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Determination of workpiece profile and influence of singular point in helical grooving

V.H. Nguyen, S.L. Ko *

Department of Mechanical Design & Production Engineering, Konkuk University, Seoul 143-701, South Korea

Submitted by J.M. Lee (1), Seoul, Korea.

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ABSTRACT

Due to the screw motion between the grinding wheel and workpiece in helical groove machining, the determination of the generated helical groove profile in a workpiece is very complicated. The profile of helical groove can be obtained by using the common contact line of the helical groove and wheel surface. The influence of singular points in a wheel profile on a helical profile is analysed. The condition used to solve the equation of tangency is discussed. Software for design, simulation and manufacturing of the end mill as well as for solving the problem of singular points is developed. The results of simulation and experiments are compared as a verification of the suggested model.

1. Introduction

Due to the complexity of helical cutting tools like end mill and drill, special CAM software is necessary to generate the NC code of CNC grinding machine. To develop CAM software for helical tools, it is required to understand the helical groove machining because the flute profile of helical tool greatly affects the machining performance, such as cutting force, chip evacuation, tool stiffness as well as other behaviours. As input parameters, the required helical flute geometry and the geometry of grinding wheel are given to generate the wheel location. For precision grinding of helical tool, the research on this will contribute for understanding the relation between helical tool and grinding wheel.

In the past decades, the problem of finding a helical groove profile or a grinding wheel profile has been widely studied using two main distinct approaches. The first approach [1,2] is based on graphic reasoning, which slices a grinding wheel into a finite number of thin disks and then forms the helical groove by enveloping the trajectory of each thin wheel. This method can be applied to various wheel profiles but it has high calculation load and low accuracy. The second approach is based on the tangency condition; it finds the contact line between the wheel surface and the helical groove, which has been studied for the machining of a helical surface of gear teeth [3]. Based on this method the relationship between a helical flute profile and a wheel profile were analysed [4–6]. However, these methods cannot be applied to a wheel profile with a singular point at which the normal vector cannot be specified. A grinding wheel with such a profile is usually used by most tool grinding manufacturers. Moreover, even after an equation of tangency condition is established, at certain setting conditions this equation is unsolvable. The previous works do not address the solution to this equation at such conditions and do not show the calculation of the workpiece profile in such a case.

Using the same concepts of tangency condition and contact line, this paper is focused on the generation of a helical groove in both cases of the regular wheel surface or the wheel with sharp edge involved in a material removal process. A closed form equation of the contact line between a wheel surface and a helical groove is determined based on enveloping theory which has been studied for its industrial applications in areas such as collision detection and machining simulation [7,8]. Furthermore, the condition at which the tangency equation cannot be solved is discussed and the cross-section of the helical surface is determined exactly even when the tangency equation is unsolvable. Based on the proposed method, a program for finding the setting conditions to generate an end mill with the use of design factors like rake angle, web diameter and margin thickness is developed. The simulation and experimental results and an illustrated example are compared for verification.

2. Determination of helical flute cross-section

Assuming that a grinding wheel moves relatively around a stationary workpiece, a fixed coordinate system OXYZ is attached to the workpiece as in Fig. 1(a). During the machining process there always exists a contact line A–B–C–D–E–F (Fig. 1(b)) between the grinding wheel surface and the generated helical groove. In general, there are two types of contact lines: The first type (B–C, D–E) is called a regular contact line, which is generated by the regular part of the wheel surface and the second type (A–B, C–D, E–F) is called a singular contact line, which is generated by the edge part of the wheel surface or by a singular point in the wheel profile.

To simplify the mathematical expressions used in the calculations, the initial position vector of the wheel centre is set to $r_{G_0} = [0, Y_0, Z_0]$ and the orientation of the wheel axis is set parallel to plane OXY. To generate a helical flute with a helix angle, β, the

* Corresponding author.

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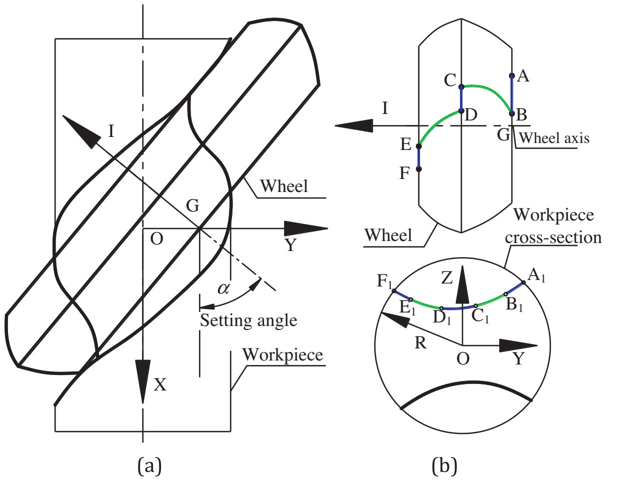

Fig. 1. Illustration of machine setting and contact line between wheel surface and machined workpiece.

grinding wheel rotates around the workpiece axis, OX, at angle $\varphi(t) = \omega t$ and translates along the X-axis a distance of $X(t) = -R\varphi(t)/\tan\beta$. The wheel axis is oriented such that it makes an angle α with the workpiece axis which is called the setting angle as depicted in Fig. 1(a). First, the contact line is calculated at the initial position of the wheel ($t = 0$) and then the helical flute profile is determined by shifting the obtained contact line into plane OYZ, which is chosen as the cross-section.

2.1. Determination of regular contact line

Based on the above notations and assumptions, the wheel centre location and the wheel axis can be determined as follows:

$$r_G(t) = [-R\varphi/\tan\beta, Y_0\cos\varphi + Z_0\sin\varphi, -Y_0\sin\varphi + Z_0\cos\varphi] \tag{1}$$

$$\hat{I}(t) = [-\cos\alpha, -\sin\alpha\cos\varphi, \sin\alpha\sin\varphi] \tag{2}$$

At a point P along the regular contact line (B–C and D–E segment in Fig. 1(b)), the velocity vector $V(P)$ is perpendicular to the normal vector of the wheel surface $N(P)$, thereby establishing tangency condition, $N(P) \times V(P) = 0$. This tangency condition was proven theoretically [7]. Based on the tangency condition, the regular contact line is calculated explicitly in this paper.

To calculate the velocity and the normal vector at a point on wheel surface, a local coordinate system, $X_LY_LZ_L$, located at the wheel centre, G, is established as:

$$\begin{cases} \hat{Z}_L = \hat{I} = [-\cos\alpha, -\sin\alpha\cos\varphi, \sin\alpha\sin\varphi] \\ \hat{X}_L = \dfrac{\dot{I}}{||\dot{I}||} = [0, \sin\varphi, \cos\varphi] \\ \hat{Y}_L = \hat{Z}_L \times \hat{X}_L = [-\sin\alpha, \cos\alpha\cos\varphi, -\cos\alpha\sin\varphi] \end{cases} \tag{3}$$

In the cross-section of the wheel surface normal to the wheel axis $I(t)$, offset from wheel centre a distance u as depicted in Fig. 2(a) by taking a point P in that cross-section at angle, θ, measured from the axis X_L as in Fig. 2(b). Then the velocity vector of point P is determined as:

$$V(P) = \dot{r}_G(t) + u||\dot{I}||\hat{X}_L - ||\dot{I}||r(u)\cos\theta\hat{Z}_L \tag{4}$$

The normal vector at point P is calculated as:

$$N(P) = \frac{\cos\theta\hat{X}_L + \sin\theta\hat{Y}_L - \dot{r}(u)\hat{Z}_L}{\sqrt{1 + \dot{r}^2(u)}} \tag{5}$$

By applying the tangency condition, $V(P) \times N(P) = 0$ yields:

$$A\cos\theta + B\sin\theta + C = 0 \tag{6}$$

where A, B, C are:

$$\begin{cases} A = \dot{r}_G \cdot \hat{X}_L + ||\dot{I}||r(u)\dot{r}(u) + ||\dot{I}||u \\ B = \dot{r}_G \cdot \hat{Y}_L \\ C = -\dot{r}(u)\dot{r}_G \cdot \hat{Z}_L \end{cases} \tag{7}$$

At the initial position of the wheel ($t = \varphi = 0$), A, B, C are calculated as:

$$\begin{cases} A = -Y_0 + \sin\alpha[r(u)\dot{r}(u) + u] \\ B = R\sin\alpha/\tan\beta + Z_0\cos\alpha \\ C = \dot{r}(u)(-R\cos\alpha/\tan\beta + Z_0\sin\alpha) \end{cases} \tag{8}$$

under the following condition:

$$|-C/\sqrt{A^2 + B^2}| \le 1 \tag{9}$$

The angle of point P along the regular contact line in the local coordinate system is determined by solving Eq. (6) as:

$$\theta = \sin^{-1}(-C/\sqrt{A^2 + B^2}) - \tan^{-1}(A/B) \tag{10}$$

2.2. Determination of singular contact line

Finding the contact line when singular points of a wheel profile are involved in the cutting state is not answered explicitly [9]. At a singular point of a wheel profile, the normal vector of a wheel surface cannot be specified; therefore, the tangency condition cannot be satisfied. Kang [5] suggested a method for calculating the points generated at a singular point by setting the first derivative of the wheel profile equation to zero in the equation of tangency condition. This method unintentionally ignores the calculation of the C_1D_1 segment in Fig. 1(b). Because one point in a regular part of the wheel generates one point in the workpiece profile whereas one singular point in the wheel profile generates a segment in workpiece profile.

In this paper, a wheel profile is given with singular points as in Fig. 2(a). To determine the singular contact line CD, which is generated by the singular point S at $u = u_0$ (in a similar way to the points at $u = 0$ and $u = L$), which includes two vectors n_{2C} and n_{3D} normal to surface 2 and 3, respectively, a new normal function is defined as:

$$n_{CD} = \xi n_{2C} + (1 - \xi)n_{3D} \quad \text{where,} \quad 0 \le \xi \le 1 \tag{11}$$

Substitute Eq. (11) into the expression of $N(P)$, and solve the equation of tangency condition to obtain the singular contact line (C–D). The obtained angle, θ_{CD}, from solving the equation of tangency condition in this case satisfies:

$$\theta_{CD} = \xi\theta_C + (1 - \xi)\theta_D \tag{12}$$

where θ_C and θ_D obtained from solving Eq. (6) correspond to normal vectors n_{2C} and n_{3D}.

A closed-form solution of the contact line including the regular and the singular kinds is determined as:

$$\begin{aligned} r_P[x_P, y_P, z_P] &= r_G + r(u)(\hat{X}_L\cos\theta + \hat{Y}_L\sin\theta) + u\hat{Z}_L \\ &= [-u\cos\alpha - r(u)\sin\alpha\sin\theta, Y_0 - u\sin\alpha \\ &\quad + r(u)\cos\alpha\sin\theta, Z_0 - r(u)\cos\theta] \end{aligned} \tag{13}$$

where θ is obtained from Eqs. (10) and (12).

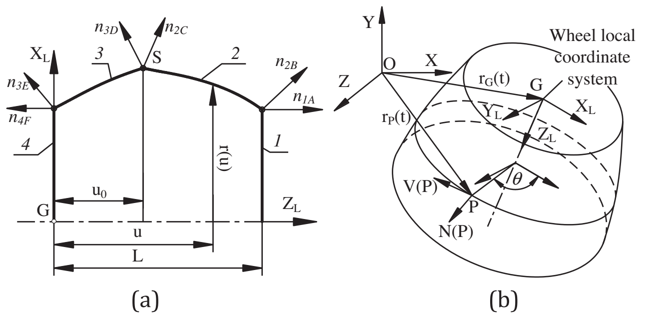

Fig. 2. Notation for calculation of contact line.