A New Regulating Wheel Truing Method for Through-Feed Centerless Grinding

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A new regulating wheel truing method for through-feed centerless grinding is presented. In conventional regulating wheel truing systems, a single-point diamond tool is traversed across the regulating wheel in a straight line. The interference between the regulating wheel and workpiece exists. This interference problem, a main source of error in precision through-feed centerless grinding, is due to the radius of curvature of the regulating wheel and workpiece. A new concept for regulating wheel truing is developed to eliminate the interference problem. In this new truing system, the rotary diamond truing tool has the same size as the finished workpiece, locates at the same center-height of the workpiece, and moves across the regulating wheel in the direction parallel to axes of workpiece and grinding wheel. A mathematical model is developed to calculate the surface profile for the regulating contact and to study the curved line of contact between workpiece and regulating wheel. An example is used to illustrate the model and to demonstrate that the interference between regulating wheel and workpiece has been eliminated.
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1 Introduction

Through-feed centerless grinding is a manufacturing process commonly used to generate precise cylindrical form on a workpiece. As shown in Fig. 1, grinding occurs when the workpiece is fed through the gap between the regulating and grinding wheels while being supported by a workrest blade. Through-feed centerless grinding, widely used in the bearing, automotive, and fuel system industries, is a very efficient and cost-effective manufacturing process to generate sub-μm precision cylindrical forms with fine surface finish.

The front view in Fig. 1 also shows the four major elements in a through-feed centerless grinding machine: (1) grinding wheel, (2) workrest blade, (3) regulating wheel, and (4) workpiece. The grinding action takes place between grinding and regulating wheels. A workrest blade is used to support the workpiece at a given center-height and is angled to provide the rounding action during grinding [1]. The grinding wheel, as shown in the side and top views, consists of the grinding region, where high material removal rate occurs, and the spark-out region, where the precision form is generated. The regulating wheel, usually a rubber bond wheel with high coefficient of friction, drives the workpiece to control its rotational speed during grinding. As shown in the side view in Fig. 1, the regulating wheel is tilted a small angle, α, to generate a force component in the axial direction to drive the workpiece through the gap between the regulating and grinding wheels. α is called the swivel angle of the regulating wheel.

Truing the regulating wheel to the proper form has been identified by researchers and practical engineers as the most critical step in the set-up of the precision through-feed centerless grinding process [2]. The regulating wheel surface consists of infinite number of circles with center on the regulating wheel axis. Three such circles, P_1, P_2, and P_3, are shown in the side and top views in Fig. 1. In the spark-out region, assuming the workpiece is ground to the final size, the traverse motion of the surface of the workpiece forms a cylinder, which has the same diameter as the ground part. The axis of the cylinder is parallel to the axis of the grinding wheel and the contact surface, line L in Fig. 2(a), in the workrest blade. As shown in Fig. 2(a), the objective of this research is to generate a regulating wheel surface that all the circles, for example, P_1, P_2, and P_3, in Fig. 1, on the regulating wheel surface are tangent to the workpiece cylinder. It will guide the workpiece across the gap between grinding and regulating wheels without changing its size. Figures 2(b) and 2(c) show the variation of the workpiece size due to a circle on the regulating wheel surface not tangent to the workpiece cylinder. As shown in Fig. 2(b), if the circle on the regulating wheel surface intersects the original workpiece circle at two points, a smaller diameter workpiece ($r_1 < r$) will be ground. On the contrary, as shown in Fig. 2(c), if the circle on the regulating wheel surface does not intersect the original workpiece circle, a larger diameter workpiece ($r_2 > r$) will be generated. This illustrates the importance of regulating wheel truing in precision through-feed centerless grinding.

In conventional centerless grinding, the regulating wheel truing/dressing system usually uses a stationary diamond tool, such as the single-point diamond, traversing along a straight line at an angle relative to the regulating wheel axis. Mathematically, the surface of the regulating wheel consists of infinite number of straight lines generated by the single-point diamond. These lines are called the generator. The surface of the regulating wheel is a hyperboloid of one sheet [2–4]. Since the beginning of centerless grinding machine development in the early 20th century, researchers have known this type of truing method is not exact. The interference of regulating wheel and workpiece at the contact area exists due to the radius of curvature of the workpiece and regulating wheel [2,5–7]. Some alternative regulating wheel truing methods have been studied, for example, using the grinding wheel to true the regulating wheel [8] and CNC profile truing of the regulating wheel [4]. However, a mathematically exact solution for truing the regulating wheel for through-feed centerless grinding has not yet been developed. This paper presents a new regulating wheel truing method to fulfill this need [9].

In this paper, an example is first presented to illustrate the interference of the regulating wheel and workpiece using the conventional truing method in through-feed centerless grinding. The new regulating wheel truing method is then introduced. A mathematical model is developed to calculate the regulating wheel surface and line of contact. An example is used to illustrate the analysis results.

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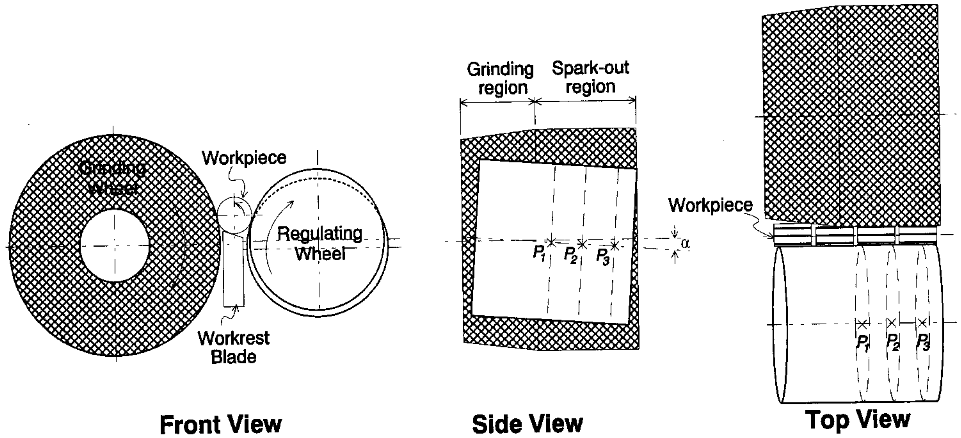


Fig. 1 Configuration of the through-feed centerless grinding

2 Conventional Regulating Wheel Truing Method

An example is presented to demonstrate the interference between the workpiece and regulating wheel for through-feed centerless grinding machine using conventional single-point diamond truing. As shown in Fig. 3, the diamond tool is traversed across the regulating wheel on the side opposite to the workpiece. The diamond tool is moving in the direction parallel to the axes of the workpiece and grinding wheel. Mathematical models for this type of through-feed centerless grinding system have been derived and examples have been presented in previous publications [2,5,6]. Therefore, the derivation of these mathematical models is omitted in this paper. Only an example is presented in Figs. 3 and 4 to illustrate the interference between the regulating wheel and workpiece. The actual regulating wheel truing configuration used in production through-feed centerless grinding is a lot more complicated than the setup shown in Figs. 3 and 4.

Figure 3(*a*) shows the front view of a through-feed centerless grinding machine with 400 mm diameter grinding wheel, 80 mm diameter workpiece, and 50 mm center-height of the workpiece. An XYZ Cartesian coordinate system is first defined. The swivel plane of the regulating wheel is parallel to the YZ plane, i.e., the axis of the regulating wheel is located in the plane $X=0$. The point of swivel on the axis of the regulating wheel locates on the XY plane $(Z=0)$. The *Z*-axis is parallel to the axes of grinding wheel and workpiece. The *X*-axis passes through and is perpendicular to the axis of the grinding wheel. *Y*-axis is perpendicular to both *X*- and *Z*-axis. The single-point diamond tool is located on the side of the regulating wheel opposite to the workpiece and workrest blade. It moves along a straight line in the direction parallel to the *Z*-axis. The height on the diamond tool is set at 40 mm above the XZ plane. The distance between the swivel plane of the regulating wheel YZ plane) and the axis of the workpiece is set at 200 mm.

As shown in Figs. 3(*a*) and 4, at the area where the workpiece and regulating wheel are in contact, another straight line can be seen. This line is represented by a point, the point of intersection of the front, middle, and rear circles in the enlarged view of the contact area between the workpiece and regulating wheel. In mathematical term, this line is the conjugate generator line of the hyperbolic of one sheet surface [10]. The surface of the regulating wheel consists of an infinite number of circles. Three circles, i.e., the front, middle, and rear circle, are selected to represent the regulating wheel. Different line widths are used to distinguish these three circles. The enlarged view of the contact area in Fig. 4 illustrates the interference between the workpiece and regulating wheel due to their radius of curvature. The workpiece cannot be guided along a straight line as desired.

The setup shown in Figs. 3 and 4 is not typical for through-feed centerless grinding. It is only used to illustrate the problem. Practically, there are different truing systems for through-feed centerless grinding, and many adjustments can be made to reduce the magnitude of interference to a much smaller level than in Fig. 4. However, the same problem that not all the circles on the regulating wheel are tangent to the constant radius workpiece still exists. This is one of the reasons that the set-up for truing the regulating wheel for μm-scale precision through-feed centerless grinding is often time-consuming and experience-based.

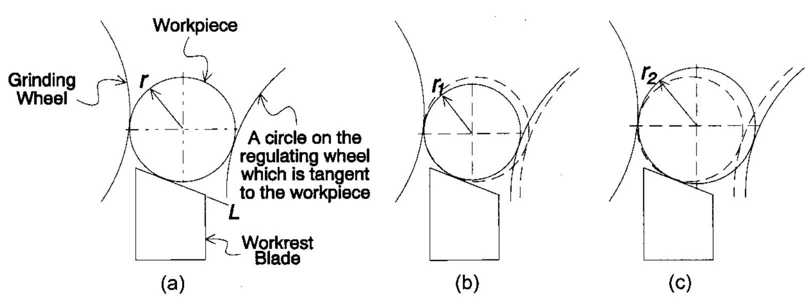
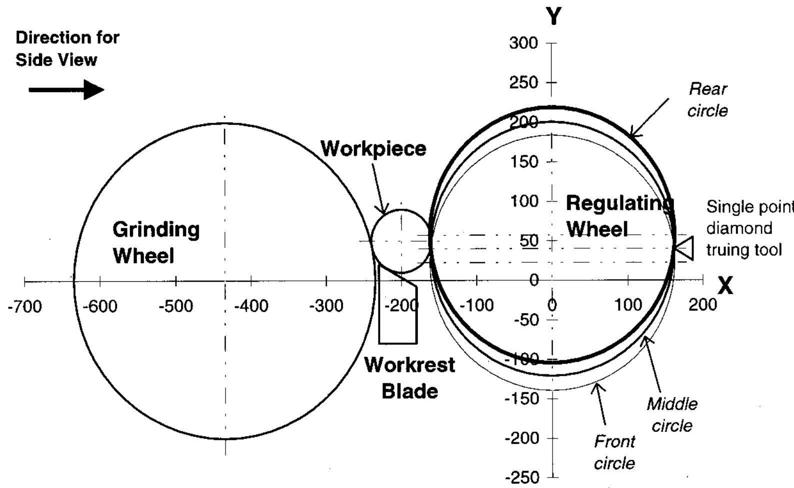
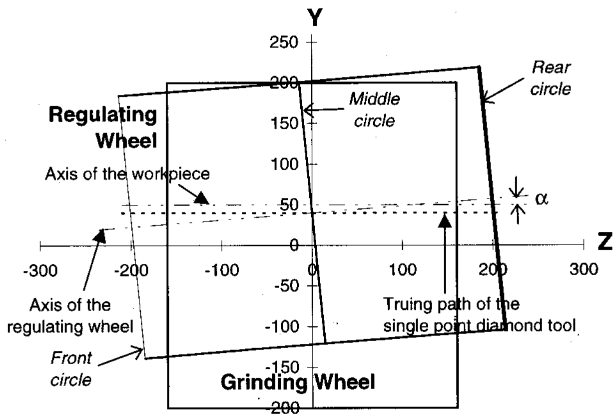


Fig. 2 Front view of the circles on the regulating wheel surface with center on the regulating wheel axis (*a*) a circle tangent to the workpiece circle of radius *r* (*b*) a smaller diameter workpiece is generated if the circle on the regulating wheel surface intersects the original workpiece circle at two points, and (*c*) a larger diameter workpiece is generated if the circle on the regulating wheel surface does not intersect the original workpiece circle



(a) Front View



(b) Side View

Fig. 3 Front and side view of the conventional through-feed centerless grinding machine truing using the single point diamond (unit: mm)

3 New Regulating Wheel Truing Method

This paper discloses a new method to generate the regulating wheel surface for through-feed centerless grinding without the interference problem seen in Fig. 4. As shown in Fig. 5, the idea is to use a rotary diamond truing disk that

(1) has the same diameter as the desired workpiece diameter,
(2) locates at the same height as the workpiece, and
(3) traverses across the regulating wheel on the side opposite to the workpiece and in the direction parallel to the axes of the workpiece and grinding wheel.

The surface on the regulating wheel generated by this method also consists of infinite number of circles with center at the axis of the regulating wheel. These circles are all tangent to the surface of the workpiece cylinder, as illustrated in Fig. 2(*a*) and in Figs. 5 and Fig. 6(*a*). There is only one point of contact between a circle on the surface of the regulating wheel and the surface of the workpiece. For the front, middle, rear circles on the regulating wheel surface in Fig. 5, the point of contact is illustrated as B_f, B_m, and B_r in Fig. 6(*a*). The single point of contact between a circle on the regulating wheel and the workpiece is the advantageous characteristic of the proposed regulating wheel truing method. As shown in Fig. 2(*a*), it eliminates the interference between the regulating wheel and workpiece and the variation of workpiece size due to the interference.

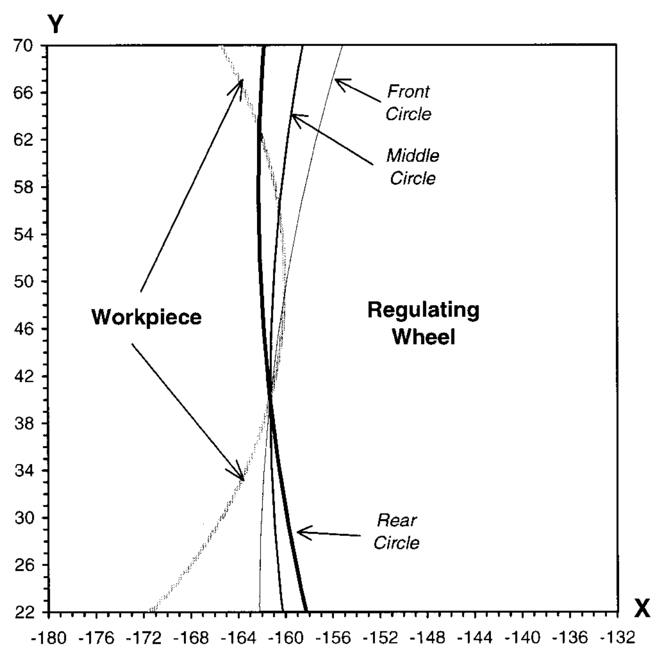


Fig. 4 Enlarged front view of the interference of the workpiece and regulating wheel in the conventional through-feed centerless grinding machine truing system (Unit: mm)

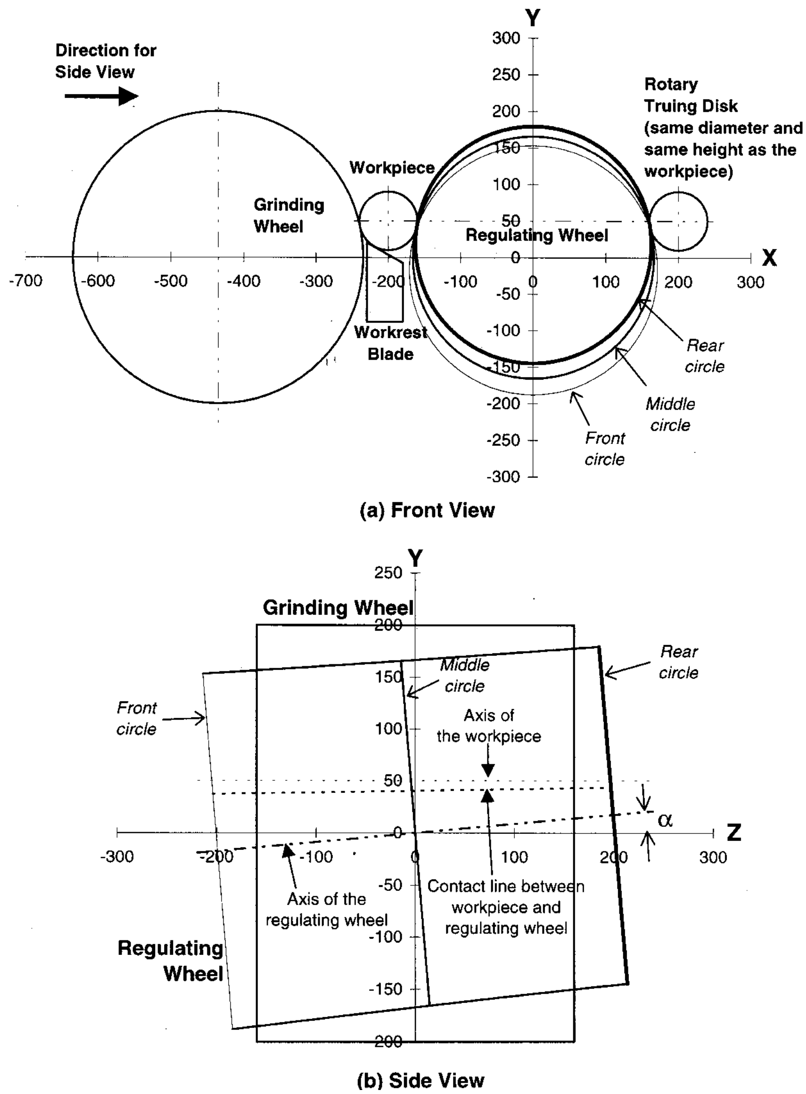


Fig. 5 Front and side view of the new rotary truing system for through-feed centerless grinding (Unit: mm)

4 Mathematical Model of the New Truing Method

The goal of this mathematical model is to find the numerical representation of the regulating wheel surface generated using the proposed rotary truing method. First, an XYZ Cartesian coordinate system is defined for the new truing system. The definition of *X*, *Y*, and *Z* axes is the same as in the conventional truing method discussed in Sec. 2. The YZ plane ($X=0$) is the swivel plane of the regulating wheel. The *Z*-axis is parallel to the axes of the grinding wheel, workpiece, and traverse direction of the rotary truing disk. The *X*-axis is perpendicular to the swivel plane of the regulating wheel and passes through the grinding wheel axis. The swivel point on the regulating wheel axis locates on the XY plane ($Z=0$).

There are six input parameters to define the configuration of the new truing system. These parameters are:

(1) Radius of the workpiece and rotary truing disk, r,
(2) Center height of the workpiece and truing disk, h,
(3) Swivel angle of the regulating wheel, α,
(4) Distance between the two parallel axes of the workpiece and truing disk, W,
(5) Radius of the grinding wheel, R, and
(6) The *Y* coordinate of the swivel point on the regulating wheel axis, y.

The values of these input parameters for the truing configuration in Fig. 5 are: $r=80$ mm, $h=50$ mm, $\alpha=5$ deg, $W=400$ mm, $R=400$ mm, and $y=0$ mm.

The surface of the regulating wheel is represented by a series of circles with their centers located on the axis of the regulating wheel. For each point *A* on the axis of the regulating wheel, a circle on the surface of the regulating wheel with *A* as the center can be found. This circle and the workpiece surface, which is represented by a cylinder, have only one point of contact. By varying the point *A* along the regulating wheel axis, a family of circles is generated. These circles represent the regulating wheel surface.

As shown in Fig. 7, an input parameter l is used to define the location of point **A** from the swivel point on the regulating wheel axis. Because the regulating wheel is swiveled in the plane $X=0$, the *X* coordinate of the swivel point and the point **A** is equal to 0. The *Z* coordinate of the swivel point is also equal to 0 because the swivel point is fixed in the $Z=0$ plane. The coordinate of point **A** is:

$$A=[0,\ y+l\sin\alpha,\ l\cos\alpha] \tag{1}$$

where

$-w/2<l<w/2$ and w is the width of the regulating wheel

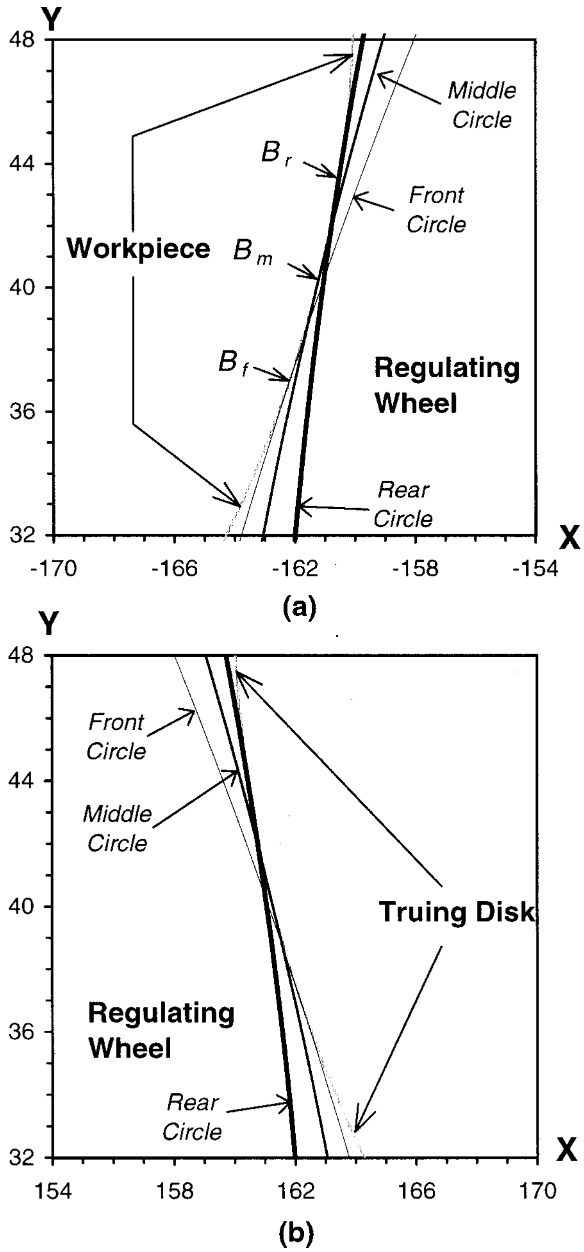


Fig. 6 Enlarged front view of the contact area between (*a*) workpiece and regulating wheel and (*b*) truing disk and regulating wheel in the through-feed centerless grinding machine with the new truing system (unit: mm)

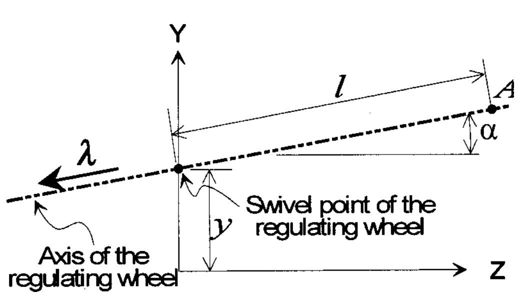


Fig. 7 Definition of point *A* on the axis of the regulating wheel and the directional vector λ

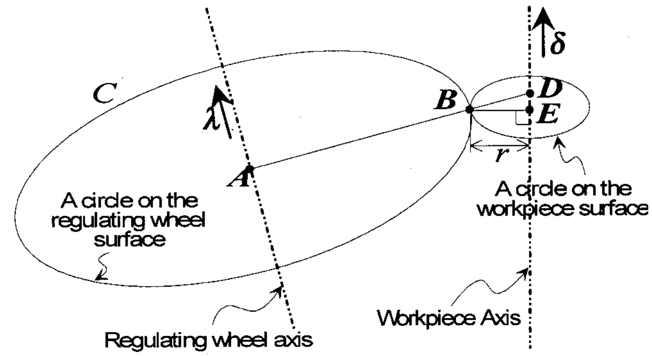


Fig. 8 Mathematical model to find the contact point *B* between the regulating wheel and workpiece

Figure 7 also defines the directional vector of the axis of the regulating wheel, $\boldsymbol{\lambda}$.

$$\boldsymbol{\lambda}=[0,-\sin\alpha,\ -\cos\alpha] \tag{2}$$

As shown in Fig. 8, each point $\boldsymbol{A}$ on the regulating wheel axis corresponds to a circle, C, on the regulating wheel surface. This circle is tangent to another circle on the workpiece surface at point $\boldsymbol{B}$. A plane, which passes through point $\boldsymbol{A}$ and is perpendicular to vector $\boldsymbol{\lambda}$, intersects the axis of the workpiece at point D. On the line $\boldsymbol{AD}$ is the point $\boldsymbol{B}$, which is located on both the workpiece surface and regulating wheel surface. A point $\boldsymbol{E}$ on the workpiece axis is defined so that vector $\boldsymbol{BE}$ is perpendicular to the axis of the workpiece. The distance between $\boldsymbol{B}$ and $\boldsymbol{E}$ is equal to $\boldsymbol{r}$. Line $\boldsymbol{BE}$ is perpendicular to the workpiece axis with directional vector $\boldsymbol{\delta}=[0,0,-1]$.

The X coordinate of point $\boldsymbol{D}$, D_x, is equal to $-W/2$ (W is the given distance between the axes of the workpiece and rotary truing disk). D_y is equal to the given center-height of the truing disk, h. D_z is the only unknown to be solved. Since vector $\mathbf{DA}$ is perpendicular to $\boldsymbol{\lambda}$, the following equation can be used to solve D_z.

$$(\boldsymbol{D}-\boldsymbol{A})\cdot\boldsymbol{\lambda}=0 \tag{3}$$

By substituting $\boldsymbol{D}=[-W/2,h,D_z]$ and $\boldsymbol{A}$ and $\boldsymbol{\lambda}$ from Eqs. (1) and (2), respectively, Eq. (3) can be rewritten as:

$$D_z=l\cos\alpha+(y+l\sin\alpha-h)\tan\alpha \tag{4}$$

A new parameter $\beta(0<\beta<1)$ is introduced to define the position of point $\boldsymbol{B}$ on the line between points $\boldsymbol{A}$ and $\boldsymbol{D}$.

$$\boldsymbol{B}=\boldsymbol{A}+\beta(\boldsymbol{D}-\boldsymbol{A}) \tag{5}$$

β can be solved based on the constraint that the distance between $\boldsymbol{B}$ and workpiece axis is equal to r.

$$(B_x-E_x)^2+(B_y-E_y)^2=r^2 \tag{6}$$

Using $D_x=E_x$ and $D_y=E_y$ and substituting the components of B_x and B_y from Eq. (5), Eq. (6) becomes

$$[(1-\beta)(A_x-D_x)]^2+[(1-\beta)(A_y-D_y)]^2=r^2. \tag{7}$$

Equation (7) is rearranged to solve for β.

$$\beta=1\pm\frac{r}{\sqrt{(A_x-D_x)^2+(A_y-D_y)^2}} \tag{8}$$

The negative sign in Eq. (8) is selected because $0<\beta<1$.

After β is solved, the position of $\boldsymbol{B}$ can be calculated from Eq. (5). The circle with center at point $\boldsymbol{A}$ and line $\boldsymbol{AB}$ as the radius is part of the surface of the regulating wheel. By varying l from $-w/2$ to $w/2$, different locations for point $\boldsymbol{A}$ on the regulating wheel axis are specified. Equation (4) is then used to calculate the location of point $\boldsymbol{D}$. And, the coordinates of point $\boldsymbol{D}$ are substituted in Eq. (8) to solve for β. β is used in Eq. (5) to solve the

Table 1 Results of A, D, β, and B at $l=-200$, 0, and 200 mm

	Front Circle, l=200 mm	Middle circle, l=0 mm	Rear circle, l=−200 mm
Point $\boldsymbol{A}$ (mm)	(0, 17.43, 199.2)	(0, 0, 0)	(0, −17.43, −199.2)
Point $\boldsymbol{D}$ (mm)	(−200.0, 50.00, 196.4)	(−200.0, 50.00, −4.374)	(−200.0, 50.00, −205.1)
β	0.803	0.806	0.810
Point $\boldsymbol{B}$ (mm)	(−160.5, 43.57, 197.0)	(−161.2, 40.30, −3.526)	(−162,1, 37.22, −204.0)

position of point $\boldsymbol{B}$. A curved line is traced by point $\boldsymbol{B}$. This is the contact line between the regulating wheel and workpiece. A surface is generated by circle C. This is the regulating wheel surface.

The regulating wheel surface is no longer the hyperboloid of one sheet, as shown in Fig. 3, generated by the single-point diamond tool. Instead of using a line for surface generation, this method uses a cylinder to generate a new type of the hyperboloid-shaped surface.

5 Example

An example is presented to illustrate the mathematical model. The six input parameters are the same as in Sec. 4. The results are shown in Figs. 5 and 6. The directional vector of the regulating wheel $\boldsymbol{\lambda}=[0,-0.087,-0.996]$. There is an infinite number of circles on the surface of the regulating wheel surface. Three of them, $l=-200$, 0, and 200 mm are selected for illustration. Table 1 lists the positions of point $\boldsymbol{A}$, $\boldsymbol{D}$, and $\boldsymbol{B}$ and the value of β for the front ($l=200$ mm), middle ($l=0$ mm), and rear ($l=-200$ mm) circles that illustrate in Figs 5 and 6.

Figure 6(a) shows the enlarged view of the contact area between the regulating wheel and workpiece, and Fig. 6(b) shows the enlarged contact area between the regulating wheel and truing disk. The interference between regulating wheel and workpiece has been prevented in this truing system. Figures 5 and 6 also illustrates that, along the contact line, the Y-coordinate is varying with the change in Z-coordinate.

6 Concluding Remarks

In this paper, a new regulating wheel truing method for through-feed centerless grinding was discussed. The method that eliminated interference between regulating wheel and workpiece was explained. A mathematical model was developed to calculate the contact line between regulating wheel and workpiece. An example was used to illustrate the analysis results.

Practically, it is difficult to maintain exactly the same diameter of the rotary diamond truing disk due to the wear of the diamond truing disk. As shown in Fig. 9, an alternative method to use a 90 deg tilted truing spindle with a formed rotary diamond wheel with the same diameter as the ground workpiece was proposed [9] for small diameter application. This spindle will traverse in the direction parallel to the axis of the grinding wheel. The regulating wheel will be trued under the same condition as shown in Figs. 5 and 6.

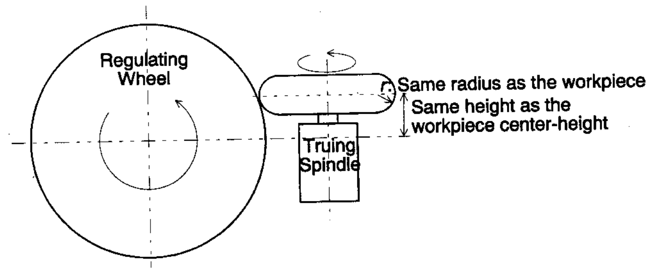


Fig. 9 Regulating wheel truing method for small diameter part

This paper presented a mathematically exact form of the regulating wheel surface for through-feed centerless grinding without the inference problem inherent in the typical method. However, the advantage of this concept still needs to be proved by experimental validation, which is an ongoing research activity. To make this concept a reality in production centerless grinding, other complimentary techniques need to be developed. Theoretically, the thickness of the rotary truing disk does not affect the results. In reality, wear occurs during truing and the size of the truing disk varies. It is apparent that a sensitivity study is necessary to identify the effects of different truing and grinding parameters on the accuracy of the through-feed ground workpiece.

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