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Analysis of Grinding Wheel Profile in Feeding-Through Centerless Grinding of Tapered Roller

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ABSTRACT: Conical surface of the tapered roller used in rolling bearing is generally processed by the method of feeding-through centerless grinding. This paper presented theoretical analysis on the grinding wheel profile within this process, and the results show that the linear profile grinding wheel may lead to middle concavity of roller profile after grinding; the ideal profile of grinding wheel, which can avoid the inside concavity of roller profile, is the complex curved profile; the ideal profile curve can be simplified as a hyperbola. The mechanism for linear profile grinding wheel leading to middle concavity of roller profile is: the blade is of limiting effect to tapered roller posture, creating a spatially intersected angle between tapered roller axis and grinding wheel axis, and thus causing middle concavity of roller profile; The larger, the semi-cone angle of roller is, the larger, the concavity degree will be; The larger, the oblique angle of the blade slant to horizontal plane is, the smaller the middle concavity degree will be. The hyperbolic angle of simplified grinding wheel hyperbolic profile equals to the spatial crossing angle between roller axis and grinding wheel axis. the calculation formulars for such hyperbolic angle were deduced.

KEYWORDS: Rolling Bearing; Tapered Roller; Feeding-Through Centerless Grinding; Grinding Wheel Profile; Roller Profile

Rolling bearing is an important kind of basic mechanical components. Tapered roller is one kind of rolling element in rolling bearing, and the conical surface of tapered roller is the major working surface, which needs to be grinded. Linearity of the tapered roller profile is an important technical requirement in the grinding process... Feeding-through centerless grinding is a main approach for tapered roller profile grinding, wherein linearity of the roller profile after grinding is affected by the motion relation and geometric relation among grinding wheel, roller, blade, and guide wheel [1].

Currently, researches on feeding-through centerless grinding of tapered roller mainly focus on roller profile convexity and guide wheel, while seldom focus on grinding wheel profile and blade [2-3]. In fact, grinding wheel profile directly affects the shape of roller profile; blade indirectly affects roller profile shape by limiting roller posture. In this paper, the geometric and motion relation among tapered roller, grinding wheel and blade is firstly analyzed. Moreover, based on basic principle of part surface machining, and with the aim of acquiring sound linearity of roller profile, this paper analyzed the grinding wheel profile with the consideration of blade's limiting effect on roller posture.

FEEDING-THROUGH CENTERLESS GRINDING METHOD OF TAPERED ROLLER

The feeding-through centerless grinding processing method of tapered roller is shown in Figure 1. It can be seen that grinding wheel and guide wheel are in fixed-axis rotation; Supported by guide wheel and blade and driven by guide wheel and grinding wheel, Tapered roller is fed through grinding zone of grinding wheel while rotating. Grinding wheel axis is vertically and horizontally distributed without adjustment; while grinding wheel axis is generally vertically and horizontally distributed, and of small adjustment in horizontal and vertical plane, therefore the geometric relation between guide wheel axis and grinding wheel axis can be either parallel, intersected or spatially crossed during grinding. During grinding, the spin motion of roller is resulted by tangential grinding force of grinding wheel and tangential friction force of guide wheel and blade, wherein the autorotation speed of roller is controlled by guide wheel; The feeding-through motion of roller is driven by the helical flange of guide wheel, wherein the feeding through speed is controlled by guide wheel; The roller posture is determined collaboratively by guide wheel spiral working face profile and blade; the track of roller feeding-through motion is determined collaboratively by guide wheel axial direction, variation of guide wheel spiral working face along its axial direction, and blade direction.

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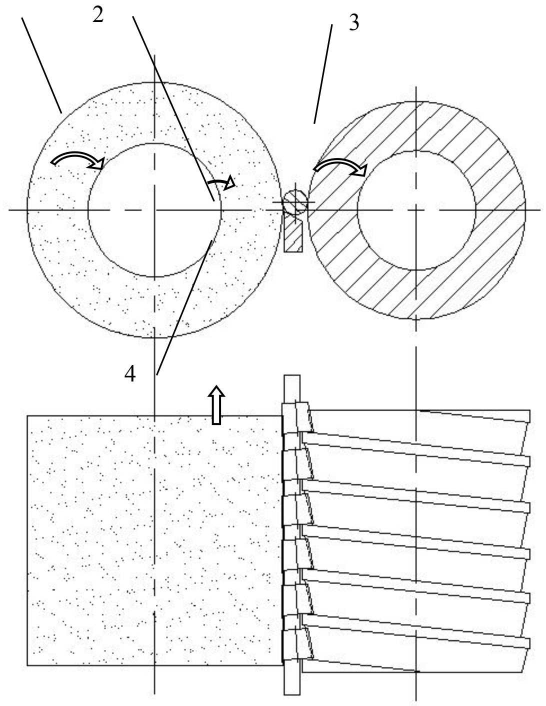

1—grinding wheel；2—tapered roller；3—guide wheel；4—blade

Figure 1. Feeding-through centerless grinding of tapered roller.

INFLUENCE OF LINEAR PROFILE GRINDING WHEEL ON THE LINEARITY OF TAPERED ROLLER PROFILE

An ideal roller-grinding wheel relation in grinding linear profile roller by linear profile grinding wheel

According to basic principle of part surface machining , in feeding-through centerless grinding of tapered roller, as long as that roller and grinding wheel are in certain geometric and motion relation, the conical surface of linear profile tapered roller can be grinded by linear profile grinding wheel in theory. An ideal roller-grinding wheel relation is: grinding wheel is finished into linear profile cylindrical surface; roller is fed through in a straight line; roll axis intersects with grinding wheel axis, and the intersect angle equals roller semi-cone angle; the center through straight line of roller is parallel to grinding wheel axis. Such relation is shown in Figure 2.

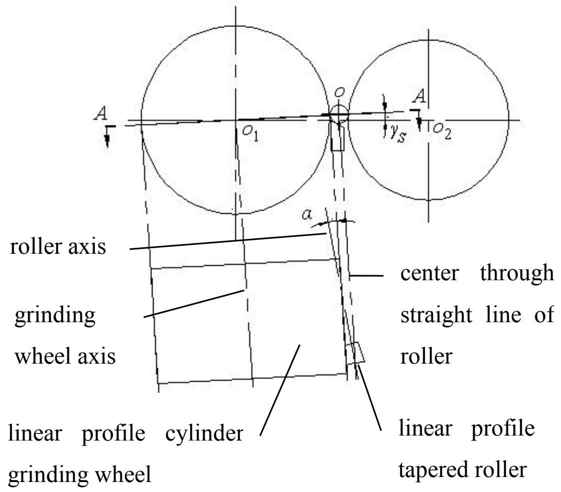

Figure 2. An ideal roller-grinding wheel relation in grinding linear profile roller by linear profile grinding wheel.

In Figure 2, O_1 is the rotation center of grinding wheel;$O_2$is the rotation center of guide wheel;O is large end circle center of tapered roller; O_1O_2 length is the center height of roller;grinding wheel axis and the link line between O_1 and O_2 exist in the same horizontal plane,while the link line between O_1 and O incline to horizontal plane by angle of γ_s (contact angle between roller and grinding wheel);*A-A* plane is a plane where grinding wheel axis and link line between O_1 and O both exist in; in *A-A* plane, the straight profile of grinding wheel is parallel to grinding wheel axis(grinding wheel is linear profile cylindrical surface). The relation between roller and grinding wheel is: roller axis and grinding wheel axis both exist and intersect in *A-A* plane,wherein the intersect angle is roller semi-cone angle α;the center through straight line of roller also exists in *A-A* plane and is parallel to grinding wheel axis, so that it can guarantee that in such plane the roller isoline and grinding wheel isoline always overlap in the same line.

Limiting effect of blade on roller posture

The ideal roller-grinding wheel relation proposes specific requirements on roller posture. To determine whether these requirements can be met, it needs to analyze the impacting factors to roller posture. As one of impacting factors to roller posture, in this paper the blade is analyzed for its limiting effects on roller posture. Roller posture can be expressed by roller axis direction.

Blade contact with roller on a fixed incline plane. Therefore such contact must be linear contact and the contact line must be the generatrix of roller. The angle between roller generatrix and roller axis is the semi-cone angle of roller. The roller must be in linear contact with blade, and the angle between roller-blade contact line and roller axis must equal roller semi-cone angle. These two constraint conditions determine that whether the roller posture will be limited by blade.

In normal condition, roller-blade geometric relation is shown in Figure 3 From Figure 3, it can be seen that *A-A* plane is where both grinding wheel axis and roller large end center exist;*B-B* is the horizontal plane;*C-C* plane is parallel to grinding wheel axis and vertical to *A-A* plane;*D-D* is blade slope;*F-F* plane passes through small end circle center of roller and is parallel to blade slope plane;O_E,O_A and O_C are projections of large end circle center of roller on cross section *E-E* (a section which is vertical to grinding wheel axis, not shown in the figure), *A-A* plane and *C-C* plane, respectively;O'_E,O'_A and O'_C are projections of small end circle center of roller on cross section *EE*, *A-A* plane and *C-C* plane, respectively;P and P' are the contact point between roller large end arc and blade plane and the roller small end arc and blade plane,PP' is the contact line between roller and blade;β is the angle between blade slope plane and horizontal plane, simplified as blade slope angle hereinafter;λ is the angle between projection $O_EO'_E$ of roller axis on cross section and *A-A* plane; θ is the angle between projection $O_CO'_C$ of roller axis on *C-C* plane and grinding wheel axis;φ is the angle between projection $O_AO'_A$ of roller axis on *A-A* plane and grinding wheel axis. Direction of roller axis is determined by any two of three parameters including λ, θ and φ.

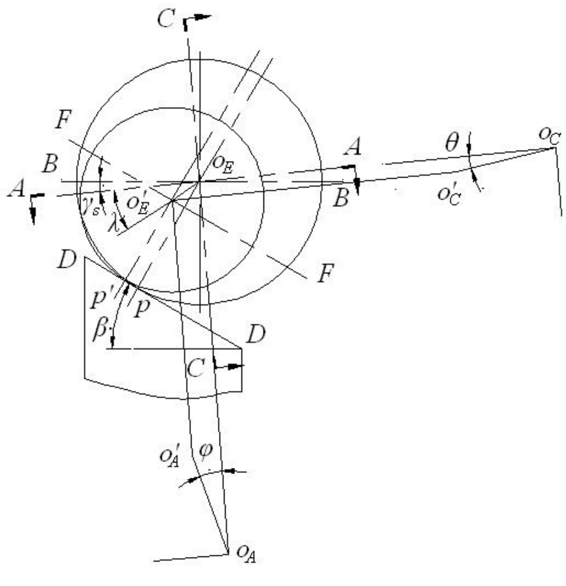

Figure 3. Geometric relation between roller and blade under normal condition.

Under the constraint of blade, roller axis direction can still change. For example, when geometric parameters such as roller large/small end diameter and roller conical angle change, the direction of roller large/small end circle center will change accordingly, so that the roller axis direction can be changed; when the direction of guide wheel axis or guide wheel profile changes, roller small end circle center can change on F-F plane (considering that the roller axis direction is determined by the relative direction of roller small end circle center and large end circle center, here we assume the roller large end circle center is fixed), so that the roller axis direction can be changed.

Although roller axis direction is adjustable under the constraint of blade, it needs further analysis to determine whether the roller posture can meet the requirement for ideal roller-grinding wheel relation prescribed in 2.1. Therefore, this paper investigates a typical roller axis direction, i.e. roller axis and grinding wheel axis are coplaned both exist in A-A plane. Under such typical situation, the roller-blade geometric relation is shown in Figure 4.

Compared with Figure 3, the points of changed positions in Figure 4 are subscripted with “1”;φ_1 corresponds to φ in Figure 3 φ;λ and θ in Figure 3 are not existed any more as in Figure 4 (their values are changed to 0).

from Figure 4, it can be known

$$\sin\varphi_1 = \frac{O_E O'_{E1}}{O_{A1} O'_{A1}} \tag{1}$$

$$O_E O'_{E1} = \frac{O_E P_1 - O'_{E1} P'_1}{\cos\angle P_1 O_E O'_{E1}} \tag{2}$$

$$\angle P_1 O_E O'_{E1} = 90^\circ\text{-}(\gamma_s + \beta) \tag{3}$$

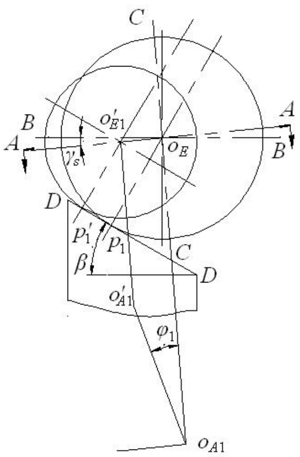

Figure 4. Roller-blade geometric relation when roller axis and grinding wheel axis are coplaned.

Roller-blade contact line *PP′* is the generatrix of roller, which is co-planed with roller axis. In such plane, the relation between roller geometric parameters and line segment *OP* and *O'P′ (*which respectively represents the distance between large end circle center to blade slope plane and small end circle end to blade slope plane*)′*is shown in Figure 5. In Figure 5, roller large end radius is *R*, roller small end radius is *r*, roller length is *l*, roller semi-cone angle is *α*.

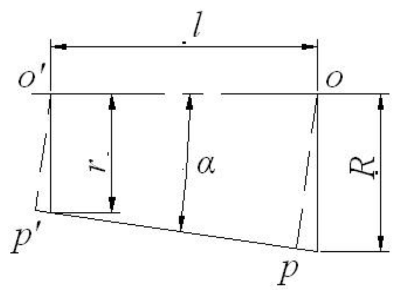

Figure 5. Relation between roller geometric parameters and distance from roller large/small end circle center to blade slope plane.

From Figure 5, it can be seen

$$OP = R\cos\alpha \tag{4}$$

$$O'P' = r\cos\alpha \tag{5}$$

$$(R - r) = l\tan\alpha \tag{6}$$

From equation (4)~(6), it can obtain

$$OP - O'P' = l\sin\alpha \tag{7}$$

Since the O_EP_1-$O'_{E1}P'_1$ in equation(2) and OP-$O'P'$ in equation (7)both represents the difference between distance from large end circle center to blade slope plane and distance from small end circle center to blade slope plane, they equal in value;As $O_{A1}O'_{A1}$ in equation(1)represents the large end center-small end center distance in A-A plane where roller axis exists, the length is l;By substituting equation (3) into equation (2), which is then substituted into equation(1), it can obtain

$$\sin\varphi_1 = \frac{\sin\alpha}{\sin(\gamma_s + \beta)} \tag{8}$$

If roller axis direction meet the requirement for ideal roller-grinding wheel relation prescribed in 2.1, the φ_1 value in equation (8)should meet $\varphi_1=\alpha$, then $\gamma_s+\beta=90°$.

Both grinding wheel diameter and guide wheel diameter are bigger, while tapered roller diameter is relatively smaller,so the value of γ_s is very small(normally from 1°~3°);on the other hand,being subjected to space and self-rigidity, the blade slope angle β is normally under 60°, therefore, $\gamma_s+\beta=90°$ cannot be met actually,indicating that the ideal roller-grinding wheel relation prescribed in 2.1 is never to be realized in fact.

Actual roller-grinding wheel relation and its influence on the linearity of roller profile

As the grinding of tapered roller is subjected to requirement of conical profile linearity as well as requirement of conical angle accuracy, therefore, the actual roller-grinding wheel relation should make the angle between projection of roller axis in A-A plane and grinding wheel axis equals roller semi-cone angle α, so as to secure the accuracy of grinded roller cone angle. Therefore, this paper investigates another typical roller axis direction, i.e. roller axis does not exist on A-A plane, while the angle between its projection in A-A plane and grinding wheel axis equals roller semi-cone angle α. Under such typical situation, the roller-blade geometric relation is shown in Figure 6. Compared with Figure 3, the points of changed positions in Figure 6 are subscripted with "2";α corresponds to φ in Figure 3;φ_2 corresponds to φ in Figure 3; λ_2 corresponds to λ.

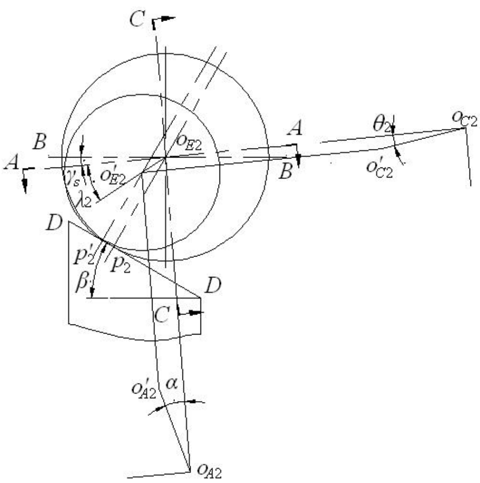

Figure 6. Roller-blade geometric relation under actual roller-grinding wheel relation.

It can be known from Figure 6

$$O_{E2}O'_{E2} = \frac{O_{E2}P_2 - O'_{E2}P'_2}{\cos\angle O'_{E2}O_{E2}P_2} \tag{9}$$

$$\angle O'_{E2}O_{E2}P_2 = 90°\text{-}(\gamma_s + \lambda_2 + \beta) \tag{10}$$

For the given roller geometric parameters, when roller axis direction changes, the distance between roller large/small end circle center to blade slope plane remains unchanged, so we have

$$O_{E2}P_2 = O_{E1}P_1 \tag{11}$$

$$O'_{E2}P'_2 = O'_{E1}P'_1 \tag{12}$$

By substituting equation(5)~(7) into (11),(12),and then substituting equation (10)~(12) into equation(9), it can obtain

$$O_{E2}O'_{E2} = \frac{l\sin\alpha}{\sin(\lambda_2 + \gamma_s + \beta)} \tag{13}$$

In the typical roller axis direction shown in Figure 6, the relation among roller axis and its projections on *A-A* plane, *C-C plane and* cross section *E-E* is shown in Figure 7. In this figure, *O* and *O′* represent roller large end circle center and roller small end circle center, respectively, and the distance between them equals the roller length *l*.

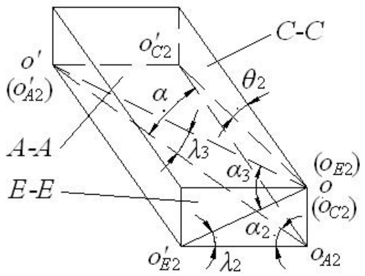

Figure 7. The geometric relation along roller axis direction under actual roller-grinding wheel relation.

It can be known from Figure 7

$$OO_{A2} = l\sin\lambda_3 = l\cos\alpha_3\sin\lambda_2 \tag{14}$$

$$O'O'_{E2} = l\sin\alpha_3 = l\cos\lambda_3\sin\alpha_2 \tag{15}$$

$$O_{E2}O'_{E2} = l\cos\alpha_3 \tag{16}$$

$$\alpha_2 = 90^\circ - \alpha \tag{17}$$

By finishing equation(15) and(16), it can obtain

$$\cos\alpha_3 = \frac{\cos\alpha_2}{\sqrt{1-(\sin\alpha_2\sin\lambda_2)^2}} \tag{18}$$

$$\sin\alpha_3 = \frac{\sin\alpha_2\cos\lambda_2}{\sqrt{1-(\sin\alpha_2\sin\lambda_2)^2}} \tag{19}$$

By substituting equation (17),(18) into equation(16), it can obtain

$$O_{E2}O'_{E2} = \frac{l\sin\alpha}{\sqrt{1-(\cos\alpha\sin\lambda_2)^2}} \tag{20}$$

By comparing equation (13) and equation (20), it can be known that

$$\sin(\lambda_2 + \gamma_s + \beta) = \sqrt{1-(\cos\alpha\sin\lambda_2)^2} \tag{21}$$

Equation(21) can be further written as

$$\sin^2(\lambda_2 + \gamma_s + \beta) + (\cos\alpha \sin\lambda_2)^2 = 1 \quad (22)$$

Based on equation(22), the equation for calculating λ_2 can be abtained that

$$\sin^2 \lambda_2 = \frac{-b + \sqrt{b^2 - ac}}{a} \quad (23)$$

$$a = \sin^4 \alpha + 4\cos^2 \alpha \cos^2(\gamma_s + \beta)$$

$$b = -(1 + \cos^2 \alpha)\cos^2(\gamma_s + \beta)$$

$$c = \cos^4(\gamma_s + \beta)$$

From Figure 7, it can also find that

$$\tan\theta_2 = \frac{OO_{A2}}{O_{A2}O'_{C2}} = \frac{OO_{A2}}{O'O'_{E2}} = \frac{l\cos\alpha_3 \sin\lambda_2}{l\sin\alpha_3} \quad (24)$$

By substituting equation(17)~(19)into equation ⋏(24), it can obtain

$$\tan\theta_2 = \tan\alpha \tan\lambda_2 \quad (25)$$

Under actual roller-grinding wheel relation, roller axial direction can be expressed by two angle of α and θ_2. Here we select two reference planes, the first one is *A-A* plane where grinding wheel axis and roller large end circle center exist, and the other one is *C-C* plane which is parallel to grinding wheel axis and vertical to *A-A* plane. α is the angle between roller axis and grinding wheel axis in reference plane *A-A*. θ_2 is the angle between roller axis and grinding wheel axis in reference plane *C-C,* also known as the spatial crossing angle between roller axis and grinding wheel axis. When α is given, we can first calculate λ_2 by equation (23), and then calculate θ_2 by equation (25). Here below is a calculation example:giving α=2°, β=30°, γ_s=1.5°, from equation(23)it can calculate λ_2=29°15′34″, and then by equation (25) it can calculated θ_2=1°7′15″.

From above analysis, we can find that under actual roller-grinding wheel relation, roller axis and grinding wheel axis are spatially intersected. Therefore, as a grinding tool, linear profile grinding wheel will lead to middle concavity of roller profile after grinding. Moreover, the larger the intersection angle is, the lager the concavity degree will be. A simple understanding for the middle concavity generation mechanism is that: a line is rotating around another spatially intersected line, so that a hyperboloid will be generated. The larger the intersected angle between two lines is, the larger the concavity degree of axial section shape of the hyperboloid will be.

It can be known from equation (25)that the increase of α will directly lead to the increase of θ_2;From equation(22), it can be known that when α increases, λ_2 will increase accordingly, while from equation(25)it can be find that the increase of λ_2 will also lead to the increase of θ_2. All these indicate that after grinding, the roller with large cone angle suffers a large middle concavity of the profile than roller with small cone angle does.

From equation(22)it can be seen that when β increases, λ_2 will decrease, which leads to the decrease θ_2 according to equation(25). This indicates that increasing blade slope angle will reduce the middle concavity degree of roller profile.

AN IDEAL GRINDING WHEEL PROFILE AND ITS SIMPLIFICATION METHOD

Under actual roller-grinding wheel relation, roller axis and grinding wheel axis are spatially intersected, therefore, to avoid the middle concavity of roller profile, it can be known according to basic principle of part surface machining that an ideal grinding wheel profile must not be linear but be curved one which is calculated based on principle of conjugation surface. However, it is a really complex process to calculate ideal grinding wheel profile curve based on principle of conjugation surface, and the expression of curve is also complicated, therefore it is necessary to seek a simplified one for the complicated curve of grinding wheel profile.

Since roller diameter is very smaller as compared with grinding wheel diameter, the influence of roller diameter can be ignored, and ideal grinding wheel profile can be simplified as a curved profile which is formed by a line rotating around grinding wheel axis. Based on the analysis prescribed in 2.2, such line can be regarded as the generatrix of tapered roller: in reference plane A-A mentioned in 2.2, such generatrix is crossing with roller axis by angle of α and parallel to grinding wheel axis; while in reference plane C-C mentioned in 2.2, such generatrix is crossing with grinding wheel axis by angle of θ_2. On this basis, the simplified grinding wheel profile curve is just a hyperbola.and the hyperbolic angle equals the spatial intersected angle θ_2 between roller axis and grinding wheel axis as mentioned in 2.2,,which can be calculated by equation(23)and(25)

CONCLUSIONS

Regarding the feeding-through centerless grinding of tapered roller, this paper presents conclusions as below:

(1) Using linear profile grinding wheel will lead to middle concavity of roller profile after grinding, and the mechanism within is: blade is of limiting effect to tapered roller posture, making an occurrence of spatially intersected angle between roller axis and grinding wheel axis, and thus resulting in middle concavity of roller profile; The larger the roller semi-cone angle is, the larger the middle concavity degree will be; the more the blade slope plane inclines to horizontal plane, the smaller the middle concavity of roller profile will be.

(2) To avoid inside concavity of roller profile, the ideal grinding wheel profile is a complex curved profile. The simplified grinding wheel profile curve is double curve, of which the hyperbolic angle equals the spatial intersected angle between roller axis and grinding wheel axis, and the calculation formulars for such hyperbolic angle are equation(23)and(25).

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