Available online at www.sciencedirect.com
SCIENCE DIRECT
Computers in Industry 57 (2006) 11–25
COMPUTERS IN INDUSTRY
www.elsevier.com/locate/compind

Computer aided parametric design for 3D tire mold production

Chih-Hsing Chu [a,*], Mu-Chi Song [b], Vincent C.S. Luo [c]

[a] Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Hsinchu 300, Taiwan
[b] Department of Computer Information Science, National Chiao Tung University, Hsinchu 300, Taiwan
[c] STANDTECH Company, Taoyuan 330, Taiwan

Received 2 September 2004; accepted 13 April 2005
Available online 2 September 2005

Abstract

This paper presents a parametric design system for 3D tire mold production. Tire grooves commonly used in the current industry are classified according to their modeling procedures, and the design parameters for each groove type are characterized. The result serves as a foundation for standardization of the tire mold design. The presented system simplifies the construction of 3D groove surfaces by reducing the number of interactive modeling operations. The resultant surface model is parameterized, and thus, allows for rapid creation of other grooves with simple design tables. In addition, a set of geometric algorithms is proposed that first detects undesired groove geometries arising in the design process, and then corrects them automatically. In this manner, 3D mold models are created with minimal user interactions. This work is implemented in an integrated CAD/CAM system for actual mold production. Test examples demonstrate that it provides an effective approach to reducing the time yet improving the quality of tire mold development.

Keywords: Tire mold; Parametric design; Groove pattern; Computer aided design

1. Introduction

The tire industry has received much attention since the late 1960s. Not only is there an everlastingly large demand on tires, but the significance also lies in the fact that tire design and manufacturing directly determine the safety and comfort of driving. New tire development is a highly complex process consisting of many engineering activities such as tire pattern design, material selection, tribological analysis, prototyping, testing, tire mold manufacture, and mass production [1]. Each task requires specialized technologies, and is often performed by companies who own the required knowledge. As a result, the tire industry has become a globally outsourced business [2].

Tire mold development plays a key role in the tire production. Good tire design needs high quality molds that subsequently produce the tire compliant with its specifications. Tire mold manufacture involves different technologies from tire production, e.g. CAD/CAM, precision casting, multiple-axis machining, and metrology are. Hence, it is generally outsourced by most tire companies. The entry barrier of mold making is high but its economical return is also rewarding.

Mold design is the most important in tire mold production. A tire is composed of many intricate grooves specified by corresponding tire design pattern. Sometimes the term ‘‘tread’’ is used and refers to the positive shape of a groove. The groove shape is usually represented with free form geometry, and the construction process of its 3D model is time-consuming and error prone. The groove geometry must be created on the surface of a tire without treads, usually with multiple-axis CNC machining. This requires proper tool path planning and precise tool motions control. Approximately, CAD/CAM tasks consume half to two thirds of the entire mold production time [3]. Unfortunately, there were very few studies focused on this topic. Most of them concerns pitch pattern arrangement and sequencing. Chen et al. [4] developed an expert system that facilitates reuse of previous designs similar to new tread patterns. Jung et al. [5] proposed a systematic approach to matching tire patterns using fuzzy methods. Different tread patterns can be effectively recognized and classified according to their design features. Chiu et al. [6] adopted Tabu search method for optimized sequencing of tire pitches. On the commercial side, most general-purpose CAD/CAM software

* Corresponding author. Tel.: +886 35742698; fax: +886 35722685.
E-mail address: chchu@ie.nthu.edu.tw (C.-H. Chu).

0166-3615/$ – see front matter
doi:10.1016/j.compind.2005.04.005

has a lack of support to mold design or manufacturing. Tire mold production has thus become a bottleneck in new tire development.

To overcome this problem, this study develops an advanced CAD system that enables 3D mold design in a parametric approach. First, the groove shapes commonly used in the current industry are analyzed and categorized into different types. The mold design process is standardized by characterizing the geometric parameters comprising of each type and the corresponding modeling procedure. These parameter values form a design table that allows the user to create, delete, and modify the groove surface with minimal interactive operations. The groove pattern construction in different pitches can be performed in the similar manner. In addition, geometric algorithms are developed for detecting invalid geometries arising in the parametric design process. Automatic shape modifications are also provided to correct them. The construction process of 3D tire mold can be significantly simplified with these functions. As a result, the time of the mold design is shortened but the modeling errors are reduced. Finally, the proposed system is implemented and successfully applied to actual production, demonstrating the practicality of the parametric design approach. It provides an effective solution to improving the tire mold development process.

This paper is organized as follows: the next section describes the design and manufacturing processes of tire mold and their current deficiencies. Section 3 introduces the proposed system framework with a focus on the parametric design mechanism. Section 4 presents a set of geometric algorithms that automatically eliminate undesired geometries occurring during the design process. The next section highlights the application of the system using a commercial tire mold as a test example. The final section summarizes the contributions and future development of this work. The classification of common groove shapes is discussed in Appendix A.

2. Tire mold design and manufacturing

Tire manufacturing starts with selection of rubber compounds and other additives that combine to provide the design characteristics [7]. The next step is to assemble innerliner, body piles and belts, and strands of steel wire firmly together. The result after this stage is usually called a green or uncured tire. The last step is to cure the tire, which is placed inside a mold and inflated to press it against the mold, forming a groove (or positively, a tread) and the tire information on the sidewall. It is then heated at an elevated temperature for some period of time, vulcanizing it to bond the components and to cure the rubber [8].

One important task is to make the metallic mold required in the tire curing operation. Currently, two different approaches are adopted in the mold production. Grooves can be carved out of the inner surface of a metal ring, usually by multi-axis CNC machining. This method directly creates the groove pattern, and thus, has a shorter production time. However, the complex groove geometry increases, to a great extent, the difficulty of the machining process, which becomes requires precise process control and error prone. The sharp corners produced from the reverse shape of a groove often induce serious tool wear and collision problems during the machining. Therefore, direct machining only applies to very simple groove geometry in the current industry. A variant of this approach is to machine the tread shape, which is easier to create due to its convexity. It then serves as an electrode in the subsequent EDM process to form concave grooves. However, this method is very limited to complex geometries, too. The total production time is also increased because of the relatively low material removal rate of the EDM process.

A more commonly used method is to produce the metallic mold with precision casting [9]. It consists of several steps shown in Fig. 1. First, groove pattern is created in a shape like the green tire but made of non-metallic material (usually epoxy or other polymers). To generate concave shapes with a sharp cutting tool is less problematic in this case because of the

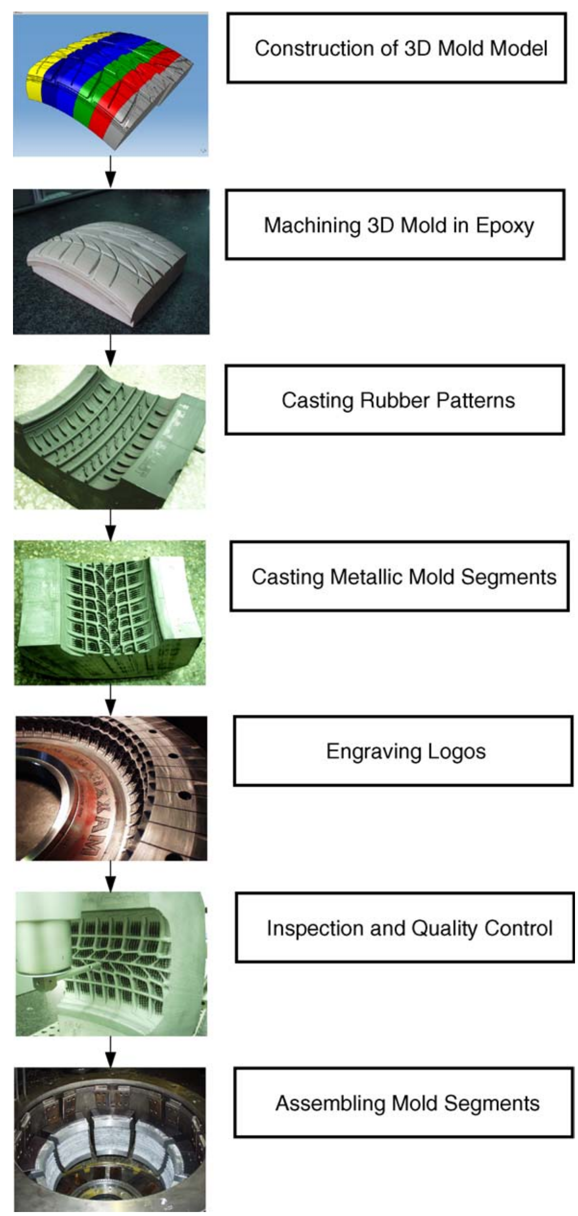


Fig. 1. Production procedure of a segmented tire mold.

material removal nature of cutting and the lower strength of these materials. The finished part with all the grooves created resembles to an actual tire except that the groove size has been properly adjusted to account for the material shrinkage in casting. It then serves as a casting mold for making a batch size of rubber patterns with the groove shapes imprinted on the surface. These patterns become a core in the following low-pressure casting process that actually produces the final metallic mold. The mold produced by this method is actually assembled with a number of mold segments, as the process control (e.g. casting temperature and molten metal flow rate) is easier to attain in the smaller segments. This process is, thus referred to as segmented tire molding in practice. Common mold materials include aluminum alloys and stainless steel. The last step is to make company logos or tire series numbers on the side surface of the mold with multi-axis CNC engraving. Important dimensions and groove profiles need to be inspected before the final shipping.

In theory, a tire mold looks like the negative shape of the tire made from it. The tire geometry consists of a donut shape (the green or uncured tire) and a series of groove patterns on the peripheral of the shape. Fig. 2 shows typical groove patterns in a 2D drawing. The outer surface of a tire is referred to as the road surface, which is generated by revolving a given profile relating to an axis. A groove pattern (or tread pattern) contains a group of 3D grooves in various sizes and shapes that repeat at every certain distance along the tire circumference. The portion within such a distance range is called a pitch. The grooves of a given tire design can be decomposed into a number of repetitive pitches. Each pitch has the same number of grooves. The connectivity among these grooves remains unchanged from one pitch to another, i.e. the position of any groove relative to the others in one pitch does not change across pitches (see Fig. 2). However, their actual locations and sizes may change in different pitches. This characteristic allows for effective parametric design and manufacturing of tire mold.

The groove shape is determined by factors from many aspects such as tribology, heat transfer, fluid dynamics, and aesthetics. The shape becomes highly complex in certain occasions. Parametric design of tire mold starts with standardization of the geometric modeling procedure of the grooves. A classification scheme for different grooves is a priori, which unfortunately does not exist. In addition, it is not clear which portions of the mold design process can be parameterized and how the parameterization should be conducted.

One critical issue in any parametric design system is to identify a proper set of variables that construct the design model in a parameterized manner. It is also important to characterize how the modeling operation is conducted for each design and the commonalities among the different operations. The focus is to derive certain patterns that support reuse of an existing model and/or its operation procedure in different designs. An effective approach is to classify the design models, analyze the parameters comprising them, synthesize the results, and deduce possible generalization [10]. Following the same concept, we first categorize the groove shapes that are commonly used in practice. Appendix A illustrates the classification result in detail.

3. System architecture

Fig. 3 illustrates the software framework for the proposed design system. It consists of two major parts—interactive design and parametric design modules. The former contains three functions with which the user can interactively construct 2D geometric entities required for the 3D mold design. The parametric design module consists of a number of tools that facilitate the construction of 3D tire mold in a parametric fashion. Each function is described as follows.

3.1. Tire design importer

Currently, most tire designs are specified with 2D engineering drawings. Tire mold design and manufacturing, on the other hand, have adopted 3D CAD/CAM software since the late 1990s. To import the tire design data into the mold production remains a manual and tedious process. In contrast,

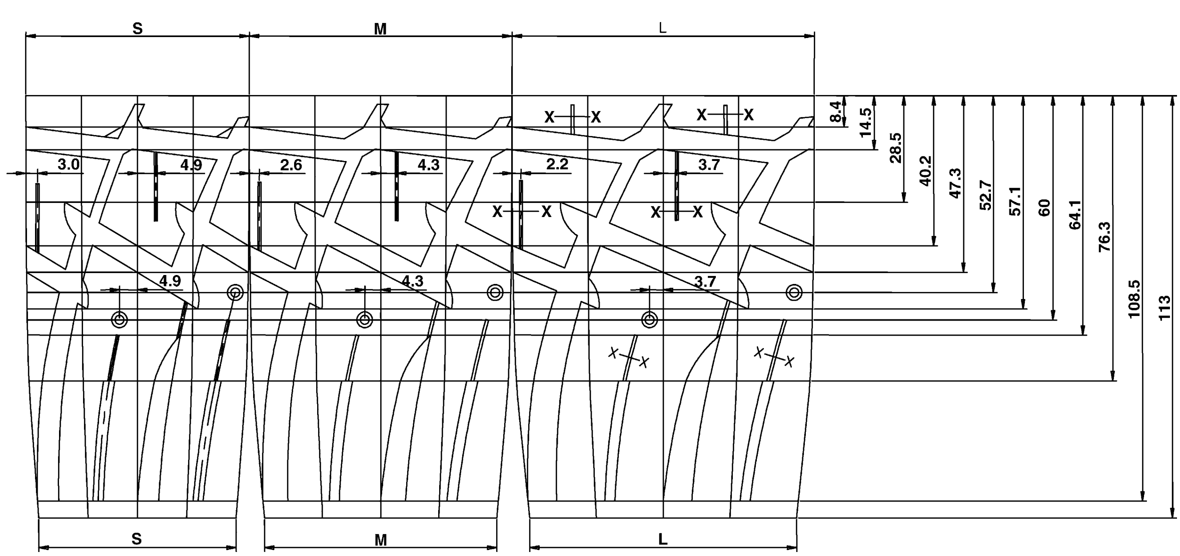


Fig. 2. Three pitches (small, medium, and large) in a tire design.

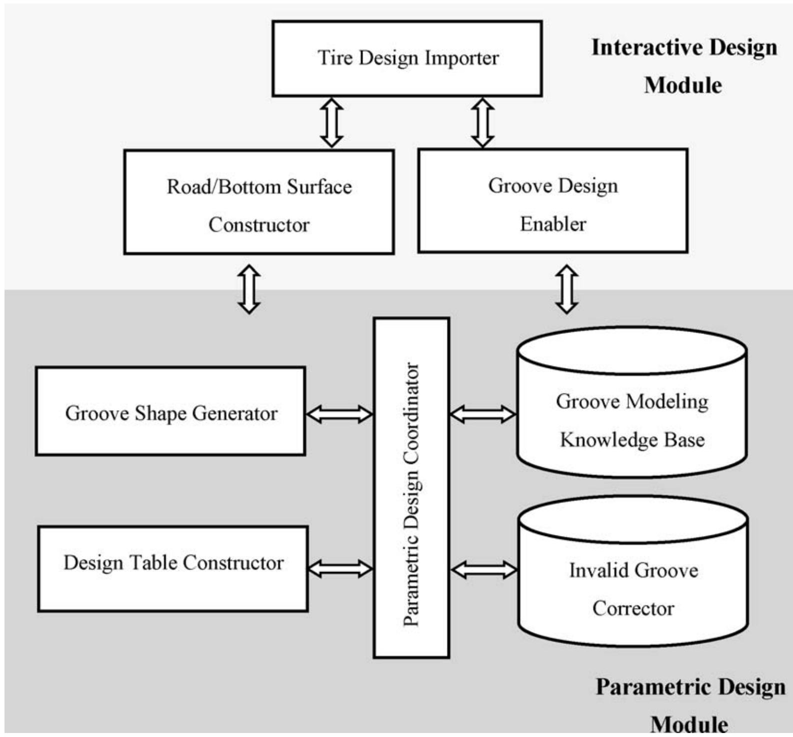


Fig. 3. Framework of the parametric design system.

the proposed system acquires the 2D design information (including tire profile, guide curves for the groove pattern, and cross-section profiles of each groove) with the assistance of an intelligent software program—Tire Design Importer. This program assures two critical issues during the data importing process. First, the number of guide curve segments for any given groove does not change across different pitches. A guide curve is normally approximated by a series of discrete points in the 2D tire design. They are interpolated with spline curves under some tolerance control for the 3D mold modeling. The number of the interpolating curves has to remain the same for every pitch. Second, the connectivity of the grooves in one pitch should be retained. Fig. 4 shows that the connectivity relationship is represented by a non-directional graph [11].

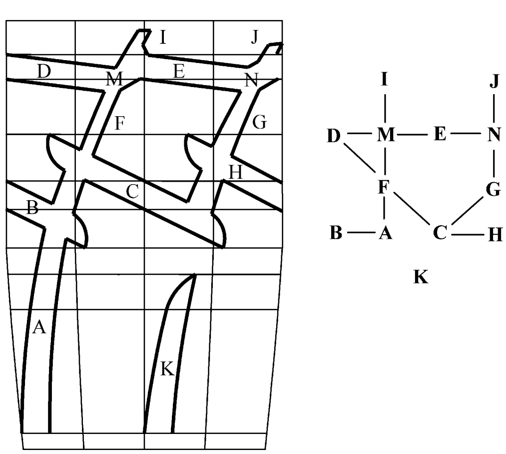


Fig. 4. Connectivity of a groove pattern in one pitch and its non-directional graph.

3.2. Road/bottom surface constructor

A tire mold normally contains one road surface and several bottom surfaces corresponding to different groove depths. Revolving a cross-sectional profile along a coordinate axis with a given extended angle generates the road surface, as shown in Fig. 5. The profile can be highly complex and consist of many line/curve segments with geometric constraints (e.g. positional and tangent continuities) among them. The user has to interactively specify these relationships until the resultant shape becomes fully constrained with no degrees of freedom. It is important to maintain the fully constrained condition, which ensures intact of the parametric design form.

3.3. Groove design enabler

The groove geometry is characterized with a number of cross-section profiles along a guide curve (or guide curves). Fig. 6 shows a typical example. The guide curve(s) determines the location and orientation of a groove on the road surface. It can be the boundary curves of the grooves with varying width. The center curve is used in the case of fixed width. The cross-sectional profiles describe the groove shape at a number of positions along the guide curve. Groove design enabler imports the profile information and provides a table for the user to select at each position. The matching process between each groove and its constructing profiles is simplified and the matching errors are reduced. The matching relationship is stored in groove design enabler and becomes an integral part of the parameterized groove model.

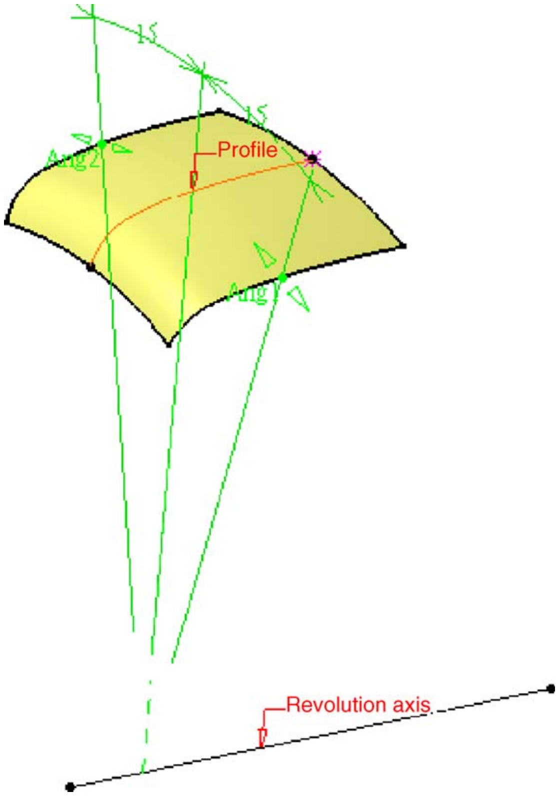


Fig. 5. Construction of the road/bottom surface by revolving a profile along a given axis.

3.4. Groove modeling knowledge base

General groove shapes have been analyzed and classified into various categories (see Appendix A). The focus is to obtain the design parameters comprising each different groove and the geometric operations required in the corresponding modeling process. They serve as a base for standardization of the 3D groove construction. These pieces of information are stored in the form of templates. Totally 30 types of groove are stored in the current knowledge base. In addition, it compiles the shrinkage factors in casting, engineering change records, important inspection dimensions, and special treatments for each groove type. The user can query the knowledge base about all the production information. More importantly, the other software modules can programmatically access necessary templates during the design process.

3.5. Groove shape generator

Groove shape generator performs the actual 3D modeling process for tire mold. A groove cross-sectional profile is specified with two sets (right and left) of design parameters. Each set contains the top point, wall angle, and rounding radius. The corresponding guide curve has been in place with the aid of Groove design enabler. Next, this module queries the knowledge base and obtains the template for the constructing groove. All the geometric operations are wrapped up into one command, and thus hide the design complexity from the user. The 3D CAD model is created automatically without the user's interactions after the required parameters have been chosen. If the modeling

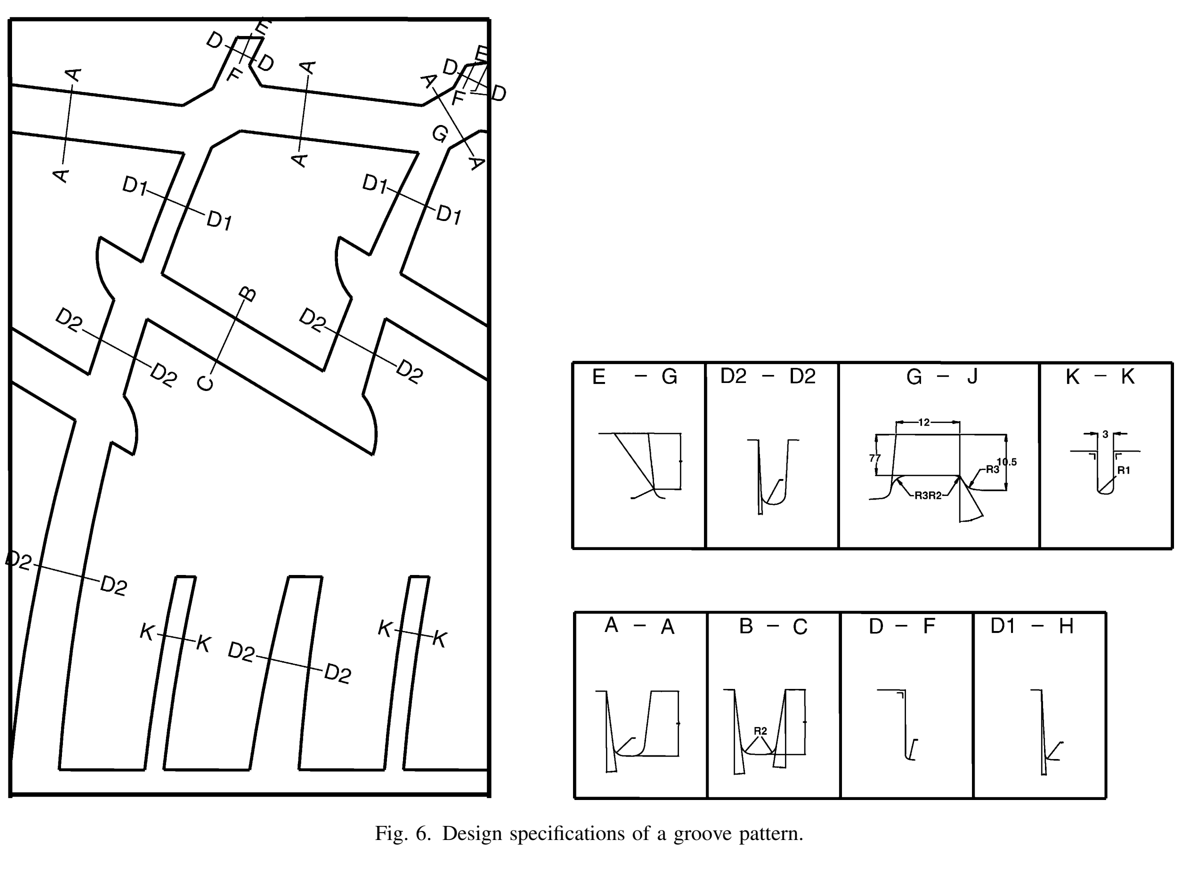


Fig. 6. Design specifications of a groove pattern.

process fails, error messages will be logged into Program Coordinator for prompting the user for the command status.

3.6. Design table constructor

The user needs to interactively perform some design tasks, mainly in road/bottom surface constructor and groove type preparatory. However, after a first pitch has been constructed, the system stores the resultant grooves according to their parameterized, which accelerates the pattern creation in other pitches. Design table constructor outputs these parameters into the form of design tables. The following information is recorded for a groove surface: the type, guide curves, cross-sectional profiles, connectivity to other grooves, and all the values of the geometric elements constructing the groove. Note that the number of these parameters remains the same across pitches, but their values may change. The table can exist in a text file, Excel document, or Product Data Management (PDM) system. The user only needs to modify the parameter values for the next pitch design and input the file back into the system. The corresponding 3D grooves are then automatically generated without the user interaction.

3.7. Invalid groove corrector

The proposed system allows the user to design the entire set of grooves in a next pitch by modifying the parameter values from an existing one. This function is based on the fact that any given groove is geometrically constructed in the same manner at different pitches. However, the change of the parameter values may induce invalid groove shapes or cause geometric operations to fail during the design process. Geometric algorithms are needed to detect these problematic situations and correct them automatically. Invalid groove corrector is mainly responsible for such an auto-correction mechanism. The later section will discuss in detail when these problems occur and how they can be resolved.

3.8. Parametric design coordinator

This module serves as a coordinator among the other modules. It parses the design tables from an external medium for the groove pattern of a new pitch; then interrogates with groove modeling knowledge base for the modeling procedure of each groove. The next step is to invoke groove shape generator and produces a set of 3D groove surfaces with the new parameter values. Invalid groove corrector handles the invalid geometries when they occur during the design process. The coordinator is also responsible for error logging, exceptional handling, and interactions with the user.

4. Geometric algorithms for correcting invalid groove geometries

One major problem in any parametric design process is to assure the validity of the resultant geometries, as the user interaction has been minimized and it is no longer possible to prevent the modeling errors with manual handling. Invalid

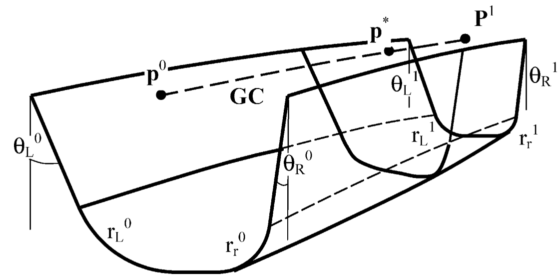


Fig. 7. Construction of groove shape by lofting cross-sectional profiles.

CAD models often take place in the mold design due to the poor interface with the tire design. One major problem is that most of the tire design activities such as creation of the groove pattern, guide curves, and cross-sectional profiles are conducted in 2D CAD. The design engineer has difficulties in visualizing the corresponding 3D models. It is inevitable that these models often become invalid or simply cannot be created in 3D space. Intelligent algorithms are required to automatically the occurrence of the errors, adjust the related geometric operations, and subsequently generate correct results. The invalid groove geometries may arise in a number of conditions, which are analyzed and described as follows.

4.1. Intersection of rounding surfaces

The shape of a groove is specified with its guide curve and cross-sectional profiles along the curve. The loft operation [12] interpolates these profiles along the guide curve according to certain pre-defined rules. For example, the shape change between the consecutive profiles maintains a linear relationship in Fig. 7. To exactly predict the final shape of a groove constructed is not an easy task in this condition. Frequently, the user chooses the rounding radii that are oversized, resulting in the surface intersection shown in Fig. 8. We develop an algorithm that detects this problem by solving a univariate equation instead of directly computing the intersection between two rounding surfaces, which normally involves a highly non-linear system of equations.

Fig. 9 shows a cross-sectional profile consisting of two walls, two rounding radii, and a bottom. In this example, the bottom section is approximated with a straight line, given that

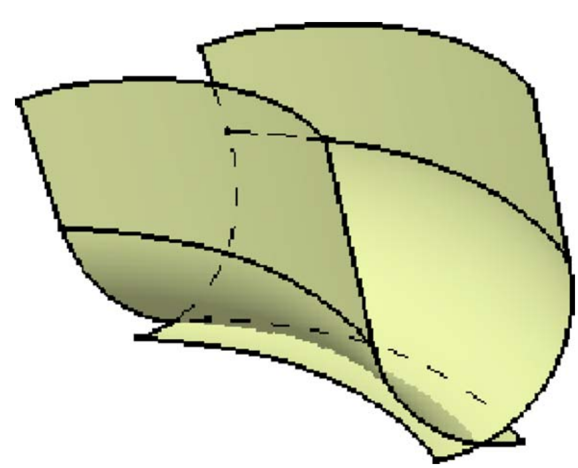


Fig. 8. Intersection of rounding surfaces.

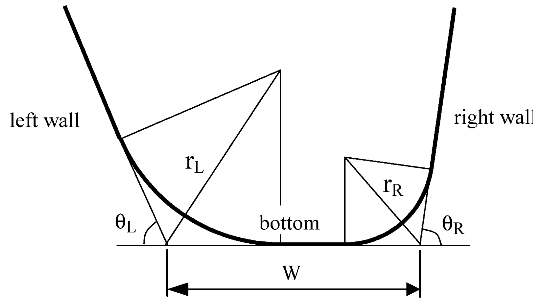


Fig. 9. Definition of the width in a groove cross-section.

the curvature radius of the bottom is usually much greater than the rounding radius. Note that coordinate transformations have been applied to the profile so that the bottom line aligns with the horizontal direction. The groove width W can be expressed as:

$$W \geq \frac{r}{\tan\left(\frac{1}{2}\theta_L\right)} + \frac{r}{\tan\left(\frac{1}{2}\theta_R\right)} \tag{1}$$

where r_L, r_R, θ_L, θ_R are the rounding radii and the wall angles at the left and right sides, respectively. The above equation becomes equality when the two rounding surfaces intersect at one point. As mentioned previously, lofting a set of profiles along the guide curve in a linear manner generates the shape of a groove. Hence, the wall angle θ, the rounding radius r, and the groove width W must vary along the guide curve according to:

$$\begin{aligned} r &= r^0 + \lambda(r^1 - r^0) \\ W &= W^0 + \lambda(W^1 - W^0) \\ \theta &= \theta^0 + \lambda(\theta^1 - \theta^0) \end{aligned} \tag{2}$$

where λ is the ratio of the accumulated length ($\mathbf{p}^0\mathbf{p}^*$) to the total length ($\mathbf{p}^0\mathbf{p}^1$) along the curve **GC**. The subscript 0 indicates the start profile of the groove and 1 indicates the end profile (see Fig. 7). These parameters change their values linearly with respect to the length ratio λ. Note that the rounding arcs become tangent when the width specified by Eq. (1) equals the one determined by Eq. (2). Also, the radii in Eq. (1) must be calculated from Eq. (2), which can be written as:

$$\frac{r_L}{\tan\left(\frac{1}{2}\theta_L\right)} + \frac{r_R}{\tan\left(\frac{1}{2}\theta_R\right)} = W^0 + \lambda(W^1 - W^0)$$

i.e.

$$\frac{r_L^0 + \lambda(r_L^1 - r_L^0)}{\tan\left\{\frac{1}{2}[r_L^0 + \lambda(r_L^1 - r_L^0)]\right\}} + \frac{r_R^0 + \lambda(r_R^1 - r_R^0)}{\tan\left\{\frac{1}{2}[r_R^0 + \lambda(r_R^1 - r_R^0)]\right\}} = W^0 + \lambda(W^1 - W^0) \tag{3}$$

This equation contains only one variable λ. Therefore, we only need to solve a univariate non-linear equation, Eq. (3). The solution λ^* corresponds to the position along the guide curve at which the arc tangency occurs.

The rounding surfaces of a groove begin to intersect from the position determined by λ^*. The resultant geometry is not valid for the mold design, and thus, needs to be modified. Two approaches are proposed for the surface modification.

4.1.1. Approach I

The two rounding surfaces merge at the tangent position and becomes one single surface with a full rounding radius. This condition continuously holds for the rest of the groove. The full radius r_f also varies along the groove and is given by:

$$r_f = \frac{W}{\tan\left(\frac{1}{2}\theta_L\right) + \tan\left(\frac{1}{2}\theta_R\right)} \tag{4}$$

where W, θ_L, and θ_R are computed according to Eq. (2).

4.1.2. Approach II

The two rounding surfaces touches at the position determined by λ^* and remains tangent for the rest of the groove. Note that the linear variation rule, Eq. (2), no longer holds in this case. (Otherwise there would be no intersection between the surfaces.) Instead, the groove width is first calculated according to Eq. (2); then the radii are computed while their ratio α at the start profile is maintained all the way through the groove, i.e.

$$\alpha = \frac{r_R^0}{r_L^0}$$

and the radius at the right side becomes:

$$r_R = \frac{W}{a \cdot \tan\left(\frac{1}{2}\theta_L\right) + \tan\left(\frac{1}{2}\theta_R\right)} \tag{5}$$

where W, θ_L, and θ_R have to be computed according to Eq. (2).

4.2. Avoidance of surface crease

The groove geometry does not allow the formation of singular points or crease, which tend to occur near the "shoulder" area where the road surface has a rapid change of the surface normal while the bottom surface has a smoother

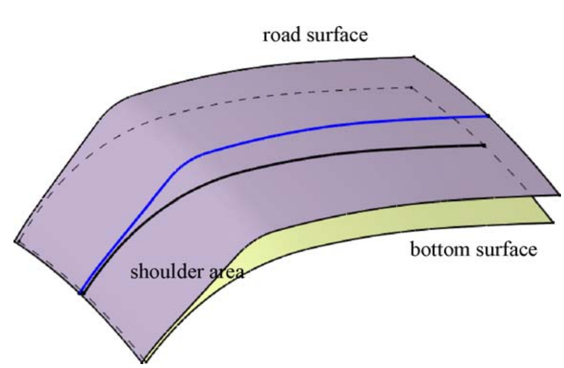


Fig. 10. Shoulder area in a tire mold.

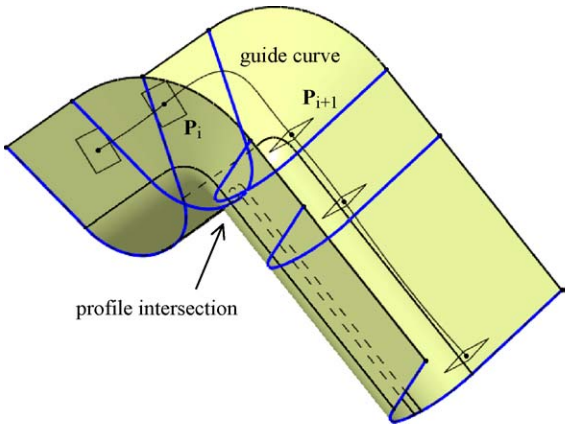


Fig. 11. Intersection of profiles results in creases.

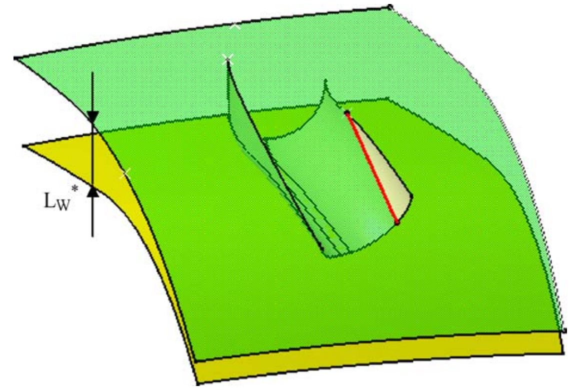


Fig. 13. Blending operation fails at shallow grooves.

change, as shown in Fig. 10. Alternatively stated, the former has a larger curvature around this area than the latter. Since the groove surface is produced by lofting 2D cross-sectional profiles along the guide curve, we conclude that the problem takes place at the position where consecutive profiles intersect with each other. Fig. 11 shows that a profile $\mathbf{P}_i$ intersects with the next one $\mathbf{P}_{i+1}$. Note that these profiles are specified at a plane normal to the guide curve on the road surface. A simple heuristic is adopted to correct this situation. First, the intersection test is computed between profiles to detect whether it happens and where it begins. If yes, the groove construction is automatically switched to an alternative procedure. A given point $\mathbf{p}_i$ is projected along the surface normal of the road surface, producing a projection point on the bottom surface denoted as $\mathbf{q}_i$. Interpolating all the projection points creates a new guide curve on the bottom surface. Next, a plane passing $\mathbf{q}_i$ and normal to the new curve is constructed. Each profile $\mathbf{P}_i$ is then projected onto the corresponding new plane, denoted as $\mathbf{Q}_i$ in Fig. 12. The groove surface is, thus lofted with the projected profiles $\mathbf{Q}_i$'s for $1 \leq i \leq n$. The bottom surface normally does not have a shoulder region. As a result, creases or other unfavorable features do not arise in the lofting operation with respect to it. Note that the groove surface generated in this manner does not necessarily conform to the one generated from the original profiles. In practice, the tire designer will be informed of the outcome through an engineering change process.

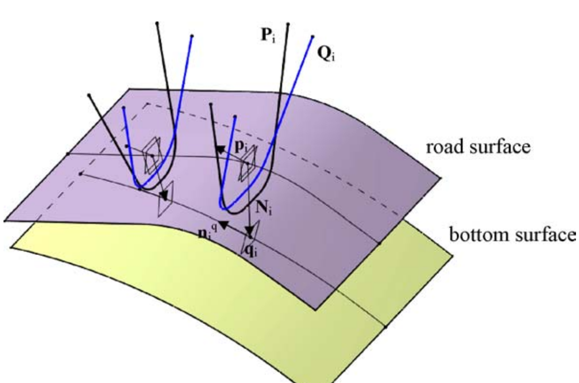


Fig. 12. Crease avoidance in 3D groove construction.

4.3. Rounding surface for shallow groove

Rounding radius is created by edge blending between the bottom and wall surfaces. A variety of rolling-ball algorithms [13,14] have been proposed that construct the blending surface with a constant or variable radius. In these methods, the ball has to roll along the two base surfaces (bottom and wall) while maintaining contact with one another. However, this condition does not hold for shallow grooves (see Fig. 13), where the wall surface has vanished. The rounding radius must be properly adjusted in proportion to the distance between the road and bottom surfaces.

Fig. 14 shows that the distance between the road and bottom surfaces L_{W}^* is too short to accommodate the rounding radius R_{r}. The blending operation will normally fail in this case. In fact, the maximum radius that contacts both the wall and the bottom is expressed as:

$$R_{\mathrm{r}}^* = R_{\mathrm{r}} \frac{L_{\mathrm{W}}^*}{L_{\mathrm{W}}} \tag{6}$$

where L_{W}^* and R_{r} are specified values in tire design. The above equation can be rewritten as:

$$R_{\mathrm{r}}^* = \tan\beta \cdot L_{\mathrm{W}}^*$$

$$R_{\mathrm{r}}^* = \tan\left(\frac{\pi}{4} + \theta_{\mathrm{W}}\right) \cdot L_{\mathrm{W}}^* \tag{7}$$

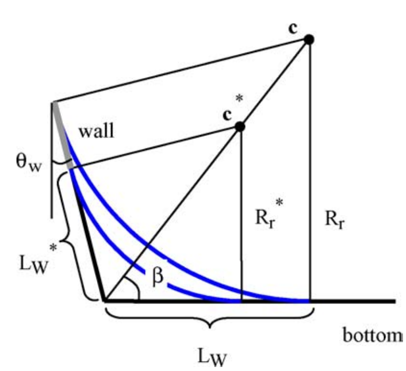
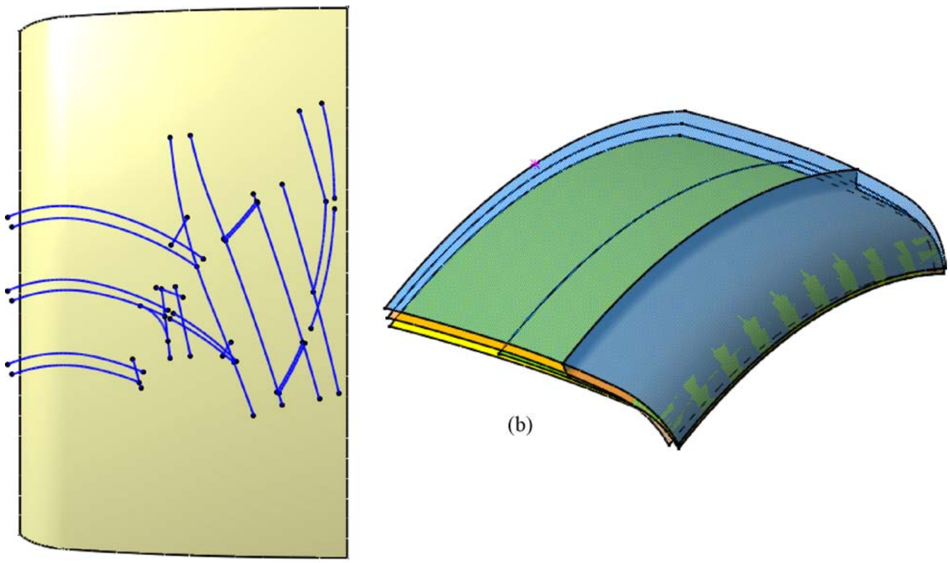


Fig. 14. Adjustment of rounding radius in a shallow groove.



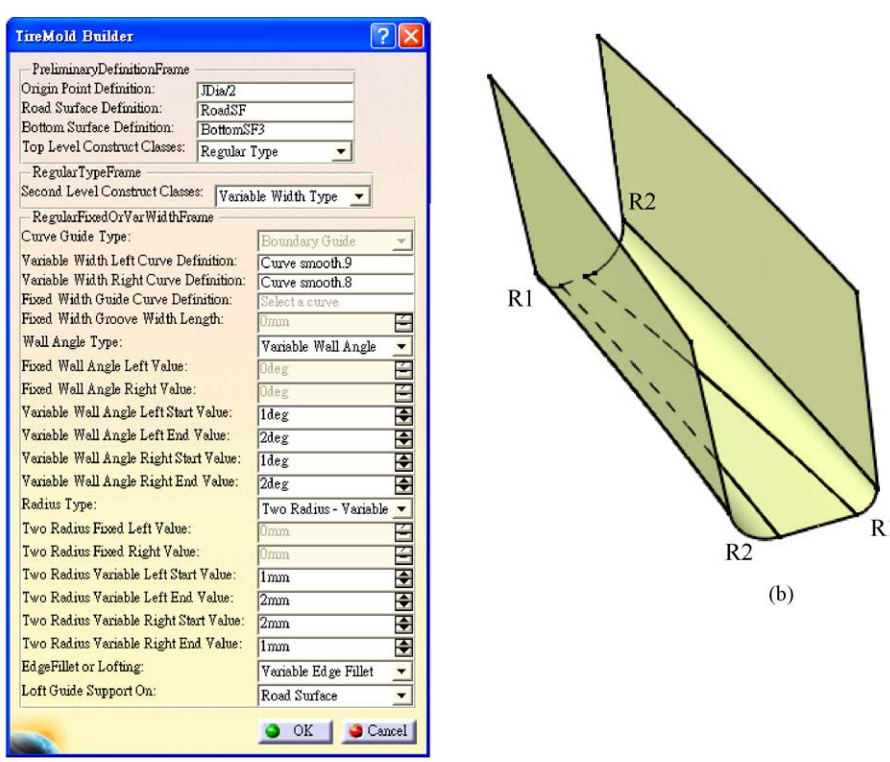
(a)

Fig. 15. (a) Guide curves of one pitch extracted with tire design importer and (b) road and bottom surfaces.

Note that half of the corner angle β is equal to $(\frac{\pi}{4}+\theta_{\mathrm{W}})$. This shallow-groove problem can be detected by comparing the specified radius with the one calculated from Eq. (7). The radius has to be adjusted accordingly.

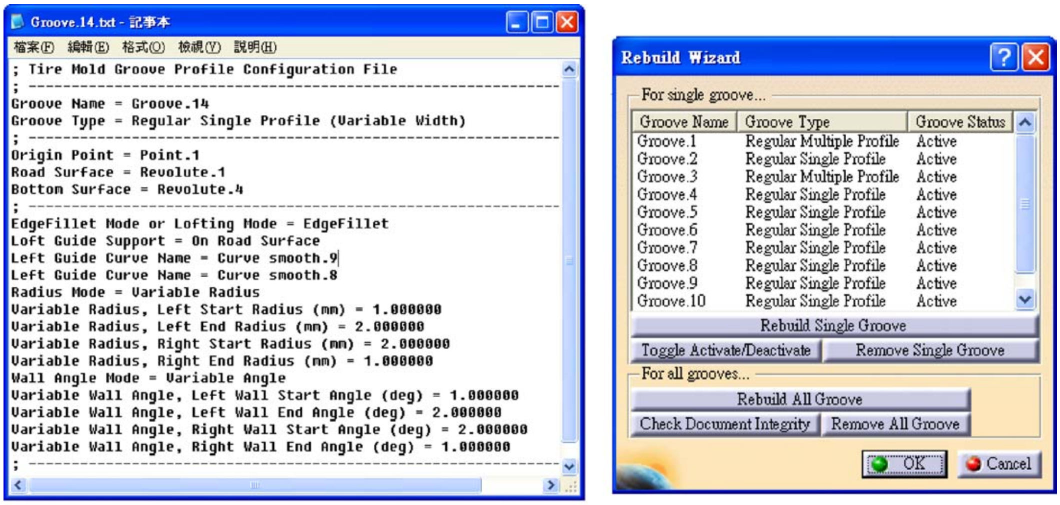
5. Implementation

This work has been implemented in a local company of tire mold manufacturing. First, international tire companies make new tire pattern designs with 2D CAD system (AutoCAD™ 2002 in this case), and then send the pattern drawings in DWG™ format to the mold company via FTP and emails. The mold company manually checks the completeness of the data, including tire profiles, pitch arrangement, groove specifications, quality control instructions, and auxiliary information. Currently the 3D mold is modeled with the GSM module in CATIA™ V5 system. Surface model is adopted instead of solid model in this case, as the former facilitates the subsequent tool



(a)

Fig. 16. GUI in Groove design enabler and the resultant groove surface.

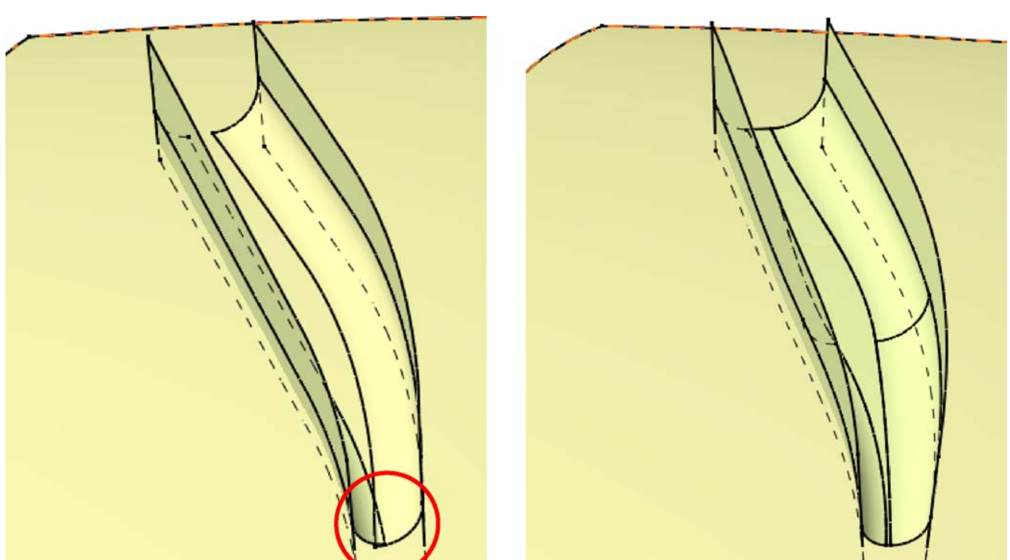


(a) (b)

Fig. 17. (a) Groove parameter values in a text file and (b) GUI in parametric design coordinator.

path planning. To demonstrate the feasibility of the design framework, a customized mold creation module has been developed in CATIA using Component Application Architecture (CAA) [15], which allows an effective integration with the system. The proposed geometric algorithms are also implemented with CAA C++ API's and other programming resources (e.g. GUI's, memory management tools, and graphics) provided by CATIA V5.

A real mold is used as a test example to illustrate the implementation results. The first step is to create a tire without treads by revolving a planar profile specified with geometric dimensions in 2D drawings. Fig. 15(a) illustrates a set of guide curves in one pitch extracted with tire design importer. In addition, a number of groove bottom surfaces corresponding to different groove depths are generated with road/bottom surface constructor, as shown in Fig. 15(b). Next, the groove pattern is constructed with the parametric design module. The user determines the type for each groove based on the classification scheme summarized in Appendix A. For instance, Type 36 is a regular single-profile groove with variable width, two variable radii, and two variable wall angles. Since the groove width is variable, the user has to select two boundary curves. After all the necessary geometric elements have been specified interactively via groove design enabler (a screen shot of the corresponding GUI is shown in Fig. 16(a)), the groove surface is created automatically. Actually, a series of geometric operations are performed behind the scene of groove shape generator in a batch manner, in order to simplify the modeling process and hide its complexity from the user. The resultant surface is shown in Fig. 16(b). At the same time design table constructor stores the parameter values of each groove in an external file (see Fig. 17(a)). The user can modify, delete



(a) (b)

Fig. 18. (a) Intersection of rounding surfaces and (b) automatic correction of the intersection.

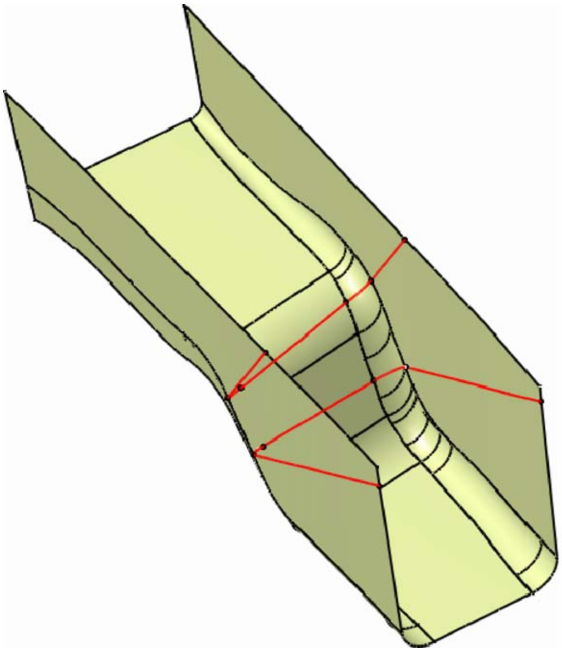


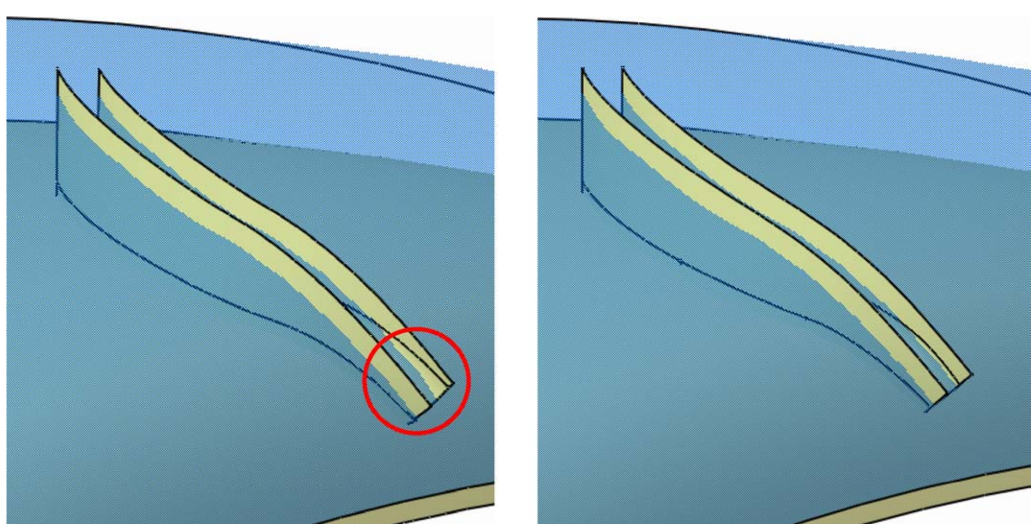
Fig. 19. Elimination of the surface crease caused by the intersection of lofting profiles.

existing grooves, or build new ones directly through the GUI's provided by parametric design coordinator, as shown in Fig. 17(b). The similar approach also applies to the pattern design across pitch. A design table is created after all the grooves in the first pitch have been constructed. Modifying the parameters in the table and exporting the modified values back into the system with the assistance of parametric design coordinator can easily build the grooves of the following pitches. No interactive design actions are required once the first pitch design is completed.

As mentioned above, automatic design modification is a key technique enabling parametric design. Fig. 18(a) illustrates a groove with two rounding surfaces mistakenly intersecting with each other. Invalid groove modifier automatically detects this situation and adjusts the groove based on Approach I described in Section 4.1.1. The rounding radii are reduced in proportion to the groove width along the guide curve, as shown in Fig. 18(b). Note that the adjustment is applied from the location where the radii begin to overlap. In addition, the system can eliminate the crease of the groove and generate a new groove surface with smooth geometries. Fig. 19 shows the groove surface that has been automatically modified based on the approach discussed in Section 4.2, which properly adjusts the orientation of the lofting profiles to eliminate the crease.

The rounding surfaces of a groove also need be automatically adjusted to accommodate the wall length that becomes shortened near the shoulder area. The result is shown in Fig. 20 with the road surface displayed in semi-transparent blue. Note that the wall surface is intended to be over the road surface. Finally, Fig. 21 compares the complete groove pattern in two different pitches that are created with the proposed parametric design system. Minimal user interactions are required for the creation of the second pitch.

The proposed system has been deployed in real production environment of STANDTECH Company, a leading tire mold manufacturer in Asia. A four-pitch commercial tire is used as a test example for the 3D tire mold construction. Fig. 22 illustrates the complete 3D model generated with the system. The introduction of the parametric design significantly enhances the efficiency of the mold design process. The company estimates that the time of the 3D model construction is shortened by around 30% for the test example. The task takes 15 working hours with standard CATIA functions, whereas it needs roughly 10 h using the parametric design functions. However, note that the complexity of 3D tire mold design varies a lot with different factors such as groove pattern, pitch arrangement, pitch number, and more importantly, the user experience. Thus, the above time savings may not apply in general.



(a) (b)

Fig. 20. (a) The rounding surface protrudes out of the road surface near the shoulder area and (b) automatic correction of the rounding surface protrusion.

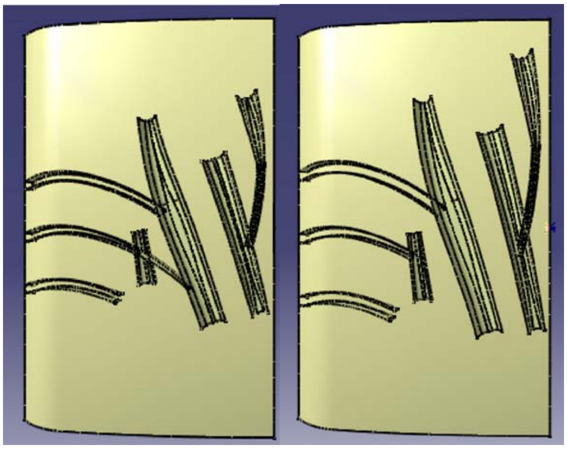


Fig. 21. Groove patterns constructed with the parametric design system for two pitches.

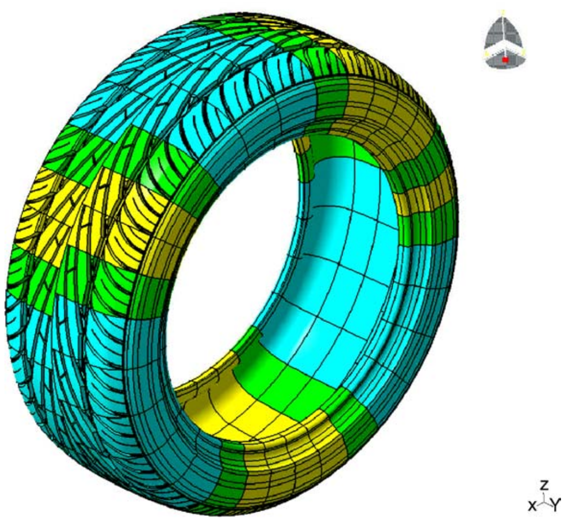


Fig. 22. Complete 3D tire mold constructed with the proposed system.

6. Conclusions

This paper proposes a parametric design system that effectively enables 3D tire mold design with minimal user interactions. Groove shapes commonly used in the tire industry have been analyzed and classified into distinct types. The design parameters for each groove and its geometric modeling procedure with these parameters are also obtained. The results serve as a foundation for standardization of the 3D mold design process. To demonstrate this concept, a software framework has been established that consists of a number of modules for both interactive and parametric designs. The construction process of 3D groove surface based on 2D tire drawings is significantly simplified by reducing the number of the modeling steps, and potential user errors are thus prevented. In addition, the proposed system stores a set of parameter in a design table for each constructed groove. The user can modify, build, or delete any groove surface simply by editing a text file and directly importing it into the system via GUI's. This process does not involve interactive selection of 3D geometric entities, which is tedious and error prone. After the first pitch has been completed, the groove pattern of other pitches can be generated with the design table in the same manner. One important function facilitating the parametric design is a mechanism that automatically detects and corrects the occurrence of certain invalid geometries without the user's awareness. This study has developed a set of geometric algorithms that eliminates three unfavorable conditions: intersection between the rounding surfaces, the surface crease, and shallow grooves near the shoulder area.

This work has been implemented in a high-end CAD/CAM system for actual production. A commercial tire mold is used as a test example for demonstration of its practicality and effectiveness. The results have indicated several advantages of introducing the parametric design system over the previous approach. First, the complexity of the mold design is hidden from the user. Modeling errors are reduced due to fewer user interactions resulted from the automatic groove construction by the design table. As a result, the quality of the mold design is enhanced. More importantly, the parameter values of the groove pattern in a first pitch can be utilized to accelerate the pattern creation in other pitches, saving a great amount of the time for the mold design. This study has provided an effective approach to accelerating the tire mold development as well as the related new tire manufacturing. Our future research will be focused on parametric tool path planning with the mold models generated from the proposed system. An intelligent interface is also worth of studying for better integration between the tire design and the mold modeling.

Acknowledgements

This work was supported by the National Science Council of Taiwan under grant number 92-2622-E-007-015-CC3. The authors also want to thank StandFord Inc. Co., Taoyuan, Taiwan, for their technical support.

Appendix A

The *Rotary* group contains the grooves that are generated by revolving a given profile along the same axis as that of the road surface construction. They normally have a full radius (Type 11) or two radii (Type 12) connecting the bottom and wall surfaces. A simple plane (*Chamfer*, Type 13) that intersects a rotatory groove at an angle also belongs to this group (Fig. A.1).

The groove geometry of the second group (*Regular*) is not symmetric to any axis. *Single section* is specified by the profiles given in two planes passing and normal to a guide curve. The *Fixed width* group contains the grooves with equal width along the guide curve measured along the geodesics on the road surface. The guide curve can be either the boundary (*Boundary Guide*, Types 21-26) or the centerline (*Center Guide*, Types 31–36) of the groove. There are three subgroups under each one: *full radius*, *two fixed radius*, and *two variable radius*. Each of them includes two different wall surfaces: *fixed wall angle* and

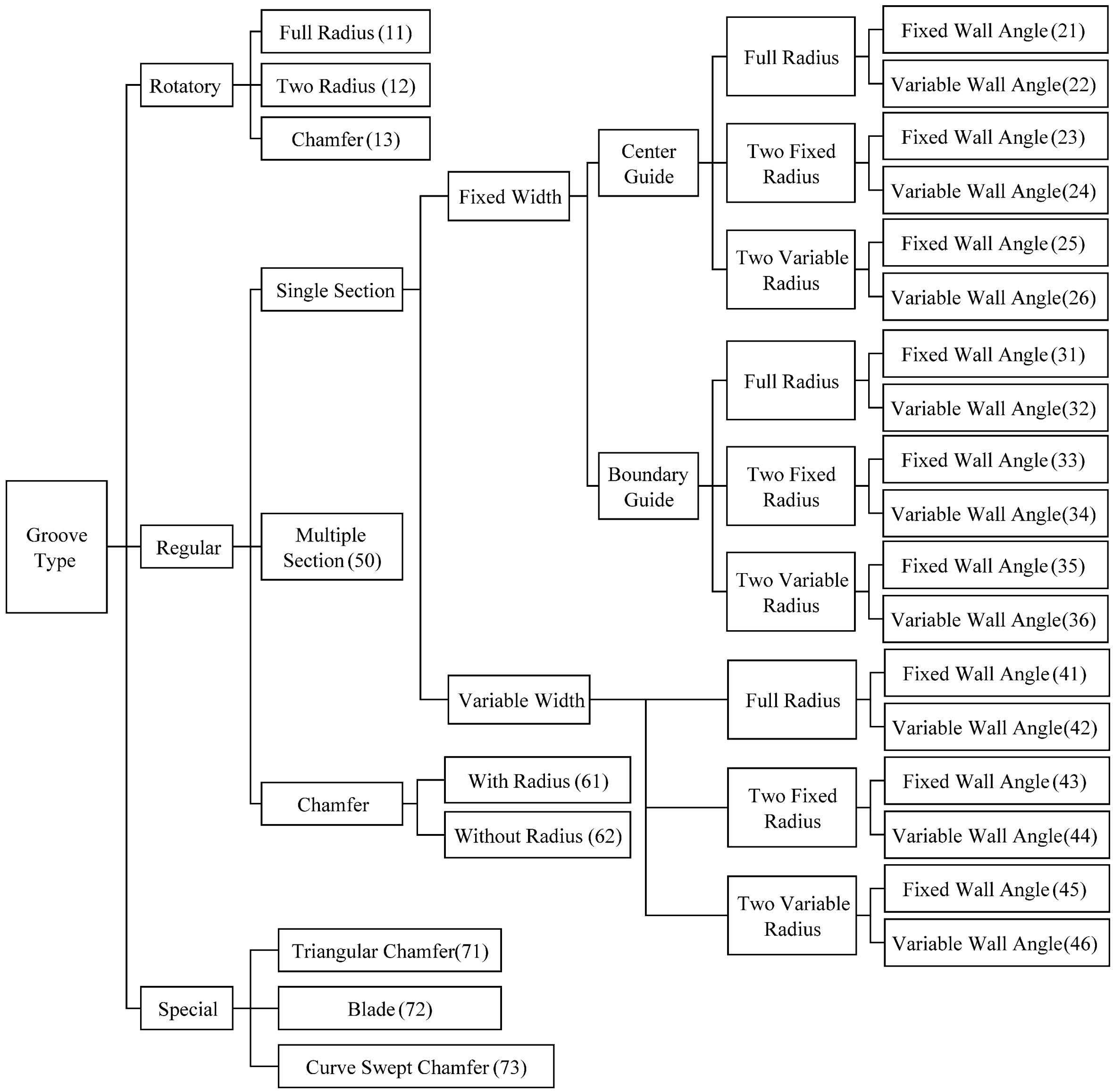


Fig. A.1. Classification of common groove shapes.

variable wall angle. The same classification also applies to the second group, *variable width* (Types 41–46). In this case, the user can only specify the boundary curves, as the groove width varies on the road surface. The grooves in *multiple section* are created by the profiles given in more than two planes normal to the guide curve. Hence the modeling procedure is similar to that of the *single section* group. Note that only grooves with a variable width arise in this group. Next, the *Chamfer* group includes simple planes (*without radius*, Type 62) oblique to the regular grooves, with a rounding surface in some cases (*with radius*, Type 61).

The grooves of the last group cannot be classified into *Rotary* or *Regular*. *Triangular Chamfer* (Type 71) is a three-sided plane that usually connects two wall surfaces of regular grooves intersecting with each other. *Blade* (Type 72) is a curve generated by developing a curve into the road surface. *Curved Swept Chamfer* (Type 73) is a special chamfer surface created by sweeping a curve instead of a line in the regular case.

The design parameters that construct each groove are listed in Tables A.1–A.4, corresponding to *Rotatory*, *Regular*, *Chamfer*, and *Special* groups in the classification.

Table A.1
Design parameters for *Rotatory* Group

Parameter	Type		
	11	12	13
Groove width	ν	ν	
Chamfer wall angle			ν
Left radius		ν	
Right radius		ν	
Left wall angle	ν	ν	
Right wall angle	ν	ν	

Table A.2
Design parameters for *Regular* Group

Parameter	Type																	
	21	22	23	24	25	26	31	32	33	34	35	36	41	42	43	44	45	46
Left curve definition													ν	ν	ν	ν	ν	ν
Right curve definition													ν	ν	ν	ν	ν	ν
Guide curve definition	ν	ν	ν	ν	ν	ν	ν	ν	ν	ν	ν	ν						
Groove width	ν	ν	ν	ν	ν	ν	ν	ν	ν	ν	ν	ν						
Left wall angle	ν		ν		ν		ν		ν		ν		ν		ν		ν	
Right wall angle	ν		ν		ν		ν		ν		ν		ν		ν		ν	
Left wall angle left—start		ν		ν		ν		ν		ν		ν		ν		ν		ν
Left wall angle—end		ν		ν		ν		ν		ν		ν		ν		ν		ν
Right wall angle—start		ν		ν		ν		ν		ν		ν		ν		ν		ν
Right wall angle—end		ν		ν		ν		ν		ν		ν		ν		ν		ν
Left radius			ν	ν					ν	ν					ν	ν		
Right radius			ν	ν					ν	ν					ν	ν		
Left radius—start					ν	ν					ν	ν					ν	ν
Left radius—end					ν	ν					ν	ν					ν	ν
Right radius—start					ν	ν					ν	ν					ν	ν
Right radius—end					ν	ν					ν	ν					ν	ν
Edge or lofting option					ν	ν					ν	ν					ν	ν
Loft guide support					ν	ν					ν	ν					ν	ν

Table A.3
Design parameters for *Chamfer* Group

Parameter	Type	
	61	62
Wall angle	ν	ν
Fillet radius	ν	
Chamfer curve	ν	ν

Table A.4
Design parameters for *Special* Group

50	Left guide curve Points on left guide Left wall angles Left radii	Right guide curve Points on right guide Right wall angles Right radii
71	Tritengent curve guide Guide surface 1 Guide surface 2	Depth from road surface Check rounding surface 1 Check rounding surface 2
72	Blade curve	
73	Left curve Right curve	Start depth End depth

References

[1] A.R. Williams, Tire design, CHEMTECH 14 (12) (1984) 756–764.
[2] H. Hutchinson, Tire maker outsources CAD/CAM support, Mechanical Engineering 121 (4) (1999) 14–18.
[3] K.F. Sarver, CAD/CAM—a look at tire design engineering, Elastomerics 117 (9) (1985) 41–46.
[4] Z. Chen, M. Tu, H. Bai, Research of tire tread pattern design expert system, Journal of Wuhan University of Technology 17 (1) (1995) 85–88.
[5] S.W. Jung, S.W. Bae, G.T. Park, A design scheme for a hierarchical fuzzy pattern-matching classifier and its application to the tire tread pattern-recognition, Fuzzy Sets and Systems 65 (2–3) (1994) 311–322.
[6] J.T. Chiu, W.C. Weng, C.F. Hung, Optimization of pitch sequencing for pneumatic tire by Tabu search method, Japan Journal of Industrial and Applied Mathematics 19 (3) (2002) 399–414.
[7] J.A. Conesa, A. Fullana, R. Font, Tire pyrolysis: evolution of volatile and semivolatile compounds, Energy and Fuels 14 (2) (2002) 409–418.
[8] H.J. Pohl, Machines and complete lines for the production of tire components, Kautschuk Gummi Kunststoffe 49 (11) (1996) 790–792.
[9] R.A. Fleming, Tire molding technology in die casting and venting: an overview, Die Casting Engineer 39 (5) (1995) 111–117.
[10] J. Shah, M. Mäntylä, Parametric and Feature-Based CAD/CAM: Concepts, Techniques, and Applications, Interscience, 1995.
[11] B. Bollobas, Modern Graph Theory, Springer-Verlag, GTM, 1998.
[12] B.K. Choi, Surface Modeling for CAD/CAM, Elsevier Science, 1991.
[13] B.K. Choi, S.Y. Ju, Constant radius blending in surface modeling, Computer Aided Design 21 (4) (1989) 213–220.
[14] J.H. Chuang, C.H. Lin, W.C. Hwang, Variable-radius blending of parametric surfaces, Visual Computer 11 (10) (1995) 513–525.
[15] http://www.caav5.com.

Chih-Hsing Chu attended National Taiwan University in Taipei, Taiwan, and received his BS and MS degrees from the Mechanical Engineering Department. He worked as a visiting researcher for 1 year at the Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen, Germany. He received his PhD degree in mechanical engineering at the Laboratory for Manufacturing Automation, University of California at Berkeley. His project work at Berkeley concerned Internet-based product design and manufacturing. He worked as a web applications engineer at RedSpark Inc., an Autodesk Venture, on development of web-based collaboration software. His past work experiences also include a research intern at DaimlerChrysler AG, Stuttgart, Germany, and a technical consultant for Standford Co. Ltd., Taoyuan, Taiwan. Prior to joining National Tsing Hua University in 2002, he was on the faculty of Industrial and Systems Engineering Department, Virginia Tech, Blacksburg. His research interests include product development, collaborative design, geometric modelling, CAD/CAM, and precision manufacturing. He is a member of the SME, ASME, SCC, and PDMA.

Mu-Chi Song is a graduate student in Department of Computer Information Science, National Chiao Tung University, Hsinchu, Taiwan. He received his BS degree from the same department in 2005. His research interests include computer graphics, 3D animation, and distributed systems.

Vincent C.S. Luo obtained his MS degree from Department of Naval Architecture and Ocean Engineering, National Taiwan University, Taipei, Taiwan. He is working as a R&D deputy manager in StandFord Inc. Co., Taoyuan, Taiwan. His research interests include CAD/CAM, five-axis CNC machining, and 3D precision metrology.