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Research on and Application of Feature Recognition and Intelligent Retrieval Method for Multi-Component Alloy Powder Injection Molding Gear Based on Partition Templates

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Abstract: The forming process of multi-alloy gears by metal powder injection molding is tedious, and the current design process mainly depends on the experience of designers, which seriously affects the product development cycle and forming quality. In order to solve the problem of the gear feature expression being missing, which hinders the automatic retrieval of similar parts in the analogical design process, a feature recognition and intelligent retrieval method for a multi-alloy powder injection molding gear based on partition templates is proposed in this paper. The partition templates of the gear are defined, and gear digitization is completed by using the automatic recognition algorithm. Searching for similar gear parts in the knowledge base, designers can analogically design the forming process for new parts according to the mature process of the parts in the knowledge base. The automatic identification and intelligent retrieval system developed according to this method has been implemented in two MIM (metal injection molding) product manufacturing enterprises. Case studies and industrial applications have proved the effectiveness of the system, the efficiency of identification and retrieval has been improved by more than 97%, and the number of mold tests has been reduced by 60%.

Keywords: multi-alloy gear; MIM; forming process; automatic identification; intelligent retrieval

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1. Introduction

The gear is a standard transmission component that plays an irreplaceable role in the aerospace industry, military applications, automobile manufacturing, precision instruments, 3C products, and other fields [1,2]. The multi-alloy gears made by metal powder injection molding technology can not only improve the strength, hardness, corrosion resistance, and wear resistance of gears but can also improve production efficiency and meet the needs of large-scale production [3–7]. The multi-alloy gear powder injection molding process is tedious and complex and includes feedstock process design, injection mold design and manufacture, and the injection process, degreasing process, and sintering process, which require a high level of knowledge for designers. This knowledge can only be realized through years of practical experience [8–11]. At present, the design process for multi-element alloy gear powder injection molding basically relies on the designer's technology and experience to complete the trial-and-error process. Even with mature process experience with similar parts, designers still need to rely on memory and experience for analogical design through text retrieval, and the retrieval process is complex, slow, and often inaccurate. Therefore, it is of great significance to realize the analogical design of the multi-alloy gear metal powder injection molding process through automatic feature recognition and intelligent retrieval.

In the manufacturing field, feature recognition is a method to obtain geometric shapes or parameter sets with certain engineering significance from the CAD model of parts [12–14], which mainly includes pattern recognition methods based on rules and graphs, voxel recognition methods based on topological relations, and information recognition methods based on processing units [15–18]. Different recognition methods are used for different recognition purposes. Gear feature recognition for the purpose of analogical design is generally based on rule and graph pattern recognition. Hao Yang et al. [19] define the feature parameters of rotating parts by fillet, height, length, and other key dimensions. According to the structural characteristics of round cup parts, Choi et al. [20] use feature lines to extract key dimensions to describe the structural features of parts. Liang Guo et al. [21] proposed a method of process feature recognition in the bevel gear shaft manufacturing field based on knowledge graphs. This method systematically forms a product processing path by identifying the knowledge graph, production rules, and two-dimensional data-linked list of the gear shaft. Xinxin Lu et al. [22] define geometric deviation parameters such as tooth surface deviation and tooth thickness deviation to represent the complex spatial characteristics of face gears and put forward a mathematical model for accurate measurement of planar gears, which can accurately predict the accuracy error of gears by identifying characteristic parameters. Zehua Lu et al. [23] defined 46 gear features as target parameters, including tooth profile, material, machining accuracy, and other information through parameter calculation and adjustment to achieve the purpose of lightening the product. Omar D.M. [24] defined gear geometry, torsion, and meshing requirements as characteristic parameters. By identifying and calculating characteristic parameters, the influence of tooth profile micro-geometry on gear performance is discussed. Wenzheng Liu et al. [25] carried out dynamic analysis and fault diagnosis of gears by identifying the characteristics of cracks, pitting, and other defects. The above feature definition and recognition focus on the parameters which are easy to calculate and measure, such as tooth profile and accuracy, and the feature expression of gears should include two parts: one is fixed feature expression, including modulus, tooth number, and other tooth profile features, and the other is non-fixed feature expression, including gear structure and local features. The difference between the special rotary structure and external interface of gears increases the difficulty of gear feature description. In recent years, the feature recognition of gears has mainly focused on the recognition of measured signals to detect gear faults [26–29]. At present, there is no recognition method for gear structure features.

Building on extensive research into feature expression and feature recognition in various 3D models, this paper proposes a feature recognition and intelligent retrieval method for a multi-alloy powder injection molding gear based on partition templates. By defining the partition templates of a cylindrical spur gear, the digital calculation of the gear model is completed automatically. And through the intelligent retrieval algorithm based on similarity calculation, a similar model can be found in the knowledge base, and then designers can use this information to analogically design the forming process of gear products based on the mature process of similar models. Based on this method, we have developed an automatic identification and intelligent retrieval system that significantly improves the manufacturing efficiency and quality of products. Above all, the main sections of this paper are as follows:

1. Section 1 provides a summary of the research conducted with the existing methods for feature parameterization.
2. Section 2 introduces the process of this method and the gear partition templates defined by this method in detail.
3. Section 3 introduces the two key algorithms of feature recognition and intelligent retrieval. Section 3.1 introduces the tooth profile parameter calculation formula and structure parameter identification process in detail, and Section 3.2 introduces the similarity calculation formula and weight automatic adjustment.
4. Section 4 is the intelligent system implementation and results discussion. The intelligent system is developed based on the NX platform. The experimental result shows the superiority of the system.

5. Section 5 is the conclusion. In this section, the advantages of the method and the future work are detailed and summarized.

2. Feature Identification and Intelligent Retrieval Method

2.1. Flow of the Method

The method flow for the feature recognition and intelligent retrieval of a multi-alloy powder injection molding gear based on partition templates is illustrated in Figure 1. The input to this method is a 3D gear model. Through two processes, namely property definition and feature recognition, the 3D model is transformed into a parameters model. Subsequently, a similarity calculation is employed to identify similar models in the knowledge base. Then, the process information for similar parts is called up in the product library. Designers can use the analogical design information for the process flow of the current parts.

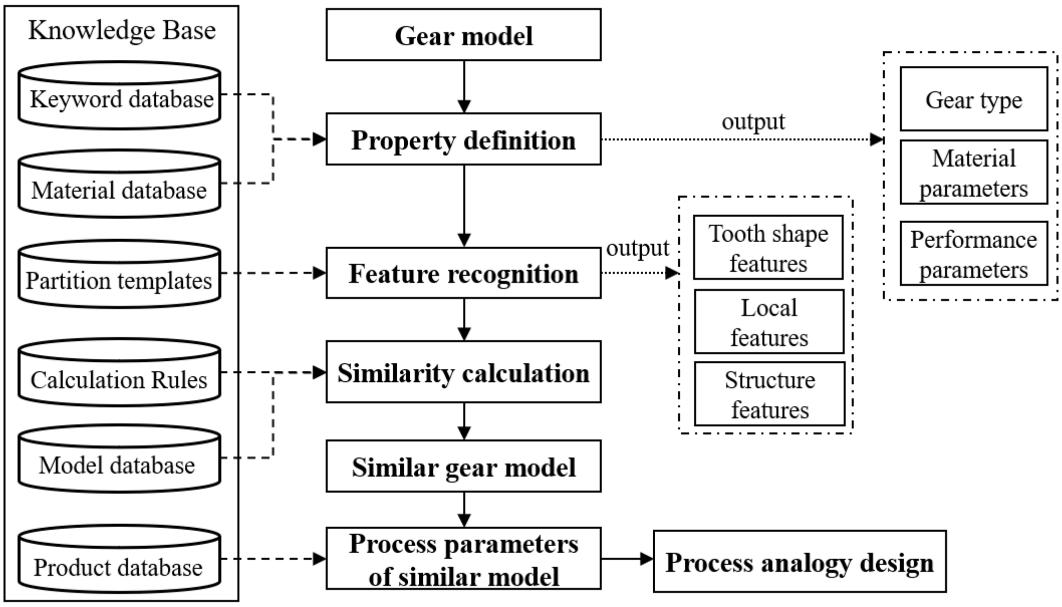


Figure 1. The method flow for feature recognition and intelligent retrieval of multi-alloy powder injection molding gear based on partition templates.

The property definition module is a human-computer interaction module, where designers manually input parameter values that cannot be automatically identified by the algorithm. These values include gear type, gear material, and gear performance. The parameter names are determined by the keyword database and material database in the knowledge base. The input to this module is a 3D gear model, and the output includes gear type parameters, material parameters, and performance parameters such as gear accuracy, gear strength, and gear bearing capacity.

Feature recognition is the process of digitizing the gear model. The algorithm automatically extracts the geometric features and topological relations from the gear model and calculates the gear feature parameters, including tooth profile feature parameters, local feature parameters, and structure feature parameters, which are determined based on the preset partition feature templates. The input to this process is the 3D gear model, and the output is the gear's characteristic parameters.

Similarity calculation is the process of retrieving similar gears in the knowledge base. According to the similarity calculation formula, the algorithm traverses the characteristic parameters of the same type of gear stored in the knowledge base and calculates the similarity with the characteristic parameters of the gear. Gears whose similarity is within the threshold are similar models. Then, the system calls out the process information of the similar model from the product database, which is convenient for designers to carry out analogical design. The input model is the characteristic parameters of the gear and the outputs are the similar gear models and the process information.

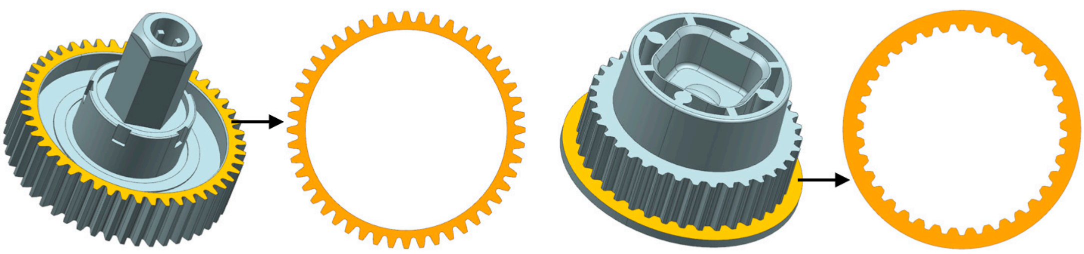
Therefore, the feature recognition and intelligent retrieval method for a multi-alloy powder injection molding gear based on partition templates automatically completes the keyword retrieval and design condition input, which depends on the experience of the designer and ensures the accuracy and stability of analogical design. The advantages of this method are summarized as follows:

1. To reduce the dependence on the designer's experience: through summarizing the method and experience, establish the gear feature partition templates, realize the digitization of the gear model, and intelligently retrieve the similar model through the similarity calculation and greatly reduce the dependence on the designer's experience;
2. To improve design efficiency: the use of mature process information of similar parts is helpful to realize the analogical design of the metal powder injection molding process for multi-alloy cylindrical spur gears and can significantly improve the design efficiency;
3. To reduce design errors: utilizing intelligent retrieval based on similarity matching with mature knowledge at the product level can help control design error to a lower level.

2.2. Partition Templates

Cylindrical spur gears have different shapes and structures. In order to accurately express the structure of the gear, this method proposes the concept of partition templates. Since the gear has a rotary structure, the shape and structure of the gear can be represented by cross-section lines. The cross-section lines are divided into several areas based on special points. The structural characteristics of the gear can be represented by the combination of each partition template. The accuracy of the partition templates determines the accuracy of tooth number feature recognition, which in turn affects the accuracy of knowledge reuse. Therefore, the partition templates are the basis of this method.

The premise for dividing the section line is to define the gear surface. The plane in the gear that contacts the tooth shape is the gear surface. As shown in Figure 2, there are two situations for the gear surface of cylindrical spur gears: one is TOC (tooth is outer contour), which is the outer contour of the gear surface. The line is the tooth shape. The other is TIC (tooth is inner contour); that is, the inner contour line of the gear surface is the tooth shape.



(**a**) (**b**)

Figure 2. The two situations for the gear surface of cylindrical spur gears: (**a**) The tooth shape is the outer contour. (**b**) The tooth shape is the inner contour.

The cylindrical spur gear feature templates are divided into two situations according to the different tooth surfaces, as shown in Figure 3. One is that both tooth surfaces of the gear are TOC (the gear model is shown in Figure 2a), and the other is the gear in which the two tooth surfaces are TOC and TIC, respectively (the gear model is shown in Figure 2b). The section line partitions of cylindrical spur gears include the main interface area, main reinforcement area, toothed area, vice reinforcement area, vice interface area, and via area. The tooth shape area template has no parameters, and the tooth shape parameter calculation is shown in Section 3.1.1.

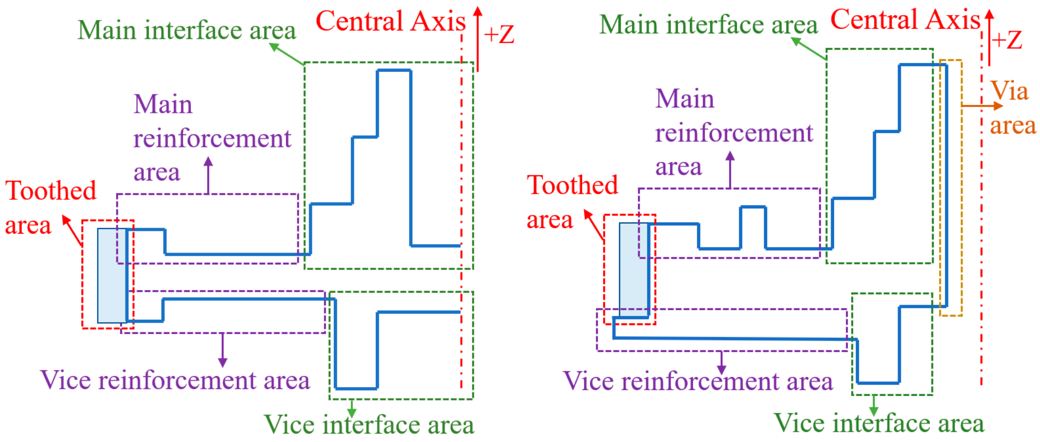
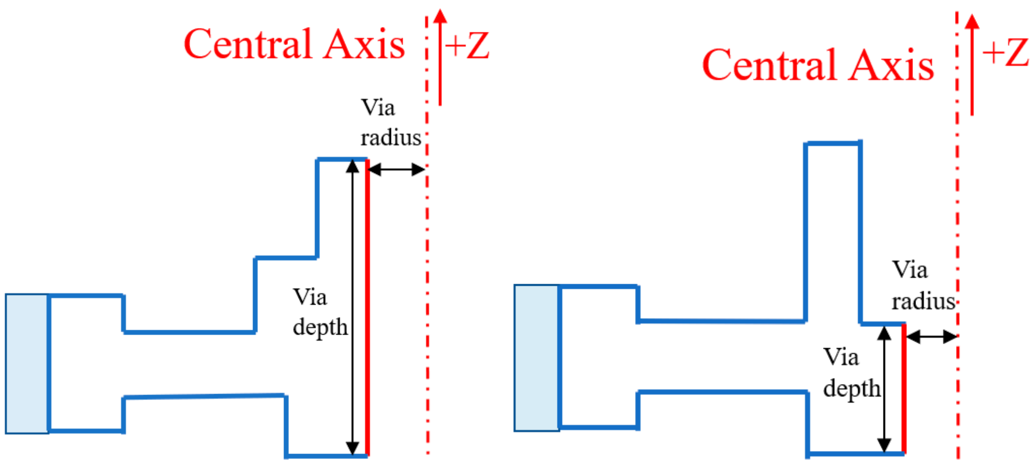


Figure 3. The two situations for the cylindrical spur gear feature templates: (**a**) Both tooth surfaces are TOC. (**b**) The two tooth surfaces are TOC and TIC, respectively.

2.2.1. Via Area

The via area refers to the through hole of the gear with the central axis as the center, and the parameters include the through hole radius and the through hole depth. The through holes of gears can take two forms: the through hole and stepped through hole. The cross-sectional lines are shown in Figure 4 (the red line denotes the via area). For gears with stepped through-holes, the via area is the first-order through hole with the hole boundary closest to the central axis. The via area is an unnecessary partition template. In some gear structures, the via area does not exist. By identifying whether there is an intersection between the section line and the central axis, it is determined whether the gear model has a via area.



(**a**) (**b**)

Figure 4. The two situations for the via area: (**a**) through hole and (**b**) stepped through hole.

2.2.2. Reinforcement Area

The reinforcement area referred to in cylindrical spur gears is the area that connects the toothed area with the gear's external interface (as shown in the red surface of the example column in Table 1). There are eight types of reinforcement areas. The cross-sectional line shapes of each type and corresponding examples and parameters are shown in Table 1. Both the main reinforcement area and the vice reinforcement area in cylindrical spur gears share the same partition templates. However, they differ in that their normal directions are opposite.

Table 1. Reinforcement area types and parameters.

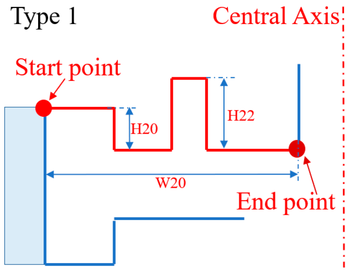
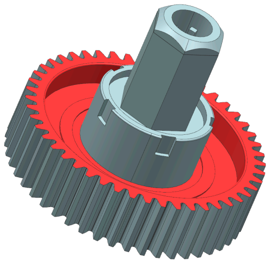
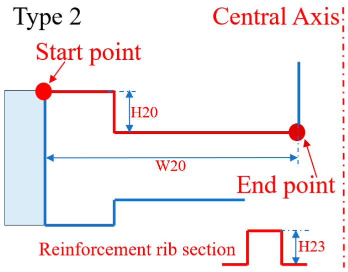
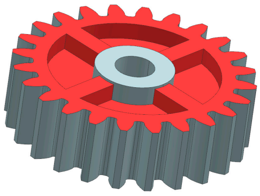
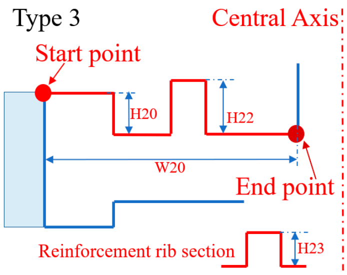
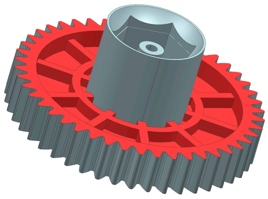
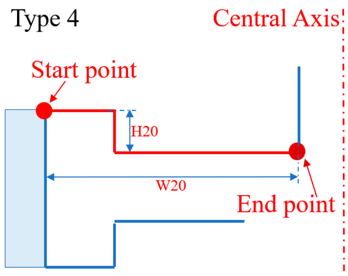
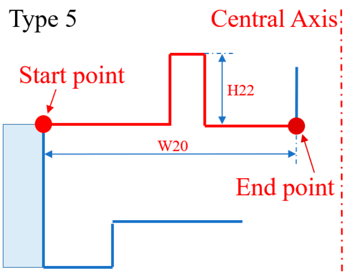
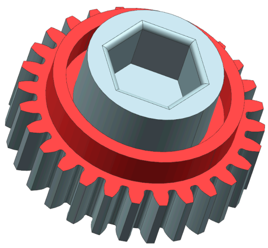
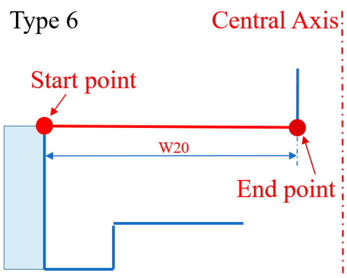
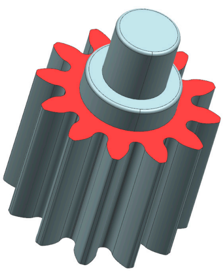
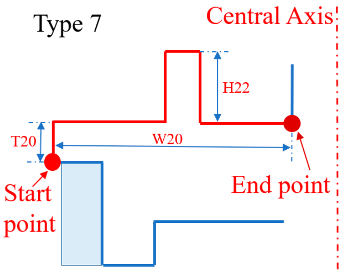
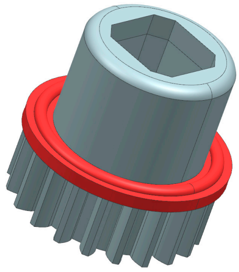
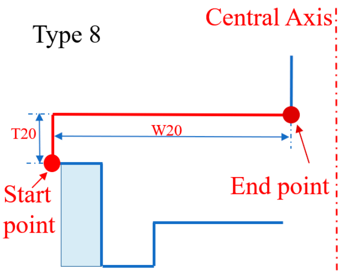
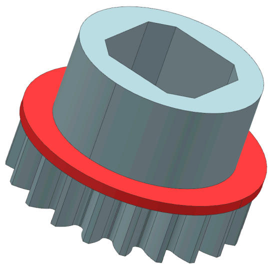
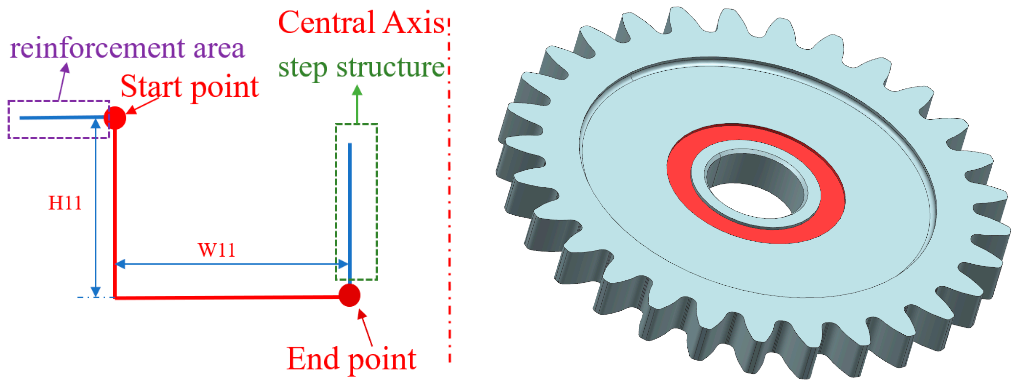
Type	Example	Feature Parameters
Type 1 		W20: Reinforcement area length H20: Reinforcement area depth H22: Ring rib height
Type 2 		W20: Reinforcement area length H20: Reinforcement area depth H23: Reinforcement rib height N23: Number of Reinforcement ribs
Type 3 		W20: Reinforcement area length H20: Reinforcement area depth H22: Ring rib height H23: Reinforcement rib height N23: Number of Reinforcement ribs
Type 4 		W20: Reinforcement area length H20: Reinforcement area depth
Type 5 		W20: Reinforcement area length H22: Ring rib height
Type 6 		W20: Reinforcement area length

Table 1. *Cont.*

Type	Example	Feature Parameters
Type 7 		W20: Reinforcement area length T20: Reinforcement area thickness H22: Ring rib height
Type 8 		W20: Reinforcement area length T20: Reinforcement area thickness

2.2.3. Interface Area

The interface area in cylindrical spur gears refers to the area that connects to external components. In this study, the interface area of the gear is defined as a combination of three sub-feature structures: the groove structure, step structure, and hole structure. The cross-section line of the groove structure is shown in Figure 5a, with an example shown in the red side of the gear model in Figure 5b. The groove parameters include the groove depth H11 and the groove width W11; the starting point of the groove structure is connected to the reinforcement area, and the end point is connected to the step structure of the interface area.



(**a**) (**b**)

Figure 5. The groove structure: (**a**) the cross-section line of groove structure and (**b**) example model.

There are two types of step structures, as indicated in red in the example column of Table 2. The section line structures of each type, along with corresponding examples and parameters, are detailed in Table 2.

There are two types of hole structures, as shown in Table 3. The red line in the type column is the section line of the hole structure. The gear model in the example column includes these two structures, the red cross-section line is type 1, and the purple cross-section line is type 2. The feature parameters column lists the parameters corresponding to the two structures.

Table 2. Step structure types and parameters.

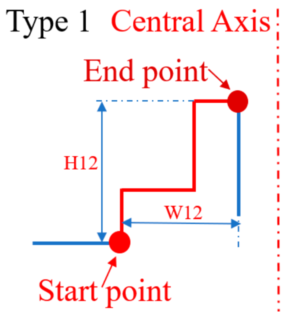
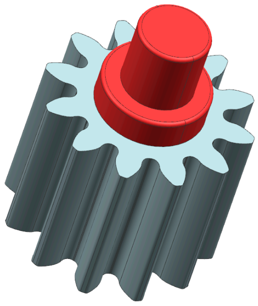
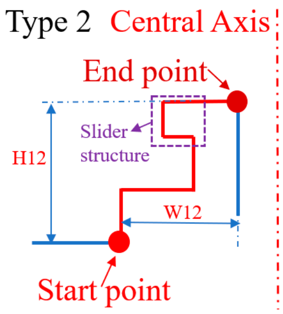
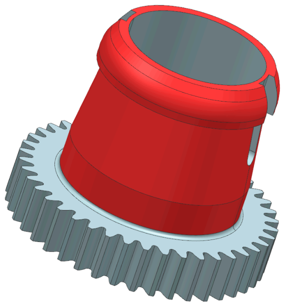
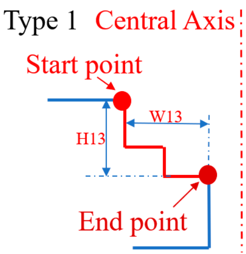
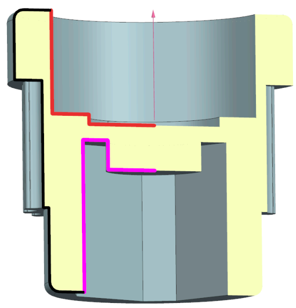
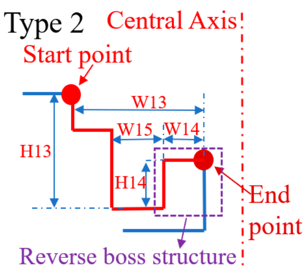
Type	Example	Feature Parameters
		W12: Step structure length H12: Step structure height N12: Number of steps False: No slider structure
		W12: Step structure length H12: Step structure height N12: Number of steps True: Exists slider structure

Table 3. Hole structure types and parameters.

Type	Example	Feature Parameters
		W13: Hole structure radius H13: Hole structure depth N13: Number of steps in the hole
		W13: Hole structure radius H13: Hole structure depth N13: Number of steps in the hole W14: Reverse boss structure radius H14: Reverse boss structure height N14: Number of reverse boss steps W15: Groove width

The interface area is a combination of three sub-feature structures, with five types, as shown in Figure 6. The parameters of each type are a combination of corresponding sub-feature structure parameters. Both the main interface area and the vice interface area share the same partition templates, differing only in their opposite normal directions. The interface area is a non-essential partition template. In some gear structures, the interface area does not exist.

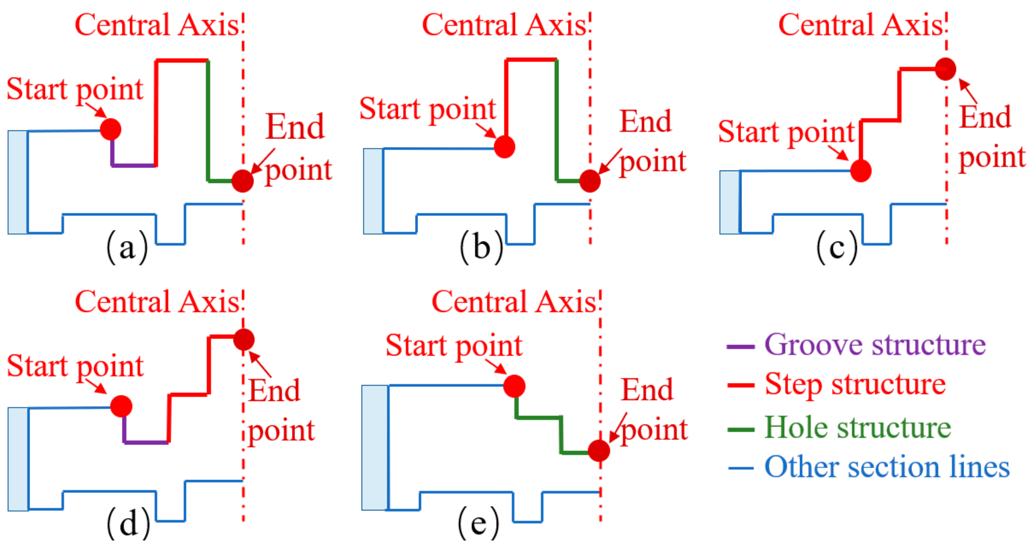


Figure 6. The five situations for the interface area: (**a**) Type 1: groove + step + hole. (**b**) Type 2: step + hole. (**c**) Type 3: step. (**d**) Type 4: groove + step. (**e**) Type 5: hole.

2.2.4. Overall Structure

In metal powder injection molded cylindrical spur gears, the overall structural type consisting of the main reinforcement area and vice reinforcement area types is a key factor influencing the molding process. There are eight types of overall structure, with the cross-section lines and parameters of each type detailed in Table 4. Type 1, type 2, and type 3 are classified as Web class; type 4 and type 5 are categorized as T class; type 6 and type 7 are defined as Thicken class; and type 8 is Normal class. In the design of the MIM forming process, gears within the same class exhibit similar mold gate design and parting surface design in the mold structure. Consequently, the forming process parameters are also similar for gears within the same class. The gears belonging to different classes do not have the condition of analogy design in the forming process design.

Table 4. Overall structure types and parameters.

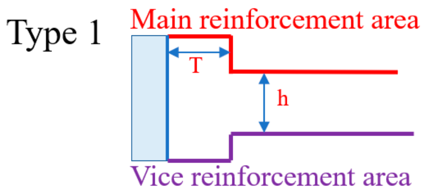
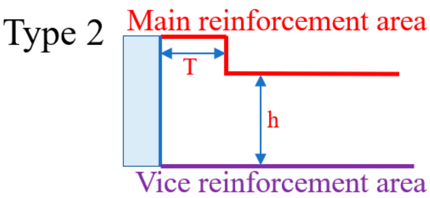
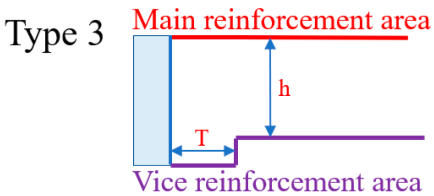
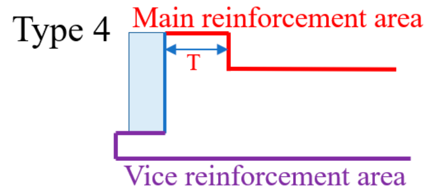
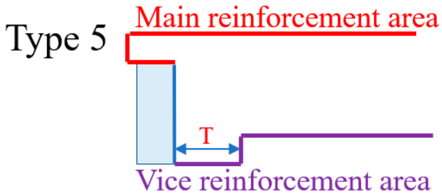
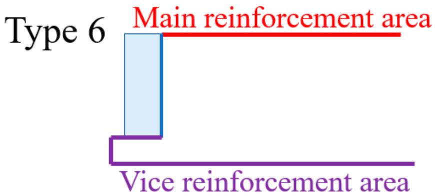
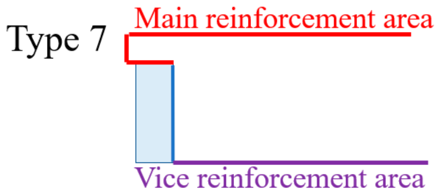
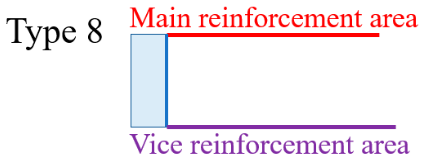
Type	Subtype	Feature Parameters
Web		T: Gear radial thickness h: Web thickness
		
		

Table 4. *Cont.*

Type	Subtype	Feature Parameters
T	 	T: Gear radial thickness
Thicken	 	None
Normal		None

3. Key Algorithm

3.1. Feature Recognition

Feature recognition is an automated process of gear digitization accomplished by the algorithm, which includes three parts: (1) calculation of tooth profile parameters, (2) identification of local feature parameters (calculation of the number, location, and size), and (3) identification of structural parameters based on partition templates. The input model for feature recognition is the PD (property-defined) gear model (the gear model's added properties), and the output model is the gear feature parameter group.

Figure 7 shows the automatic feature recognition process based on the partition templates. Initially, all gear faces are traversed to determine the gear surfaces, enabling the extraction of the tooth profile and calculation of tooth shape parameters. Subsequently, local features are identified through the surface topological relationship. Finally, section lines are created and simplified, and structural parameters are identified according to the partition templates.

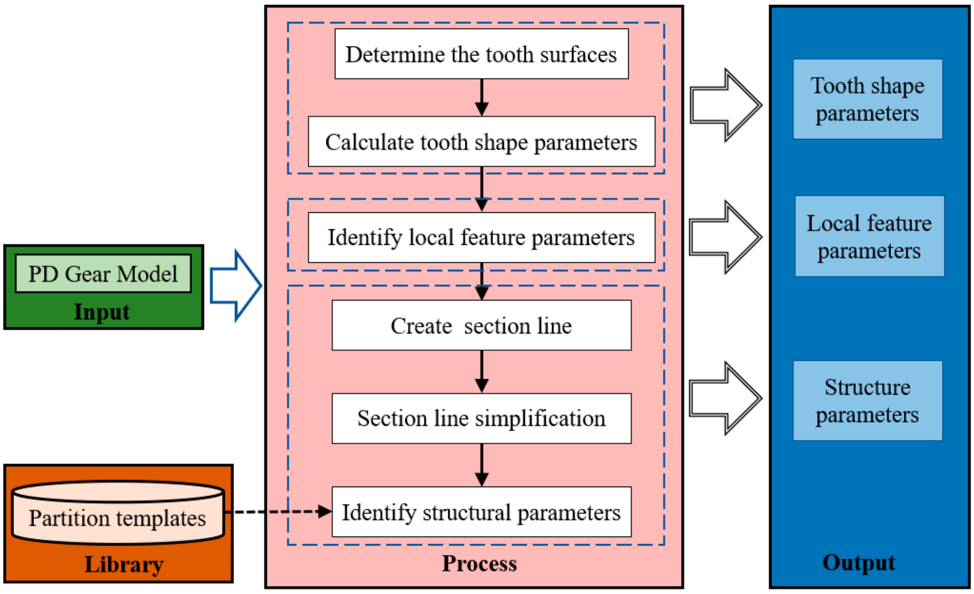


Figure 7. Feature automatic recognition process based on partition templates.

3.1.1. Tooth Shape Parameters and Local Feature Parameters

The tooth shape parameters are divided into main parameters and secondary parameters. The main parameters include m (modulus), Z (tooth number), α (pressure angle), x (modification coefficient), and b (tooth width). The secondary parameters include h_a* (tooth top height coefficient), c* (top clearance coefficient), d (indexing circle diameter), d_b (base circle diameter), h_a (tooth top height), h_f (root height), h (full-tooth height), d_a (tooth tip circle diameter), d_f (tooth root circle diameter), p (tooth distance), s (tooth thickness), e (tooth slot width), ρ_a (tooth tip inverted circle radius), and ρ_f (root guide circle radius).

Figure 8 shows the calculation flow of tooth shape parameters. Initially, the TIC-type tooth surface is determined, with the center of the tooth surface serving as the origin and the axis through the origin and consistent with the normal direction of the face as the central axis. The outer profile of TIC is then extracted as the tooth profile, and the parameters Z, b, d_a, d_f, ρ_a, ρ_f are measured and calculated, and the remaining parameters are calculated using Formula (1)–(10). Due to the error of the model and the uncertainty of the coefficient, the obtained tooth shape parameters are approximate. The module provides a human-computer interface, allowing users to modify these parameters values.

$$h = \left(d_a - d_f\right)/2 \tag{1}$$

$$m = h/(2 \times h_a^* + c^*) \tag{2}$$

$$d = m \times Z \tag{3}$$

$$d_b = d \times cos\alpha \tag{4}$$

$$h_a = (d_a - d)/2 \tag{5}$$

$$h_f = \left(d - d_f\right)/2 \tag{6}$$

$$x = (h_a - m \times h_a^*)/m \tag{7}$$

$$p = \pi \times m \tag{8}$$

$$s = (p/2) + |2mx \times tan\alpha| \tag{9}$$

$$e = p - s \tag{10}$$

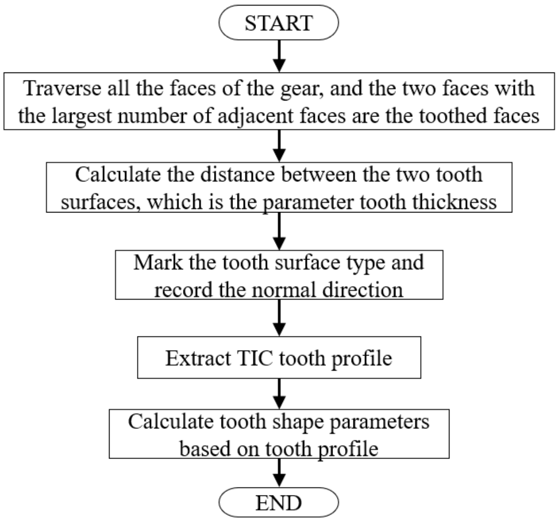


Figure 8. Tooth shape parameter calculation process.

The gear's local features comprise the local hole, local groove, convex platform, external mounting column, inner gear baffle, and outer gear baffle. These features are identified based on the topological relationship of the surface [30,31], with feature parameters including size, position, and quantity. Taking the convex platform as an example, the characteristic parameters include the width of the convex platform, the length of the convex platform, the height of the convex platform, the number of the convex platform, the distance between the center axis of the convex platform, and the central shaft of the gear, and the convex platform is on one side of the main gear surface or the side of the secondary gear surface. It is worth noting that local feature parameters are considered unnecessary in some cases because these gears have no local features.

3.1.2. Structure Parameters

The gear structure feature recognition mainly includes four steps:

Step 1: Distinguishing the main tooth surface and the vice tooth surface and establishing the recognition coordinate system;

Step 2: Creating the section line according to the position of the local feature and fan-shaped surface;

Step 3: Optimizing the section line;

Step 4: Identifying the gear structure feature parameters according to the partition templates and outputting the recognition results.

The result of each step is shown in Figure 9.

The establishment of the identification coordinate system hinges on distinguishing between the main tooth profile surface and the vice tooth profile surface of the gear. The type and normal direction of the tooth profile surface are identified in Section 3.1.1. As shown in Figure 10, the distance between the top and bottom surface of the model and the tooth profile surface are recorded as h1 and h2, respectively. If h1 > h2, then tooth surface 1 is the main tooth surface; otherwise, tooth surface 2 is the main tooth surface. If the main tooth surface is TOC, the normal direction of the main tooth surface is the Z direction of the identification coordinate system, and if the main tooth surface is TIC, the reverse direction of normal for the main tooth surface is the Z direction of the identification coordinate system. By establishing the coordinate origin at the center of the main tooth surface and selecting any direction within the main tooth surface as the X direction of the identification coordinate system, the recognition coordinate system is created.

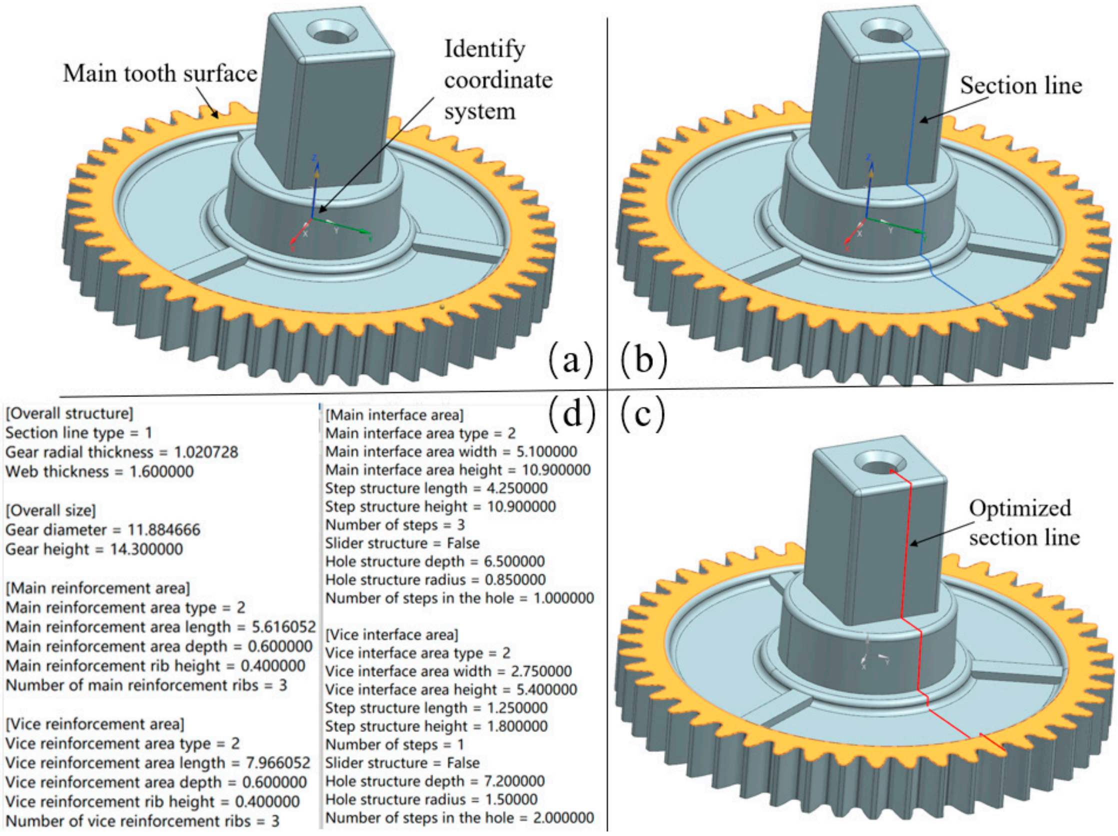


Figure 9. Four steps of gear structure parameter recognition: (**a**) creating identification coordinate system; (**b**) creating section lines; (**c**) section line optimization; (**d**) output structure feature parameters.

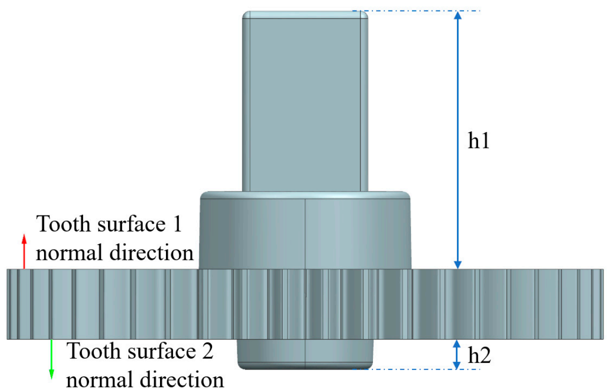


Figure 10. Determining the main tooth surface.

If there are no ribs and local features in the gear model, we can create a section line by identifying the coordinate system XOZ plane. If there are ribs or local features in the gear model, you need to avoid the above structure to create the section line. Take the gear shown in Figure 11 as an example; there are ribs on both sides of the gear, and the fan-shaped surface is distributed between the ribs. First, the fan-shaped surface is grouped according to the normal direction of the fan surface and the end Z value in the identification coordinate system. Secondly, one of the fan-shaped faces in any group traverses with the other group members to find an overlap area, as shown in Figure 12; finally, a section line is created in the middle of the overlap area.

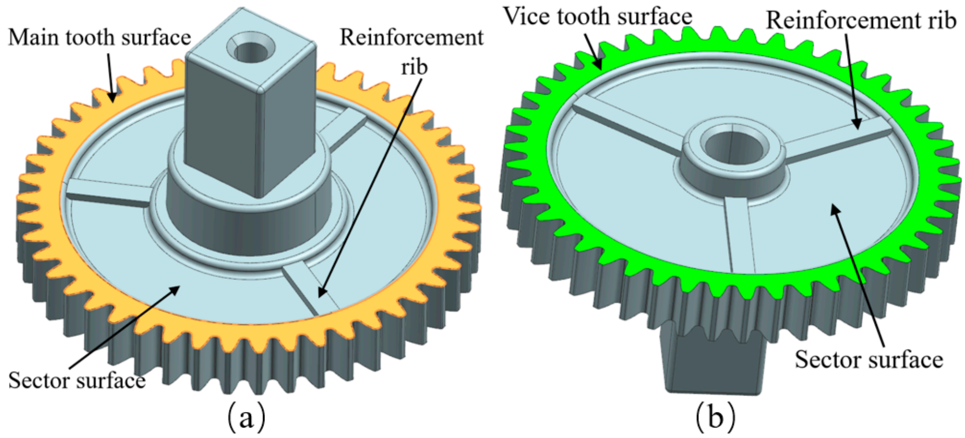


Figure 11. Sector surface distribution: (**a**) Sector surfaces on one side of the main gear surface. (**b**) Sector surfaces on one side of the vice gear surface.

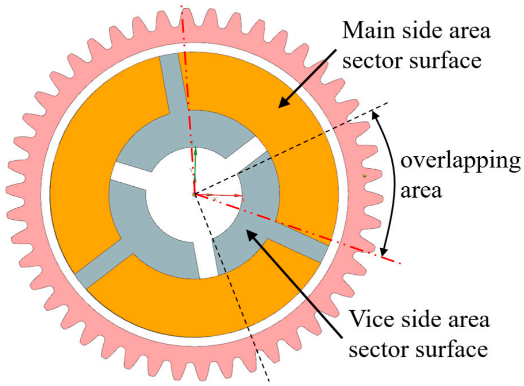


Figure 12. Calculation of overlap area of sector surfaces.

The optimization of the section line is the process of eliminating noise and standardizing the section line. As shown in Table 5, the optimization part includes: removal of round corner and chamfer, arc reconstruction, removal of microgroove, removal of micro convex structure, removal of thread, etc.

The optimized cross-section line is segmented into the primary side cross-section line and the secondary side cross-section line is based on the gear surface position, and the partition structure type and parameters of the gear are calculated according to the partition templates set in Section 2.2.

Table 5. Section line optimization processing.

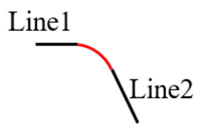
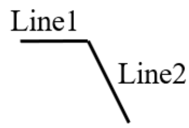
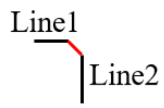
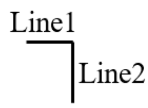
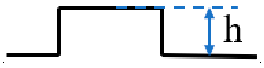
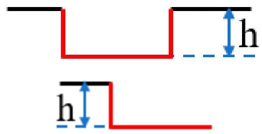
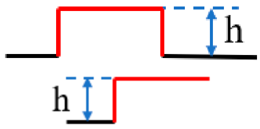
Type	Before Optimization	After Optimization
Removal of round corner		
Removal of chamfer		

Table 5. *Cont.*

Type	Before Optimization	After Optimization
Arc reconstruction		h < default value h ≥ default value 
Removal of microgroove		h < default value
Removal of micro convex structure		h < default value
Removal of thread		

3.2. Intelligent Retrieval of Similar Gear Models

Figure 13 illustrates the process flow for the intelligent retrieval of similar gears. This retrieval process is based on calculating the similarity of feature parameters and recommending library part models with high similarity. Designers or design systems can then utilize the mature manufacturing processes of the library parts to design the manufacturing process for the new parts, thereby enabling knowledge reuse.

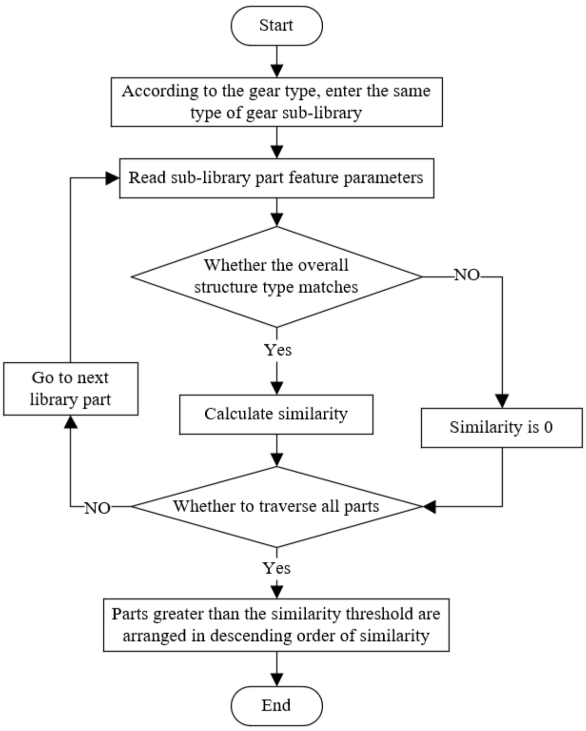


Figure 13. Intelligent search process.

As depicted in Figure 14, the similarity calculation for gear products encompasses material similarity, shape similarity, performance similarity, and a judgment on additional condition consistency. The last refers to user-specified conditions, such as mold structure and hole number. Initially, the process evaluates these additional conditions. If the conditions are not met, the product similarity is 0. Conversely, if there are no additional conditions or they are met, the similarity calculation proceeds. This calculation is divided into three main categories: material similarity, shape similarity, and performance similarity, each assigned a respective weight, with the total summing to 1. Shape similarity further includes tooth profile similarity, local feature similarity, and structural similarities similarity, and the feature parameters corresponding to each part are automatically recognized feature parameters. The sum of the similarity weight for these three categories also equals 1.

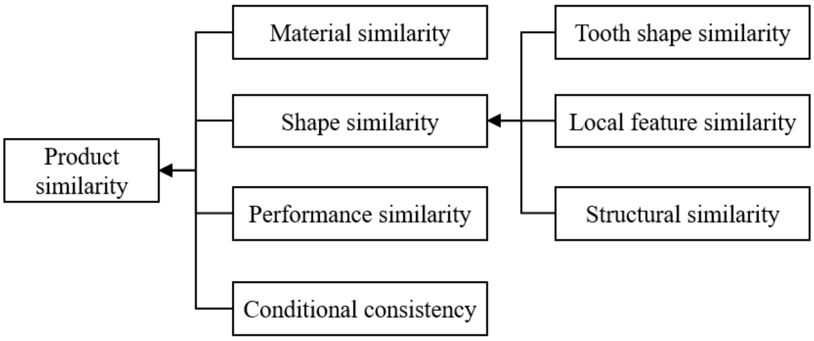


Figure 14. Calculation structure of product similarity.

3.2.1. Similarity Calculation Formula

The similarity between the target model and the library model is calculated by weighted method, that is, the set value of the characteristic parameters of the target model is x, $x = (x_1, x_2, x_3, \ldots, x_n)$. The set value of the characteristic parameters of the library model is y, $y = (y_1, y_2, y_3, \ldots, y_n)$; then, the similarity between them is calculated by Formula (11).

$$sim = \sum_i a_i * sim(x_i, y_i) \tag{11}$$

Here, a_i is the corresponding weight, and sim(x_i, y_i) is the similarity of the feature parameter i between the template partition and the target partition. The expert scoring method is used to determine the weight of each feature parameter in the similarity calculation. The characteristic parameters of gears include numerical attributes and Boolean attributes, and the calculation methods of similarity are not the same. For numerical types, such as partition size, the similarity can be calculated by Equation (12):

$$sim(x_i, y_i) = \begin{cases} 1 - \frac{|x_i - y_i|}{max(x_i, y_i)} & x_i \neq 0 \; and \; y_i \neq 0 \\ 1 & x_i = y_i = 0 \end{cases} \tag{12}$$

The Boolean-type characteristic parameters are calculated according to the Boolean value, the Boolean value is the same, the weight is 1, the Boolean value is different, and the weight is 0.

3.2.2. Weight Adjustment

The gear structure is composed of the subtypes of each partition template. When calculating the similarity between gears with different partition structures, it is necessary to adjust the weight of the parameters. The principles of weight adjustment are as follows:

1. If the structures of the two gears being compared are inconsistent, calculate the similarity based on the gear structure with a larger number of partition templates;
2. If the two gears being compared lack a certain area, the weight of the area is evenly distributed to other areas. For instance, if a gear structure lacks a main interface area,

distribute the weights of the main interface area evenly to the overall structure, the main reinforcement area, the vice reinforcement area, and the vice interface area;

3. If neither gear has a via area, add the weight of the via area to the overall structure weight;
4. If the slider structure does not exist in the two gear interface areas involved in the calculation, the weight will be added to the step structure weight in the interface area;
5. If the hole reverse structure is not present in the interface areas of both gears, add the weight to the hole structure weight in the interface area.

4. System Implementation and Case Studies

The proposed multi-alloy cylindrical spur gear automatic identification and intelligent retrieval system for metal powder injection molding is implemented as an intelligent CAD system that is seamlessly integrated with NX, which is an interactive CAD/CAE/CAM system with high-performance design functions that provide high performance and flexibility for design and manufacturing [32].

The system architecture has four layers, as shown in Figure 15: user, application, data, and driver. The user layer includes menus, dialogs, and tips; the interactive dialogs between the designer and the system are used to obtain the user's intention and parameters.

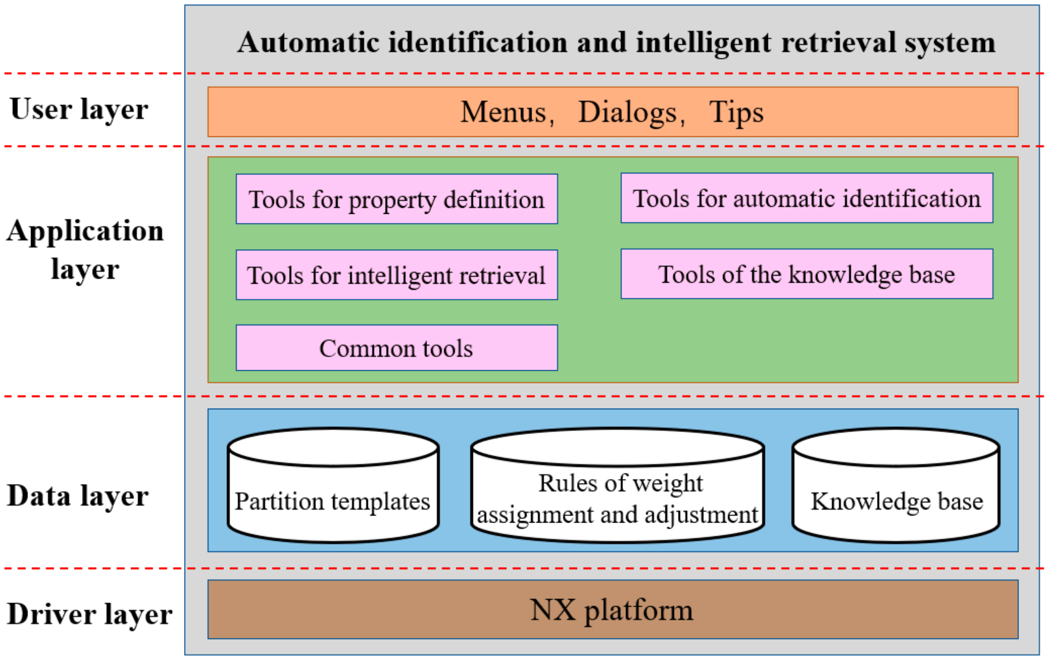


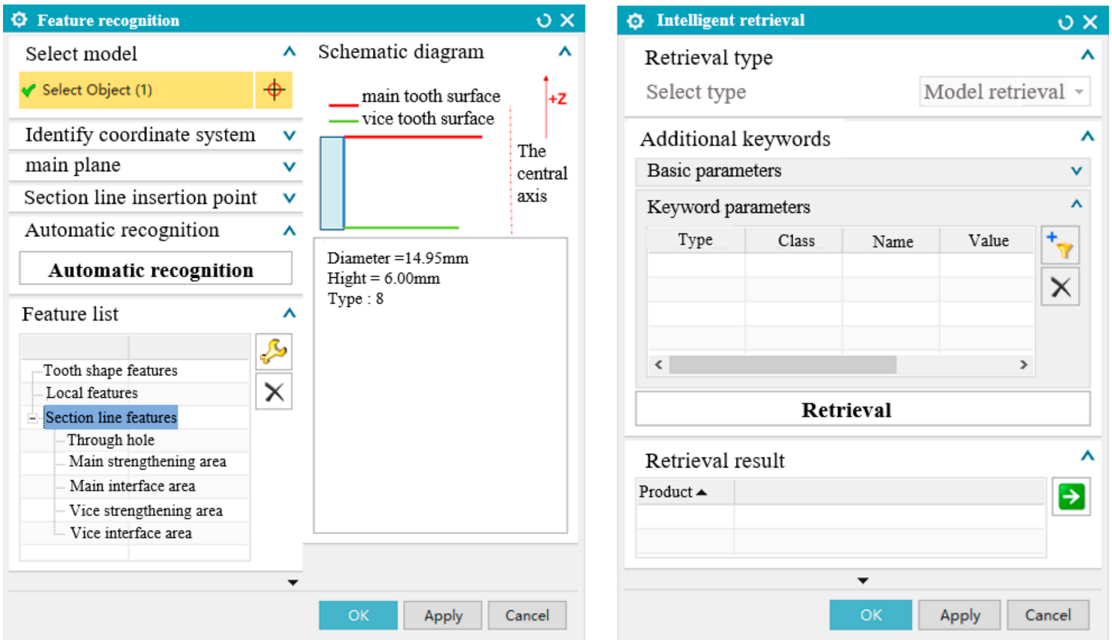
Figure 15. System architecture.

The application layer is the main program interface and core module of the system, which consists of five submodules: (1) Tools for property definition are used to define parameters that cannot be automatically recognized, such as gear type, gear material, and machining accuracy, and the output is a gear model with additional attribute parameters. (2) Tools for automatic identification are used to recognize tooth profile parameters, local characteristic parameters, and structural parameters of gears. (3) Tools for automatic identification are used to search similar parts in the knowledge base. (4) The tools of the knowledge base are tools for maintaining the knowledge base, including uploading, downloading, creating, deleting, previewing, etc. (5) The common tools are a set of simple tools that are useful to designers, for instance, select point.

The data layer consists of three parts: partition templates, rules of weight assignment and adjustment, and knowledge base, which are the basis of automatic identification and intelligent retrieval and can be customized by enterprises.

The driver layer is the NX software (NX 11.0.2.7), which provides all API functions for the system. MenuScript is utilized to link the system menu with the user interface, and NXUIStyler is used for designing system interfaces. NX/OPEN API is a crucial module and development tool within the NX software [33], serving as a bridge between NX and external applications. This system uses C++ programming to invoke these function interfaces, including geometric kernels, topological diagrams, etc., to implement system features.

The interface for feature recognition and intelligent retrieval is shown in Figure 16. In the feature recognition interface, as shown in Figure 16a, the designer only needs to select the gear model to be identified through the SelectObject control and click the automatic recognition button so the feature list will be updated automatically. By clicking the list node, the recognition results will be displayed on the right side of the interface. In the retrieval interface, as shown in Figure 16b, there is a human–computer interaction interface; the designer can add search conditions to the keyword list and click the retrieval button, and the retrieval result list will be automatically updated to display the search results. The interface has a guiding structure, making it easy for designers to operate.



(a) (b)

Figure 16. The system interface: (**a**) Feature recognition. (**b**) Intelligent retrieval.

The developed system has been applied in the two biggest MIM production enterprises in China and has been tested with 80-spur gears to validate its ability for automatic feature recognition and intelligent retrieval. A case study of an output gear of a gearbox is presented in Figure 17 to illustrate the major steps of the intelligent CAD system and evaluate its performance, as shown in Figure 18. The performance of the design process is evaluated according to the time spent in the design process and the number of die testings. Performance data comparing designing with NX generic modeling commands and design with this intelligent CAD system are presented in Table 6. The second and third columns of the table show that through the intelligent system, the recognition efficiency and retrieval efficiency are increased by 97.8% and 98.9%, respectively, and the fourth column shows that the mold opening period is shortened from 20 days to 13 days, and the efficiency is increased by 35%. The fourth column shows that the number of mold tests is reduced from 5 to 2, the efficiency is increased by 60%, and the mold opening cycle and the number of mold tests are reduced, indicating the accuracy of the intelligent system in automatic identification and intelligent retrieval.

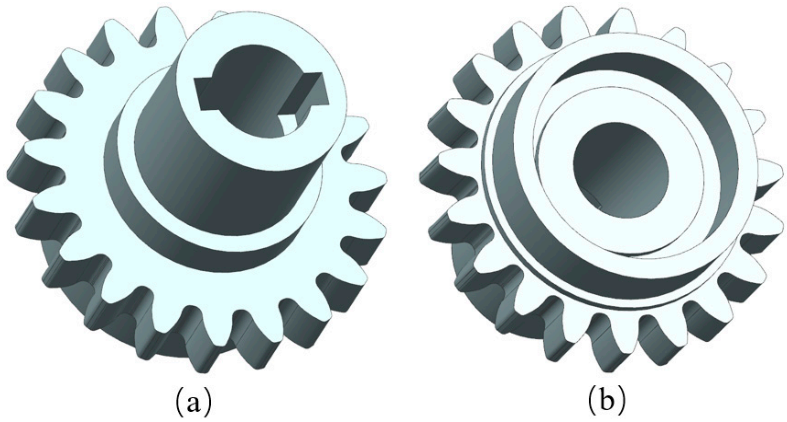


Figure 17. Output gear of gearbox: (**a**) Shape and structure of one side of the gear. (**b**) Shape and structure of the other side of the gear.

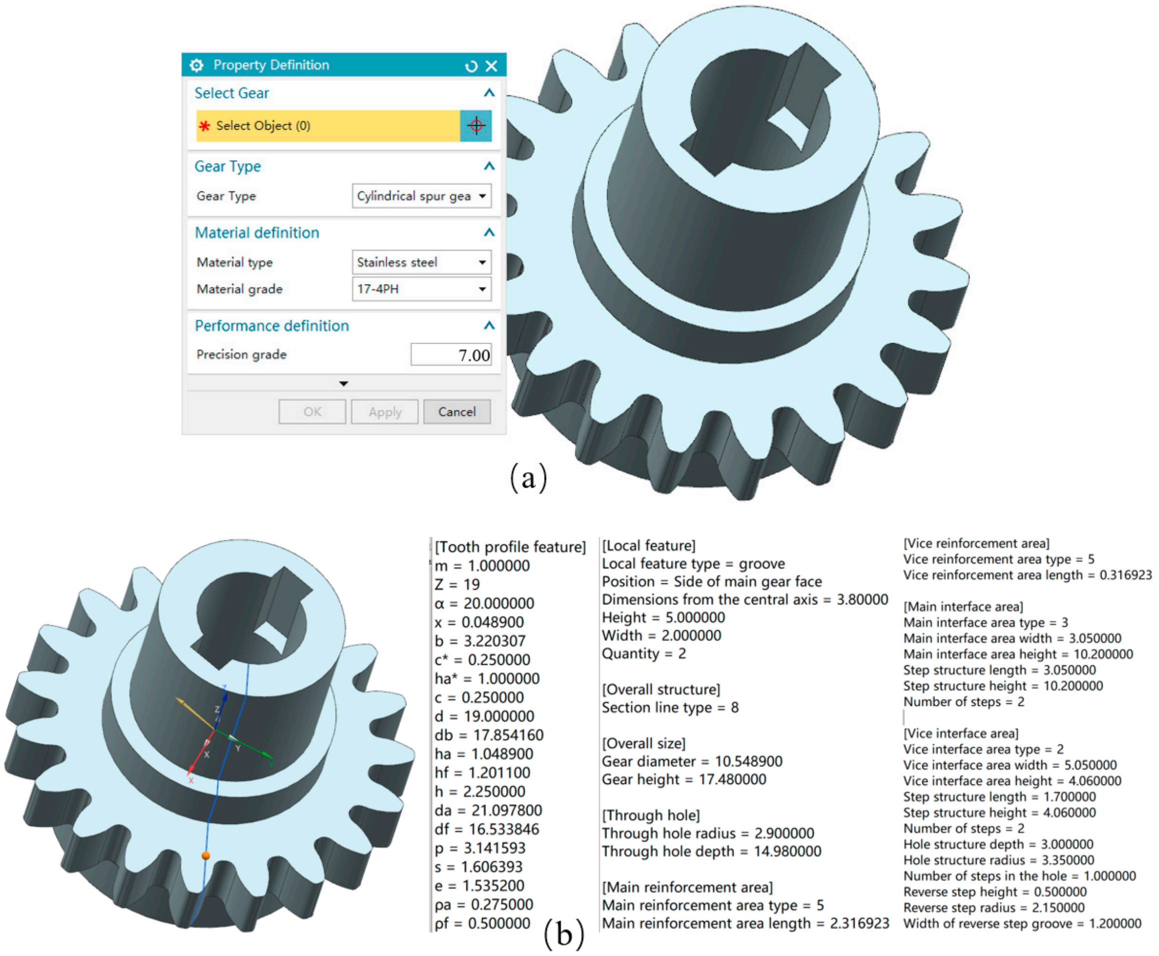


Figure 18. *Cont.*

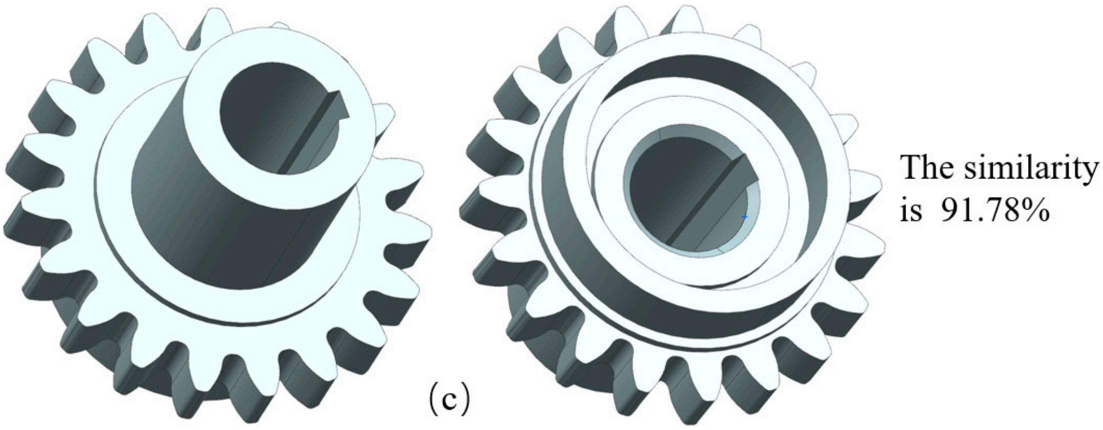


Figure 18. Process of the intelligent system: (**a**) Property definition. (**b**) Automatic identification. (**c**) The similar model in the knowledge base.

Table 6. Performance evaluation.

Performance Data	Performance Calculation	Retrieve Similar Parts	Mold Opening Cycle	Number of Test Molds
Without intelligent CAD system	About 20 min	About 90 min	About 20 days	About 5
With intelligent CAD system	0.5 min	1 min	13 days	2
Savings (%)	97.5	98.9	35	60

5. Conclusions

An automatic identification and intelligent retrieval system has been developed on the NX platform based on the feature recognition and intelligent retrieval method of multi-alloy cylindrical gears in metal powder injection molding based on partition templates. This system's automatic identification, a key technology, incorporates partition templates and a recognition algorithm. The system identifies gear profile parameters, local feature parameters, and structural feature parameters based on the partition templates and recognition algorithm. It digitally processes the gear, considering gear type, material, machining accuracy, and other feature parameters defined by the property definition module. Intelligent retrieval is achieved by calculating similarities to find similar gear parts in the knowledge base. Subsequently, designers design the manufacturing process of new parts based on the mature mold structure and manufacturing process of the found parts, aiming for knowledge reuse. This method has the following advantages: (1) reduced dependence on designer's experience; (2) improved design efficiency; and (3) reduced design errors. The developed system has been applied in the two largest MIM product manufacturing enterprises in China, and 80-spur gears are tested as an example to verify the accuracy of automatic identification and intelligent retrieval, and the identification and retrieval efficiency is improved by more than 97%. The mold opening time is shortened by 35%, and the number of mold tests is reduced by 60%. Therefore, it can not only greatly save the time and cost of MIM gear die design and process design but also provide good design quality.

Currently, this method enables the identification and retrieval of cylindrical spur gears. Future work can expand both vertically and horizontally. In the vertical dimension, feature recognition and intelligent retrieval represent the initial steps in the intelligent analogical design of product manufacturing. Subsequently, the design and manufacturing experience can be incorporated into a knowledge base, and then the intelligent design methods of the injection mold and process based on the mature experience of similar models can be studied. Horizontally, further investigations could explore the scalability of the methodology to accommodate various gear types.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy reason.

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