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Five-Axis CNC Grinding of End-Mills with Generic Revolving Profiles

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Abstract

Manufacturing end-mill cutting tools of non-traditional revolving profiles have been recently increasing with the increasing demands on smooth and curvy products. Among many tool design features, rake faces are considered the most crucial as they control the cutting forces, guide the tool flutes for smooth chips evacuations, and affect tools vibrations. Thus, the need arose to build a CNC grinding approach to grind the rake faces of end-mills having a generic cutting edge model. A revolving profile of a free-form curve, Non-periodic Uniform Rational Basis Spline (NURBS), is adopted in the present work, and a generic cutting edge model is established. The model can represent the cutting edges of both end-mills with traditional and end-mills with non-traditional revolving profiles. The importance of the model is very obvious in the tools manufacturing, specifically in the rake face grinding. A computer simulation for grinding rake faces of end-mills with free-form revolving profiles using a five-axis CNC grinding approach is conducted. The end-mills are obtained with accurate cutting edges and precise normal rake angles along those edges.

Keywords: *Five-Axis CNC Grinding; End-Mill Cutting Tools; Rake Face Grinding; NURBS Curves*.

1. Introduction

The end-mill cutting tools are commonly used in milling, profiling, plunging, etc. In profiling, the revolving shape of the end-mill is imposed on the side walls of the machined workpiece. With the increasing demands on smooth and curvy products, it becomes necessary to manufacture end-mill cutting tools with free-form revolving profiles. In the present work, the free-form revolving profiles are represented with NURBS curves as they are the most generic. Beside the free-form profiles, NURBS can easily represent the straight lines and the circular arcs [1]. Hence, both traditional and non-traditional end-mills can be modeled using NURBS curves.

The end-mill cutting tools consist of many design features as the side cutting edges, the rake faces, the primary and the secondary relief surfaces, the flute surfaces, the bottom cutting edges, the cores, etc. (Figure 1). Among these features, the rake faces are considered the most crucial and they are the main concern of the present work. The rake faces are always guided by the side cutting edges. Therefore, many researchers were concerned to establish optimal mathematical models for the side cutting edges. The models can be classified into three major categories: side cutting edges with constant helical angles between their tangents and the tool axis [2-4], side cutting edges with constant helical angles between their tangents and the tool generatrix [5-12], side cutting edges with constant pitches [13, 14], and in some situations, a combination of two mathematical models [15]; a ball-end cutter having a side cutting edge with a constant helical angle to its axis will not have a mathematical description at the top of the ball. For the top of the ball, a constant pitch or a constant helical angle to the generatrix should be adopted. At the common point of the two segments of the cutting edge, the continuity and the smoothness should be maintained.

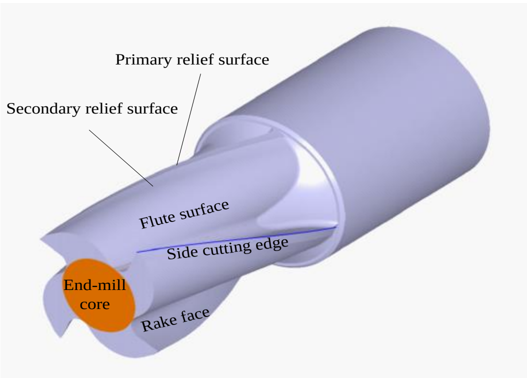

Figure 1. A simple model of an end-mill with its designed features

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Figure 2 describes, in more details, the aforementioned definitions of the side cutting edges. For any point **P** on the side cutting edge, the helical angle is measured between the tangent vector **T** and either the tool axis **A** or the generatrix **G**. Thus, modeling cutting edges with a constant helical angle to the generatrix, or to the tool axis, leads to completely two different cutting edges. The cutting edges with a constant helical angle between their tangents and the tool generatrix are adopted in this work.

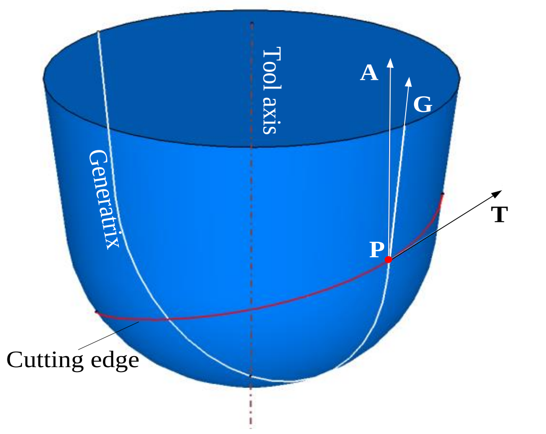


Figure 2. The helical angle definitions of the side cutting edges

Beside the aforementioned models, a mathematical model of the APT cutting edge was first introduced by Engin and Altintas [16]. Cutting edges of many cutters found in industry, such as cylindrical end-mills, fillet end-mills, ball end-mills, can be represented using this model; however, many others cannot. Hence, the present work establishes a generic cutting edge model for end-mill cutters of generic revolving profiles.

After deriving the cutting edge model, the five-axis CNC grinding approach proposed by Rababah *et al*. [17] is extended to grind the rake faces of end-mills with generic revolving profiles. As will be shown, the approach revealed rake faces with constant normal rake angles and accurate cutting edges along the rake faces.

2. The Generic Model of the Side Cutting Edge

In order to derive the cutting edge equation, the end-mill envelope is obtained. However, the revolving profile of the end-mill cutting tool is first established as a free-form curve and is expressed as:

$$\mathbf{C}(u)=\begin{bmatrix} x(u) \\ y(u) \\ z(u) \end{bmatrix}=\sum_{i=0}^{n}\mathbf{P_i}R_{i,k}(u)\ , \quad (1)$$

where

$$R_{i,k}(u)=\frac{w_i N_{i,k}(u)}{\sum_{i=0}^{n} w_i N_{i,k}(u)}\ , \quad (2)$$

and $N_{i,k}$ are the basis functions and are expressed as:

$$N_{i,k}=(u-u_i)\frac{N_{i,k-1}(u)}{u_{i+k-1}-u_i}+(u_{i+k}-u)\frac{N_{i+1,k-1}(u)}{u_{i+k}-u_{i+1}} \quad (3)$$

where

$$N_{i,1}=\begin{cases} 1 & u_i \le u \le u_{i+1} \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

The knot vector u can be obtained from the formula:

$$u_i=\begin{cases} 0 & i<k \\ i-k+1 & k \le i \le n \\ n-k+2 & i>n \end{cases} \quad (5)$$

where k is the curve order, n+1 is the number of the control points. As the curve is free-form, its shape can be controlled using the control points $\mathbf{P_i}$ and the weighted parameters w_i.

Back to the envelope, the parametric equation is written as:

$$\mathbf{t}(u,\theta)=\begin{bmatrix} r(u)\cdot\cos\theta \\ r(u)\cdot\sin\theta \\ z(u) \end{bmatrix}, \quad (6)$$

where $r(u)=\sqrt{x^2(u)+y^2(u)}$ is the radius of the corresponding circle on the plane with coordinate $z(u)$, and u is the curve parameter (Figure 3). Based on Eq. 6, the first partial derivatives of the envelope $\mathbf{t}(u,\theta)$ in terms of z and θ are derived as:

$$\frac{\partial\mathbf{t}}{\partial z}=\begin{bmatrix} \frac{\partial r/\partial u}{\partial z/\partial u}\cdot\cos\theta \\ \frac{\partial r/\partial u}{\partial z/\partial u}\cdot\sin\theta \\ 1 \end{bmatrix}, \quad (7a)$$

and

$$\frac{\partial\mathbf{t}}{\partial\theta}=\begin{bmatrix} -r(u)\cdot\sin\theta \\ r(u)\cdot\cos\theta \\ 0 \end{bmatrix}. \quad (7b)$$

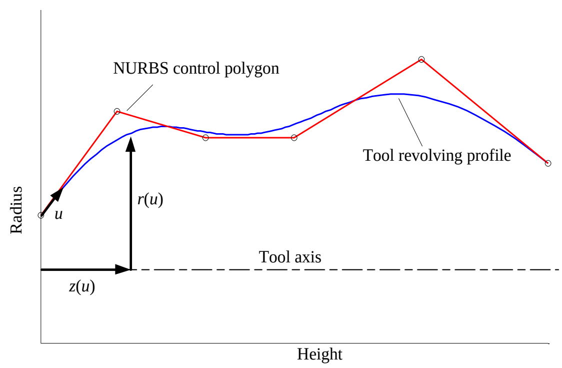


Figure 3. Illustration of the parameters of a generic end-mill revolving profile

In the present work, the differential 1-forms of the tangent vectors of the helical curve and the generatrix are denoted as $d\mathbf{t}$ and $\delta\mathbf{t}$, respectively. They can be obtained with the following equations:

$$d\mathbf{t} =: \frac{\partial \mathbf{t}}{\partial z} \cdot dz + \frac{\partial \mathbf{t}}{\partial \theta} \cdot d\theta \text{, and } \delta\mathbf{t} =: \frac{\partial \mathbf{t}}{\partial z} \cdot \delta z \ . \qquad (8)$$

Thus, the relationship between the helical angle ψ and these two vectors can be formulated as:

$$\cos\psi = \frac{d\mathbf{t} \cdot \delta\mathbf{t}}{\|d\mathbf{t}\| \cdot \|\delta\mathbf{t}\|} \ . \qquad (9)$$

By substituting Eq. 8 into Eq. 9 and simplifying, the relationship between the parameters u and θ can be formulated as:

$$d\theta = \int \tan\psi \sqrt{\frac{\left(\dfrac{\partial r / \partial u}{\partial z / \partial u}\right)^2 + 1}{\left(r(u)\right)^2}} \frac{dz}{du} du \ . \qquad (10)$$

Hence, for any value of the curve parameter u, the cutting edge angle θ and the tool axis parameter z are obtained from Eq. 10 and Eq. 6, respectively. As both parameters are correlated, the side cutting edge can now be expressed as:

$$\mathbf{CE}(u) =: \begin{bmatrix} r(u) \cdot \cos\theta(u) \\ r(u) \cdot \sin\theta(u) \\ z(u) \end{bmatrix} . \qquad (11)$$

3. Five-Axis CNC Grinding Approach

Due to the complexity of the end-mill profiles, two-axis CNC grinding approaches are unable to grind rake faces with constant normal rake angles and accurate cutting edges [18]. Thus, the approach proposed by Rababah *et al.* is adopted to accomplish the task [17]. The approach is developed on the principle that at any point on the side cutting edge, the normal vector of the rake face and the normal vector of the grinding-wheel lateral surface should be aligned. This principle leads to a complete derivation for the grinding-wheel path (locations and orientations). However, seeking brevity, the approach is not re-elaborated here. Complete details on the approach, the grinding-wheel shapes, and the grinding-wheel path derivations are discussed in literature [17-21].

4. Rake Face Grinding Simulation

Two end-mills with generic revolving profiles are considered for computer simulation. The cutting edges are first established with MATLAB, and then, imported to CATIA to perform the grinding simulation using Boolean operations. The revolving profile of end-mill I is constructed with 6 control points, as shown in Figure 4. Beside the control points' locations, their weights can also alter the shape of the revolving profile. Rotating the revolving profile about the tool axis will generate the end-mill envelope. The side cutting edge of a helical angle of 20 deg. on the end-mill envelope is represented in Figure 5.

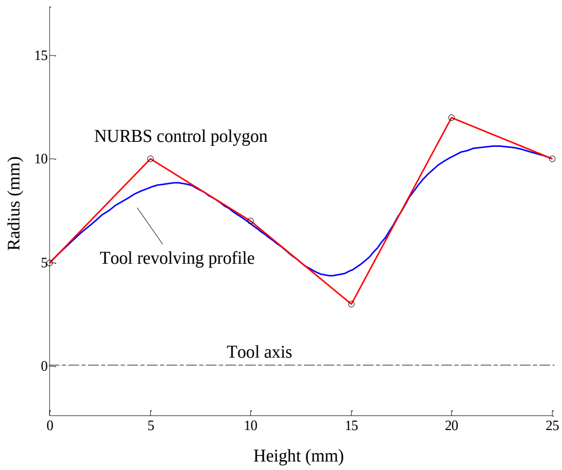


Figure 4. The revolving profile of end-mill I

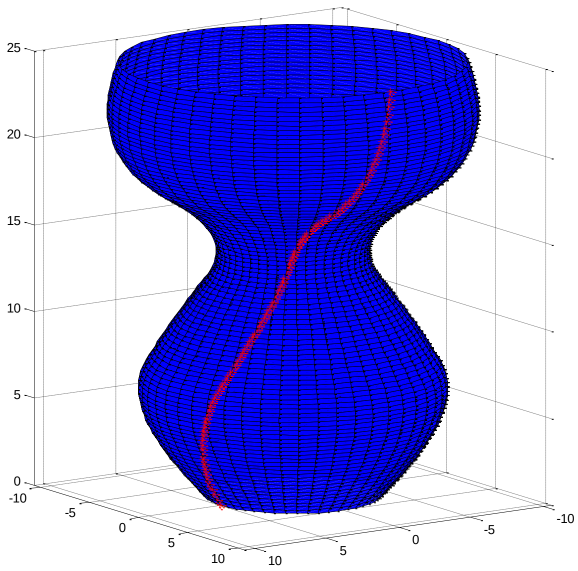
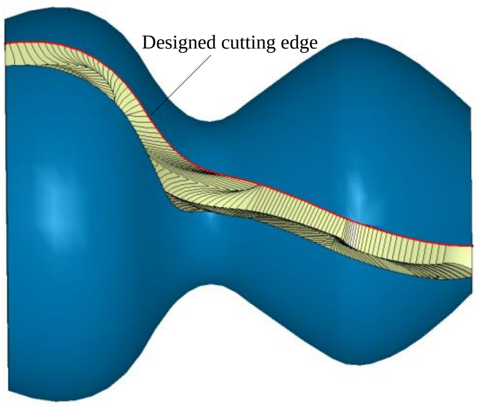
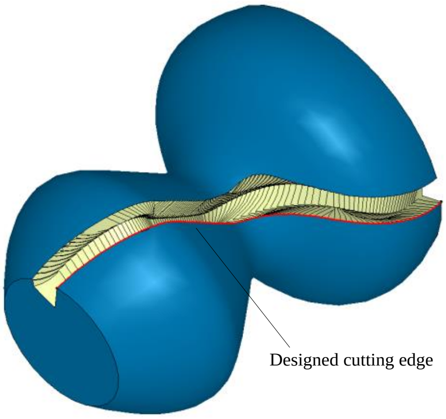


Figure 5. The side cutting edge on end-mill I envelope (mm)

The grinding simulation proved to produce rake faces with accurate side cutting edges as obviously shown in Figure 6, and a constant normal rake angle as will be discussed below.



(*a*) view *a*



(*b*) view *b*

Figure 6. Rake face grinding of end-mill I with an accurate side cutting edge (different views)

A constant normal rake angle of 10 deg. is adopted in the simulation. Three arbitrary sections normal to the side cutting edge are considered to verify the accuracy of the machined normal rake angle (Figure 7). At any point **P** on the side cutting edge, the normal rake angle is defined as the angle between vectors **M** and **N**, as shown in Figure 8. Vectors **M** and **N** are both laying on a plane normal to the side cutting edge. Vector **M** is aligned with a line connecting point **P** and the tool axis, and vector **N** is the intersection of the rake face with the normal plane. From the Figure, the accuracy of the machined normal rake angle is obvious.

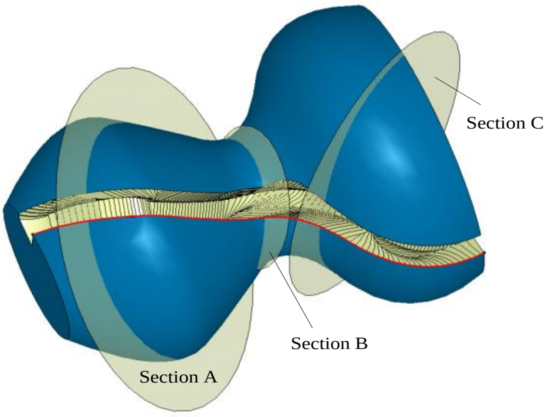
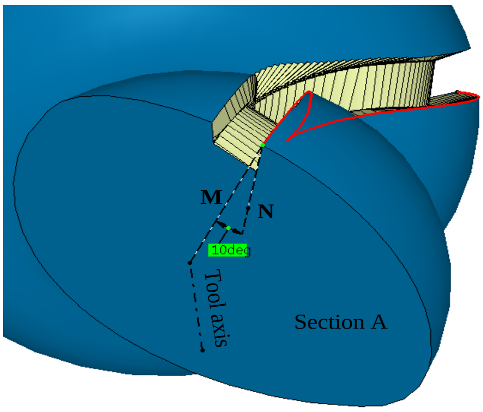
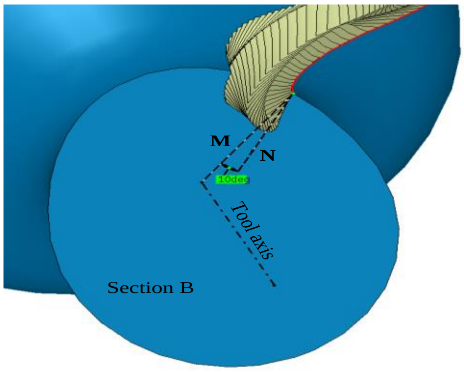


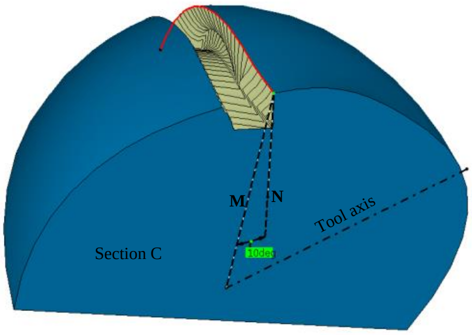
Figure 7. The arbitrary sections normal to the side cutting edge for end-mill I



(***a***) The normal rake angle at section A normal to the cutting edge for end-mill I



(***b***) The normal rake angle at section B normal to the cutting edge for end-mill I



(***c***) The normal rake angle at section C normal to the cutting edge for end-mill I

Figure 8. The normal rake angle at three arbitrary sections normal to the side cutting edge of end-mill I

As a second grinding simulation example, the revolving profile, used to produce the envelope of end-mill II, consists of 7 control points and is demonstrated in Figure 9. The side cutting edge on the end-mill envelope is shown in Figure. 10 ($\psi = 20^{\circ}$).

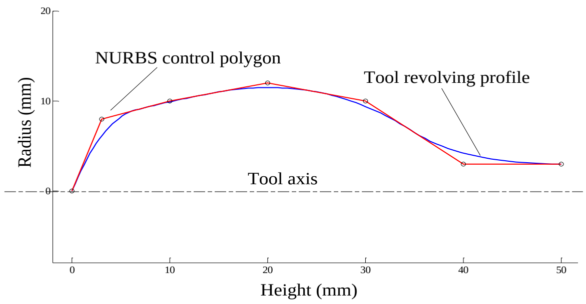


Figure 9. The revolving profile of end-mill II

The grinding simulation of end-mill II is again proved to produce rake faces with accurate side cutting edges (Figure 11), and constant normal rake angles, as shown in Figures 12 and 13.

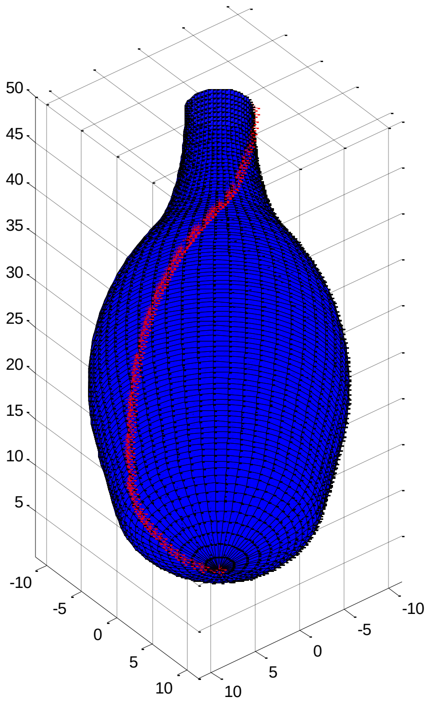
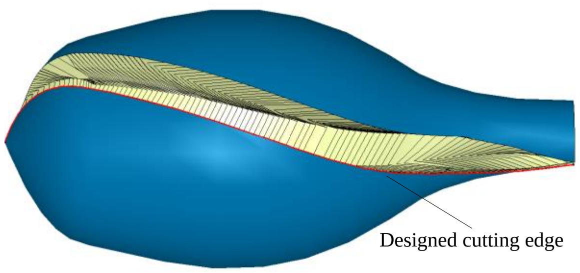
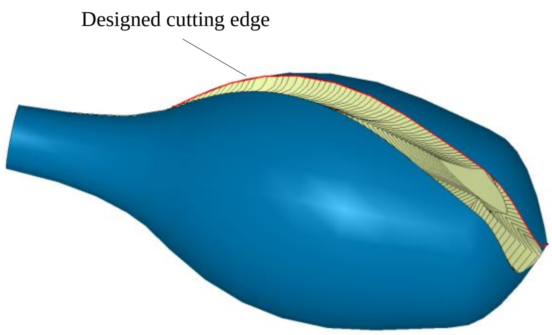


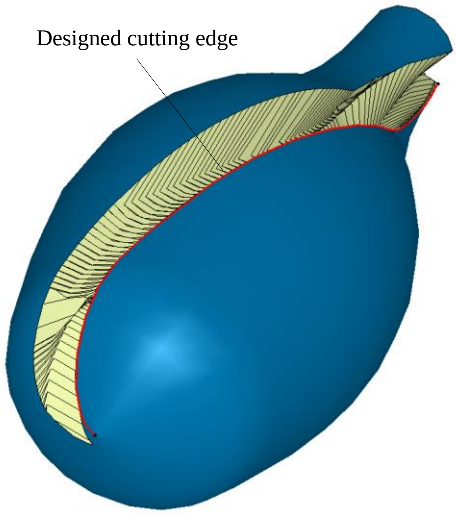
Figure 10. The side cutting edge on the end-mill II envelope (mm)



(*a*) View *a*



(*b*) View *b*



(*c*) View *c*

Figure 11. Rake face grinding of end-mill II with an accurate side cutting edge (different views)

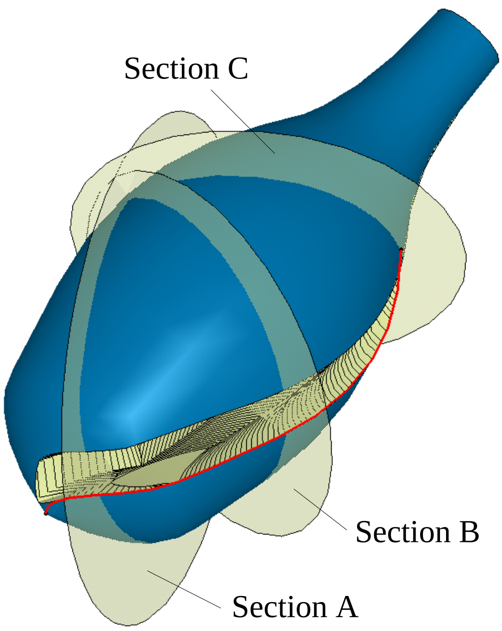
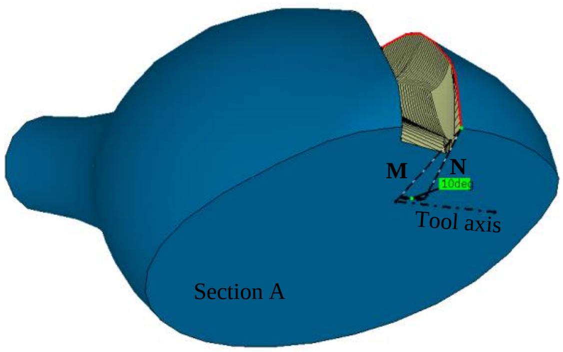
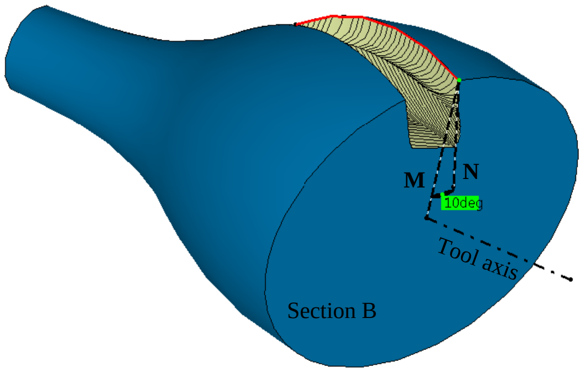


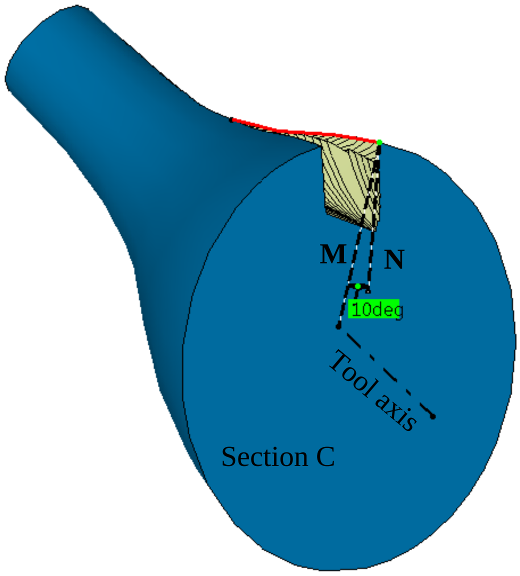
Figure 12. The arbitrary sections normal to the side cutting edge for end-mill II



(*a*) The normal rake angle at section A normal to the cutting edge for end-mill II



(***b***) The normal rake angle at section B normal to the cutting edge for end-mill II



(***c***) The normal rake angle at section C normal to the cutting edge for end-mill II

Figure 13. The normal rake angle at three arbitrary sections normal to the side cutting edge of end-mill II

5. Conclusion

Generic cutting edge models are established using NURBS curves. The generic models facilitated the flutes grinding by adopting a five-axis CNC grinding approach. The approach is proved to produce end-mills flutes with accurate side cutting edges and precise normal rake angles. The approach is considered to be generic five-axis CNC grinding as traditional and non-traditional end-mills can both be built from free-form revolving profiles (NURBS curves).

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