Automatic Hole Recognition and Classification for a Set of B-rep Models Representing an Injection Mold

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***Abstract*—A hole recognition algorithm for all hole types in a mold set is proposed. The algorithm can recognize holes of both circular and non-circular types, and blind and through types. It can also detect ladder holes, each of which is composed of a series of holes connected in sequence, and related holes that pass across different CAD models. The proposed hole recognition algorithm is divided into five steps: (1) facial composition is searched for each hole, (2) the holes are evaluated as either through or blind, (3) related holes are detected on each CAD model, (4) related holes passing across different CAD models are detected, and (5) data is output. Three mold sets were used to demonstrate the feasibility of the proposed method, and the results were compared with those from commercial software.**

***Index Terms*—Hole recognition, Feature recognition, Feature classification, Injection mold, B-rep model**

I. Introduction

In mold flow analysis, it is necessary to convert the computer-aided design (CAD) models of an injection mold into solid meshes so that the solver can perform the desired computations. An injection mold is composed of many parts, such as the core, cavity, runner system, cooling channels, and mold base. A mold base can further be divided into many parts. Conventionally, the solid meshes for the core, cavity, runner system, and cooling channels are carefully generated, whereas the mold base is typically modeled as a rectangular box to simplify the mold structure. However, the required accuracy in mold flow analysis has increased in recent years. In some applications, it is now necessary to consider all parts of a mold base and to generate solid meshes for them. As the total number of meshes increases tremendously, mesh reduction becomes an important issue to address.

One of the methods to reduce the number of meshes in mold flow analysis is to simplify unimportant features in the CAD models. The most common feature on a mold base is holes. Various types of holes exist in mold parts for assembly via screws, ejector pins, guide bushes, and return pins. As most holes are assembled with other parts during the injection process, the simplification of holes on a mold base would not affect the results of the mold flow analysis. To simplify holes in a mold base composed of different mold parts, there must be an implementation of a hole recognition process, so that all holes in mold parts can be determined. The most critical issue in this procedure is that most holes are related to each other across different CAD models. If the topology of the related holes is not established, then hole simplification would become difficult and error-prone. In contrast, if the relationship of neighboring holes were established, then it would become easy to handle related holes both within a part and across different parts.

In feature recognition, most investigations employ the topological relationship of adjacent entities for the recognition of features. Ref. [1] (2011) proposed a method for feature recognition, using the topological relationship of the boundary representation (B-rep) model to solve the problem that the boundary of the holes is not filleted in the attributed adjacency graph (AAG) method. The proposed method utilized the property that a hole is always accompanied by an inner loop in the B-rep model. All adjacent faces corresponding to an inner loop were found, and the type of the loop was determined by the angle between adjacent faces. However, the types of hole that can be recognized are limited in this proposed method.

When a hole is filleted on its boundary, it may be necessary to recognize the fillet first, and then perform the hole recognition in accordance with the fillet information. A fillet is also known as a blend face. Ref. [2] reported an algorithm that recognized edge blend faces as face-face blend faces and cliff blend faces as face-edge blend faces. This algorithm used the curvature on the smooth edges to detect the edge blend faces. Ref. [3] indicated that a fillet with both an edge blend face and a vertex blend face may exist, and named it as a hybrid-convex vertex blend face. Ref. [4] provided three

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classifications of blend faces: edge blend face, vertex claimed that the cliff edge blend face was a special type of edge blend face and was generally discussed individually. An algorithm was introduced using the smooth edge, support face, and span angle for the recognition of edge blend faces. A flowchart for the recognition of vertex blend faces was also introduced. Ref. [5] introduced an algorithm using the smooth edges, normal vectors, span angles, and the area of the target feature for the automatic recognition and screening of blend faces. Ref. [6] elaborated on the recognition and simplification of blend faces on freeform surfaces. Unlike other algorithms that solely employ edge information, these authors employed the surface information for the recognition of blend surfaces. The surface was converted into a NURBS data structure, with the curvature of any point on the surface evaluated using the second derivative in both the *U* and *V* directions.

When a feature is located on multiple planes or surfaces, feature recognition becomes more complex and difficult, as more topological relationships and information must be considered and evaluated. Ref. [7] proposed an algorithm that projects surfaces onto a projected plane, and then combines this with the volume decomposition method for feature recognition. This method was primarily used for the efficient planning of NC tool cutting paths. Ref. [8] presented an algorithm to recognize the surface features on an STL model by proposing an algorithm to evaluate the curvature on triangular meshes. Ref. [9] proposed an algorithm to recognize and classify convex features in terms of the parameters of B-spline surfaces, which was applied to sheet metal parts. Ref. [10] isolated the surface features by eliminating all filleted features from the CAD model, and then established an algorithm in terms of the AAG graph for the recognition of the remaining surfaces. Ref. [11] provided a method for the recognition of aircraft structural parts in terms of a holistic AAG algorithm. Several algorithms were presented to modify the operating parameters and to slice and filter the surfaces. Several realistic examples of aircraft structures were presented to demonstrate its feasibility.

II. Problem Statement

The objective of this study was the recognition of all holes in an injection mold. The most critical issue in hole recognition is that most holes are related to each other, not only within a mold part, but also across different mold parts. The main issue in this study was the recognition of all related holes, not only within a mold part, but also across different mold parts, so that each set of related holes can be accessed and processed simultaneously.

In the proposed hole recognition procedure, the approach based on the loop data of the B-rep model was developed to search for holes, and the composition of the faces of each hole was recorded. The attribute of being either blind or through for each hole was also detected. By using the facial composition of each hole and its attribute of being either blind or through, holes that are blend face, and mixed blend face. These investigators related to each other can be detected and classified. There are four main hole classification types, namely single-blind, single-through, ladder-blind, and ladder-through. In addition, an algorithm was also developed to find holes that are related to each other across different mold parts. The primary contribution of the proposed method is that all types of holes in an injection mold can be recognized completely and efficiently in comparison with current methods in literature that typically deal with holes in a single CAD model only. Several example mold sets are presented to demonstrate the feasibility of the proposed technique.

III. Hole Classification and Terminology

A hole is called a single hole if it exists alone, such as the cases in Fig. 1(a). Several holes that connect to each other can form different hole structures. If all holes connect to each other in series, it is called a ladder hole, such as the cases in Fig. 1(b), which contains two and three holes connected in series on the left and right plots, respectively. If several holes inside a larger hole are arranged in parallel, such as the case in Fig. 1(c), it is called a parallel hole structure. Coaxial holes may be across different mold parts, such as the case in Fig. 1(d). When the bottom of a hole is empty, it is called “through”; the left plots in Figs. 1(a) and (b) are through. In contrast, when the bottom of a hole is not empty, it is called “blind”; the right plots in Figs. 1(a) and (b) are blind.

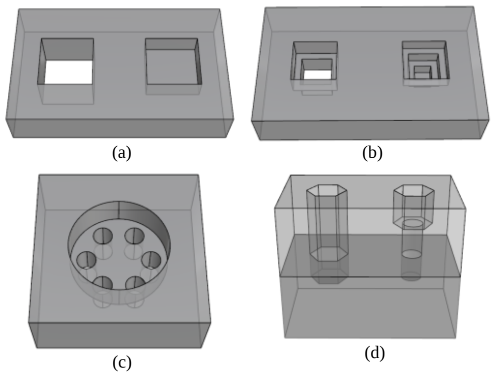


Figure 1. Classification of hole features for feature recognition and simplification, (a) single hole, (b) ladder hole, (c) parallel hole structure, and (d) related holes across different components.

The composition of the faces of a hole is shown in Fig. 2. A hole is essentially composed of three face types, namely base, side, and bottom faces. A base face is a face where a hole resides; the hole can form an inner loop on the base face. A bottom face is at the bottom of a hole. The side face is a face that connects to both base and bottom faces simultaneously. The angle between the side and base faces is always convex. For a blind hole, the angle between the side and bottom faces is concave (Fig. 2(a)), whereas it is convex for a through hole (Fig. 2(b)). A fillet may exist between the base and side faces, or the side and bottom faces. Figure 2 depicts an example with a fillet, called a top blend face, between the base and side faces. The topological data between a fillet and its neighboring faces can be obtained from the database of fillets.

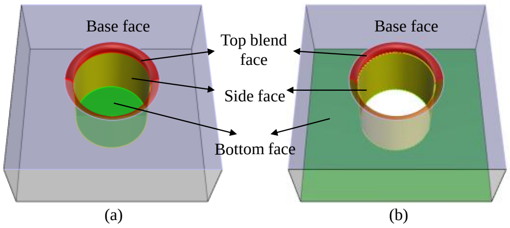


Figure 2. Faces composition of a hole, (a) blind hole and (b) through hole.

IV. Hole Recognition

Fig. 3 demonstrates the proposed hole recognition algorithm on a sample mold set, where the inputs are the loop and fillet data on each CAD model of the mold set and the outputs are the composition of the faces of each hole and the relationship between the holes. In Fig. 3(a), two mold parts are illustrated. The input loop and fillet data are obtained from an edge and face AAG database [12]. A loop can reside either on a single surface or across faces that are G^0, G^1, or G^2 continuous. A single loop is the current loop recorded in the B-rep model, whereas the loops across multiple surfaces are computed by using a loop recognition algorithm [13]. Sharp edges on 3D CAD models are typically filleted to yield smooth edges, creating a blend face to connect to its neighboring faces smoothly. When a hole is filleted at its boundary edge, the fillet data is employed to find the neighboring faces on both sides of the blend face. The fillet data is established by using a fillet recognition algorithm [14]. The proposed hole recognition algorithm can be divided into five steps: (1) search the facial composition of each hole (Fig. 3(b)), (2) evaluate the through or blind attribute (Fig. 3(c)), (3) detect related holes on each CAD model (Fig. 3(d)), (4) detect related holes across different CAD models (Fig. 3(e)), and (5) output data for hole simplification.

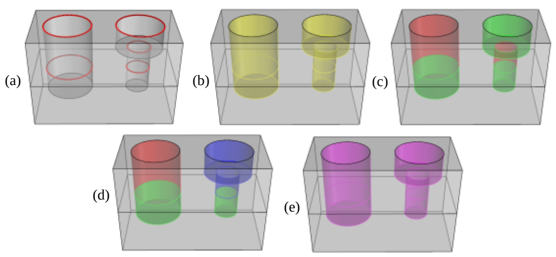


Figure 3. Hole recognition procedures, (a) input loop data, (b) search faces composition on each hole, (c) compute type and associated properties of each hole, (d) detect related holes on each CAD model, and (e) detect related holes across different CAD models.

A. *Search Faces Composition on Each Hole*

Consider a loop L_i, where i is the loop index. If all its neighboring faces are convexly connected, then a hole exists. The following procedure is employed to judge whether a hole exists on L_i and if it exists, to compute the facial composition.

First, the base face where L_i resides and the number of edges on L_i are evaluated. In the loop data, a loop can be either an inner loop of a face or a loop across multiple faces. A base face is found for the former, whereas multiple base faces are found for the latter. The edges corresponding to a loop can be found from the loop data.

Second, each of the edges, e_j, in L_i, is checked whether they are convex or concave. If all edges on L_i are convex or potentially convex (the face neighboring the base face is G^1 continuous and convex in shape), then a hole is added to the hole data and all neighboring faces are recorded. Otherwise, no hole exists on L_i. The process then jumps to the next loop. When a hole exists, the side faces are computed. For each face neighboring e_j, if it is not a blend face, then it is recorded as a side face. Otherwise, it is recorded as a blend face, and then the side face is evaluated along the principal direction of the blend face. A side face may be divided into several patches in a CAD model. A procedure must be implemented to find all side faces.

Finally, the neighboring face of each side face is evaluated. A side face has many neighboring faces. The ones that are already regarded as either base, side, or blend face are ignored, whereas the remaining ones are checked one by one. If it is not a blend face, then it is regarded as a bottom face. If it belongs to a blend face, then the fillet data is employed to cross over this blend face to obtain a bottom face. Once all bottom faces are obtained, the search on L_i is ended.

This process is performed for all loops sequentially to obtain all holes and their corresponding base, side, and bottom faces. Fig. 3(b), the result of this procedure on a sample mold, shows that four holes with respect to four loops for two mold parts are detected, where all side and bottom faces are yellow.

B. *Evaluate through or Blind Attribute*

A hole is a through hole if all its edges between the side and bottom faces are convex, whereas it is a blind hole if all its edges between the side and bottom faces are concave. The attribute of being either a blind or through hole can be determined by checking this condition. In the previous step, a blind hole is counted once as the hole is obtained from its top end face only. However, a through hole is counted twice as the loops on both of its end faces are checked individually. Therefore, repeated through holes must be detected and deleted. The following three conditions are proposed to detect and delete repeated through holes.

(1) <u>The side faces obtained from both loops are identical</u> (Fig. 4(a)): the hole is uniform in cross section, and hence the side faces obtained from both loops are identical. In this case, one of the holes is deleted from the hole data.

(2) <u>The side faces obtained from both loops are different</u> (Fig. 4(b)): the hole is non-uniform in cross section, but some side faces are still shared by both holes. In this case, one of the holes is deleted from the hole data.

(3) <u>One loop exists on a through hole</u> (Fig. 4(c)): in this case, a through hole has one loop only, and hence no hole is deleted.

For the example in Fig. 3, two blind holes and two through holes for two mold parts were detected, with the blind and through holes shown in green and red, respectively, in Fig. 3(c).

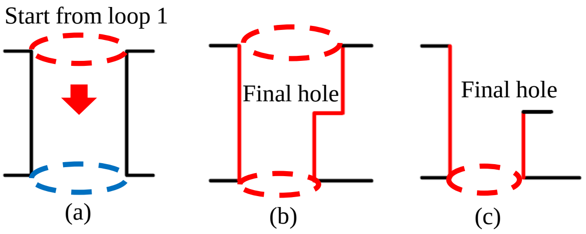


Figure 4. Three kinds of through holes: (a) the side faces evaluated from both loops are identical, (b) the side faces evaluated from both loops are different, and (c) only one loop exists.

C. Detect Related Holes on the Same Part

As mentioned previously, related holes are divided into two types: ladder holes, and parallel hole structures. For a parallel hole structure, each of the holes inside a larger hole could be either a single hole or a ladder hole. Therefore, the focus is on evaluating ladder holes hereafter. This is divided into two steps. First, the neighboring conditions of every two connected holes are established. Second, the holes on each ladder hole are evaluated.

The neighboring conditions of every two connected holes are divided into two types: those connected by base faces and those connected by bottom faces. Consider the blind hole H_c shown in Fig. 5 as an example. The base face of H_c can be compared with the bottom faces of all other holes H_i. If the indices of two faces are the same, say H_1 in Fig. 5, then H_C connects to H_1 by its base face. Similarly, H_c connects to H_2 by its bottom face, as shown in Fig. 5. As the relationship of two connected holes is bilateral, the data record for H_1 and H_2 is that H_1 connects to H_c by its bottom face, and H_2 connects to H_c by its base face. As a hole can either be blind or through and it can connect to its neighboring hole by either its base or bottom face, there are 16 kinds of relationships between two connected holes, as listed in Table I. However, only six of them exist in real CAD models and must be verified, while the others do not need to be checked, as they do not occur. Table II lists an array recording the neighboring relationship of the holes from the example in Fig. 5. In Table II, "hole index" refers to the hole sequence, "connect by base face" records the neighboring hole to the base face of the hole indicated in "hole index", and "connect by bottom face" records the neighboring hole to the bottom face of the hole indicated in "hole index". For a parallel hole structure, the hole number in the third column could be multiple.

A ladder hole is composed of a series of holes connected in sequence, each of which is called a layer. Fig. 6 depicts three typical ladder holes, where the bottom faces are through and blind respectively in Figs. 6(a) and (b), and Fig. 6(c) shows two ladder holes inside a parallel hole structure. The evaluation of a ladder hole involves sequentially searching for the composition of the holes. It is divided into two steps: (1) searching for the first layer, and (2) sequentially searching for the remaining layers. First, for each candidate hole H_c in the hole data, the following three conditions are checked to determine whether it can be regarded as the first layer or not:

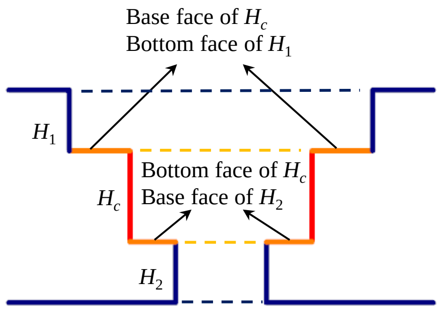


Figure 5. Relationship between neighboring holes, where the hole H_c neighbors holes H_1 and H_2 with its base and bottom faces, respectively.

TABLE I. THE NEIGHBORING CONDITIONS OF TWO CONNECTED HOLES, WHERE SIX OF THEM EXIST IN REAL CAD MODELS.

H_c \ $H_{i,\,i=1,2,\ldots}$		Blind Hole		Through hole	
		base face	bottom face	base face	bottom face
Blind hole	base face		O		
	bottom face	O		O	O
Through hole	base face		O		
	bottom face		O		

TABLE II. AN ARRAY DATA RECORDING THE NEIGHBORING RELATIONSHIP OF HOLES, WHERE THE EXAMPLE IN FIG. 5 IS ILLUSTRATED.

Hole index	Connect by base face	Connect by bottom face
H_1	H_c	N/A
H_2	N/A	H_c
H_c	H_1	H_2
…	…	…

(1) H_c should be a blind hole: a through hole can only exist at the bottom of a ladder hole, and hence cannot be regarded as the first layer.

(2) The bottom face of H_c connects to one hole: If it does not connect to any hole, then H_c cannot form a ladder hole. In contrast, if it connects to more than one hole, then H_c belongs to a parallel hole structure. This condition can be used to exclude the hole H_{mb} in Fig. 6(c).

(3) The base face of H_c connects to
   (a) zero hole: the top face on the first layer does not connect to any hole, such as H_{1st} in Figs. 6(a) and (b).
   (b) one hole that connects to multiple holes: this is used for parallel hole structures. The holes H_{sb} in Fig. 6(c) belong to this type.

If the first two conditions and either one of the third conditions are satisfied simultaneously, then H_c is regarded as the first layer.

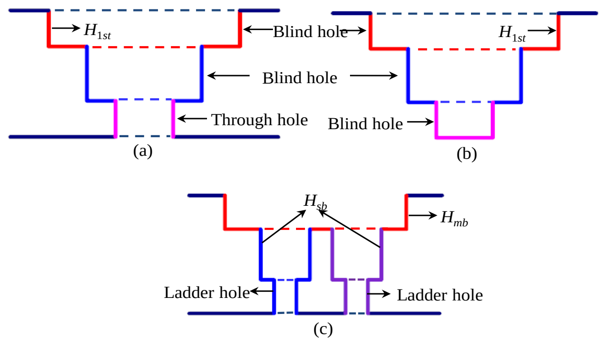


Figure 6. Various structures of ladder holes: (a) a ladder hole with a through face on the bottom, (b) a ladder hole with a blind face on the bottom, and (c) a hole that connects to multiple parallel holes is excluded from the ladder hole.

Once the first layer of a ladder hole is obtained, the second layer can be obtained by searching for the hole connected to the bottom face of the first layer. Such a search is implemented continuously. In each search, the hole connecting to the bottom face of the previous layer H_{pre} is regarded as the next layer H_{nex}. The end condition of the search is one of the three following conditions.

(1) H_{nex} is a through hole: H_{nex} is regarded as the final layer of the ladder hole.

(2) The diameter ratio of H_{nex} to H_{pre} is smaller than a pre-defined tolerance: H_{pre} is regarded as the final layer of the ladder hole.

(3) H_{nex} is a blind hole and its bottom face connects to more than one hole: H_{nex} is regarded as the final layer of the ladder hole.

D. *Detect Related Holes Across Different Parts*

When several CAD models representing different mold parts are input to a CAD system, the order of the CAD models in the data structure is arbitrarily recorded. To detect related holes between different CAD models, it is necessary to establish the relationship of CAD models that are in contact with each other. As Fig. 7 depicts, the proposed algorithm is divided into four steps: (1) sort the mold parts by using the parting direction, (2) generate the relationship among parts (Fig. 7(a)), (3) search for contact faces (Fig. 7(b)), and (4) generate the relationship between holes passing across different parts (Fig. 7(c)). A detailed description for each procedure is given below.

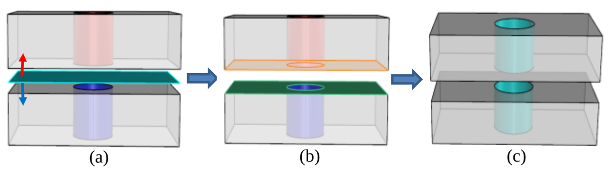


Figure 7. Procedures of detecting related holes across different parts: (a) generate the relationship between parts, (b) search the contact faces, and (c) generate the relationship of holes across different parts.

(1) Sort the mold parts by using the parting direction

When the CAD models of mold parts are input to a CAD system, no order exists among these CAD models. However, they should be arranged in a sequence, as it is very helpful for subsequent steps. The order of each mold part is calculated by using the parting direction. The parting direction is a parameter determined by the user, and the default is the positive *z* direction.

(2) Generate the relationship among parts

The facial data on each CAD model could be used to evaluate adjacent CAD models. However, considerable computational time is often required, as all the faces from the different CAD models must be checked pair by pair. A computationally efficient method was developed in this study, which employs the bounding boxes of all CAD models to evaluate adjacent CAD models. Fig. 8 depicts the concept of checking the intersection of two CAD models by using their bounding boxes. The bounding box of a CAD model is represented by two marginal points $\boldsymbol{P}_{min} = (x_{min}, y_{min}, z_{min})^T$ and $\boldsymbol{P}_{max} = (x_{max}, y_{max}, z_{max})^T$. An algorithm that compares *x*, *y*, and *z* coordinates of two sets of marginal points was developed to check the intersection of two bounding boxes. If two CAD models intersect, then the region of intersection can be represented as a range box, as shown in Fig. 8(a), which is essentially another bounding box. In contrast, if two CAD models do not intersect, then no range box is found. If two CAD models are in contact at a plane, then the range box is reduced to a plane, as shown in Fig. 8(b), where the minimum and maximum coordinate values on one axis are equal.

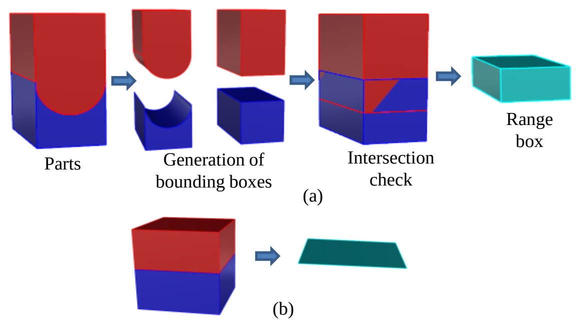


Figure 8. Determine the range box of two intersected CAD models, (a) evaluate the range box of two CAD models, and (b) the range box is reduced to a plane when two CAD models contact at a plane.

In the proposed procedure, the bounding boxes of all CAD models are checked pair by pair. A range box is obtained when two CAD models are in contact with each other. Two marginal points for a range box and the indices of these two CAD models are recorded.

(3) Search for contact faces

The range box of two adjacent CAD models is used to search for contact faces. First, a set of candidate contact faces from each CAD model is evaluated. The bounding box of each face on a CAD model is compared with the range box. If they intersect, then the corresponding face is inside the range box. Two sets of candidate contact faces can be obtained, one from each CAD model. Second, the faces on both sets of candidate contact faces are compared one by one to find the contact faces. Fig. 9 depicts the contact conditions of two faces at the contact region. The computation is different depending on the type of candidate contact face. These cases are outlined as follows.

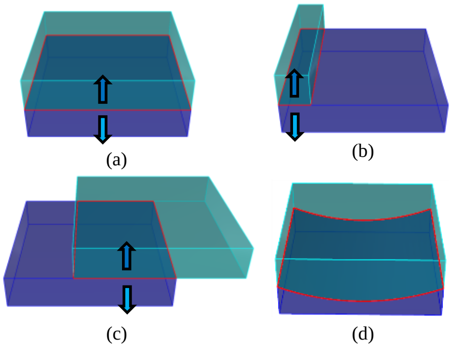


Figure 9. The contact conditions of two CAD models, (a) two equal faces completely contact, (b) two unequal faces completely contact, (c) two faces partially contact, and (d) the contact faces are surfaces.

(a) Both candidate contact faces are planes: If they are parallel to each other and their normal vectors point in opposing directions, then the intersection of the two planes is checked. If they intersect, then these two candidate planes are considered as a pair of contact faces. Otherwise, they are not regarded as a pair of contact faces. For each pair of contact faces, a closed intersection profile is computed. The contact condition is divided into either completely in contact (Figs. 9(a) and (b)) or partially in contact (Fig. 9(c)). For the condition of completely in contact, the planes in contact can be equal (Fig. 9(a)) or unequal (Fig.9(b)).

(b) Both candidate contact faces are surfaces: As the surface normal is not constant, these two surfaces must be checked to see if they intersect. If they intersect, then these two surfaces are regarded as a pair of contact faces (Fig. 9(d)). Otherwise, they are not regarded as a pair of contact faces.

(c) One is a plane and the other is a surface: As a plane and a surface do not contact each other, this pair of faces is not regarded as a pair of contact faces.

In the proposed procedure, the faces on both sets of candidate faces are checked pair by pair. When a pair of contact faces is obtained, they are put into a stack. The CAD models corresponding to each pair of contact faces are recorded too.

(4) Generate the relationship between holes passing across different parts

At this stage, holes on each CAD model are already recognized and grouped. The main issue addressed here is the generation of the relationship between holes on each pair of contact faces. All groups of holes passing across different CAD models can thus be integrated and arranged in sequence. The proposed process is divided into two steps. First, holes are searched for which are located on the contact faces. Each contact face is essentially a base face or a bottom face of a hole. Therefore, the holes located on each contact face can be obtained by searching the hole data. Second, coaxial holes across different CAD models are located and regarded as a group. For two sets of holes corresponding to the same pair of contact faces, coaxial holes are regarded as a group. After the first step, two sets of holes corresponding to a pair of contact faces are obtained. Each set of holes is located at one of these two contact faces. Therefore, each of the holes on one contact face is compared with those on the other contact face. If two holes are coaxial, then the following three conditions are checked.

(a) Two holes are not recorded in any group: these holes are placed into a new group.

(b) One of the holes is already recorded in a group: the other hole is placed into the same group.

(c) Both holes are already recorded in different groups: these two groups are combined into one group.

The above process is implemented for all pairs of contact faces. The example shown in Fig. 10(a), where two pairs of contact faces are located on three parts (P1~P3), is employed to illustrate how a group of coaxial holes from different CAD models are integrated in sequence. The procedure of integrating all holes in this example is as follows:

(a) From the first pair of contact faces, two sets of holes are obtained (Fig. 10(b)). One set of holes is obtained by the contact face located on Part 1 (red) and the other set is obtained by the contact face located on Part 2 (blue).

(b) Coaxial holes are sought out from the two sets of holes. There are two new groups in this step (Fig. 10(c)).

(c) The ladder hole data is used to extend the groups (Fig.10(d)).

(d) From the second pair of contact faces, two sets of holes are obtained (Fig. 10(e)). It should be noted that the holes located on Part 2 are already recorded in groups.

(e) The holes located on Part 3 are added into groups 1 and 2, respectively (Fig. 10(f)).

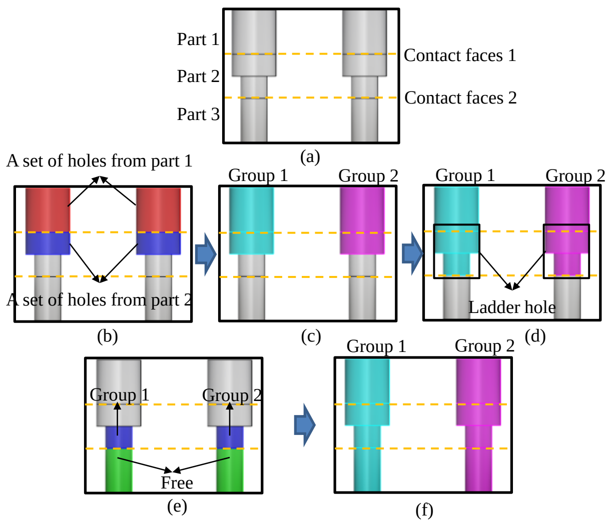


Figure 10. The contact conditions of two CAD models, (a) two equal faces completely contact, (b) two unequal faces completely contact, (c) two faces partially contact, and (d) the contact faces are surfaces.

In the proposed procedure, each hole is checked one by one. If it does not lie on any contact face, then this process does not need to be implemented. In contrast, if it lies on a contact face, then all pairs of contact faces with holes with the same coaxial axis are evaluated. Then, the above-mentioned procedure is implemented to group all the coaxial holes for the different CAD models. Whenever a hole is checked or used, it is marked. Such a process is implemented continuously until all holes have been marked.

TABLE III. ATTRIBUTES OF A HOLE.

Code	Attribute		Remark
H1	Hole index		Index of this hole
H2	Shape		Circular or non-circular shape
H3	Loops		Base and bottom loops
H4	Base face index		Indices of base faces
H5	Side face index		Indices of side faces
H6	Bottom face index		Indices of bottom faces
H7	Hole type		Through or blind hole
H8	Ladder hole	Ladder hole index	Index of the ladder hole, 0: does not belong to a ladder hole
H9		Layer	Layer of this hole on the ladder hole
H10		Base face related	Hole connected to the base face of this hole
H11		Bottom face related	Hole connected to the bottom face of this hole
H12		Members	Other members on the same ladder hole

E. Output Hole Data

Table III lists the attributes of a hole, calculated during the hole recognition procedure. H1 to H7 denote the attributes associated with an individual hole, and H8 to H12 denote the topological relationship between a hole and its neighboring holes. H3 indicates the loops on the base and bottom faces of the hole. For a through hole, two loops exist on the base and bottom faces, respectively, while for a blind hole, a loop exists only on the base face. H4, H5, and H6 denote the indices of the base, side, and bottom faces, respectively. H7 denotes the type of a hole, either a through or a blind hole. The data recorded for a hole related to a ladder hole is as follows. H8 denotes the index of the ladder hole in which the hole belongs. A value of zero indicates that the hole does not belong to any ladder hole. H9 denotes the layer of a ladder hole in which the hole belongs. A value of one indicates that the hole is the first layer. H10 and H11 denote the neighboring holes for the base and bottom faces of a hole, respectively. H12 records the other members (holes) of the ladder hole.

V. RESULTS AND DISCUSSION

A program, written in C++ and based on the Rhino CAD platform and the openNURBS functions, was implemented to test the feasibility of the proposed hole recognition and simplification algorithm for a mold set. A maximum hole perimeter d_{max} allowed for processing was set. If the perimeter of a hole was longer than d_{max}, it was preserved. The default value of d_{max} was set to 300 mm in this study. Fig. 11 depicts the results of the hole recognition algorithm for three example injection molds, where the left plots show complete CAD models of each injection mold, and right plots show different types and sets of holes recognized, corresponding to each example.

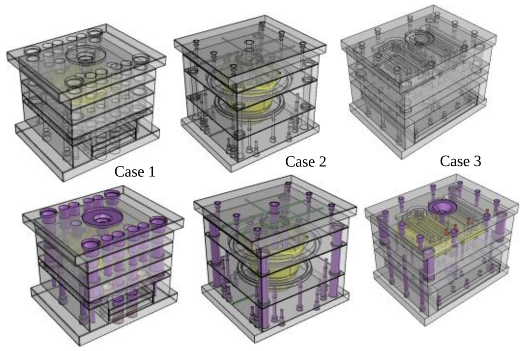


Figure 11. Three injection molds used in this study, where left plots indicate the original CAD models and right plots indicate the results of hole recognition.

The individual holes recognized on each mold part for Case 2 is shown in Fig. 12, where left and right plots show the proposed method and CADdoctor, respectively. It should be noted that five types of hole are recognized in the proposed method, which are single-blind, single-through, ladder-blind, ladder-through holes, and complex hole structures, which are colored red, pink, light blue, blue, and green, respectively, on the left plots of Fig. 12. However, all holes are yellow in CADdoctor.

Tables IV to VI compare the results of the proposed method and CADdoctor for Case 1 to 3, respectively. Each table lists the number of circular and non-circular holes in each mold part, and the success, failure, or misjudgment for each type of hole for the proposed method and CADdoctor, respectively. The results show that the data from both methods for Case 1 are identical, indicating that both methods can recognize all holes successfully. However, for Case 2, four failures and eight misjudgments for non-circular holes are observed from CADdoctor, whereas all holes are successfully recognized in the proposed method. Similarly, for Case 3, 10 misjudgments are observed for circular holes, and one failure and four misjudgments are observed for non-circular holes, whereas all holes are successfully recognized in the proposed method. These results indicate that the proposed method is more robust than CADdoctor. Fig. 13 can be used to explain the primary problem with CADdoctor. In this example, eight circular holes were erroneously recognized as non-circular holes because the loops on six of them are cut by other faces and the other two holes are intersected with tubes.

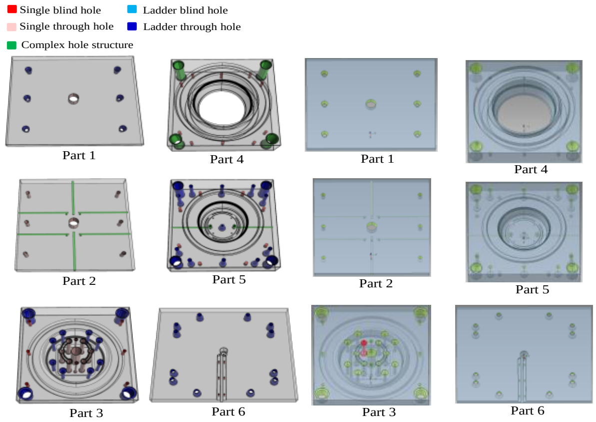
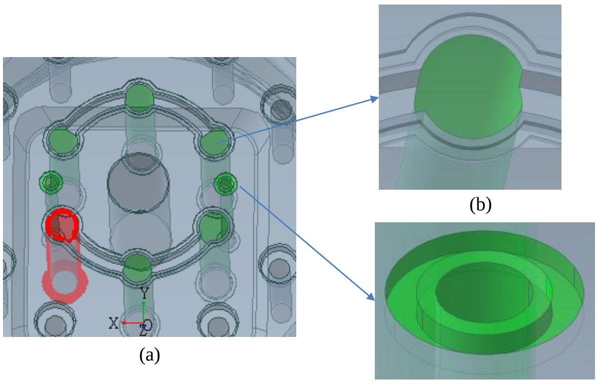


Figure 12. Results of hole recognition for Case 2, where left and right panels denote the proposed method and CADdoctor, respectively.



(c)

Figure 13. Erroneous holes recognized on CADdoctor, (a) 8 erroneous holes recognized on Part 3 of Case 2, (b) the loop of a hole is cut by other faces, (b) a hole is intersected with a tube.

The proposed method can recognize most of the holes located on the part surface. However, when holes are not located on the part surface, they cannot be recognized. As the proposed method is based on the loop data from the part surface to recognize holes, holes embedded in a volume cannot therefore be recognized. Cooling channels belong to this type of hole. A cooling channel is a series of tubes connected together and passing through one or several mold plates. The beginning and ending of a cooling channel are recognizable because they lie on the part surface, whereas the other parts cannot be recognized by the proposed method, as they are not exposed to the part surface. An individual algorithm can be employed to recognize all cooling channels using the holes that lie on the part surface of the mold parts.

TABLE IV. RESULTS OF CASE 1.

Case 1	No. Holes	Recognition results of this study		Recognition results of CADdoctor	
	Circular / Non-circular	Circular holes	Non-circular holes	Circular holes	Non-circular holes
		Success / Failure / Misjudgment	Success / Failure / Misjudgment	Success / Failure / Misjudgment	Success / Failure / Misjudgment
Part 1	13/0	13/0/0	0/0/0	13/0/0	0/0/0
Part 2	23/0	23/0/0	0/0/0	23/0/0	0/0/0
Part 3	26/0	26/0/0	0/0/0	26/0/0	0/0/0
Part 4	46/0	46/0/0	0/0/0	46/0/0	0/0/0
Part 5	16/0	16/0/0	0/0/0	16/0/0	0/0/0
Part 6	4/0	4/0/0	0/0/0	4/0/0	0/0/0
Part 7	4/0	4/0/0	0/0/0	4/0/0	0/0/0
Part 8	15/0	15/0/0	0/0/0	15/0/0	0/0/0
Part 9	8/0	8/0/0	0/0/0	8/0/0	0/0/0
Part 10	12/0	12/0/0	0/0/0	12/0/0	0/0/0
Total	167/0	167/0/0	0/0/0	167/0/0	0/0/0

TABLE V. RESULTS OF CASE 2.

Case 3	No. Holes	Recognition results of this study		Recognition results of CADdoctor	
	Circular / Non-circular	Circular holes	Non-circular holes	Circular holes	Non-circular holes
		Success / Failure / Misjudgment	Success / Failure / Misjudgment	Success / Failure / Misjudgment	Success / Failure / Misjudgment
Part 1	15/0	15/0/0	0/0/0	15/0/0	0/0/0
Part 2	43/18	43/0/0	18/0/0	43/0/0	17/1/0
Part 3	48/3	48/0/0	3/0/0	48/0/4	3/0/4
Part 4	24/0	24/0/0	0/0/0	24/0/0	0/0/0
Part 5	18/6	18/0/0	6/0/0	18/0/6	6/0/0
Part 6	9/0	9/0/0	0/0/0	9/0/0	0/0/0
Part 7	9/0	9/0/0	0/0/0	9/0/0	0/0/0
Part 8	3/0	3/0/0	0/0/0	3/0/0	0/0/0
Part 9	3/0	3/0/0	0/0/0	3/0/0	0/0/0
Total	172/27	172/0/0	27/0/0	172/0/10	26/1/4

TABLE VI. RESULTS OF CASE 3.

Case 2	No. Holes	Recognition results of this study		Recognition results of CADdoctor	
	Circular / Non-circular	Circular holes	Non-circular holes	Circular holes	Non-circular holes
		Success / Failure / Misjudgment	Success / Failure / Misjudgment	Success / Failure / Misjudgment	Success / Failure / Misjudgment
Part 1	7/0	7/0/0	0/0/0	7/0/0	0/0/0
Part 2	13/0	13/0/0	0/0/0	13/0/0	0/0/0
Part 3	37/0	37/0/0	0/0/0	37/0/0	0/0/8
Part 4	14/0	14/0/0	0/0/0	14/0/0	0/0/0
Part 5	25/4	25/0/0	4/0/0	25/0/0	0/4/0
Part 6	19/0	19/0/0	0/0/0	19/0/0	0/0/0
Total	115/4	115/0/0	4/0/0	115/0/0	0/4/8

VI. CONCLUSIONS

A hole recognition algorithm was proposed in this study to recognize all hole types located across different CAD models of a mold set when assembled together. The proposed method can recognize holes of both circular and non-circular types, and blind and through types. In addition, a series of holes arranged in sequence, or a ladder hole, is also recognizable. In addition, coaxial holes passing across different CAD models are also detected and regarded as a group. With such a method, all holes in the same group can easily be accessed and processed. One of the applications of this method is that when all holes of the same group must be simplified simultaneously, it becomes easier to develop an automatic hole simplification algorithm, as the holes are already arranged sequentially in the data structure. Similarly, when holes in the same group must be preserved, they can be saved on the same layer on the CAD platform so that they can be accessed simultaneously. As all holes on a mold set have been recognized, it could be necessary to develop an automatic hole simplification algorithm that can preserve holes required in mold flow analysis, while simplifying all unwanted holes automatically.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Jiing-Yih Lai wrote the paper and conducted the research; Pei-Pu Song conducted the research and analyzed the data; Yao-Chen Tsai and Chia-Hsiang Hsu provided some concept, review and discussion. All authors had approved the final version.

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