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ORIGINAL ARTICLE

Development of an automated structural design system for progressive dies

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Abstract The design of progressive dies is a very knowledge-intensive, complex, and time-consuming process. This paper describes a computer-aided structural design system for progressive dies with drawing, bending, and punching operations. Taking advantage of a pre-built design knowledge and database, this system is able to output designs of the main and standard parts of a progressive die upon users inputting a minimum set of design information. Our system is implemented on top of CATIA V5 software and uses its built-in modules, including Part Design, Assembly Design, and Knowledge Advisor. Our system also consists of an inference engine and a user interface. The experimental results show that our system successfully reduced the design time from about seven working days to within 2 h for the structural design of the main and standard parts of a progressive die of an upper shell for a mobile phone, which can dramatically save on design time and cost and also provide excellent design quality.

Keywords Progressive dies · Automated structural design system · Detail design · Assembly design · Knowledge base

1 Introduction

Stamping parts are widely used in products of high complexity and precision, such as vehicles, computer, communication, and consumer electronic-related products, because of their competitive performance and productivity. The stamping process has been identified as one of the most important manufacturing processes. However, designing press dies is one of the critical parts of the entire development process. Besides the highly complex die structures, interferences among various design parameters make the design task extremely difficult and time-consuming. It is generally believed that designing dies is an art rather than a science.

Recently, computer technology and 3D computer-aided design (CAD) software have been developing rapidly, and the 3D CAD software has been widely used in designing stamping dies. A solid model offers users an intuitive and concrete view of the die design, which fundamentally reduces the design time. Most 3D CAD software only offers a simple geometrical modeling function. However, they fail to provide users with sufficient design knowledge, which is of great help in most design tasks.

Therefore, the design of automatic and intelligent systems has been an active research topic around the world. Regarding the construction of a dedicated system, Sharma and Gao [1] introduced integrated design and manufacturing planning systems to support conceptual redesign and reprovisioning activities. Nahm and Ishikawa [2] utilized the set-based design approach with the parametric modeling technique to handle the uncertainties intrinsic to the early stages of the design. Myung and Han [3] constructed an expert system to design mechanical products based on a configuration design method. Lee et al. [4] developed a parametric computer-aided tool design system for cold forging using Auto-LISP. Kong et al. [5] introduced a Windows-native 3D plastic injection mold design system based on Solid Works to make the modeling process more efficient. Chu et al. [6] developed a computer-aided parametric design system for 3D tire mold production in CATIA using CAA.

In the stamping tool design area, Pilani et al. [7] proposed a neural network method for automatically generating an optimal die face design based on die face formability parameters. Based on sheet metal operations, Singh and Sekhon [8]

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developed a punch machine selection expert system which was built in AutoCAD and used AutoLISP. Lin and Kuo [9] developed an integrated CAD/CAE/CAM system for stamping dies of a trunk lid outer panel. Lin et al. [10–12] utilized CAD software integrated with an empirical formula to develop the automated design system for drawing die structure for automobiles.

In a progressive die, the workpiece is produced in a number of stamping stations. At each station, one or more die operations are performed on the sheet metal strip. The finished workpiece is produced with each strike of the press. Cheok and Nee [13] developed a knowledge-based strip layout design system in AutoCAD. Chang et al. [14] established a genetic algorithm to solve the problems of ranking the working steps in progressive dies. Kim et al. [15] developed a process planning system for an electric product with bending and piercing operation. Ismail et al. [16] developed an interactive feature-based strip layout design system using cheap CAD software. Ghatrehnaby and Arezoo [17] introduced a mathematical model based on set theory to optimize strip layout using a minimum number of stations and a torque equilibrium criteria. Tor et al. [18] introduced a knowledge-based blackboard framework for the stamping process planning to speed up the progressive die design process by automating the strip layout design. Jiang et al. [19] proposed a systematic representation scheme of insert design automation for progressive dies using an object-oriented, feature-based approach. Giannakakis and Vosniakos [20] developed an expert system for both process planning and die design of sheet metal cutting and piercing operations. Jia et al. [21] developed an automated plate hole design system for progressive dies. Jia et al. [22] introduced an automated structural design of punches and dies for progressive dies.

Though designing dies is a very knowledge-intensive, complex, and time-consuming process, technologies used throughout the process are mature, which makes the entire process routine. To make the design process more efficient and of higher quality, this paper introduces an automated structural design system for progressive dies with drawing, bending, and punching operations. Designers only need to input a minimum set of design information and the system will automatically accomplish the structural design of progressive dies.

2 Progressive die design

The outer shell of a mobile phone is fabricated by the progressive stamping process. The design of the progressive stamping consists of two parts: layout design of the sheet metal strip and structural design of the progressive die.

2.1 Sheet metal strip layout

The stamping process of shells for mobile phones, as shown in Fig. 1, consists of the following nine sub-tasks: the first and second stations are for piercing the pilot holes and blanking the raw material outline. The third station is for drawing the shell shape. The fourth station is for restriking the shell shape and piercing the pilot holes. The fifth to eighth stations are for bending the earphone and charger holes, blanking the keyboard and screen holes, and side punching the earphone and charger holes. The last station is for cutting products from the strip. The progressive process includes all sub-tasks in a single die. This die is called a progressive die. Each of the processes performed within progressive dies is called a process station.

Since sheet metal strips should be fed into the progressive system continuously, the sheet metal coils will go though the decoiler, straightener, and feeder before being fed into the progressive die, where they are processed by each of the processing stations. The strips not only provide raw materials for the stamping process but also carry workpieces from one station to another. The sections used to connect workpieces from adjacent stations are called carriers, and the sections between carriers and workpieces are called bridges. The distance strips move forward each time, which is called the progressive pitch. To correctly position workpieces in each of the process stations, there are a number of reference holes on both carriers and workpieces, which we call pilot holes.

2.2 Progressive die configuration

The design configuration of a typical progressive die, as shown in Fig. 2, consists of two categories of parts. The first category is called the main parts, which include the upper die set, lower die set, die plate, punch plate, blank pressure plate, punch back plate, upper lifting, lower lifting, cam mechanism, blanking punch, bending punch, and dies required by each process station. The design of these parts totally depends on the specification of the progressive dies and the requirements of the clients. The second category is called the standard parts, such as the socket head cap screws, dowel pins, stripper blots, guide posts, and plain guide bushings. These standard parts are available from the market in different sizes.

Progressive dies for developing shells of mobile phones consist of the following basic process stations: piercing, blanking, drawing, bending, restriking, side punching, and cutting. These process stations should be positioned at equal distances based on the progressive pitch. We may also need to design a number of structural parts for each process station. Dowel pins are used to ensure that the strips stably move forward in the progressive die. Lifters are used to completely lift the products from the die faces in each process station. To improve spotting precision, a number

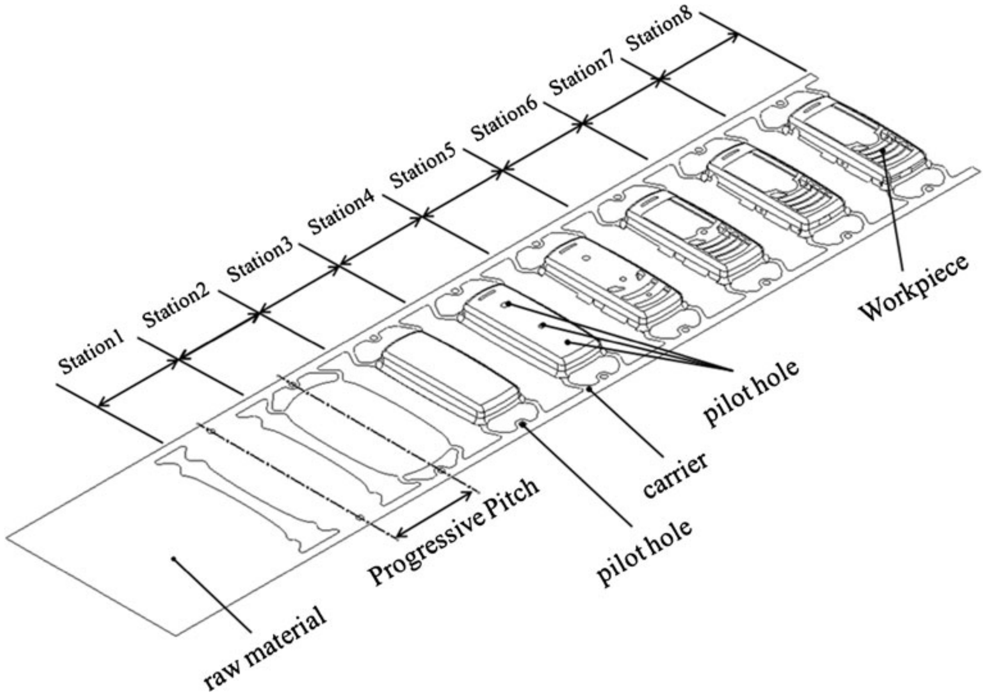


Fig. 1 Structure of a strip layout for the outer shell of a mobile phone

of guide and position parts are used, including plain guide bushings and guide posts on the upper and lower die sets, respectively. When there is not enough space between adjacent stations or there are some weak components, we need to add an idle station in between.

2.3 Designing the structural parts of progressive dies

Most progressive dies are one-off. Therefore, designers must consider both the technical requirements and the budget to offer an optimal die design to meet clients' expectations. Most die structures are very complex, and the design process of the progressive die consists of three stages: die design information, main parts design, and standard parts design.

Die design information is a minimum set of information required by the design system, including the strip layout with functional lines, sheet thickness, and progressive pitch.

- Strip layout with functional surface and lines: As shown in Fig. 3, strip layout with blanking line, die face, punch open line, piercing line, bending lines, side-punching line and cutting lines for blanking the raw material outline, drawing and restriking the shell shape, piercing the keyboard and screen holes, bending and side punching the earphone and charger holes, and cutting the shell outline
- Sheet thickness and progressive pitch: Sheet thickness is used to determine the clearance and tolerance of two matched parts for piercing, blanking, drawing, bending,

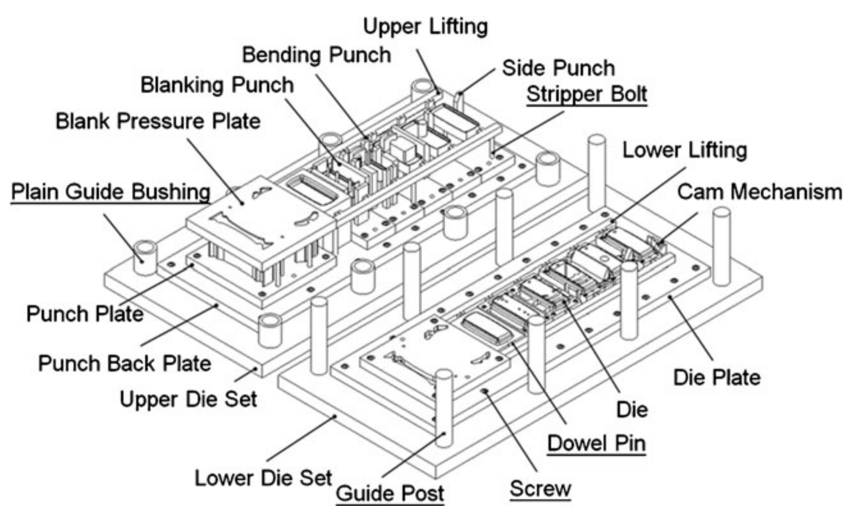


Fig. 2 Structure diagrams for the progressive die of a mobile phone outer panel

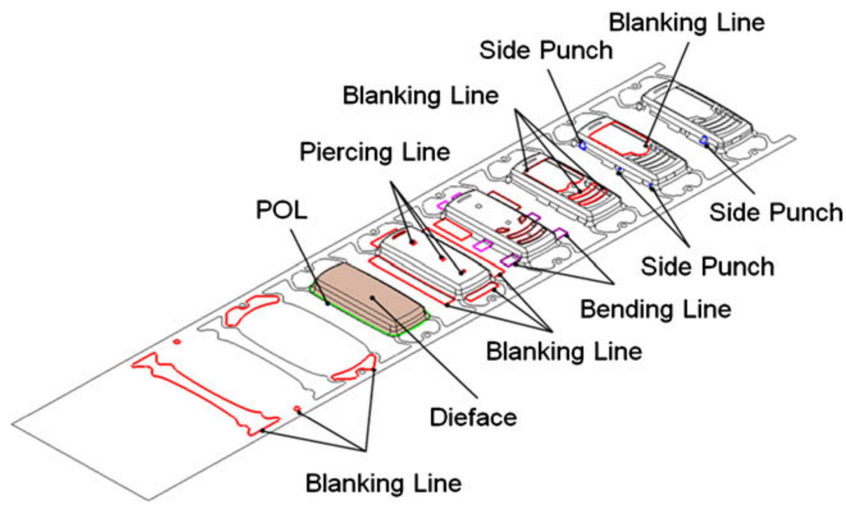


Fig. 3 Strip layout with functional surface and lines for the outer shell of a mobile phone

restriking, side punching, and cutting processes. The progressive pitch is the distance to every stamping process.

The dimension of a progressive die is determined based on its strip layout with functional surface and lines, sheet thickness, and progressive pitch. Die design engineers are able to finish parts design once the dimension of the die is fixed.

In the main parts design stage, the main parts are determined, including the shape and the dimension of the upper die set, lower die set, die plate, punch plate, blank pressure plate, punch back plate, upper lifting, lower lifting, cam mechanism, blanking punch, bending punch, and dies.

Taking the design of cam mechanisms as an example, its design guidelines are given below:

- The working stroke shall not exceed 20 mm.
- The working direction of cam mechanism shall be perpendicular to the side-punching hole.
- The maximum punching force shall not exceed 10,000 N.

Figure 4 shows its design specifications.

In the standard parts design stage, the standard parts are determined, which include the type, quantity, and size for the socket head cap screws, dowel pins, stripper blots, guide posts, and plain guide bushings. At the same time, the design engineer needs to assemble the standard parts into the main parts.

Taking the design of socket head cap screws as an example, its design guidelines are given in Fig. 5.

Figure 6 shows its design specifications.

3 System components

After receiving all the required design information from the user, this system is able to finish the design of the progressive die based on the design guidelines and specifications. The design of the proposed system, as shown in Fig. 7, includes a user interface, an inference engine, a design knowledge base, a design database, and CAD software. Each section is described in the following subsections.

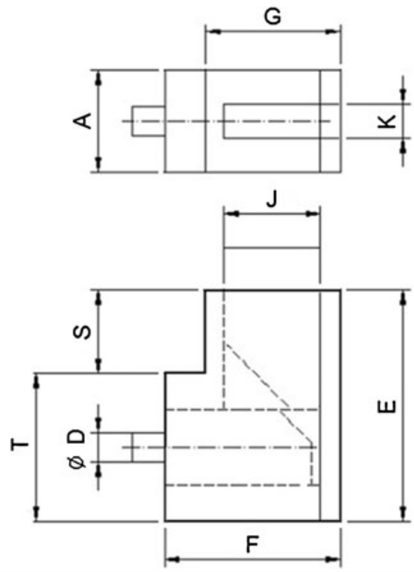
3.1 The user interface

The user interface is responsible for the communication between the designer and the system. The user interface of the proposed system allows users to input both alphanumeric and graphic information. The interface for inputting alphanumeric information is used to type the sheet thickness, progressive pitch, and path of stored files, while the interface for inputting graphic information is used to select 3D drawing files for strip layout, blanking lines, die face, punch open line, piercing lines, bending lines, side-punching lines, and cutting lines.

3.2 The inference engine

The inference engine is the core of our system. It is responsible for generating the solid design of the structural parts of progressive dies based on users' inputs. The inference engine consists of four units: a part selector, a shape calculator, a model generator, and an inference coordinator. After the design information is inputted by the user using an interactive method, the types of structural parts and their parameters of solid models are automatically selected and calculated, respectively, by the design system based on the design procedures. Therefore, solid models are generated by the 3D CAD system automatically. In case any error occurs during the modeling process, the system will send an error message to the user.

The function of the inference coordinator is to moderate the other three units in the inference engine. Starting from the input of the design information of the user interface, the inference coordinator will design each structural parts of the progressive dies based on their design processes. For each of



D (mm)	A (mm)	F (mm)	E (mm)	S (mm)	G (mm)	J (mm)	K (mm)	T (mm)
2	30	35	30	10	30	10	10	10
4	35	35	30	10	30	10	10	10
6	40	40	30	10	35	15	15	15

Fig. 4 Design specifications for cam mechanisms

the parts, the type, quantity, position, direction, and size of the part are determined by the part selector. Then, the shape calculator starts to calculate the shape of the part and triggers the model generator to finish the solid model design of the part.

The part selector provides the data of the type, quantity, position, direction, and size related to the structural parts. For each of the parts, the type of part is determined by either design guidelines for the main parts or hole identification rules for the standard parts of the part selector. The part selector is also responsible for determining the quantity, position, and size of the part. Therefore, when the system is designing parts, this selector would select the type, quantity, position, direction, and size of the parts according to the constraints and formulas derived from the design information, design guidelines, and hole identification rules.

The shape calculator can provide the shape parameters of structural parts upon fixing the type and size of the structural parts. This calculator will compute all design values for each shape parameter based on the design specification of the structural part.

The model generator can perform the 3D solid modeling process for the structural parts. It can be used to construct the solid model of the structural part by integrating all geometric operations of each structural part during the modeling process according to the type, quantity, location, direction, and shape parameters of candidate structural parts. Since the parameters of the solid model are computed automatically by the system rather than resulting from interactions with the user, the modeling process for this solid model is performed automatically by the 3D CAD system.

3.3 The knowledge base

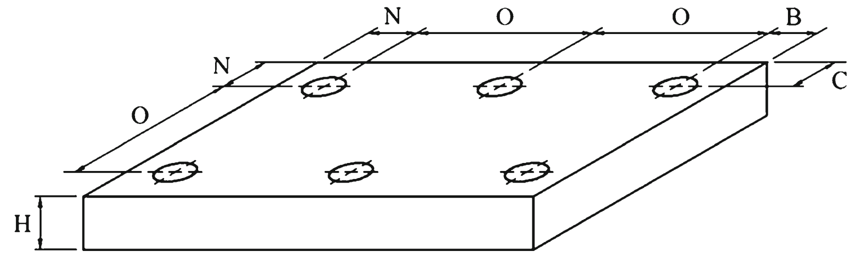
The knowledge base contains both design processes and design guidelines. The design processes outline the design and modeling process for each of the structural parts. The design guidelines are utilized to decide the type, size, quantity, direction, and position of each of the structural parts.

In the design knowledge base, dies are systematically classified into main parts and standard parts to construct progressive dies using standardized 3D approaches. The grasp of the connection among various main and standard parts is essential to obtain an appropriate design process for each of the main and standard parts. Itemized modeling processes for each part, as well as the geometric operations used in such processes, are obtainable in the knowledge base. In addition, the design guidelines of the main parts, hole identification rules of the standard parts, 3D diagrams with design parameters, itemized text, and formulas are collected in e-book forms for reference, training, and debugging missions.

3.4 The design database

The design database offers design specifications for the main and standard parts. The design specifications specify the category of each of the main and standard parts.

The design specifications for each of the main and standard parts are depicted in 2D diagrams. Besides, each diagram is followed by a table that itemizes the related shape parameters and standard sizes. All information in the design database is collected in e-book forms for easy access.



(a)

unit：mm

H	<13	13~19	19~25	25~32	>32
M	M4,M5	M5,M6	M6,M8	M8,M10	M10,M12

(b)

unit : mm

Type	N_{min}	B_{min}	C_{min}	O
M4	5	6	4.5	40±15
M5	6	7.5	5.5	50±15
M6	8	9	7	60±20
M8	10	12	9	80±20
M10	13	15	11.5	100±20
M12	15	18	14	120±30

(c)

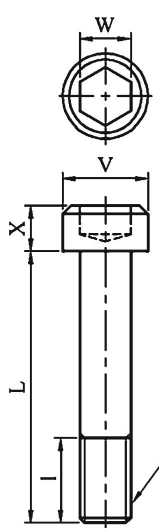
Fig. 5 Design guidelines for socket head cap screws

3.5 CAD software

This system has been implemented on top of the CATIA CAD system with its "add-on" Part Design, Assembly Design, and Knowledge Advisor modules. The Part Design module is chargeable for commanding and executing the process of constructing 3D models. Hence, the inference coordinator is built in this module. The part selector utilizes the Formula Editor and the Rule Editor modules, while the shape calculator employs the Generative Shape Design module. The model generator uses Visual Basic (VB) to develop programs for generating solid models. The Assembly Design module is used to assemble the standard parts into the main parts. The VB is also used to construct the alphanumeric and graphic user interfaces.

4 Construction procedure for the automated structural design system

The proposed system is constructed based on CATIA 3D CAD software in the Windows XP operating system. This



unit:mm

M x P	V	X	W	l	L
4 x 0.7	7	4	3	Full Thread	5,6,8,10,12,14,15,16,18,20,22,25
				20	30,35,40,45,50,55,60,65,70,75
5 x 0.8	8.5	5	4	Full Thread	5,6,8,10,12,14,15,16,18,20,22,25
				22	30,35,40,45,50,55,60,65,70,75,80
6 x 1.0	10	6	5	Full Thread	6,8,10,12,14,15,16,18,20,22,25,30
				24	35,40,45,50,55,60,65,70,75,80
8 x 1.25	13	8	6	Full Thread	8,10,12,14,15,16,18,20,22,25,30,35
				28	40,45,50,55,60,65,70,75,80
10 x 1.5	16	10	8	Full Thread	10,12,14,15,16,18,20,22,25,30,35,40
				32	45,50,55,60,65,70,75,80
12 x 1.75	18	12	10	Full Thread	15,16,18,20,22,25,30,35,40,45,50
				36	55,60,65,70,75,80

Fig. 6 Design specifications for socket head cap screws

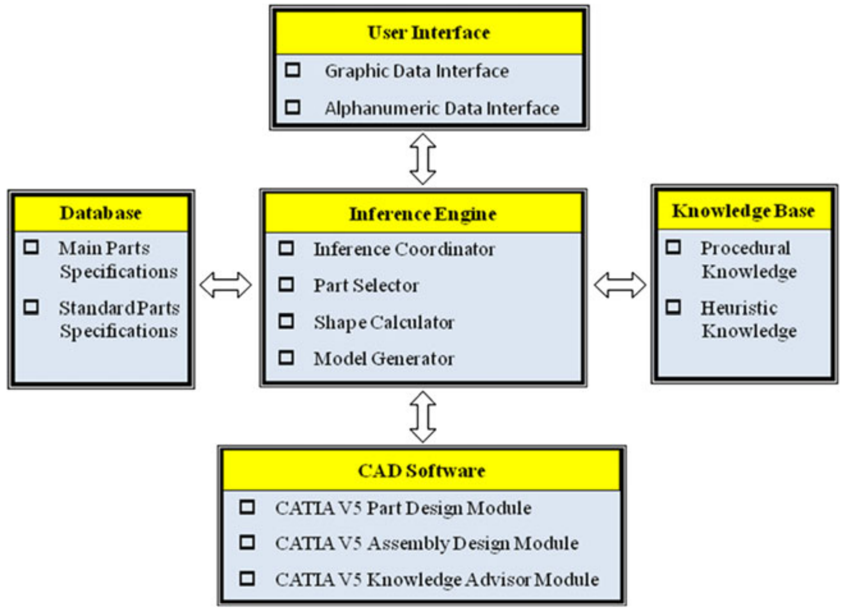


Fig. 7 System components

system is designed to be used in a PC and is developed using the CATIA software's built-in modules, including Part Design, Assembly Design, and Knowledge Advisor. Upon users' inputs of the design information, our system is able to automatically generate the designed solid model for the main and standard parts of a progressive die using the

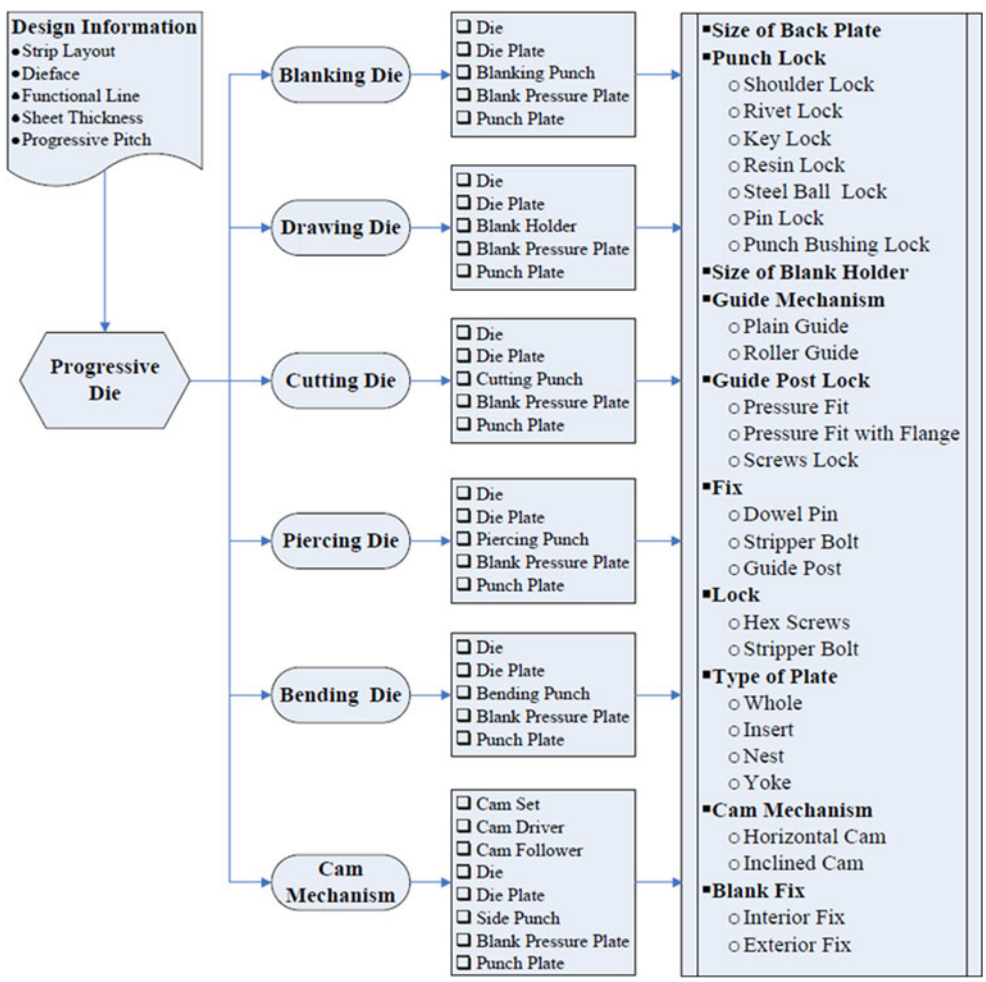


Fig. 8 Organization diagram of functional features for progressive dies

design guidelines and design specifications based on the design procedures. There are seven steps to construct the proposed system, which will be described in the following sections.

4.1 Die structure analysis

Progressive dies contain piercing, blanking, drawing, restriking, bending, and side-punching and cutting processes and have very complicated structures. It is necessary to plan a complete and systematic layout for the overall structure of the progressive dies. Therefore, for the proposed system, not only the constructional logic of die design operation could be developed, but also any possible mistakes in the die design could be prevented.

To layout the die structure, we first collect the structures of all kinds of progressive dies. Then, each progressive die is divided into blanking, drawing, piercing, bending, and cam dies according to its stamping process. After that, the main parts of the aforementioned dies are identified. Finally, we perform analyses on the design and functions of the main parts of the dies. At the same time, the parameterized die design system takes the changeable sizes of a die structure as parameters and then changes the die structure sizes by assigning appropriate values to each of the parameters based on the design formulas, constraints, and tables derived from the design information, guidelines, and specifications. However, certain functional modulus, such as the punch lock, guide mechanism, guide post lock, fix, lock, type of plate, and blank fix, cannot be designed simply by changing the design parameters because of the diversity of their structures. Therefore, various structures of the main parts for a progressive die are partitioned into functional features, and the same functions are categorized into a single identical functional module. Figure 8 shows a classification of the features for the main parts of a typical progressive die based on their functionality.

4.2 Design process standardization

The object of design process standardization is to provide a systematic procedure of designing dies. Because the CAD system has its own modeling process, the size, position, and direction of functional features cannot be determined until the size, position, and direction of certain functional features are fixed. A standardized design process of the main parts, as shown in Fig. 9, is generated based on the design guidelines and specifications for each of the functional features of the main parts as well as the cause-and-effect relationships among these functional features. This standardized process is used to guide the design of the main parts for the skeleton mechanisms of progressive dies, such as their structures and initial sizes as well as the initial sizes, positions, and directions of each functional feature on a main part.

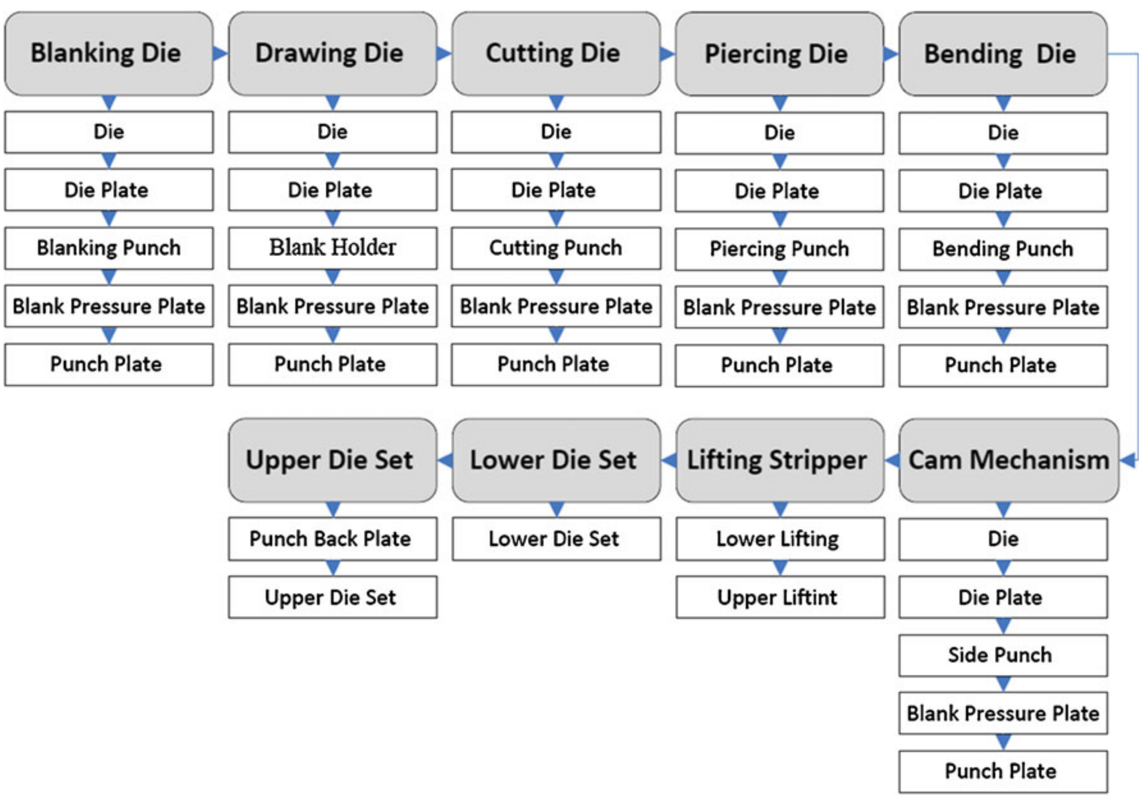


Fig. 9 A stardardized deisng process for skeleton mechanism of progressive dies

4.3 Parameter settings

After the design process is standardized, to perform parametric modeling of the progressive die in the CATIA system to conform to the design information, it is necessary to assign a parameter name to a changeable dimension. Therefore, it can define the formula of a parameter based on its relationship with the design conditions. Moreover, there are hundreds of parameters in our automatic design system, which demand a systematic and appropriate naming schema so the parameters can be well managed to facilitate coding and debugging.

The name of a parameter used in our system consists of two parts: the name of the part to which the parameter belongs and the name of the dimension. Based on the parameters' functionality, they can be divided into shape parameters and position parameters. Shape parameters can be further classified as global parameters and local parameters. Local parameters only need to meet the design specifications, while global parameters are determined by both the design specifications and any relevant local parameters. Taking the socket head cap screws shown in Fig. 6 as an example, the diameter (*M*) and pitch (*P*) of the screws are global parameters, while the other measures, such as *V*, *X*, *W*, *L* and *l*, are local parameters.

4.4 Skeleton mechanism construction

Once the parameters have been identified, a feature layer tree of the functional features for the main part of the progressive die is developed based on the design process, as shown in Fig. 10. Since various features of a progressive die can share a common functionality, all possible feature structures of a function must be pre-constructed when constructing the skeleton mechanism. When constructing a solid skeleton model of a die, only the selected functional features should be activated. All unselected functional features should be deactivated.

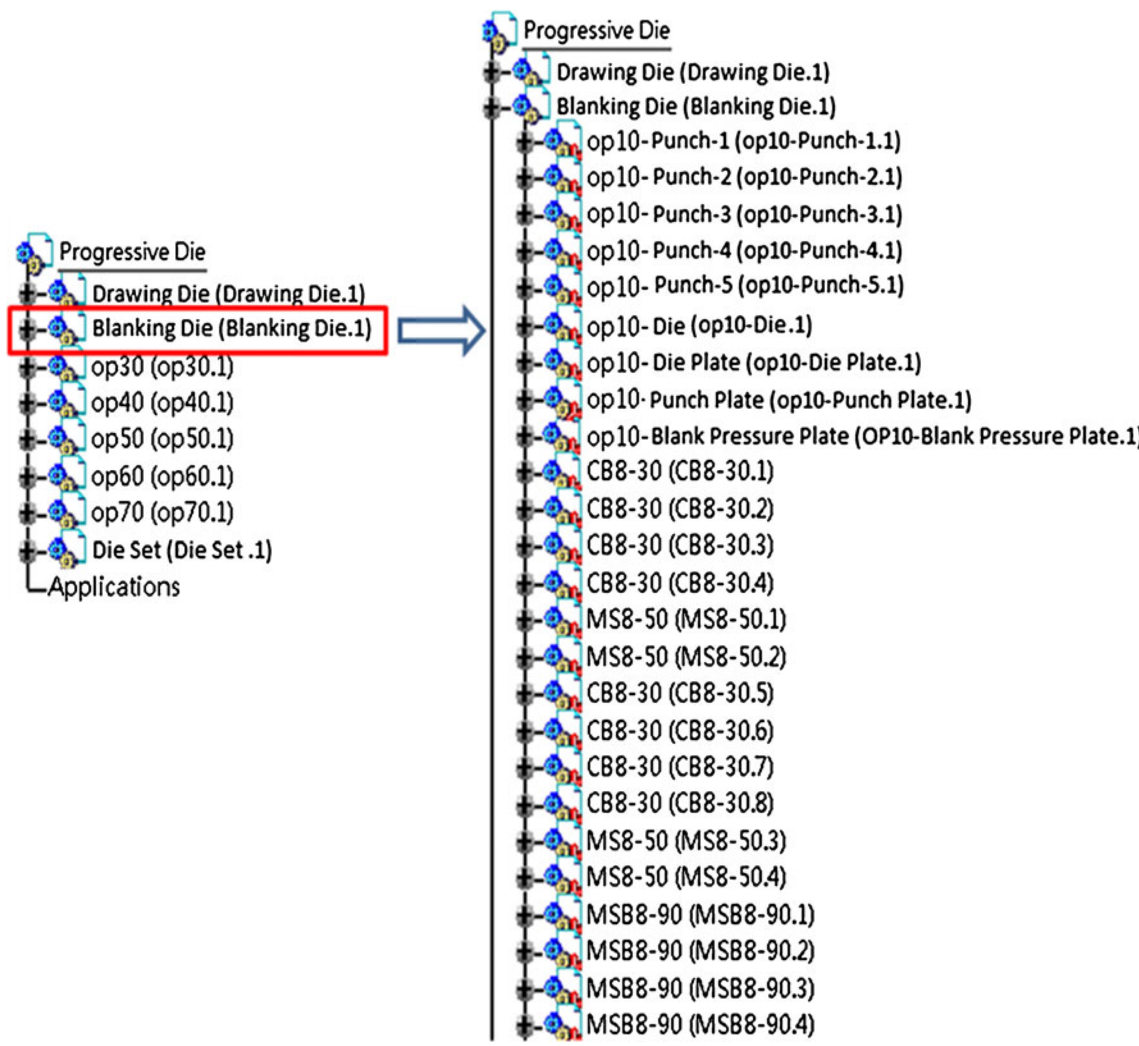


Fig. 10 Layer tree of skeleton models for progressive dies

When constructing skeleton mechanisms, design engineers should use all available preset sizes and constraints. All the dimensions are treated as parameters, whose values can be changed based on the design requirements. Since the values of the dimension parameters cannot be null or negative, every circumstance should be considered to avoid any potential problems, especially when there are cause-and-effect relationships among the various features. The number of constraints directly affects design flexibility. In most cases, the utilization of constraints can decrease the number of parameters and simplify the programming work. Therefore, an appropriate use of constraints is vital to the entire design process.

4.5 Programming

Programming aims to find all the relationships for each parameter that have been set up properly based on the input design information for such design as well as conforming to the design guidelines, design specifications, design processes, and geometric operations. Then, the built-in modulus of the CATIA is used to convert the parameter relationship into a related program.

To facilitate the design process, programs are divided into three levels. Taking the cam mechanisms as an example, the purpose of the first level is to select the main parts based on the design guidelines. This level of program takes advantage of two built-in modules of CATIA V5—Rule Editor and Formula Editor—to convert design guidelines into constraints and formulas, which are used to determine the type, quantity, position, direction, and size of the main parts, as shown in Fig. 11a, b. The second level of the program is responsible for calculating the shape of the die. This level takes advantage of the built-in modules of CATIA V5 to construct the design table of the die based on the design specifications of each main part, so this level of program can use the design table to determine related independent and dependent parameters, as shown in Fig. 11c. The third level of the program is used to construct the model. Written by VB, this level of program is used to provide a modeling procedure of the main parts based on the type, quantity, position, direction, and dimension of the aforementioned two levels, as shown in Fig. 11d.

4.6 Standard parts assembly

Once the skeleton mechanisms of the progressive dies have been programmed, the standard parts need to be assembled into main parts. The progressive die contains a large number

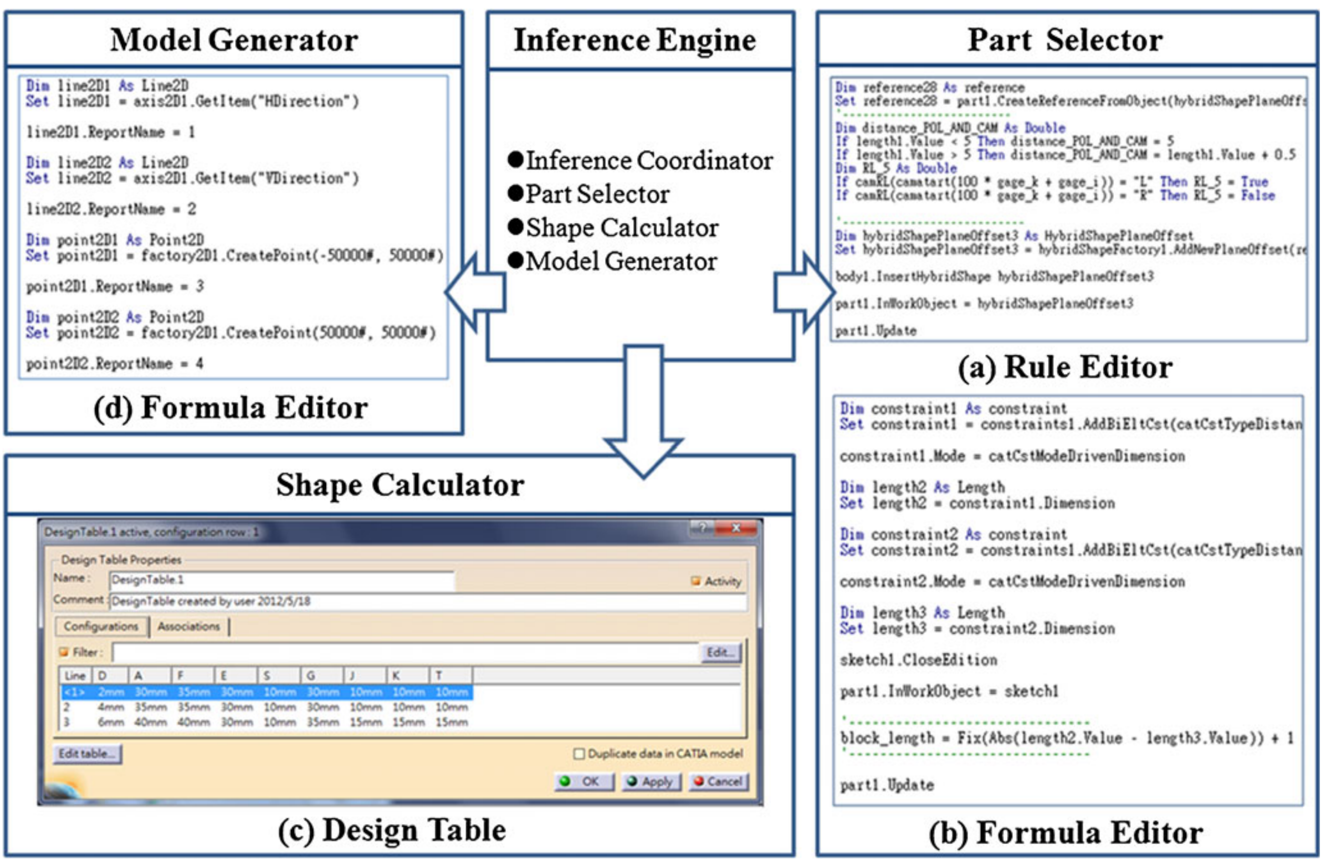


Fig. 11 Program design

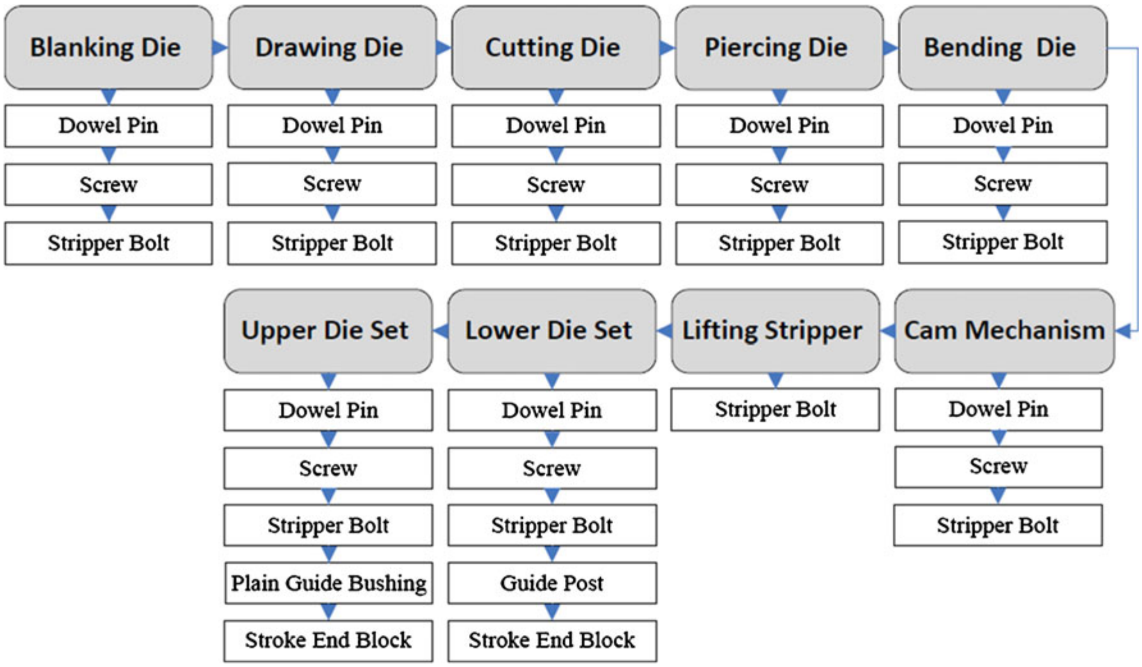


Fig. 12 Assembly design process of progressive dies

of standard parts, so it is necessary to plan a systematic process for the assembly design of the overall standard parts. Therefore, the assembly design operation could not only develop the procedural logic for the CAD system but also prevent mistakes in the assembly design.

To standardize the assembly design process, first, it is necessary to collect information related to various assembly design processes for progressive dies and then analyze all standard parts for each progressive die. It is also necessary to consider the design guidelines and specifications of the main parts. Then, it is possible to develop a flowchart for the assembly design process of a progressive die, as shown in Fig. 12.

The standard parts are assembled among various main parts according to the hole identification module, as shown in Fig. 13. In the module, there are five identification rules, and each identification rule corresponds to one standard part. After one standard part is chosen based on its shape, diameter, and length, the chosen standard part is assembled into the hole of the main parts.

4.7 User interface

The user interface allows a user to design progressive dies with the proposed system in a user-friendly environment. The user interface is constructed using the VB module contained in CATIA V5.

The user interface in our system is tabbed and classified into two categories, as shown in Fig. 14. The first category is used to input/output graphic information, such as inputting strip layout, blanking lines, die face, punch open line, piercing lines, bending lines, side-piercing lines, and cutting lines by typing the path of import files and outputting the designed progressive dies with related 3D drawing by typing the path of stored files. The second category is used to

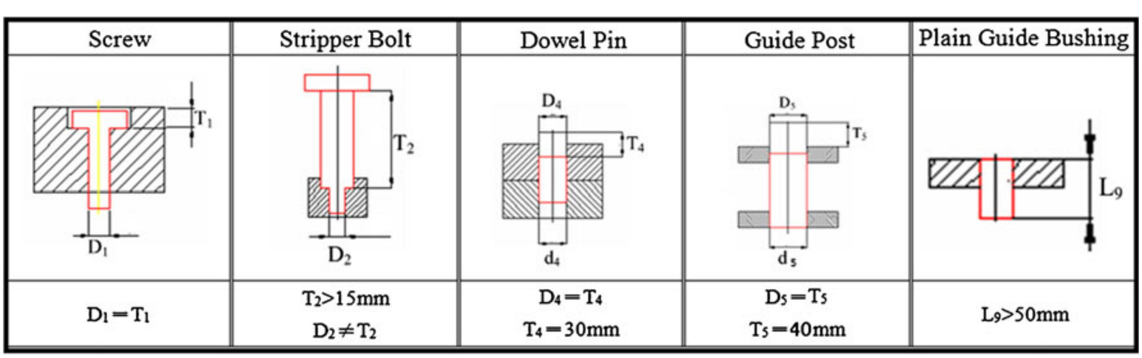


Fig. 13 Identification rules for the standard parts

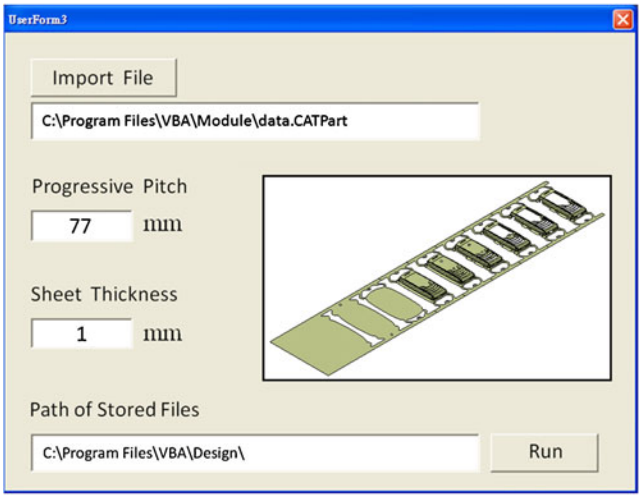


Fig. 14 User interface for automated structural design system

input alphanumeric information, such as progressive pitch and sheet thickness.

5 Case study

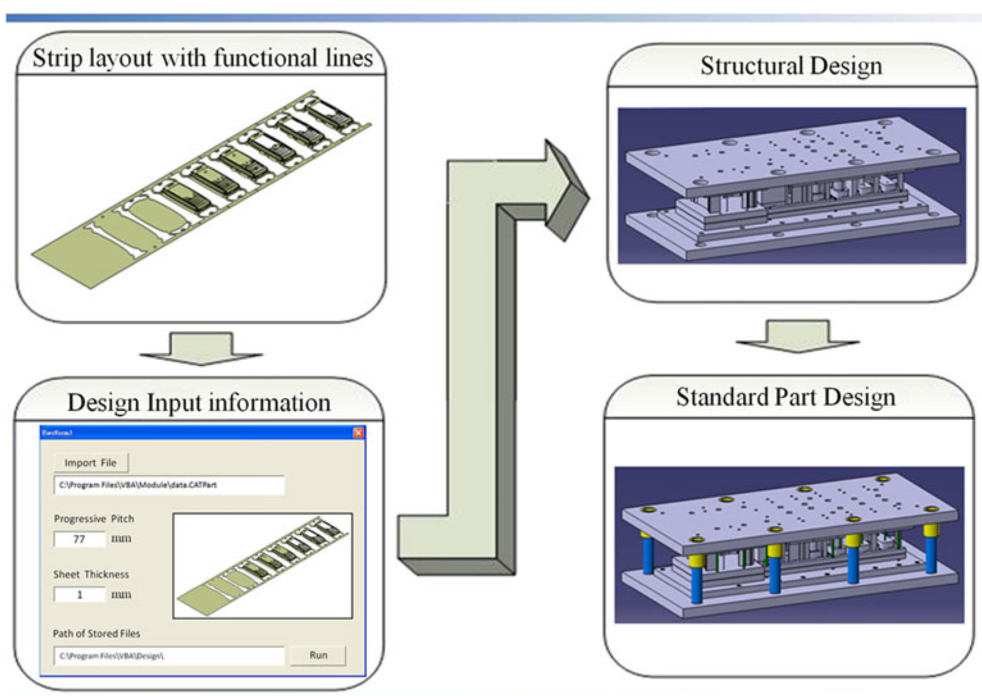
The developed system is explained with the automated structural design of progressive dies for the upper shell of a mobile phone, as shown in Fig. 15. First, the sheet metal strip layout is drawn and then its functional surface and lines, such as die face, blanking line, punch open line, piercing line, bending lines, side-punching line, cutting lines, are assigned. After the automated structural design system is started, users begin to input the strip layout with functional surface and lines, sheet thickness, and progressive pitch. After the RUN button is pressed, our system begins to generate the main parts of the progressive die based on the design processes, guidelines, and specifications. After that, the assembly design is executed. The holes of the main parts are identified and the appropriate standard parts are chosen from the standard parts database and assembled into the holes of the main parts. After every hole of the main parts is assembled into a standard part, the design of the progressive die is finished. Also, the engineering drawing of main and standard parts are generated automatically.

The progressive die for the upper shell of mobile phone includes 79 and 180 pieces of main and standard parts, respectively. The automated structural design system takes less than 2 h, while it would take the traditional 3D CAD system more than seven working days to complete the same work.

6 Conclusions and future works

This paper illustrates an automated structural design system for progressive dies with drawing, bending, and cutting operations which is built on top of the CATIA V5 software. Upon receiving the initial design information from design engineers, such as strip layout, blanking line, die face, punch open line, piercing line, bending lines, side-punching line, cutting lines, sheet thickness, and progressive pitch, the system can automatically generate the final design of the main and standard

Fig. 15 Case study



parts of the die. The main parts cover the upper die set, lower die set, die plate, punch plate, blank pressure plate, punch back plate, upper lifting, lower lifting, cam mechanism, blanking punch, bending punch, and dies; the standard parts cover the socket head cap screws, dowel pins, stripper blots, guide posts, and plain guide bushings. The design formulas, identification rule, and geometric operations of the modeling processes are generated by the system using the built-in modules of CATIA V5, such as Part Design, Assembly Design, and Knowledge Advisor. The proposed system can successfully automate the structural design of the main and standard parts of the progressive die of an upper shell for a mobile phone within 2 h, whereas a 3D CAD system would take about seven working days to accomplish the same work. Thus, it can dramatically save on time and costs for designing the main and standard parts of progressive dies and also provide excellent design quality.

In the future, an optimization module can be introduced into our system, which will enable it to output an optimal design. In addition, since our system can only handle progressive dies at this time, we would like to extend our system to be able to design mechanical products.

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