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ORIGINAL ARTICLE

Robust methodology of automatic design for automobile panel drawing die based on multilevel modeling strategy

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Abstract The automation and robustness have always been the focal points in the design system for stamping die. A robust methodology of automatic design based on multilevel modeling strategy is presented in this paper for automobile panel drawing die by analyzing and eliminating the factors that lead to design failure. The inherent attribute of geometry is blamed for the failure, which is defined as "ambiguous modeling failure (AMF) caused by orientation attribute." The methodology is aimed at guaranteeing the remodel robustness and improving the automation level of die design, which is discussed under three aspects: structure modeling, die checking, and parameter managing. (1) The multilevel modeling strategy is designed to guarantee the robustness of structure modeling through treating AMFs in advance, intensively and hierarchically by redefining the modeling procedure and building two control units. (2) Automatic check of die structure is expected to drastically promote design efficiency, which will ensure checking correctness and reduce checking cost compared with manual work. (3) The well-managed parameters facilitate the invocation of parameters for the users, which make the die alterations more convenient and faster. Finally, an automated design system for automobile panel drawing die is developed on top of CATIA V5 to verify the methodology, which can accomplish the main structures, layout of standard parts, and check of die structure automatically. Experimental results and feedback from the design office together indicate that the system can improve design efficiency and design quality dramatically.

Keywords Drawing die · Automatic design · Robustness · Multilevel modeling strategy · Die check

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1 Introduction

Stamping dies are extensively utilized for automobile, aviation, and 3C products (computer, communication, and consumer electronic product). Due to the manual design of stamping dies being time-consuming, tedious, and error prone, automatic design remains a significant requirement in the stamping industry. Scholars world-wide have paid abundant attention to automatic design systems which involve various types of stamping die.

Lee et al. [1] developed a computer-aided design prototypical system with parametric die elements for cold forging based on the procedure of die design using Auto-LISP. Chu et al. [2] presented a parametric design system for 3D tire mold production which can create grooves with simple design table and reduce user intersection. Kim et al. [3] realized an automated system for shear die and bend die depending on standard library, which is made up by die components. David et al. [4] described a new methodology for the development of a parametric system which can (re)model cutting components of compound washer dies automatically. Hussein [5] constructed a knowledge based expert system for sheet metal blanking dies built under CATIA V5 which is based on the available die design data. Naranje and Kumar [6] proposed a knowledge based system for deep drawing die for axisymmetric parts using artificial intelligence, which is capable to execute all major activities. Kumar and Singh [7, 8] developed an intelligent system AUTOPROMOD on AutoCAD for automatic modeling of progressive die of die components and die assembly with knowledge-based system, and 4 years later, they carried out an automated design system for progressive die based on production rule, which can automate all major design activities of die on AutoCAD software. Jia et al. [9] developed an automated plate hole design system for progressive dies according to structural types and relationships between the parts and the holes. Jia et al. [10] introduced an automated structural design of punches and dies for progressive dies which includes three aspects: geometry information, assembly constraint, and hole-related information on plates. Lin et al. [11] reported to implement a progressive die system of computer-aided structural design with drawing, punching, and bending operation on top of CATIA V5.

The automatic systems aforementioned, that can accomplish major task of die design, are regarded to forging die, tire mold, shear die, blank die, and progressive die, whose structures are relatively inerratic and simple compared to the automobile panel die. However, the stamping die of automobile panel is not only the most intricate but importantly also fickle among all the types of die. Therefore, tremendous changes must be taken to the method of constructing system which put forward a higher request to parametric model, knowledge reuse, and design procedure.

Lin et al. [12] proposed a knowledge-based parametric design system for drawing dies on top of the Pro/E CAD software with constructing parametric skeleton model composed of main components and standard components. Relied on the system, after inserting die face and punch open line into the structure tree and importing blank sizes, drawing strokes, and press data into user interface, the system can complete the rest design. Lin and Hsu [13] developed an automated system for drawing die on the top of CATIA V5, and sample die was built based on standardized design process, guidelines, and specifications. Replacing the graphic information in the layer tree of sample die and inputting alphanumeric information can make system generate the design automatically. Lin et al. [14] developed a computer-aided system for 3D drawing dies based on functional features with Pro/ENGINEER CAD system. The core is to construct the plane skeleton according to the die design process consisted of functional features. The system completes the design with input information. Yilin Wang and Xiangang Hu [15] described a template-based parametric design system developed on NX for drawing die which can complete the main components of drawing die. The system was realized by adopting WAVE technique and parameterized design method.

Because of the intricate structure of drawing die for automobile panel, creating components by programming directly is technologically impossible. As a consequence, four teams above have built parametric models for reconstructing the drawing die structure, called parametric skeleton model, sample die, plane skeleton, and die template, which can enhance design efficiency signally. However, when replacing old features with new ones using parametric model, it is inevitable that the problems of feature orientation will bring about unrobustness in reconstructing process, which at last leads to update failure. Unfortunately, the problem of reconstructing robustness has rarely stimulated the consideration of researchers. Thus, this paper proposes a strategy of multilevel modeling, which is aimed at solving the neglected problem. Meanwhile, a methodology of automatic system design for drawing die based on multilevel modeling strategy is introduced to improve the automation level.

2 Modeling failure analysis

CAD functional commands, such as trim body, offset curve, and extrude, are frequently applied to solid modeling according to the standard design flow. Those commands perform the directional estimation in the operation that is laid on the target objects including surface and curve. For example, trim body retains alternative based on the orientation of tool surface. And offset curve determines its offset direction by the orientation of target curve and plane normal.

Curve orientation is a consistent direction along the curve, which is determined by the directional trend of curve tangent vectors, while surface orientation is an identification to distinguish the sides of surface, which is determined by surface normal vectors. Generally, curves and surfaces in CAD system are generated and represented by the standard of NURBS (nonuniform rational basis spline). According to the constitution theory of NURBS curves or surfaces, curve tangent vectors or surface normal vectors can be opposite despite the geometric shapes are exactly the same. Hence, as shown in Fig. 1a, “Curve Orientation (+)” is the trend of curve tangent vectors (arrows on the points) when the sequence of fitting points is “V1-V2-V3.” If the sequence is inverted to “V3-V2-V1”, the orientation would turn to “Curve Orientation (−).” Likewise, Fig. 1b shows that the sequences of boundary edges constructing two surfaces are adverse, which causes “Surface Orientation (+)” and “Surface Orientation (−)” to be opposite,

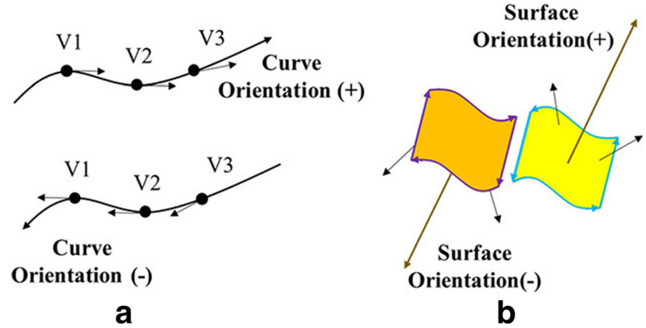


Fig. 1 The opposite orientation of curve and surface

but to be in alignment with the each surface normal vectors (short arrows on surfaces).

It is acquired from the above analysis that the orientations of surfaces or curves maybe different as the different generation methods. In 3D CAD system, the performing direction of functional command is determined by the geometry orientation. While desired modeling result is hard to achieve when remodeling die structure by replacing the old process elements (PEs) with the new PEs, because of the alternative orientations of the new and old PEs (die face, blank line, punch open line, and stamping direction) that is analyzed above, we call such phenomenon as “ambiguous modeling failure caused by the orientation attribute.” The phenomenon of ambiguous modeling failure (AMF) will definitely add the instable risk to model procedure. Table 1 shows the cases of the phenomenon of AMF caused by the orientation attribute, and the red arrows represent the orientations of curves and surfaces. Once the possible result is a failure, the whole structure will break down certainly. To distinguish the AMFs, they are categorized into surface-AMF (SAMF) and curve-AMF (CAMF).

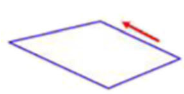
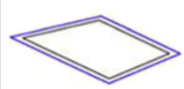
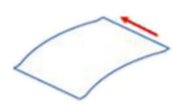
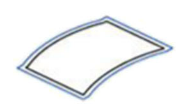
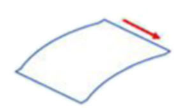
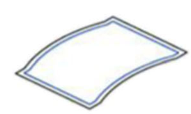
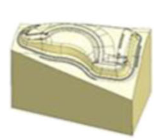
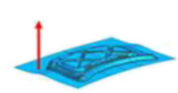
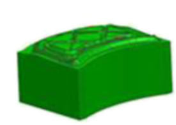
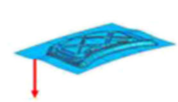
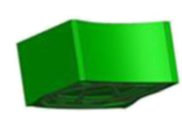
According to the above failure analysis, a methodology of automatic design for drawing die based on multilevel modeling strategy is proposed in this paper, and the strategy is designed to perform advance, intensive, and hierarchical treatment to the AMFs in design phase. Figure 2 illustrates the preview of the hierarchical relationship of multilevel modeling strategy, which involves multi-prototype die and multi-publication. The detailed description about automatic design methodology is presented in the next chapter.

3 Methodology of automatic design for drawing die

Die design, performed on 3D CAD platform, is an activity that creates structure features with external and internal data through a series of repeating operations of modeling, modifying, and remodeling. The performance of die design that satisfies the specification and customer requirement is largely dependent on the personal experience. Three portions of die design need to be taken into consideration: die structure modeling, die structure checking, and parameter managing.

The portion of die structure modeling that maintains the robustness of regeneration adopts a new strategy called multilevel modeling, which is aimed at eliminating (identifying and modifying) the AMFs in an advance, intensive, and hierarchical manner through “Multi-Prototype Die” and “Multi-Publication.” Additionally, structure checking is equally important to the former in designing drawing die. Automatic checking of die structure is expected to drastically promote the whole design efficiency, which will ensure checking

Table 1 The phenomenon of ambiguous modeling failure caused by the orientation attribute

Old PE	Item	Result	New PE	Possible result
Blank line 	Offset curve			Success 
				Failure 
Die face 	Trim body			Success 
				Failure 

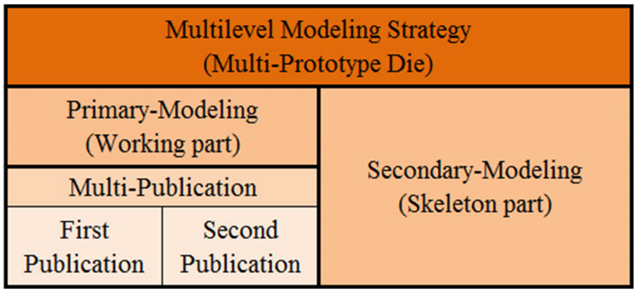


Fig. 2 The hierarchical relationship of multilevel modeling

correctness and reduce checking cost compared with manual work. Last but not the least, the well-managed parameters can be invoked obviously by users, which will further promote work efficiency. The following subsections will describe the methodology of design automation in detail.

3.1 Strategy of multilevel modeling

3.1.1 Background of modeling strategy

To achieve robust and reusable CAD models, scholars have made plentiful attempts. In terms of modeling technology, the foundations of the parametric and constraint-based CAD modeling remain practical and unchanged which were established by Roller [16], Shah [17], and Solano and Brunet [18]. Meanwhile, Shah initiated the feature-based modeling techniques that describe how design semantics were delivered through the different design stages. However, the only consideration of technology was insufficient to ensure the robustness of the reuse of CAD models; thus, the modeling strategy considering sequences of operations was carried out by the engineers and scholars. It is parent-child relationship between features that causes regeneration problem, and robust model with well-organized parent/child relationship is so hard to define that even minor alterations would lead the regeneration to failure. Three major modeling strategies that, concentrating on the interdependencies of parent and child nodes, have been published were formal and representative: horizontal modeling [19], explicit reference modeling [20], and resilient modeling [21].

Horizontal modeling strategy Horizontal modeling is proposed and patented by Delphi's engineers [19], which eliminates the parent/child relationship between features. This ensures that geometric features are isolated and changed without affecting other features. In this strategy, all features are created relying on datum planes, instead of other features which leads to a consequence that all features are set on the same layer in the feature tree. However, lack of dependencies between child and parent is proved to automate to propagate value changes impossibly. Horizontal modeling strategy is an extreme application, which can hardly apply in the scene of automobile panel drawing die.

Explicit reference modeling strategy Explicit reference modeling focused on the reference geometries decreases the number of constraints linked to existing geometry by recommending three ways when building parametric CAD models [20]. Firstly, most existing geometry as functional reference can be replaced by other datum such as sketches, points, lines, or planes. In addition, it is better understood by designer that child features should be located as close to the parent as possible which makes the model in a logical sequence. Finally, features that are possible to be altered and deleted and own important child features are recommended to be placed at the lowest layers in the tree. However, the continuous relationship of parent/child/grandchild cannot be ignored and replaced, which makes this strategy inappropriate to current application.

Resilient modeling strategy By focusing on the logical sequence and simple and intuitive structures of design tree, resilient modeling was organized in six groups depending on their importance, function, and changeability: reference group, construction group, core group, detail group, modify group, and quarantine group [21]. Reference features are top in the feature tree making them visible or available to all entities. Construction entities are applied to establish complex solid features later. The core group defines basic shape, extents, and orientation of the model. The detail group that is linked to the ref and core group is edited to make small changes to the CAD model. The modify group includes the features that altered the transformed or replicated model. The quarantine group includes the isolated features at the lowest tree such as chamfers, blends, and rounds. As a result, the six layers of resilient modeling make model robust, obvious, and reusable. It is an empirical and valid method that helps to design a well structure in all industries.

To AMFs, however, the general modeling strategy mentioned above can only identify the problematic areas easily rather than modify the AMFs automatically. Hence, this paper proposes the multilevel modeling strategy that can automatically identify and modify the AMFs, which is based on the foundation of parameterization, constraint-based technique, and "assembly semantic modeling" theory [22]. The substantiation of multilevel modeling strategy is a multi-prototype die that is applied to regenerate die structure steadily.

3.1.2 Multi-prototype die

As the substantiation of multilevel modeling strategy, a prototype die that integrates expert experience and engineer design rule is a parametric and assembly-based model, which has summarized and applied the commonalities and differences of kinds of die structures and modeling procedures. A multi-prototype die is beneficial to enhance regenerating robustness and decrease design time. On the one hand, the stage where AMF occurs can be isolated from the overall stage by the multi-prototype die, which makes the failures occur hierarchically. On the other hand, when re-constructing with integral prototype die, once AMF breaks out, updating would not stop until the end-like "domino effect" because of the continuous parent/child dependencies. Therefore, such integral prototype die is time-consuming, while multi-prototype die can update hierarchically controlled by programming units that can interrupt, inspect, and link the flow of value propagation, which will avoid invalid update.

As shown in Fig. 3, prototype die is composed of upper die base (UDB), blank holder (BH), and lower die base (LDB). According to the functional and structural characteristics, each component of a prototype die is divided into three modules: working part driven by features replacement, general skeleton part driven by parameter alteration, and standard parts with constraints, which together constitute a multi-prototype die. Working part has causal association with the PEs due to modeling procedure, for example "a punch is trimmed by die face from an extruding feature which is extruded from the punch open line," and general skeleton part is geometrically related to working part. Thus, working part is the high occurrence area of AMF, but the general skeleton part is not. Standard parts are assembled on skeleton part and working part with assembling constraints.

The working part is modeled with PEs through a series of well-organized CAD functional commands, whose structure is so complicated that it is hard to build a parametric part. Therefore, we take advantage of "PUBLICATION" in CATIA replacing the old PEs with the new ones to build working part, which has realized the reuse of design procedure and components. When build the working part of prototype die, we adopt the method of sheet modeling instead of solid modeling method. The method is sheet body oriented, which designs the sheet bodies first, and then solidifies sheet bodies that have already formed a closed region to solid body. Compared to method of solid modeling, (1) sheet modeling makes model process more succinct owning to less consideration of operating sequence; (2) it avoids the consecutive operations to one main solid body which will generate continuous and tedious parent/child dependencies making the 3D model brittle, instead of inconsecutive operations to several sheet bodies, which make the model robust; and (3) as is known, "unite" and "subtract" between irregular solid bodies are prone to cause "intersecting problems," while sheet modeling trends to "trim" solid body with sheet bodies. Therefore, we make use of sheet modeling rather than solid modeling. Working part driven by feature replacement is also called primary modeling.

General skeleton part has a regular shape as well as the child features, which makes it easy to establish parametric part based on the techniques of feature-based modeling and constraint-based modeling [17]. The feature geometry in the parametric part is driven by nongeometric feature-named parameter, and the child-parent dependencies between features can be generated by dimensional, geometrical, and algebraic constraints. The parametric part will react to the value changes through propagating the alterations from a parent node to its child nodes, which supports for reconstructing the general skeleton part. General skeleton part is associated with working part through the PEs. Figure 4 describes the dimensional association between working part of BH, general skeleton part of BH, and the PEs, in which the outer profile of LDB working part and the interprofile of BH skeleton part are generated upon the maximum box of blank line. General skeleton part driven by parameters is also called secondary modeling.

Standard parts are attached on skeleton part and working part through assembling constraints including "Touch Align," "Distance," "Concentric," "Center" and etc. The assembling constraints are created with specified rules on 3D CAD platform, and the rules that have specified functional senses are derived from design criterion and expert experience. As shown in Fig. 5, a hook is assembled on LDB with a specified rule which is defined as distance constraint. "Distance1" is the depth of hook inserted into LDB which means bending moment of hook against the base body of LDB. "Distance2" and "Distance3" are distances from hook to the boundary of LDB,

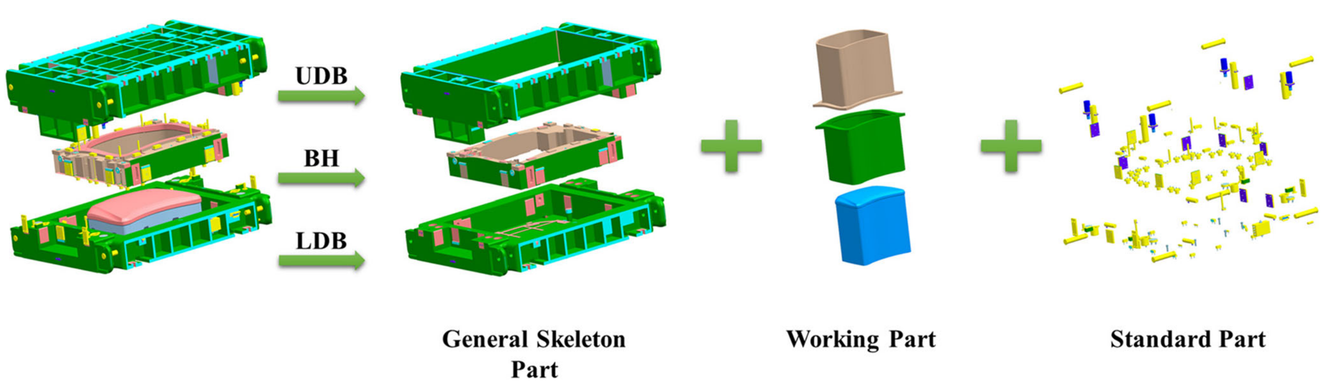
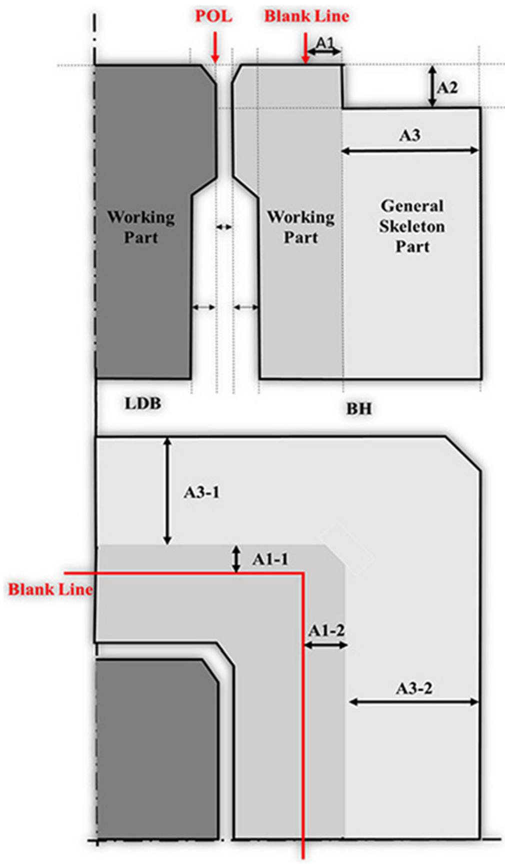


Fig. 3 Multilevel structures of prototype die

Fig. 4 The *left image* shows the front and top view of sections of punch and BH. The *right image* shows the comments of parameters



Parameter	Comment
Blank Line	Maximal box of real BL
A1	Width delta between Blank Line and working table boundary
A2	Height delta between working table boundary and non working table boundary
A3	Width of non working table relative to working table boundary

which mean the strength of LDB against hook when hoisting. Standard parts are updating with the changes of working part and skeleton part.

The AMFs have been prefixed to primary modeling using multi-prototype die. The application of multi-prototype die essentially falls into three phases: firstly, replacing the PEs to build the working part; secondly, reconstructing general skeleton part with rules which is established by the geometry dimension relationship between PEs and general skeleton part (Fig. 4); and the last, assembling working parts and skeleton parts to an integer drawing die.

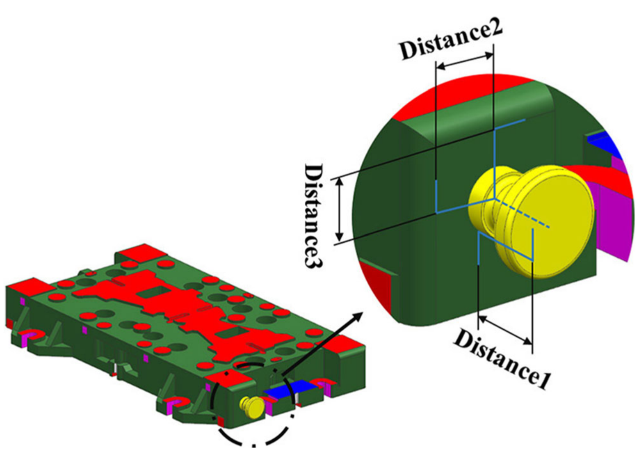
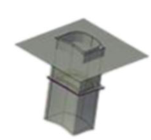
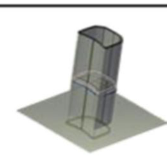
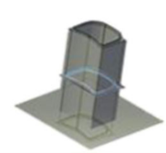


Fig. 5 Location rule of standard part: a hook is assembled on LDB with three distance constraints

Table 2 Results of first publication and second publication

	Primary modeling	
	Result of first publication: VPS	Result of second publication: WPA
UDB		
BH		
LDB		

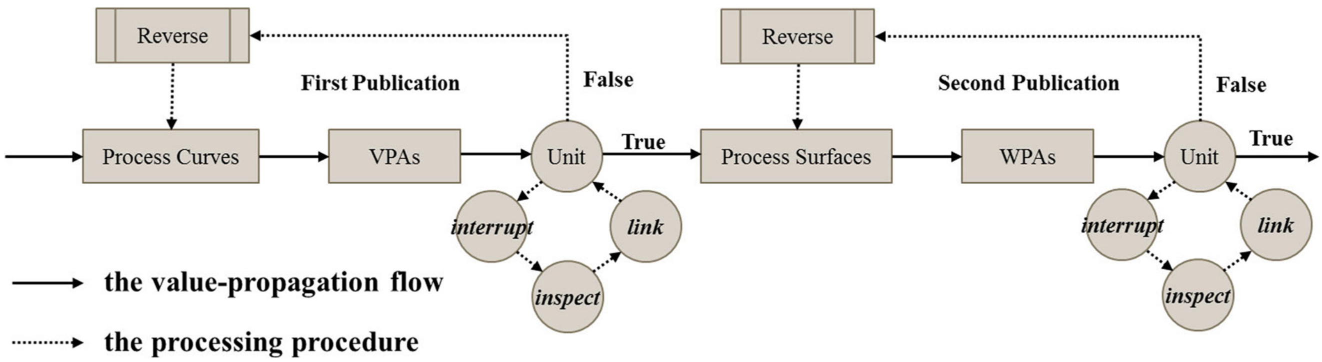


Fig. 6 The flow graph of the multi-publication stage

3.1.3 Multi-publication

In the stage of primary modeling, in order to deal with the AMFs (CAMF and SAMF) individually and further shorten the invalid update time, the paper proposes multi-publication on the base of the method of sheet modeling, with which CAMF can be eliminated in first publication and SAMF can be eliminated in second publication through publishing hierarchically. The first publication aims to create sheet bodies, while the second is to create solid bodies from the sheet bodies. The publication results will be inspected by two control units, respectively, which are designed to interrupt, inspect and link the value propagating flow.

"Publication" in CATIA is mainly applied to parametric assembly modeling. In assembly, geometry feature and parameter feature can be repeatedly published to other parts as external references, which implements context-associated modeling. The association is co-determined by the publish name of source feature and the instance name in assembly.

The core of multi-publication is virtual process assembly space (VPAS), where three groups of surface structures that are the external surfaces of working parts are built, and VPAS is also the transfer station of multilevel publication. Those surface structures are called virtual process assembly (VPA) as listed in Table 2, which are created from PEs and several key process parameters. The VPA is assembled with surface of punch, surface of blank holder, and surface of die. The procedure of multi-publication includes first publication of PEs and second publication of VPA.

First publication has published PEs to process processing box (PPBox), which results to VPA. The PPBox is composed of an ordered series of functional commands: offset, project,

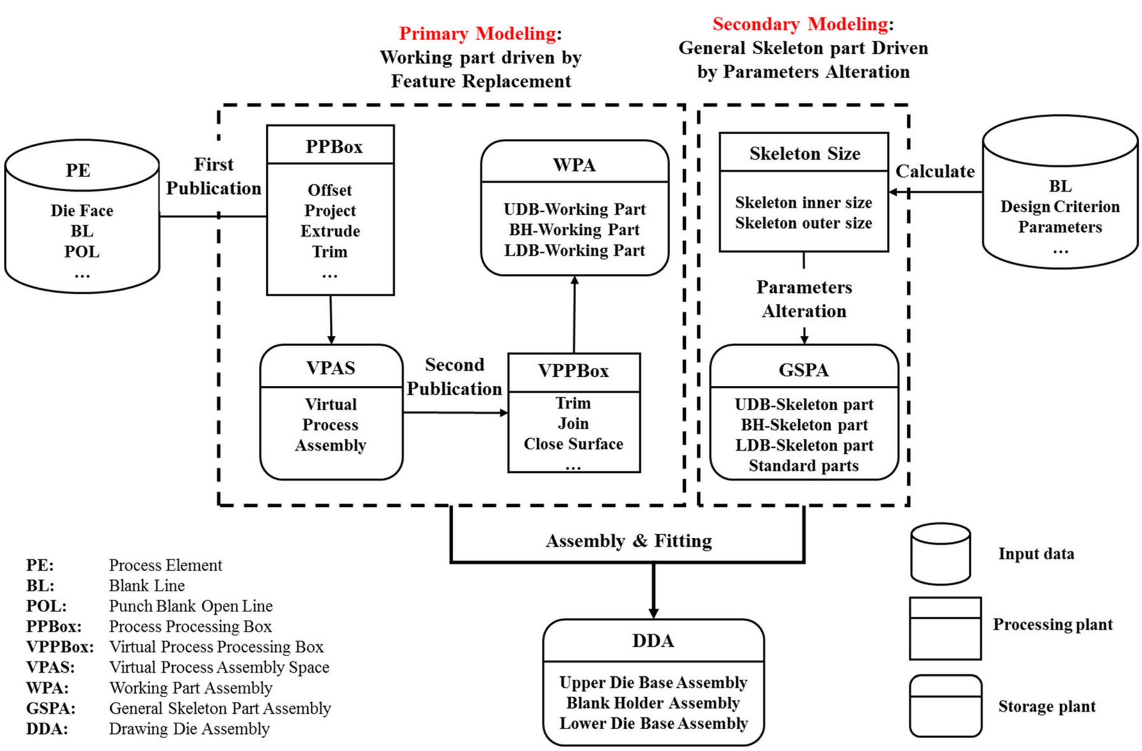


Fig. 7 The schematic diagram of multilevel modeling strategy

extrude, trim, etc. which represents for the modeling procedure. As shown in Table 2, a group of surface of VPA is consisted of several sheet loop walls and plane surfaces. The walls are created with process curves (blank line and punch open line) and their orientations by commands of offset and extrude, while the plane surfaces are created by command of offset with process surface (die face) and stamping direction. Therefore, CAMF is controlled to only occur in the first publication stage. A closed region is formed together by both sheet loop walls and plane surfaces.

Second publication has published the VPA to virtual process processing box (VPPBox) where sheet bodies are converted to solid bodies called working part assembly (WPA). The VPPBox is composed of another ordered serial of commands: trim, join, close surface, etc. The VPS and WPA are listed in Table 2, and a solid body is created by a group of VPA and the orientation of process surface (die face) through three steps, which leads to the appearance of SAMF merely in second publication:

Step1: trim each other of a group surface which is related to the orientation of die face;
Step2: join the trimmed surfaces to an integral one;
Step3: close surface the integral surface to solid body.

A control unit is inserted between first and second publication, whose function is to inspect if the first publication results are free from CAMF or not. The control unit determines whether the orientations of process curves need to be reversed. If the control unit returns true, go on to the second publication; if false, go back to reverse the orientation of process curves. Another control unit is inserted behind the second publication, whose function is to inspect if the second publication results are free from SAMF or not. It is determined that whether the orientation of process surface need to be reversed, if the control unit return true, go on to the secondary modeling; if false, go back to reverse the orientation of process surface and perform the second publication again. The flow graph of control units in multi-publication stage works as Fig. 6.

Figure 7 indicates the principle of multilevel modeling. In terms of modeling approach, the design of drawing die is sectioned into primary modeling which parts to first publication and second publication and secondary modeling. In terms of modeling structure, the structure of drawing die is divided into working part which parts to VPA and WPA and general skeleton part. As a result, the CAMF is eliminated in the first publication and the SAMF is eliminated in the second publication, which makes structure modeling more robust and efficient.

3.2 Automation of die check

Die check is essential to guarantee the integrality and validity of die structure. In industrial design, a 3D die structure is

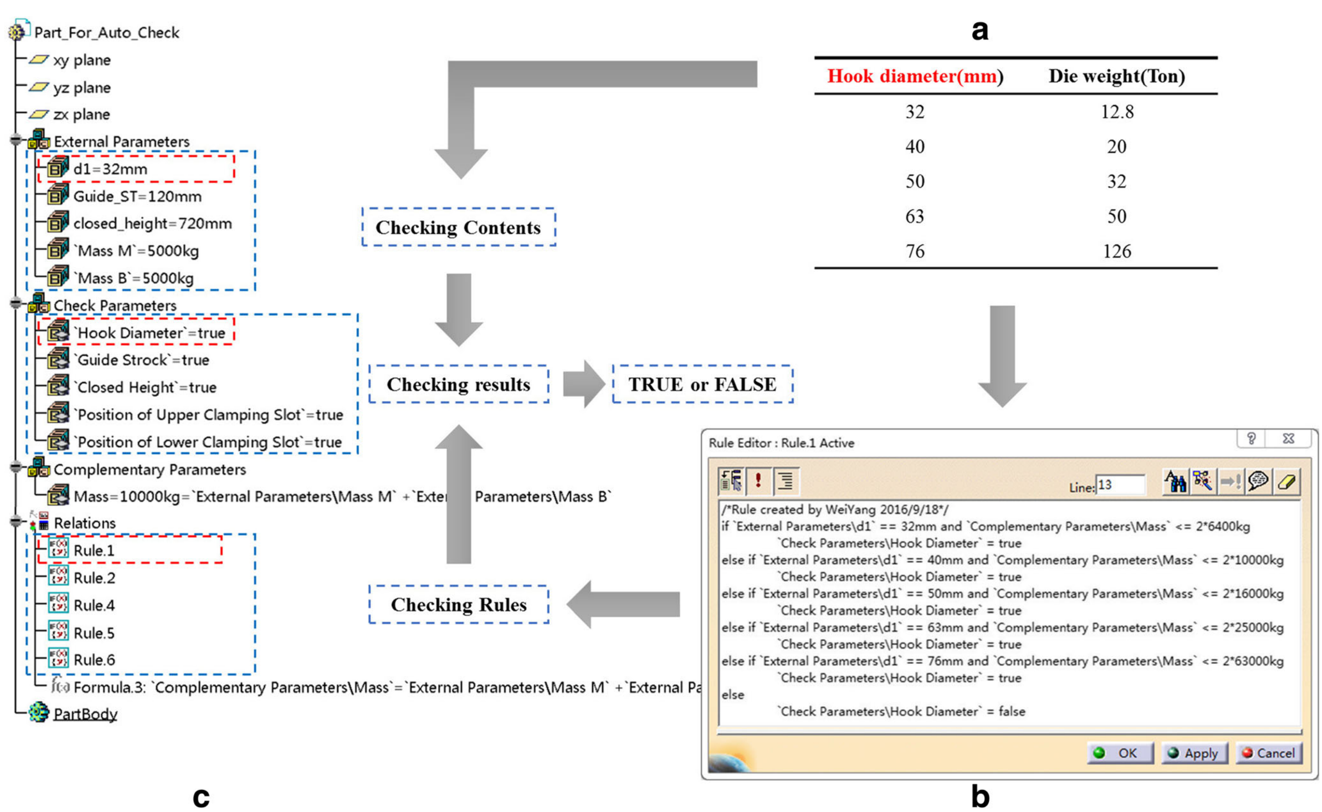


Fig. 8 Automatic check of structured content of hook diameter **a** using expression, **b** rule editor, and **c** feature tree

always checked manually from three aspects which involve existence checking, structure checking, and processing feasibility checking:

1. Existence checking is to confirm if a die is structural integrity and if the standard parts in requirement are existed, such as "A blank locator is to restrict the movement of work blank, and enough locators are able to restrict reposefully. So the number of locators must be necessarily checked."
2. Structure checking includes dimension checking, position checking, strength checking, and interference checking, such as "the blank locator is higher than the position of blank, so the interference between locators and UDB must be avoided definitely."
3. Processing feasibility checking means the feasibility of casting, forging, and machining, such as "the avoided space in UDB must be cambered-sharp for milling."

In order to achieve checking automation, digitization of checking contents, what are to be checked, and checking rules, the design criteria and standard what the contents are checked with is essential. Thus, we raise an approach of automatic die check on a multilevel model which is applied to the construction of design system.

According to the representation forms, checking contents are classified into two categories: structured and unstructured checking contents. And each of the three aspects mentioned above includes structured and unstructured checking contents simultaneously.

Structured checking contents express check list in the quantitative forms of value and formula, such as a feature parameter, expression, and dimensional range for choosing standard part. In order to check automatically, we make use of expressions to create quantitative checking rules and meanwhile, the checking result is output as Boolean value which is intuitional to users. The associated relationship among structured checking content, quantitative checking rule, and checking result that is built by the related design technology of the CAD platform makes the die checking automation practicable. The checking result will update synchronously as the geometric feature related to the checking content is generated. Therefore, numbers of parameters in the multi-prototype die can be checked as structured checking contents.

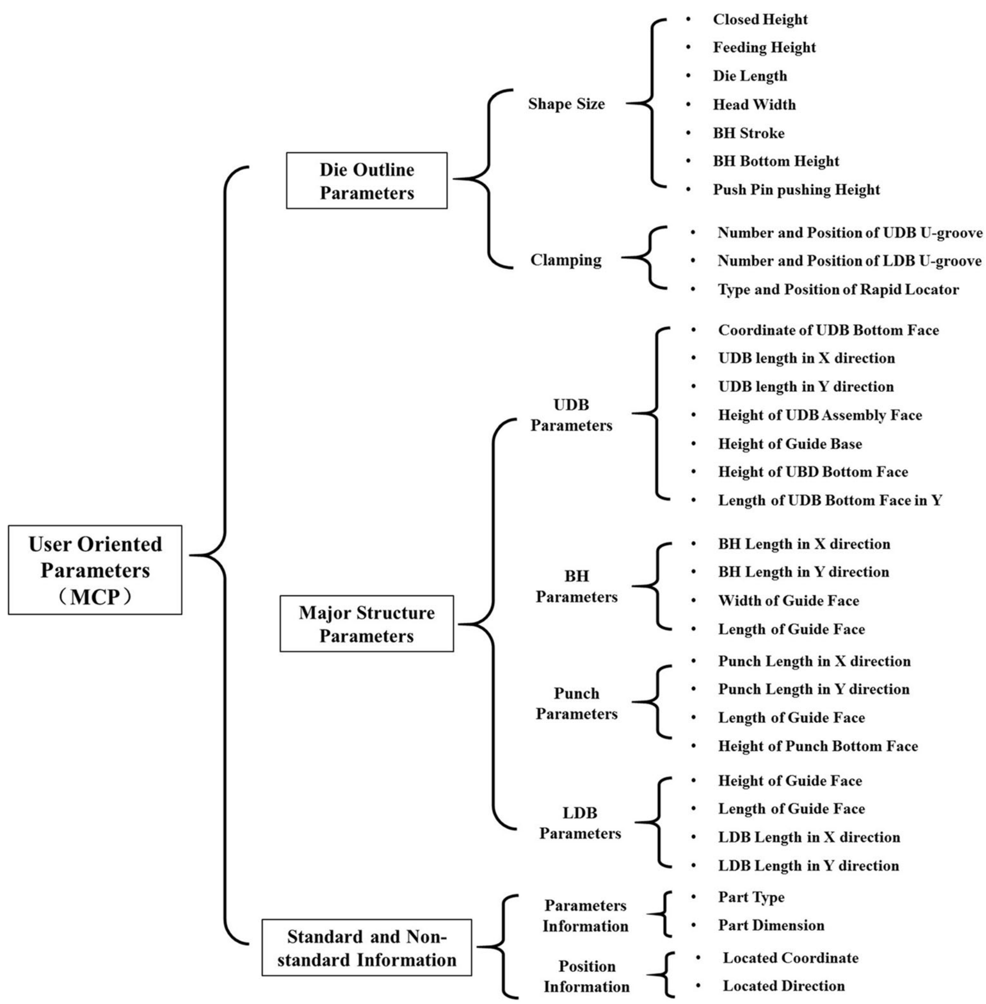


Fig. 9 The classification of main control parameters

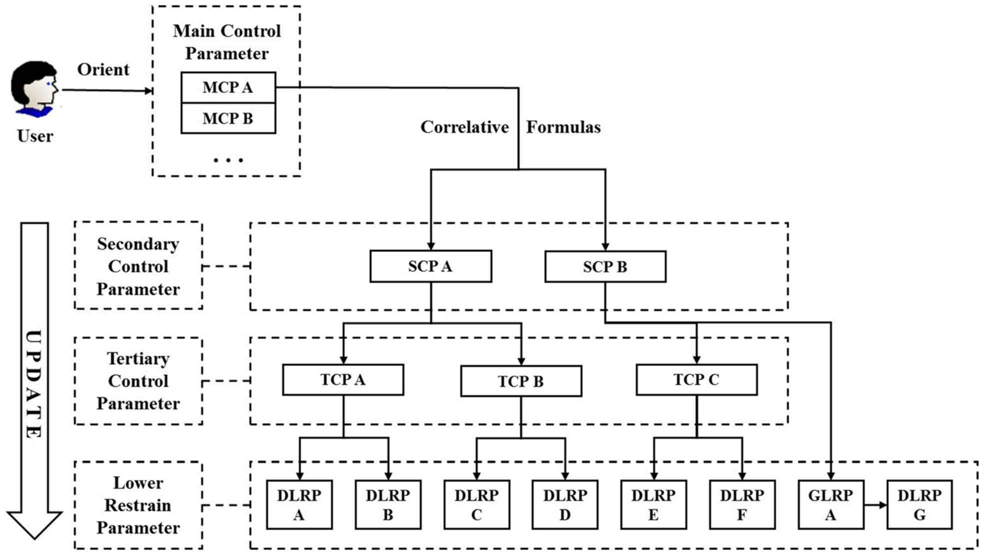


Fig. 10 The hierarchical structure of top-down value-transmitting mechanism

However, unstructured checking contents mean that the check list is described in the forms of diagrams, handbooks, and expert experience, which cannot be expressed in quantitative format. Thus, it is hard for unstructured contents to check automatically similar to structured contents. Such as a rule of "Stopper seats always use the diameter of 12mm, must be distributed equably on blank holder, and 2mm away from binder surface." The front section belongs to structured checking content, and the middle and the last are unstructured contents. For these conditions, in order to automate check, we need to deal with each unstructured rule with one particular way, while a generic way can be developed impossibly. A brief algorithm is developed for the middle section of the rule, and an automated measurement is made for the last section. Hence, parts of unstructured contents can be converted to automatic check. Nonetheless, not all unstructured contents can be checked by automatic algorithms, which are mainly depended on whether the IDs of target geometries are easily accessible by a computer and whether the descriptions of unstructured contents are in detail.

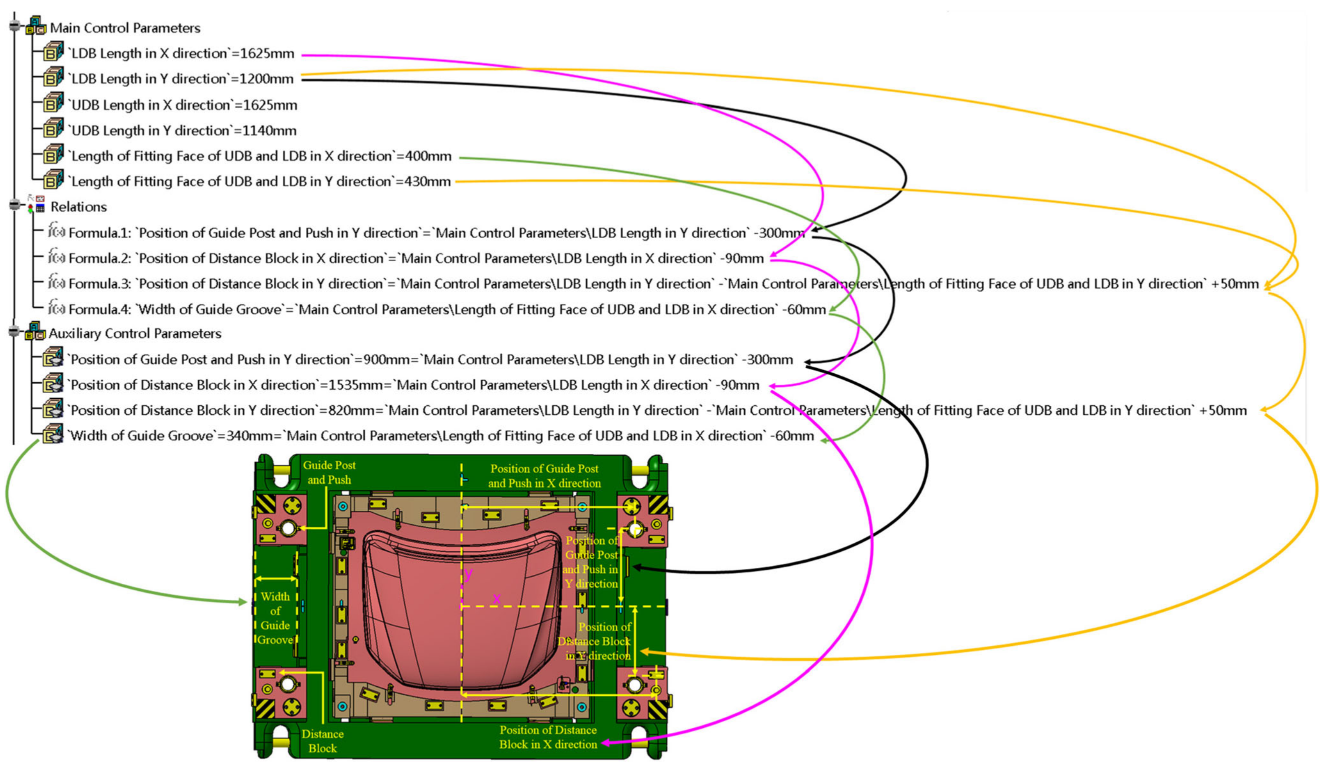


Fig. 11 The top-down value transmission of drawing dies of engine cover panel

Table 3 List of independent parameters

Name	Default Value (mm)	Comment
Undercut height	50	
Undercut thickness	10	
Undercut angle	45	For degree
Back thickness	50	
Major rib thickness	40	
Minor rib thickness	30	
Punch assemble offset distance	10	Assemble face of punch bottom face
Flange thickness	40	UDB flange, BH flange, LDB flange
BH face undercut	15	Distance between flange and BH face in BH
Blank line offset distance	15	Distance between BH face and blank line
BH and punch clearance	3	
Ribs distance along X	250	
Ribs distance along Y	250	

Figure 8 introduces how structured checking content, hook diameter, is performed on CATIA. Firstly, the hook diameter is published to the feature tree as external parameter. Secondly, the using expression is edited to quantitative checking rule by Rule Editor. Lastly, the checking results, which are a check parameter related to external parameter and relation, export true or false.

3.3 Approach of parameters manage

There are hundreds of nongeometric features called parameters in the parametric multi-prototype die, whose relationships of parent and child may lead the design intention to be unobvious. The parameters under disorder will reduce their invoking efficiency and can even cause chaos and faults. Therefore, the well-managed parameters that are summarized by veteran designers are presented, which classify parameters into three categories depending on usage frequency and topologic relationship: main control parameter (MCP), auxiliary control parameter (ACP), and independent parameter.

MCP is a user-oriented parameter which plays an important role in value propagating. The MCP is also the most commonly invoked parameter for die modification. There are three essential points of MCPs: it is the top value publisher under no constraint and owns child node; it indicates representative geometrical meaning which is significant to the die structure; and its value change will bring about major transformation of the structure. Figure 9 lists the MCPs which are composed of die outline parameters, major structure parameters, and standard and nonstandard information.

ACP is restrained through correlative formula by superior parameters which may be MCP or other ACP. The correlative formula is a function that indicates the relationship between parameters and constraints (dimension constraints and geometry constraints), as well as parameters and parameters, constraints and constraints. As shown in Fig. 10, the ACPs

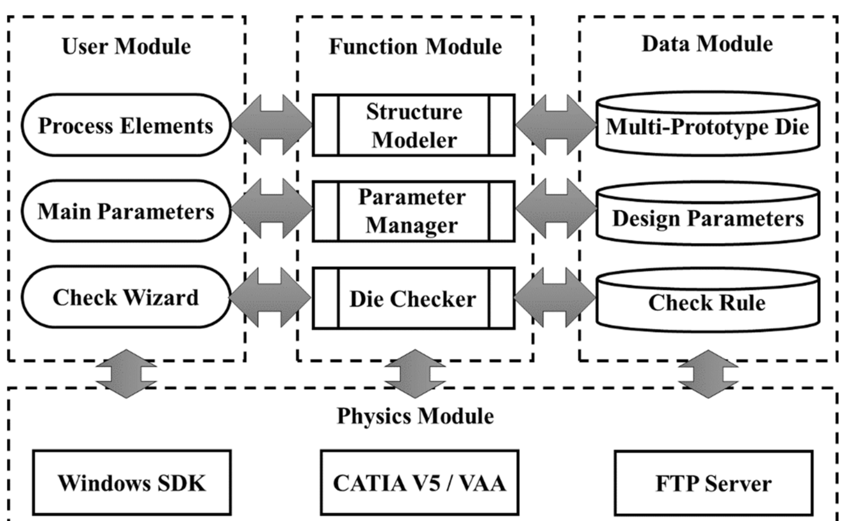
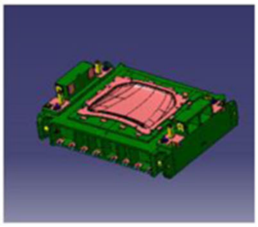
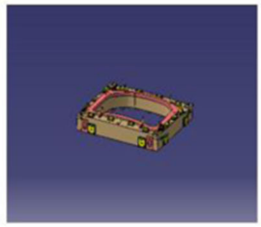


Fig. 12 The architecture of automatic design system for automobile panel drawing die

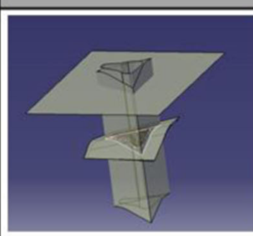
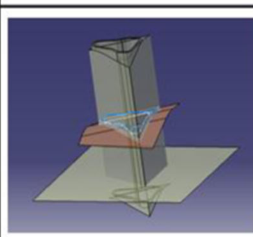
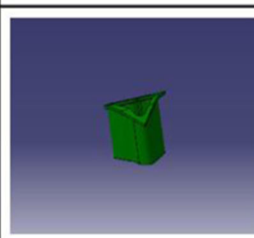
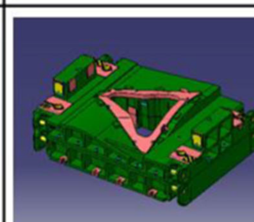
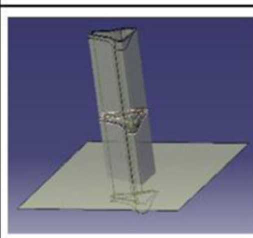
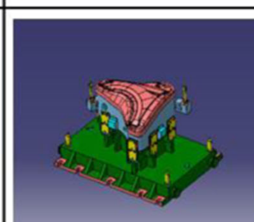
Table 4 The drawing prototype die of engine cover panel

UDB	BH	LDB
		

include secondary control parameters, tertiary control parameters, etc., and lower restraint parameters, which undertake the value propagation derived from the superior parameters. The lower restraint parameter (LRP) may be constrained with dimensional and geometric features abbreviated as DLRP and GLRP. Figure 11 indicates the top-down value transmission of drawing dies of engine cover panel, in which the geometrical shape and assembling positions are changed with the value transmitted from main control parameters to auxiliary control parameters.

Finally, as a supplement, independent parameter is independent from the value propagation mechanism, which is a default value. The default of an independent parameter is defined according to the design requirements of process design, structure design, casting, forging, machining, and production that are summarized by engineers with years of design experience. The independent parameter is merely related to independent geometric feature which has no relation with other features, parameters, and constraints. Numbers of independent parameters and their default values are listed in Table 3.

Table 5 The result of drawing die of wheel fender panel

	Primary modeling		Secondary modeling
	First publication	Second publication	
UDB			
BH			
LDB			

4 Construction and application of the automatic design system for automobile panel drawing die

4.1 Construction of the system

By adopting methodology referred above, an automatic design system for automobile panel drawing die is developed on CATIA platform. Figure 12 illustrates the architecture of automated system, which includes user module, function module, data module, and physics module. User module provides interactive interface for selecting PEs, altering MCPs, and assisting check. Function module takes charge of reconstructing die structure and checking. Data module stores and manages the internal and external data on FTP server. Physics module represents developing environment (CAITA's Part Design module, Knowledge Advisor module and CAA-RADE module) and software development kits.

Function module, the core of automatic system, is designed according to the three mentioned sections of the methodology, whose function is described as structure moder (SMer), parameter manager (PMer), and die checker (DCer). After selecting PEs, the function module executes as follows:

Step1: SMer reconstructs the drawing die automatically by downloading the prototype die, replacing the old PEs, and calculating the shape dimensions.

Step2: User performs minor alteration through interactive interfaces to the MCPs containing shape dimension, position, and part selection.

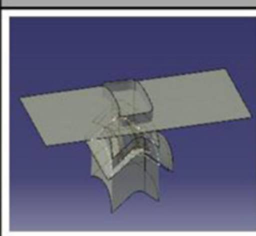
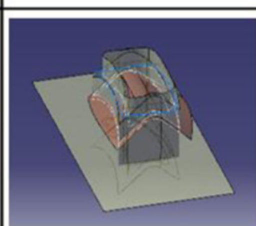
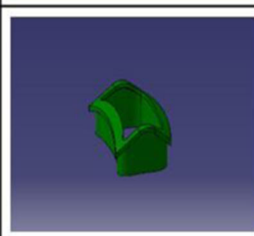
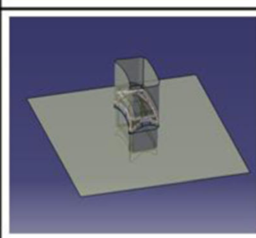
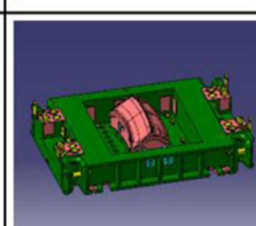
Step3: DCer checks and outputs results as EXCEL report automatically.

Step4: User takes advantage of PMer for secondary alteration on base of excel report till all reports are true.

4.2 Application of the system

In the application of the system, we make use of the prototype drawing die of engine cover panel (Table 4) to remodel drawing dies of wheel fender panel and trunk lid panel, whereby the CAMF is subsistent in the reconstruction of wheel fender panel die and both CAMF and SAMF are subsistent in the reconstruction of trunk lid panel die. By the inspection of control units, the phenomenon of AMF is eliminated without human manipulation in the design procedure. The results of every stage of drawing die design are enumerated in Tables 5 and 6.

Table 6 The result of drawing die of trunk lid panel

	Primary modeling		Secondary modeling
	First publication	Second publication	
UDB			
BH			
LDB			

Experimental results show that the system takes 2 h to *automatically* complete the main structures of UDB, BH and LDB and layout of standard parts and part of die checking which take up about 70% of design task. The remaining 30% are parameter modification including shape dimensions, the positions and types of standard parts, and some unstructured checking contents, which can be finished with *human interacting tools* provided. However, it would cost more than 3 days to complete the same work in a manual way.

Feedback from the design office using our system reveals that:

1. The modeling failure rate caused by AMFs reduces to 0%, which guarantees the update steadily.
2. About 70% of the design tasks can be done automatically including modeling of die structure and checking, and the remaining 30% can be finished by human interaction including secondary alteration of die structure.
3. A great improvement of product quality is acquired due to the less human disturbance.
4. For most automobile panels, time costing on designing drawing die is cut down from 3 days to 1.5 days, which saves 50% of the time approximately.

5 Conclusion and future

This paper proposes a robust methodology of automatic system design for drawing die based on multilevel modeling strategy, and develops an automatic design system for drawing die on top of CAITA V5. Multilevel modeling is proposed, for one thing, to eliminate AMF, which will improve the robustness of drawing die design, for another thing, to regenerate drawing die structure, which improves the automation level of die design. The system can automatically generate the main structures, lay out standard parts, and check structures. Experimental results and feedback from the design office show that the system is high-robust which can accomplish 70% of the design work in 2 h. Thus, it can save a great deal of time and labor cost and achieve high die quality and design flexibility.

The methodology of automatic system based on multilevel modeling strategy can be applied not only to drawing die of automobile panel but also to other kinds of die such as blanking die, and compound die which may be demonstrated in the following papers. However, the system fails to achieve the design automation of drawing die completely. In the future, several math algorithms and intelligent algorithms will be introduced into the system, which will enable it to complete more tasks automatically.

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