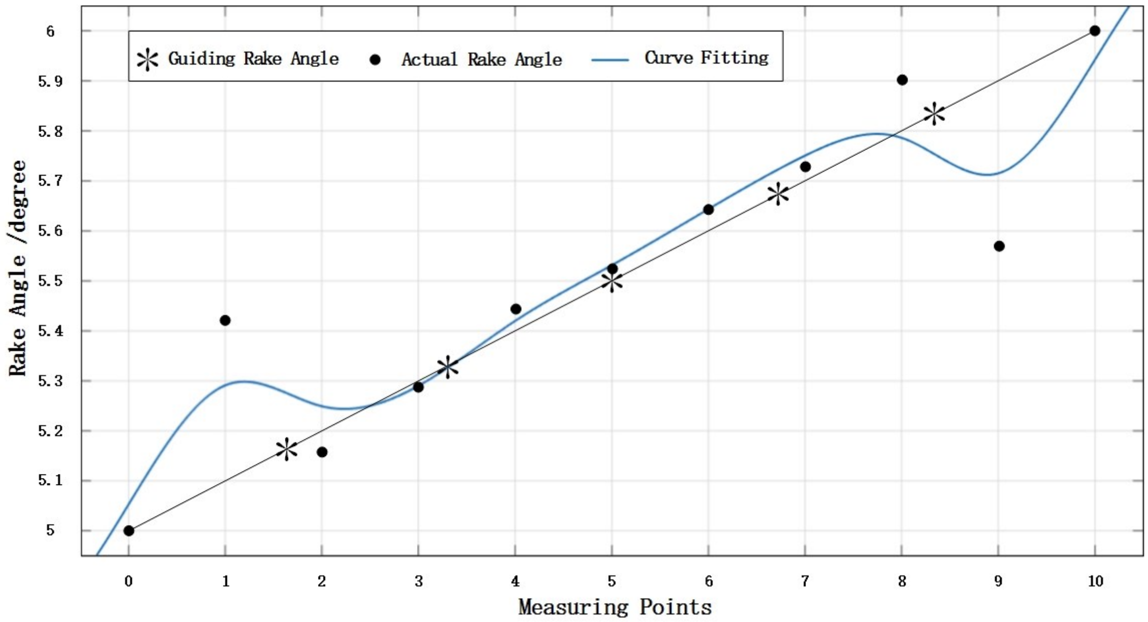

Figure 3.6 Curve fitting of actual rake angle with 7 guide profiles

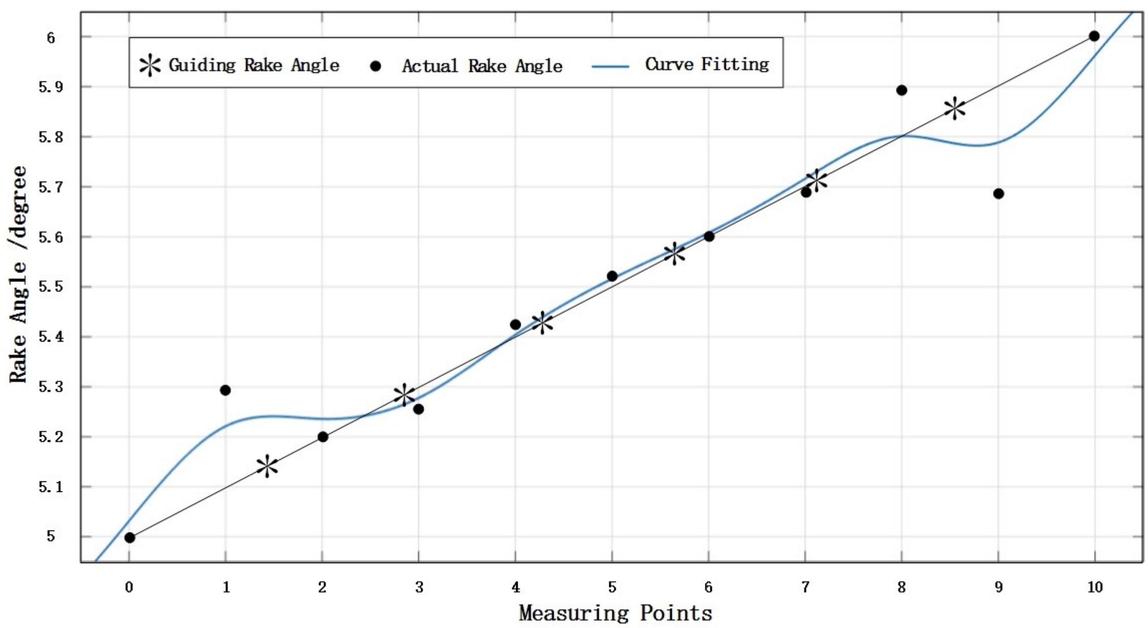

Figure 3.7 Curve fitting of actual rake angle with 8 guide profiles

In Figure 3.4, Figure 3.5, Figure 3.6 and Figure 3.7 illustrated above, the rake angle of ten test points is used for curve fitting in MATLAB. As the spline is constructed by control points which could present the tendency of the rake angle, the same spline curve fitting is applied for each group. From four charts, it can be seen that even though the guiding rake angles increase linearly, there are some fluctuation near end points of fillet cutting edge. However, obviously the extent of these fluctuations reduces gradually when the number of rake profiles get larger. And the curve fit more with the tendency of the guiding rake angle especially compared between 5 guide profiles and 8 guide profiles. In conclusion, more guide profiles can give a more desired fillet rake surface with giving guide rake angle.

In addition, the trend of rake angle can be increased and decreased by modifying guide profiles. So two more settings of guide profiles are examined for increased and decreased rake angle to see the variation compared with linearly increased rake angles shown in Table 3-3.

Table 3-3 Value of increased and decreased guiding rake angle

Different guiding rake angle	Rake Angle of Each Guide Profile/ degree						
Linear	5	5.166	5.333	5.5	5.666	5.933	6
Increased	5	6.5	7	8	8	7	6
Decreased	5	4.5	4	4	5	5.5	6

The rake angles are designed to be gradually changed so that the surface can be generated smoothly. Because steep variation between two guiding profiles may cause modeling error. The actual rake angle of two new fillet rake surfaces are listed in Table 3-4. Also, curve fitting for actual rake angle is plotted to show the tendency of the rake angle.

Table 3-4 Actual rake angle of linear and two new fillet rake surfaces

	Rake Angle (degree)		
Measuring Points	Linear	Increased	Decreased
0	5	5	5
1	5.421	6.304	5.020
2	5.158	6.661	4.338
3	5.288	6.883	4.048
4	5.444	7.470	3.971
5	5.522	8.016	4.027
6	5.642	8.150	4.634
7	5.727	7.891	5.163
8	5.902	7.304	5.506
9	5.569	6.258	5.365
10	6	6	6

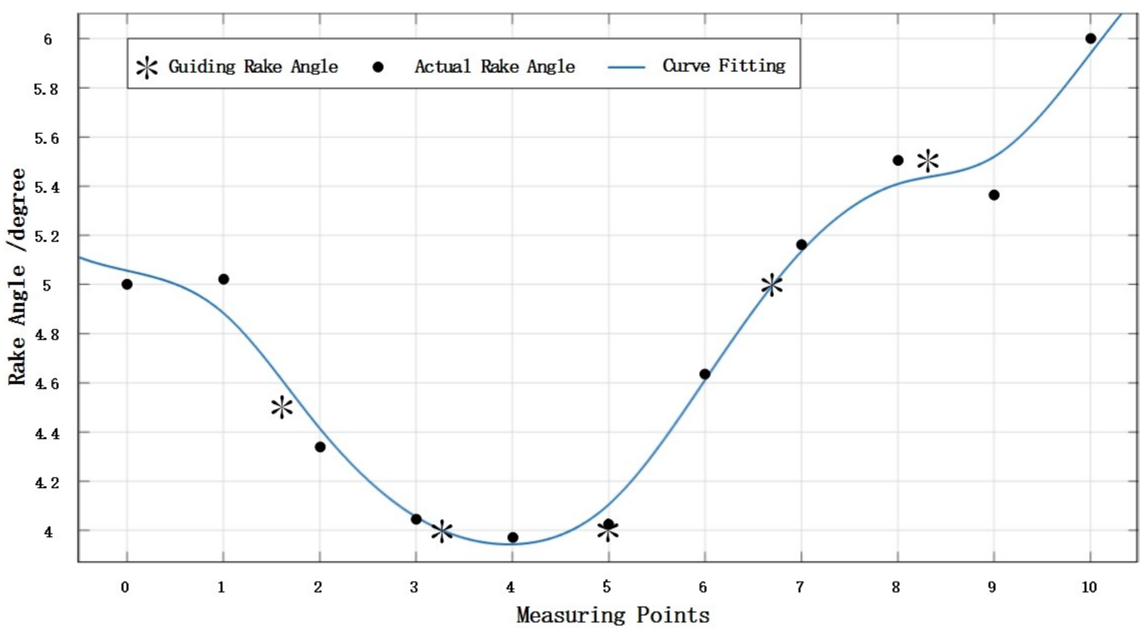

Figure 3.8 Curve fitting of actual rake angle with decreased guiding rake angle

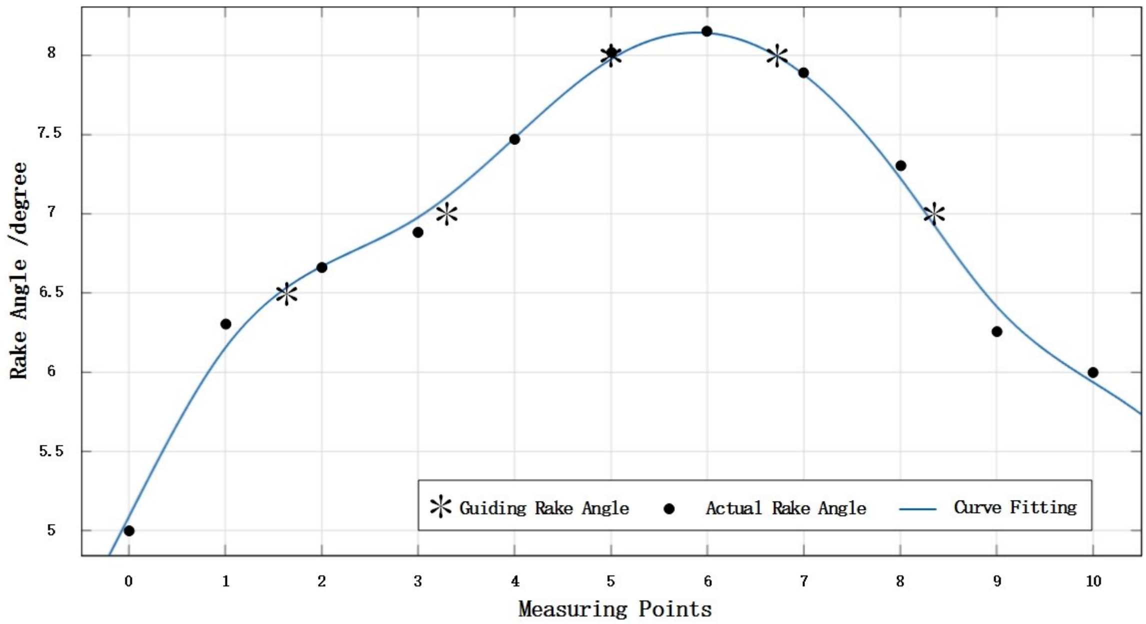

Figure 3.9 Curve fitting of actual rake angle with increased guiding rake angle

As shown in these Figure 3.8 and Figure 3.9, every guiding rake angle lies closely with the tendency curve which proves that seven guiding rake angles do present the desired shape of fillet rake surface well.

3.4 VB Development of Fillet End-mill Modeling

With the modeling method about the flank of fillet end-mill proposed, a model of a 4-flutes fillet end-mill can be generated in CATIA. However, the number of parameters of this model can reach to 33. Plus, considering more than 500 steps of procedure needs to be completed to build this model. It could not be imagined how time consuming it is when a customized fillet end-mill model is required.

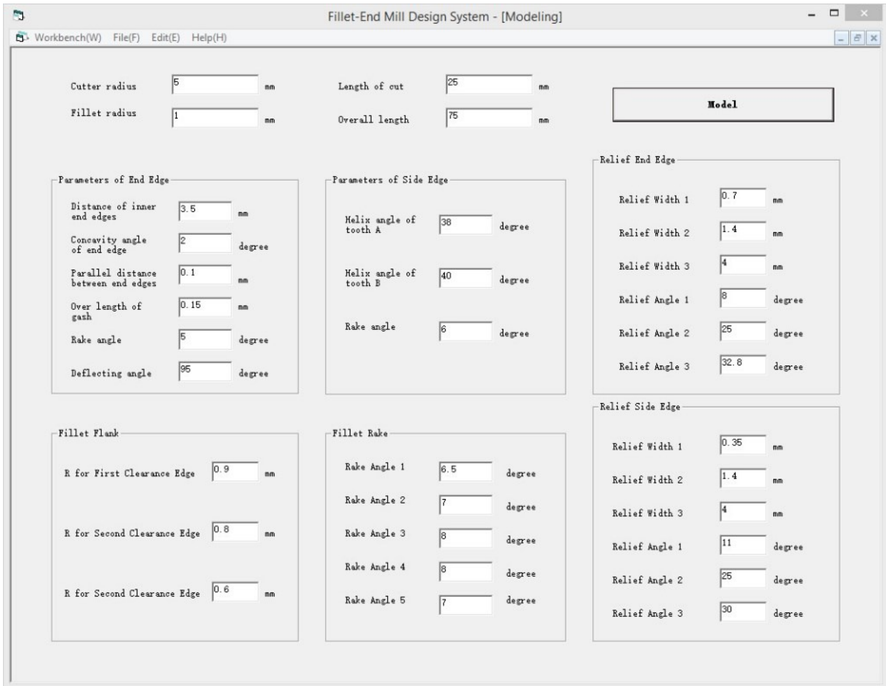

Figure 3.10 Interface of fillet end-mill modeling system

So a macro program is developed for the modeling of this end mill. The interface of this program is shown in Figure 3.10. CATIA allows users to build components automatically with macro programming in VB which can reduce the work load like building such a complicated model.

This macro program is created for modeling 4-flute fillet end-mill with different helix angles. An interface is designed to display all the parameters. Different features are categorized into different sessions for customized settings. The flank and fillet rake of the fillet end-mill can be generated for further modeling of solid cutter as shown in Figure 3.11. After Boolean operations, a solid cylinder can be modeled into a parametric fillet end-mill shown in Figure 1.3.

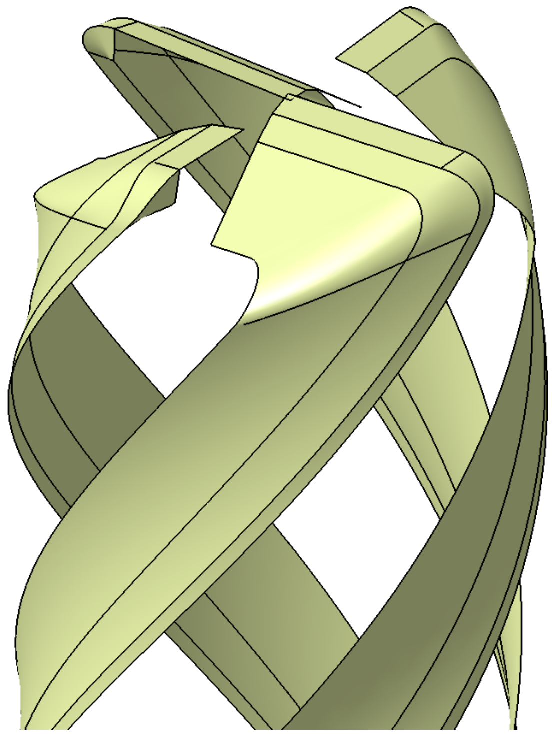

Figure 3.11 Flank and fillet rake surfaces

CHAPTER 4 APPLICATION

4.1 Cutting Tool Simulation Software

The modeling method of fillet flank and fillet rake surfaces is demonstrated in the two chapters above. Together with other modeling features, the whole fillet-cutting tool can be built in 3D modeling software like CATIA. The easiest way to verify the design and performance of the model is to conduct a simulation in a simulation software. FEA technique is widely used in many simulation softwares. Finite element method can find approximate solutions to engineering simulation problems which divide a whole part into simpler parts to get a close result.

Third Wave Advantedge is a software for optimization of metal cutting with validated finite element technique to analyze machining processes in 2D and 3D environments. The model of fillet end-mill in CATIA can be imported into Advantedge for further analysis. By defining tool's and workpiece's geometries, materials, and cutting conditions, the results of cutting process are generated, such as: temperature, stress, chip formation and power consumption.

4.2 Settings and Parameters for Simulation

4.2.1 Materials of Cutter and Workpiece

Cutting tools are mostly operated at high temperature and under heavy loads. Several major requirements for cutting tools are: Good physical and chemical properties under high temperature, especially hot-hardness. High wear resistance and high resistance to brittle fracture. [11] Of course, not all properties can be highly achieved in one material. For example, if the high-temperature resistance and wear resistance of a kind of material are high, the resistance to brittle fracture may be reduced.

Major classes of tool material in industry are carbon steels, high-speed steels, cast alloys, cemented carbide and ceramics. Cemented carbides are the most widely used materials in industry among them. Cemented carbides are categorized into three main classes: P, M and K. Cemented carbides P deals with material that produce long chips, including most steels; M for stainless and heat resistant alloys; K for cast irons, nonferrous alloys and hardened steels. In Third Wave Advantedge software, all types of carbide are provided. Carbide-Grade-M is selected as the material of the fillet end-mill, because end mills are commonly used for general purposes.

In Advantedge, a various of workpiece materials are available. As titanium alloy is one of the most high performance metals with high tensile strength and toughness, it is preferable for simulation which could give contrasting results. Titanium alloy are divided into numbers of categories among which Grade 5(Ti-6Al-4V) is the most commonly used alloy. So Ti-6Al-4V is set as the material of the workpiece in the simulation.

4.2.2 Machining Process Parameters

Among many machining operations of fillet end-mill, corner cutting is the suitable operation for examining the performance of fillet corner. Traditional milling (Up milling) is applied for simulation. The dimension of workpiece is 6mm*6mm*4mm. Adaptive remeshing technique is applied in meshing procedure. The more the element approaches the cutting section, the smaller the element gets. The minimum element size is 0.15 mm.

In order to reduce computation time, only the bottom part of end mill model which the cutting length is 7mm is imported into Advantedge for simulation. The meshing of fillet end-mill is shown in Figure 4.1. Minimum tool element size is 0.1 mm. Runout is not applied in these simulations, because only cutting force and temperature are tested within 180 degrees that runout of cutter can be neglected.

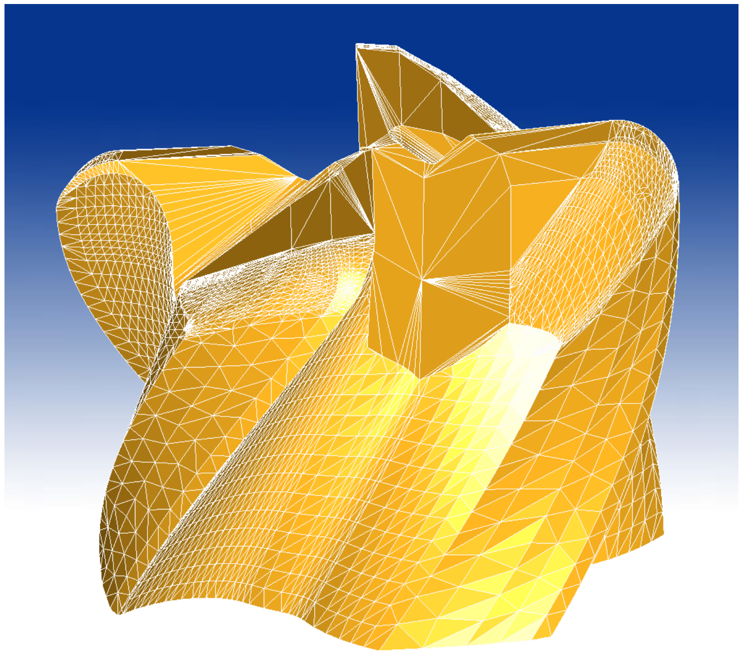

Figure 4.1 Meshing of fillet end-mill model

Spindle speed can be calculated by

$$\mathrm{R}PM = \frac{SFM}{\pi \times \frac{1}{12} \times D_e} \qquad \text{Eq. 4.1}$$

where RPM is the spindle speed(revolution per minute), SFM is the linear speed of cutter which is recommended according to different material(160 SFM), D_c is the diameter of cutter stock. After transferring to metric system, the spindle speed for simulation is 1500 r/min. And feed per tooth (FPT) of this cutter for machining Titanium alloy is recommended as 0.1mm/tooth.

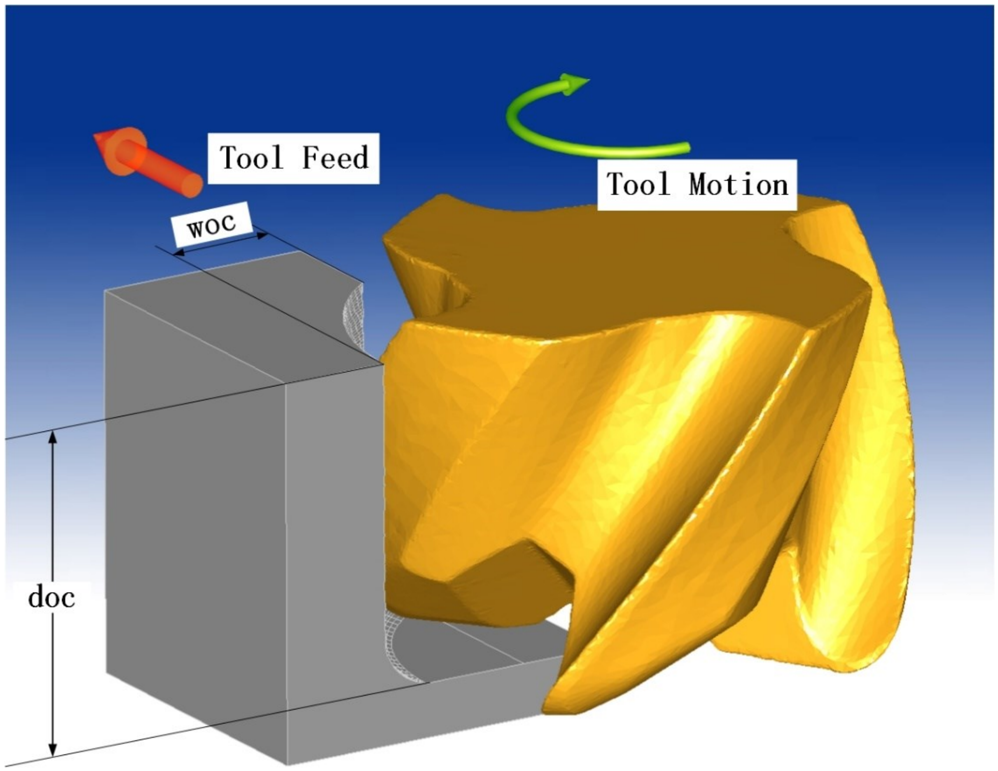

Figure 4.2 Machining with fillet end-mill in simulation software

4.2.3 Fillet End-mill Model Based on Grinding Tool Path

It is known that most manufacturing models of end mills is based on grinding wheel profile and relative movements between tool bar and the grinding wheel. A model of fillet end-mill is shown in Figure 4.3. It is noticed that flank and fillet rake surfaces are generated by numbers of segments which is derived from grinding wheel path which gives the most similar model of a real fillet end-mill. In the simulation example, another model of the fillet-cutter with same geometric parameters is used for simulation. So that differences between these two modes can be clearly seen in the results.

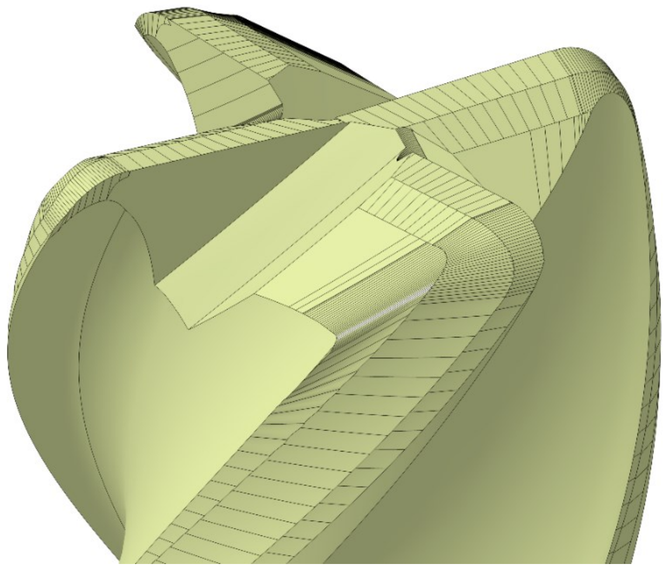

Figure 4.3 Grinding path based model of fillet end-mill

4.3 Simulation Example

With the same material and machining settings, the simulation results are shown below. The model with new method proposed is referred as New Model, the other one generated by grinding wheel path is referred as the Original Model.

First, cutting force is one of the most critical results that represent the cutting conditions which is also a general way to compare the difference of two different cutters. Figure 4.4 shows the coordinate system of which the end mill is located. The coordinate system of end mill model is $X_c - Y_c - Z_c$, while the coordinate system of the workpiece is $X - Y - Z$.

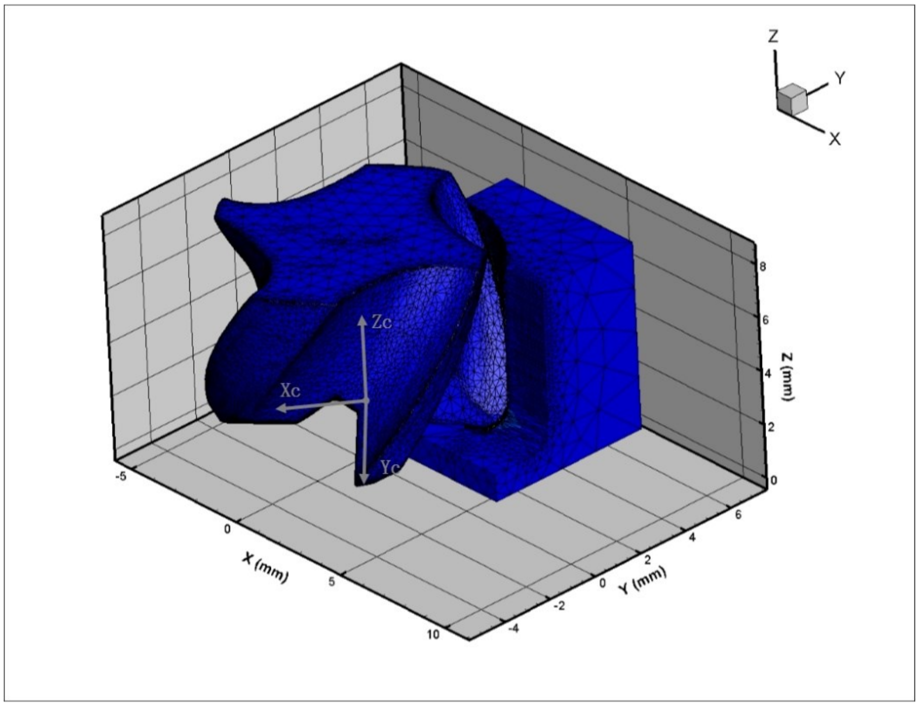

Figure 4.4 Coordinate system of the end mill in machining model

Cutting forces are derived from simulation along X, Y and Z direction. Figure 4.5, Figure 4.6 and Figure 4.7 illustrate the polynomial curve fit of cutting forces along X, Y and Z axis. It is noticeable that the tendency of two cutting forces along each axis is quite similar. In most time period of 180 degrees angular length of cut, the difference of forces between two models is below 100 N which shows the new model gives a similar simulation results compared with the original model given by the fact that the flank and fillet rake surfaces are modeled in two quite different methods.

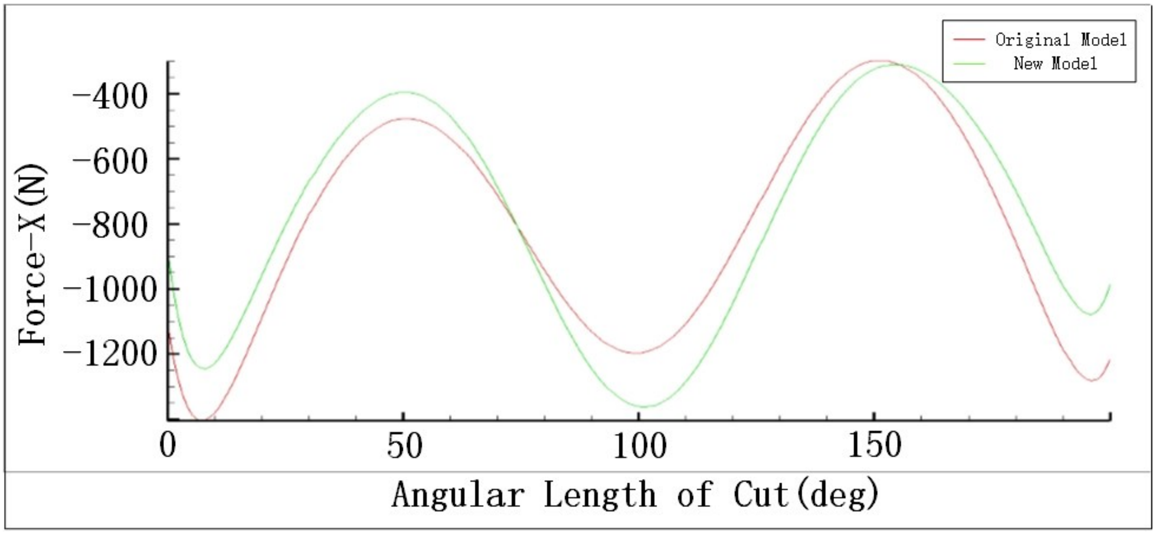

Figure 4.5 Cutting forces on X-axis of two models

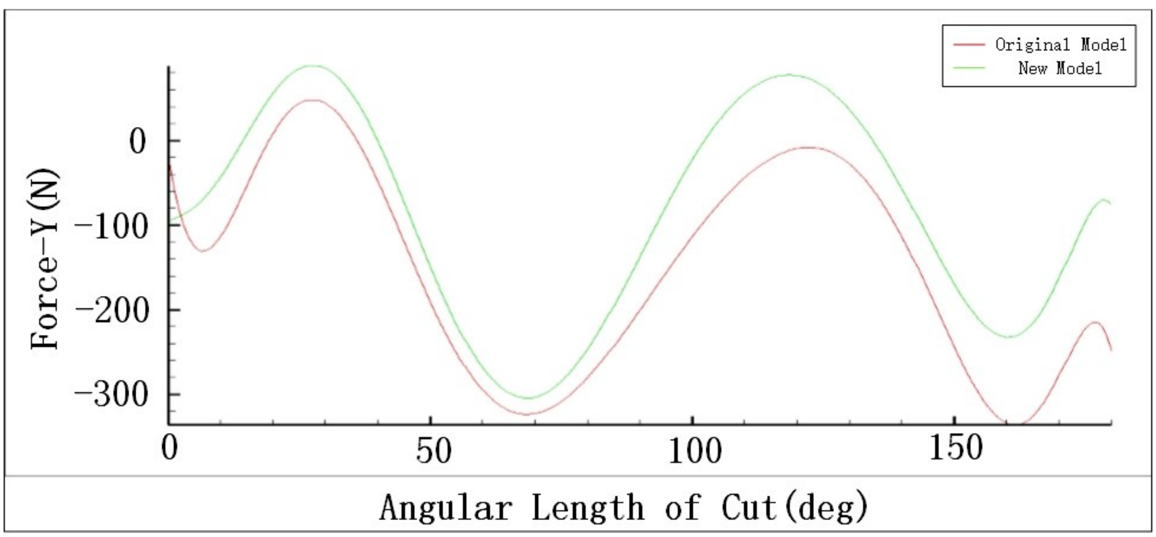

Figure 4.6 Cutting forces on Y-axis of two models

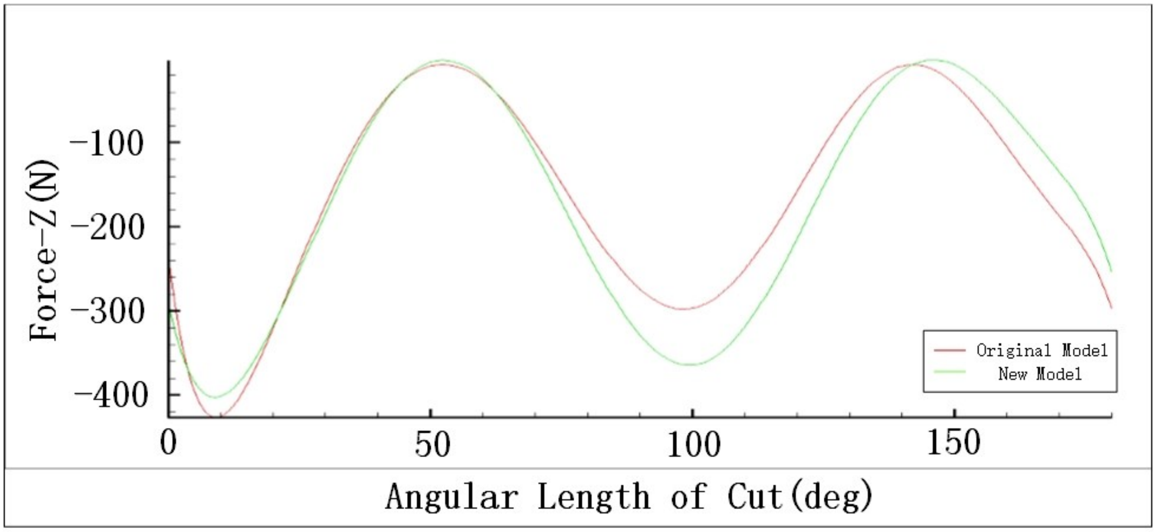

Figure 4.7 Cutting forces on Z-axis of two models

However, in some particular periods, the difference could reaches to 150 N like the cutting force along X-axis at 100 degrees. Therefore, the optimization of modeling needs to be considered in the future work.

Also, temperature is also a major element that affected by the geometry of end mill model. High temperatures are generated in the region of cutting edge. As the fillet cutting edge is the highlight of modeling in this thesis, a serious of temperatures on fillet cutting edge are extracted for comparison. The distribution of temperature is shown in Figure 4.8, as it is noted that the temperature reaches to the highest along cutting edge.

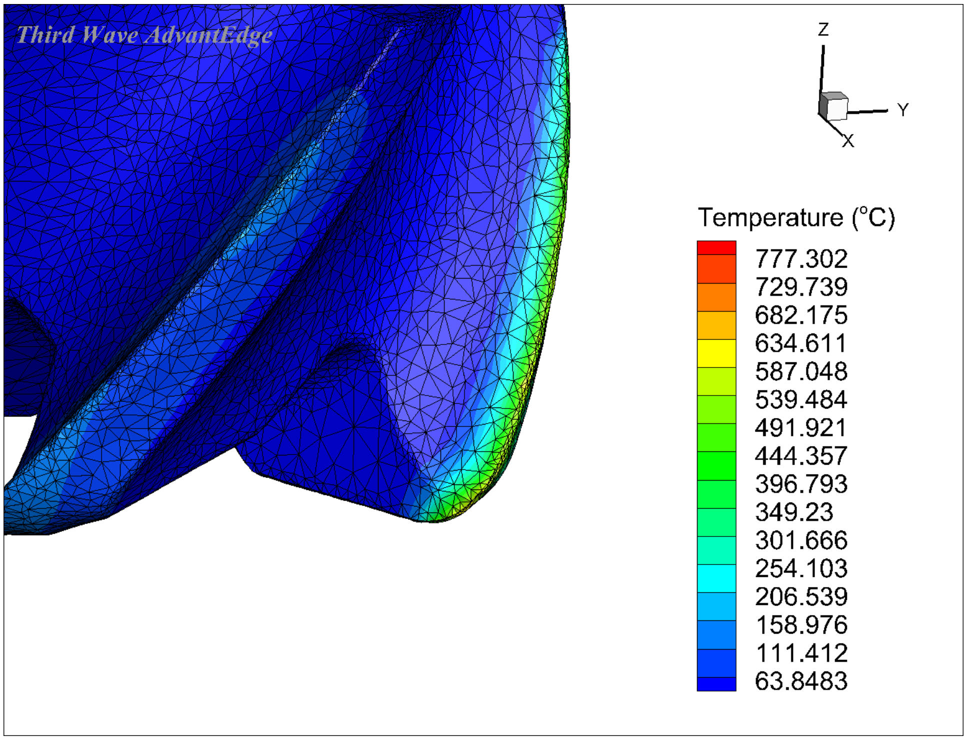

Figure 4.8 Temperature distribution on cutting edge

The cutting process of tooth A from the fillet cutting starting separating material till the fillet cutting edge finished and quit cutting is divided into 8 frames as illustrated in Figure 4.9. The highest temperature on fillet cutting edge of each frame is examined. The results of two models are shown in Table 4-1.

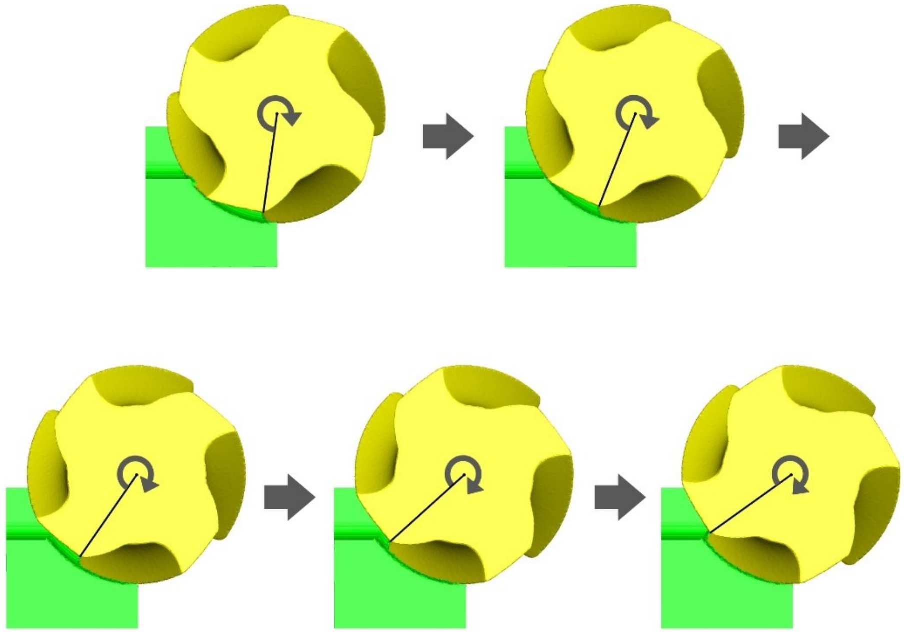

Figure 4.9 Cutting process of tooth A

Table 4-1 Highest temperature in the region of fillet cutting edge

Frames	New model	Original model
0	481.1	444.0
1	564.0	498.3
2	559.7	547.5
3	614.6	559.5
4	606.3	585.0
5	590.6	611.0
6	606.0	606.6
7	590.6	610.1

By plotting the temperatures in Figure 4.10, the change of temperature is clearly seen. As fillet cutting edge keeps machining into the workpiece, the highest temperature increased gradually from 450℃ to more than 600℃. The temperature of new model is actually a little lower than that of original model in the first four frames. After frame four, the temperature almost stays at around 600℃. In conclusion, highest temperatures on fillet cutting edge of two models are close to each other.

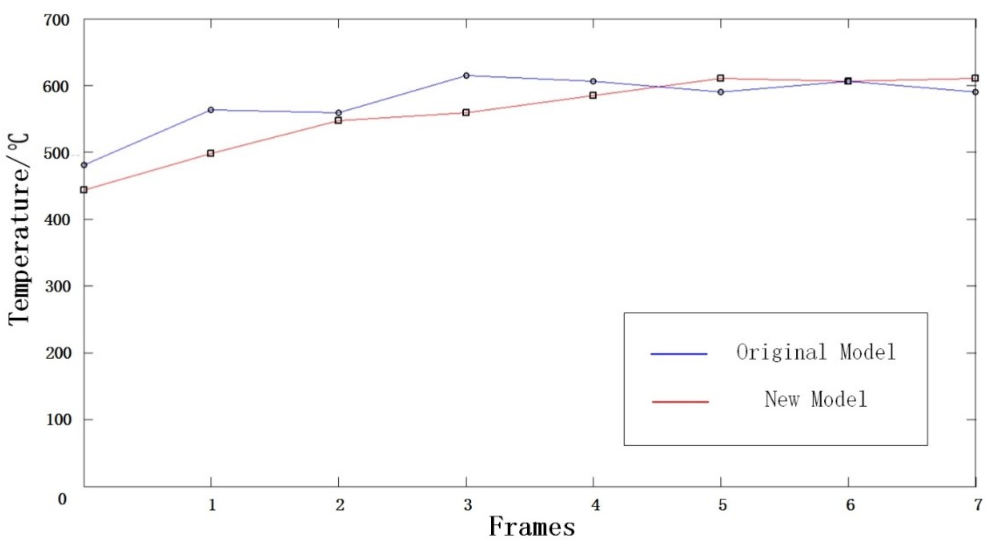

Figure 4.10 Change of highest temperature on the fillet cutting edge

CHAPTER 5 CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

In this work, in order to present a solid geometric model of fillet end-mill, a new approach to design flank and fillet rake surfaces is proposed. For modeling of flank, end and side flank are modeled based on clearance angle and the width of clearance face. As complex as the fillet flank is, a modeling method by defining radius of two-dimensional corners to construct the flank surface is presented. The shape of fillet flank can be adjusted by modifying these three parameters which can give customized results for different fillet flank design. As it is known that fillet rake surface is closely related to the performance of the fillet end-mill and the surface is largely affected by the rake angle of the fillet cutting edge, a rake angle based design is proposed to generate this surface. By comparing the different surfaces with different numbers of guiding profiles, it can be concluded that more numbers of guiding profiles generated a more matched surface as desired. This method is also a satisfying way for customized modeling for fillet rake surface.

Also, a modeling program is developed to build the solid model automatically, especially, the new modeling method of flank and fillet rake surfaces is integrated into this program with related variables input. This program can reduce the time of modeling process dramatically that the new designed model with different surfaces can be applied into simulation for examination quickly.

After the FEA cutting simulation between model with new designed flank and fillet rake surfaces and model from the grinding wheel path, the results are compared in several aspects. The cutting forces along X, Y and Z directions are compared between two models. Three similar plots of polynomial fit prove that the new model gives a quite close simulation results regards to cutting forces with the original model. Also, the highest temperatures on fillet cutting edge during machining are investigated. The results show the average highest temperature of the new model is even lower than that of the original model which indicate the new geometric model of flank and fillet can give a comparably better performance.

5.2 Future Work

For future research, the several topics are considered to expand the present research work:

The relation between the radius variable of 2D corner and the corner radius of fillet needs to be investigated in order to generate certain patterns of radius parameters for optimized fillet flank design. And also, as this thesis focus on fillet end-mill with three clearances of flank, more other end mills with different flank can be applied by this flank modeling method.

For fillet rake surface, even the variation of the rake angle of rake surface can be customized by changing the variables of guiding profiles, the difference between the guide rake angle and actual rake angle still needs to be further discussed for different fillet rake surface design.

As it is really time consuming to conduct FEA simulation, more simulations can be conducted in the future to verify all the suggested work mentioned above to improve the geometric model.

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