INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING Vol. 9, No.3, pp.75-78

Geometric Modeling and Five-axis Machining of Tire Master Models

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KEYWORDS: Tire master model, Pitch arrangement, Groove, Parametric design, Five-axis machining, Surface modeling

Tire molds are manufactured by aluminum casting, direct five-axis machining, and electric discharging machining. Master models made of chemical wood are necessary if aluminum casting is used. They are designed with a three-dimensional computer-aided design system and milled by a five-axis machine. In this paper, a method for generating and machining a tire surface model is proposed and demonstrated. The groove surfaces, which are the main feature of the tire model, are created using a parametric design concept. An automatically programmed tool-like descriptive language is presented to implement the parametric design. Various groove geometries can be created by changing variables. For convenience, groove surfaces and raw cutter location (CL) data are generated in two-dimensional drawing space. The CL data are mapped to the tread surface to obtain five-axis CL data to machine the master model. The proposed method was tested by actual milling using the five-axis control machine. The results demonstrate that the method is useful for manufacturing a tire mold.

Manuscript received: March 28, 2008 / Accepted: May 14, 2008

1. Introduction

1.1 Characteristics of tire geometry

The tread of a tire refers to the rubber on its circumference that makes contact with the road. A tire has a tread with a plurality of base pitches placed around the circumference of the tire.[1-2] There are three to five different pitch lengths (see Figure 1). The pitch sequence extends around the entire circumference of the tire. The tire pitch sequencing reduces noise. There is at least one deep tread groove that divides the tire into virtual multiple treads. These grooves make it is possible to increase the traction/breaking power, stability, and control.

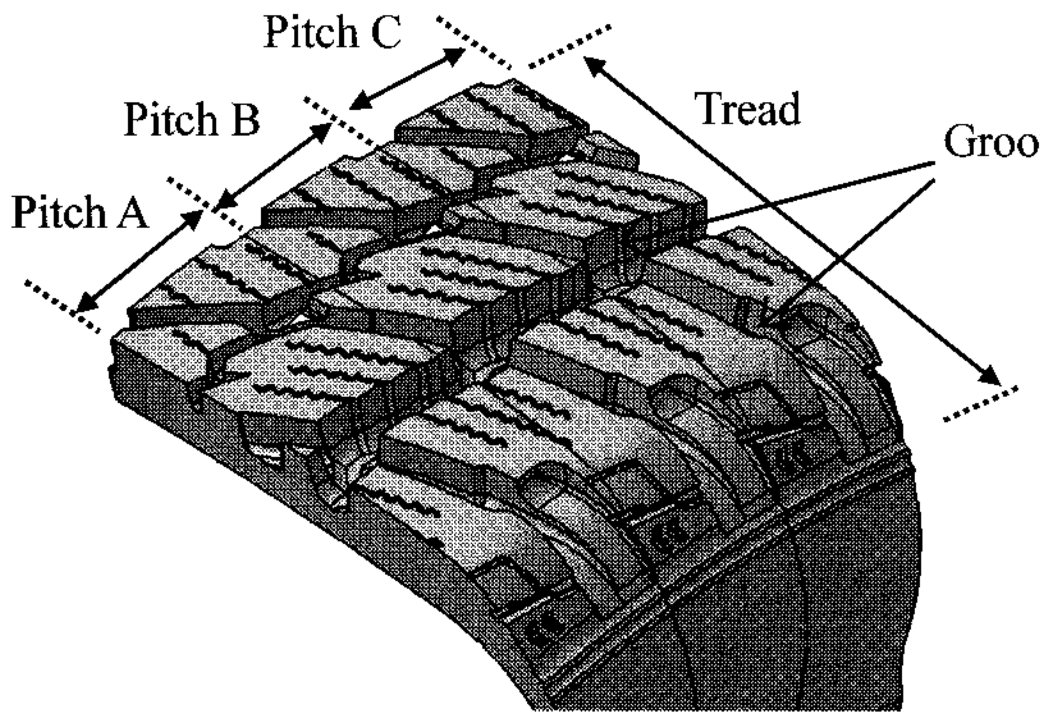


Fig. 1 Tread, pitches, and grooves of a tire

The groove geometry of a tire has the following features.

- There is a family of variants, whose application range from compact cars to luxury cars.
- A random pitch arrangement is necessary.
- The groove geometry of a pitch depends on its pitch ID and adjacent pitch IDs.

A groove geometry with the same pitch ID varies since it depends on its own pitch ID and adjacent pitch IDs. Hence, it is necessary to apply a parametric design concept to the geometric modeling of tires. Without a parametric design concept, the groove surface of all pitches must be designed separately. This is a time-consuming process that is error prone.[3]

Five-axis machining must be employed to guarantee the cutting efficiency because three-axis machining creates tire grooves with an uncut volume.

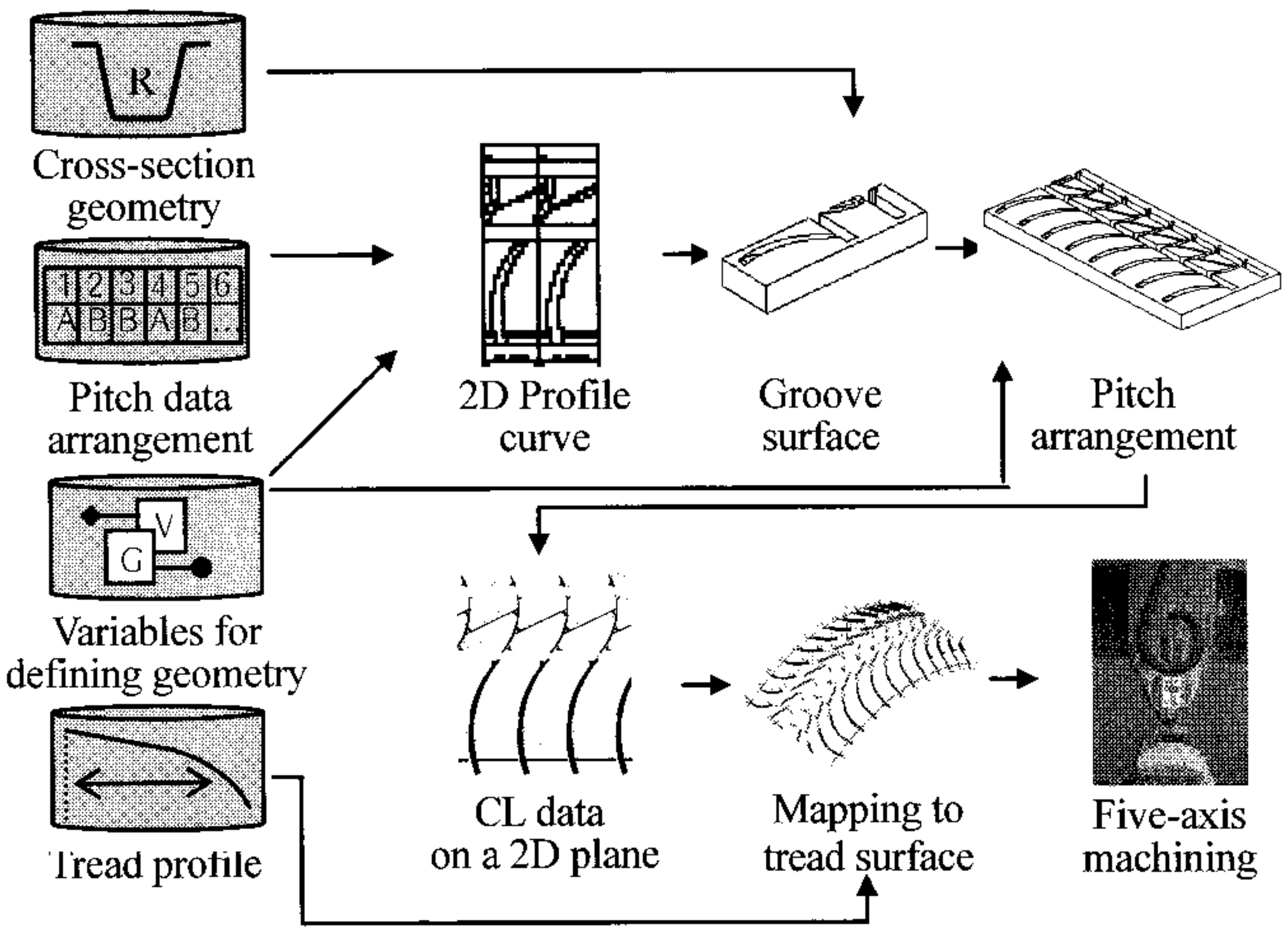


Fig. 2 Procedure for five-axis machining of a tire master model

1.2 Procedure for machining a tire master model

Figure 2 shows the modeling process and the procedure used to generate the five-axis cutter location (CL) data to machine a tire master model.

(1) The system generates a two-dimensional (2D) profile curve for one pitch using variables and adjacent pitch IDs.
(2) The groove surface can be made using profile curves, the cross-sectional geometry, and the depth of the groove. The depth can change continuously along the groove profile curve.
(3) Steps (1) and (2) are repeated with the pitch sequence data. The generated grooves are arranged according to the pitch sequence.
(4) The CL data are then generated to machine the grooves.
(5) To machine the tire master model, the CL data are mapped to the tread surface. Consequently, five-axis CL data must be generated.

2. Parametric Design of the Tire Geometry

2.1 Modeling of a groove

Currently, most tire designs are specified by 2D engineering drawings, examples of which are shown in Figures 3 and 4. Figure 3 shows groove profile curves drawn in a 2D plane while Figure 4 shows cross-sectional curves and the tread profile. If the groove profile curves are mapped to the tread surface, the actual 3D profile curves are obtained. Some studies have attempted to model tire CAD molds on a three-dimensional (3D) space directly.[3] However, we propose to model the profile curves of a groove on a 2D plane (drawing space). The groove surfaces are then created using these 2D profile curves.

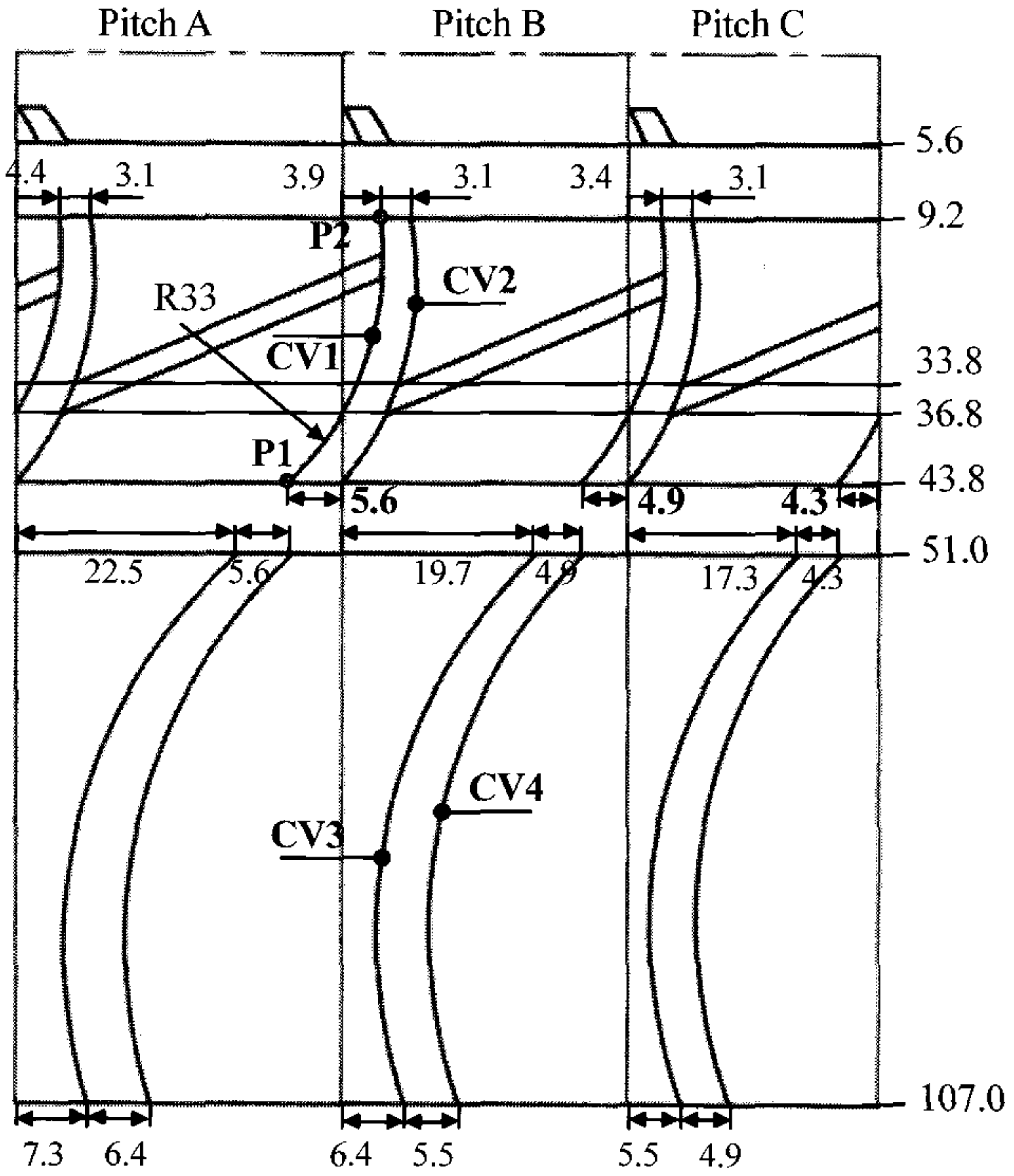
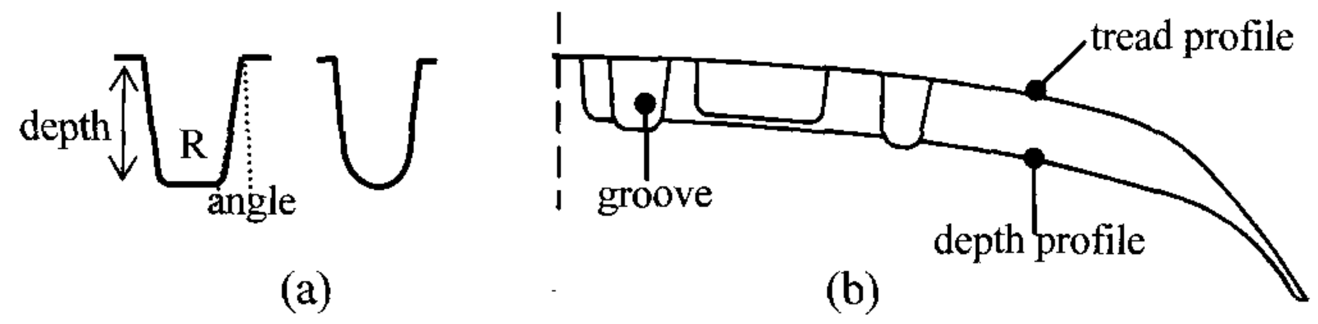


Fig. 3 An example of engineering drawing for a tire groove



(a) (b)

Fig. 4 Cross-sectional curves and tread profile

Grooves can be independent or dependent of the adjacent pitches. CV3 in Figure 3 is an example of a curve for an independent groove with an identical geometry that is independent of the adjacent pitches. CV1 represents a curve of a dependent groove whose geometry changes according to the adjacent pitches. In this case, two or four adjacent pitch IDs must be specified to model the groove. Even if a groove is independent in terms of pitch, the circumferential length will change according to its pitch ID. Given that the shape of the groove changes according to the pitch ID and the adjacent pitch IDs, modeling the groove geometry of a tire is cumbersome. To address this issue, a parametric design concept is introduced.

A simple means of parametric design is to record a script of the commands and data values used to create a geometric element. Editing this script to change the data values allows us to produce a family of variants with different dimensions.[4-8]

We propose a special language to define the geometry. Lines, circles, arcs, curves, and surfaces can be defined with this language. Flow control statements such as GOTO, FOR-LOOP, IF-THEN-ELSE, and WHILE are necessary. Subroutines can also be written.

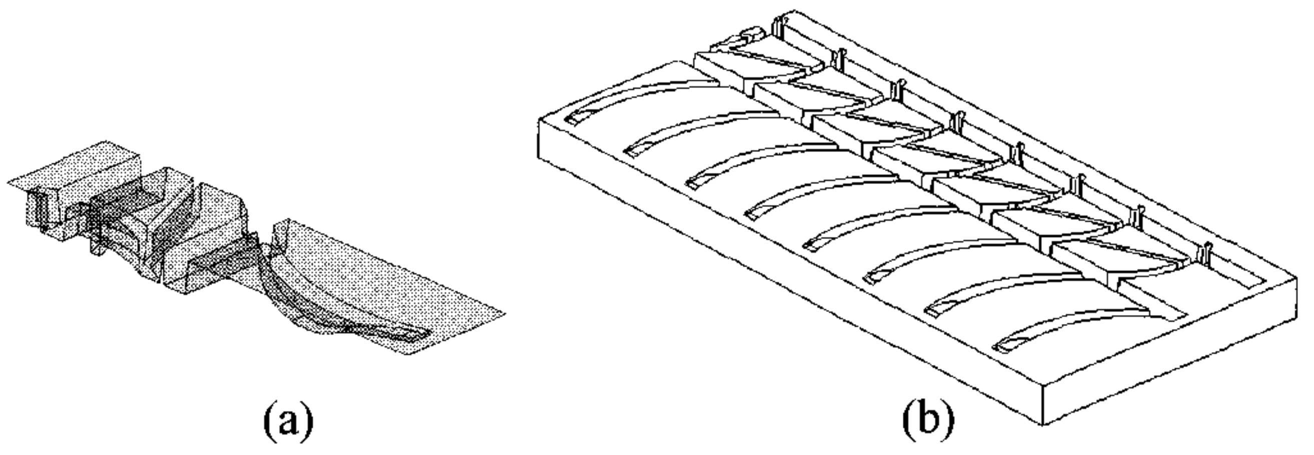
The curve CV1 in Figure 3 is defined by point P1, point P2, and the radius of a circle:

C2=P1,P2,33,B;
CV1=P1;C2,CCW, P2.

Where C2 is the circle below (B) that lies on P1 and P2; its radius is 33. CV1 begins at P1, passes C2 in a counterclockwise (CCW) direction, and ends at P2. This way of defining the geometry is similar to using automatically programmed tools (APTs).

The coordinates of P1 depend on the left pitch rather than its own pitch. If the left pitch ID is A, then P1 = (-5.6,-43.8); if it is B, then P1 = (-4.9,-43.8); and if it is C, then P1 = (-4.3,-43.8). Variables V1 and V2 can be introduced to define P1 such that P1 = (V1,V2). P2 is similarly defined by variables that depend only on its relevant pitch ID. CV1 will then be defined using P1 and P2, and a surface can be created with it. It is not difficult to generate a surface with the profile curves and cross-sectional geometry shown in Figure 4(a).[3]

Defining curves and surfaces in the manner described here enables any groove surface to be created, regardless of its pitch arrangement. As long as a subroutine defining a groove surface has been programmed, any similar groove geometry can be created automatically by merely changing the variables. Figure 5(a) shows the groove surfaces of a pitch defined by the proposed method.



(a) (b)

Fig. 5 Modeling groove surfaces and arrangement of pitches

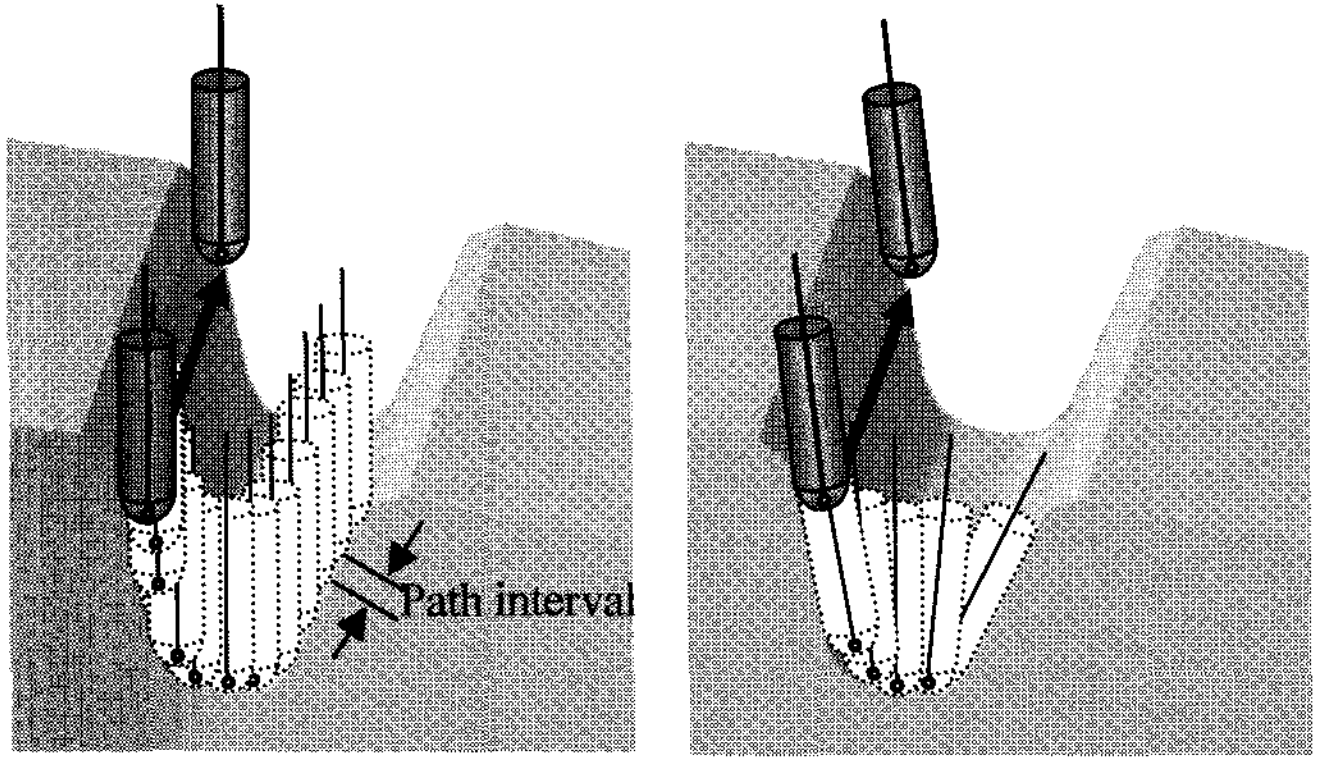
2.2 Arrangement of pitches

In the previous stage, groove surfaces were created based on a 2D plane. The arrangement of pitches is accomplished by defining and translating groove surfaces in the horizontal direction. This process is made simple by the parametric design described previously. A subroutine automatically creates groove surfaces that satisfy the pitch constraints using a pitch arrangement table as an input. Figure 5(b) shows an example of a pitch arrangement.

3. Generation of CL Data

3.1 Generation of CL data for the groove cutting

There are many ways to generate a tool path to machine the groove surfaces. The two different tool paths shown in Figure 6 are examined here. Figure 6(a) shows a tool path that moves along the profile curve of the groove with its tool axis parallel to the Z axis, resulting in three-axis CL data. Shortening the path interval is necessary to machine the sidewall of the groove accurately. However, this leads to large amounts of CL data. To reduce the amount of CL data, the tool axis can be tilted to machine the sidewall using the cylindrical part of the end-mill, as illustrated in Figure 6(b). This results in five-axis CL data at this point.



(a) (b)

Fig. 6 Two types of tool path used to cut the groove

3.2 Mapping CL data to a tread surface

The CL data generated in the previous stage were based on a 2D plane rather than on the tread surface. Therefore, these data must be mapped to the tread surface.[9] The CL data must be transformed such that the distance from the origin to a point on the CL data is identical to the 3D distance on the tread surface.

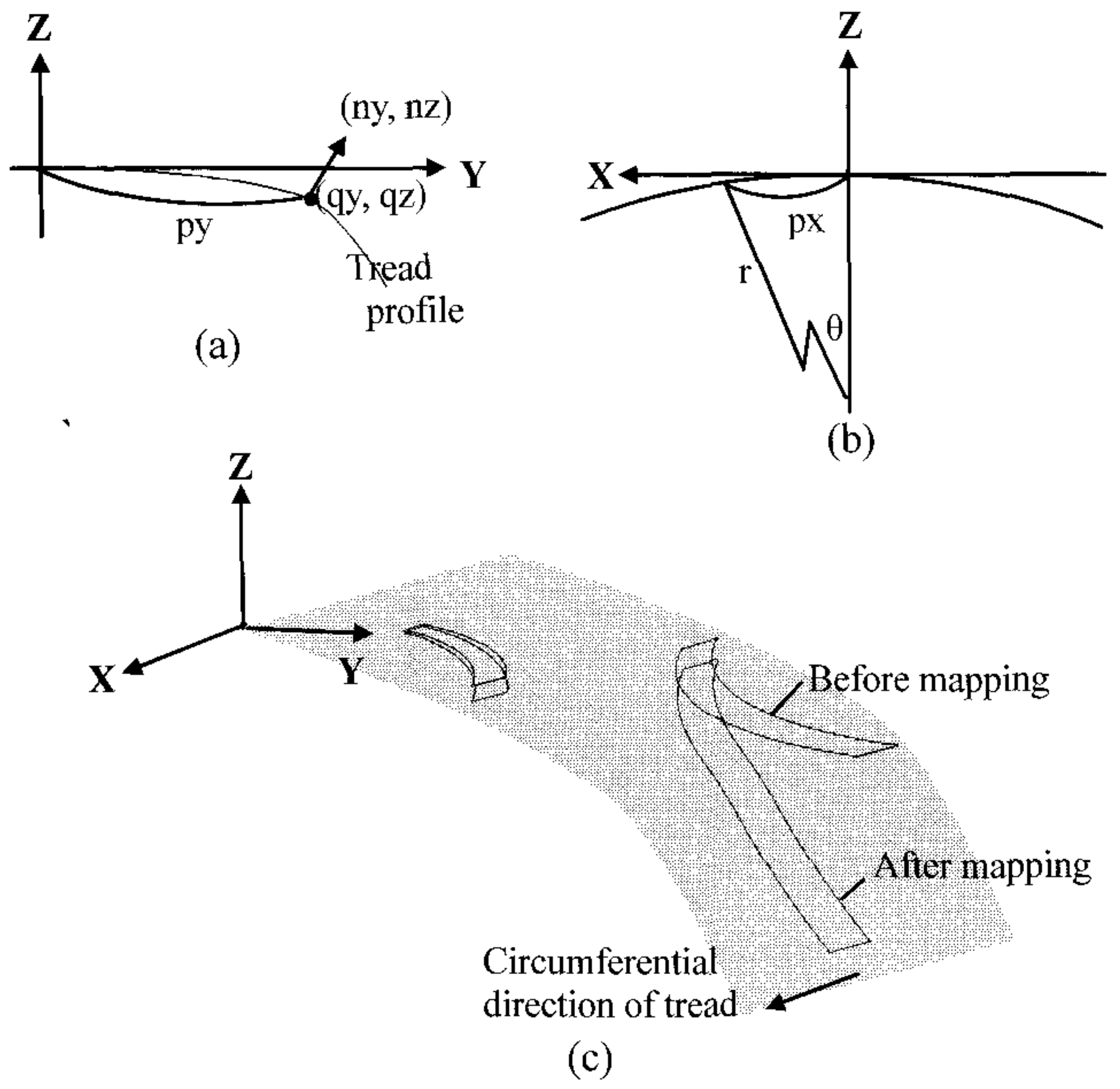


Fig. 7 Mapping the CL data to the tread surface

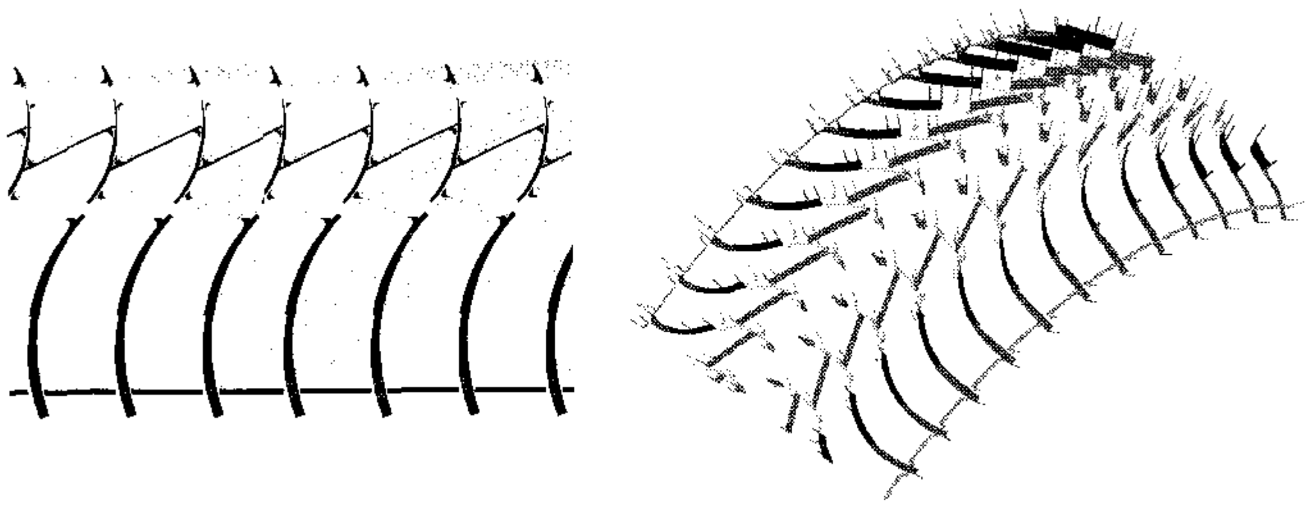
A point *(px,py,pz)* of the CL data is mapped to the tread surface using the following procedure.

(1) The point is calculated such that the arc distance from the origin to the point on the tread profile curve equals *py*, as shown in Figure 7(a). Let the point be *(qy,qz)* and the normal vector at that point be *(ny,nz)*. Let $qx = 0$ and $nx = 0$.

(2) If the maximum radius of the tread is *r*, then $\theta = px/r$, as shown in Figure 7(b). Rotate *(qx,qy,qz)* and *(nx,ny,nz)* by angle θ about the axis that passes through *(0,0,-r)* and is parallel to the y axis, obtaining *(qx',qy',qz')* and *(nx',ny'nz')*, respectively.

(3) Finally, the tool position vector $(rx,ry,rz) = (qx',qy',qz') + pz\,(nx',ny'nz')$ and the tool axis vector is *(nx,ny,nz)*. Figure 7(c) shows an example of mapping the CL data to a tread surface.

Using this procedure, the position vector of the CL data shown in Figure 6(a) is transformed, and the tool axis vector is normal to the tread surface. If the tool axis is not parallel to the z axis, like in Figure 6(b), the transformation must be applied to both the position vector and the tool axis vector. Figure 8 shows an example of mapping the CL data.



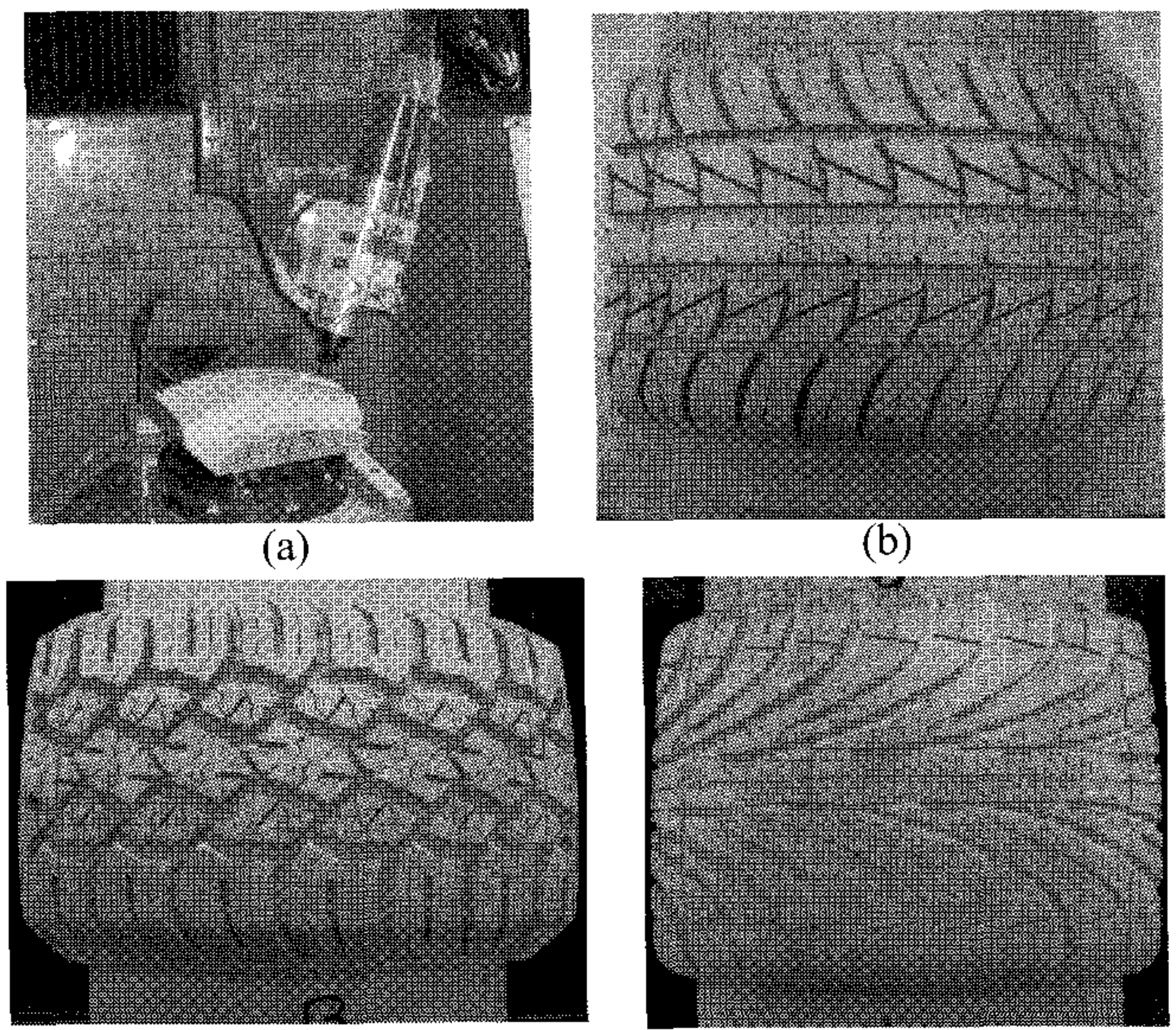
(a) Before mapping (b) After mapping

Fig. 8 Mapping CL data to the tread surface

3.3 Five-axis machining

The CL data for a five-axis machining process have a position vector and a tool axis vector for each point. They must be converted to NC code for a specific five-axis machine using post-processing.[10] There are many studies regarding post-processing for five-axis machining.[11-15]

Figure 9(a) shows the five-axis machining process. The five-axis machine has a rotary table and a tilting head added to a three-axis vertical milling machine. Figure 9(b) shows a machined result using the CL data described in this paper. Figures 9(c) and (d) are other examples created using the proposed method.



(a) (b)

(c) (d)

Fig. 9 Five-axis machining and some machined examples of tire master models

4. Conclusions

The following ideas were proposed in this paper.

(1) A parametric design concept was applied to design a tire groove surface.

(2) The groove surface and CL data were generated in 2D space.

(3) By mapping the CL data to the tread surface, five-axis CL data were obtained. This process made it easy to generate groove surfaces and CL data for five-axis machining of a tire master model.

(4) The results demonstrate that the proposed method is useful for manufacturing tire master models.

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