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A STEP TOWARDS AUTOMATED DESIGN OF INDEX-PLATE MULTI-SHOT MOLDS

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ABSTRACT

This paper describes an algorithm for automated design of index-plate type of multi-shot molds for manufacturing multi-material objects. This new algorithm is a significant improvement over previous mold design algorithms and it accounts for constraints associated with the index-plate molding process. Our algorithm works in the following manner. First, based on the index-plate process constraints, we determine whether the given multi-material object is moldable by index-plate process by analyzing the geometry of the object. If the object can be molded, then the molding sequence is determined. Finally, the mold pieces. We expect that the algorithm described in this paper will provide the necessary foundations for automating the design of index-plate molds and therefore will help in significantly reducing the mold manufacturing lead-time associated with this type of molds.

KEYWORDS

Mold Design, Multi-Shot Mold, Index-Plate Mold, Geometric Reasoning

1. INTRODUCTION

Multi-material molding processes allow designers to select different materials for different portions of the object, thus helping to improve material-function compatibility for the overall object. Moreover, the multi-material objects are produced as an integrated piece, thus eliminating the assembly process. Figure 1 shows several multi-material objects made by injection molding processes. There are several different multi-material molding processes, such as multi-shot injection molding, insert molding, over-molding, co-injection molding, sandwich molding, etc. Compared with the other processes, the multi-shot molding process can make more complex multi-material products. Based on the transfer method between two successive stages, multi-shot process has three different types: rotary-platen, index-plate and core-toggle. Mold geometries for the three types are significantly different. Compared to rotary-platen molding process, index-plate molding can make more complex multi-material object. However, index-plate molding is a more complicated process because different stages utilize different cores and different cavities, and a new mold piece, i.e., index-plate, is used. Therefore, the mold design for index-plate process is much more complicated than rotary-platen mold design.

Figure 2 illustrates an index-plate type of two-shot injection molding process for manufacturing the two-material object shown in Figure 2(a). This injection molding machine has two separate injection units, one for each material. Two materials are injected into their respective cavities in two different stages (Figure 2(b)). The mold is similar to the multi-shot process with common core, except that a mold piece called index-plate is added. The index-plate is between the core half of the mold and the cavity half of the mold. For this type of method, the cores and cavities for two stages are different. The only common mold piece for the two stages is the index-plate. Figure 2(b) shows the process in which the first shot is carried out in the first cavity, while the second shot is carried out in the second cavity. Then, the mold is

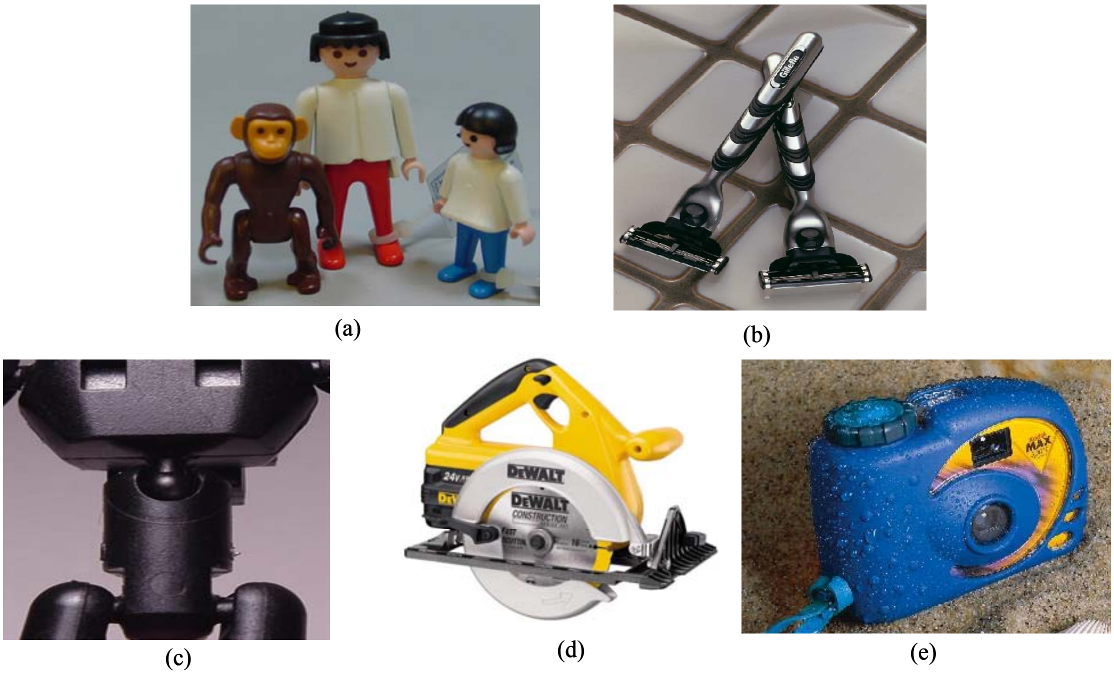


Figure 1 Examples of multi-material objects (a) 3-material toys (b) Gillette mach 3 razors (c) Ball and socket joint (d) 2-material saw housing (e) Fun saver sport camera from Kodak

opened (Figure 2(c)), and the finished object in the second cavity is removed shown in Figure 2(d). Next, the index-plate, with the partially finished object attached to it, is moved along the mold opening direction, as shown in Figure 2(e). Then, it is rotated along the axis by 180 degrees, such that it occupies the position shown in Figure 2(f). Finally, the index-plate and the cavity half of the mold are moved back to the original position shown in Figure 2(g), and two shots are carried out simultaneously in two different cavities. The process of (b)→(c)→(d)→(e)→(f)→(g) is repeated automatically in the two-shot injection molding machine to make two-material objects. Three-shot and four-shot injection molding machines are also available to manufacture three-material and four-material objects respectively. If necessary, side cores can be used to manufacture objects with undercuts.

This paper describes a geometric algorithm for automated design of molds based on index-plate process. The new algorithm is a significant improvement over algorithms developed by Gupta et al. (2002), Kumar and Gupta (2002), and Li and Gupta (2003) in the following ways. First, specific constraints for the index-plate process are used in generating molding stages. Second, the algorithm for generating mold pieces for a single material component has been extended to work on multi-lump component in order for it to work on index-plate molds. The algorithm described in this paper works in the following manner. First, based on the index-plate process constraints, we determine if the given multi-material object is moldable by index-plate process by analyzing the geometry and interface of the object. If the object can be made, then the manufacturing sequence and the mold opening direction are determined. Next, based on the manufacturing sequence determined, a set of solids, which are the mold pieces for the first lump to be made and the gross object, are generated. Finally, the mold pieces including different cavities, different cores and common index-plate are obtained by performing certain Boolean operations on the set of solids generated in the previous step.

2. PROBLEM FORMULATION AND OVERVIEW OF APPROACH

2.1. Problem Formulation

Problem: Given a multi-material object, design a multi-stage mold for the index-plate multi-shot process.

Input: The assembly of a multi-material object $O=\{(l^a, m_1), (l^b, m_2)\}$

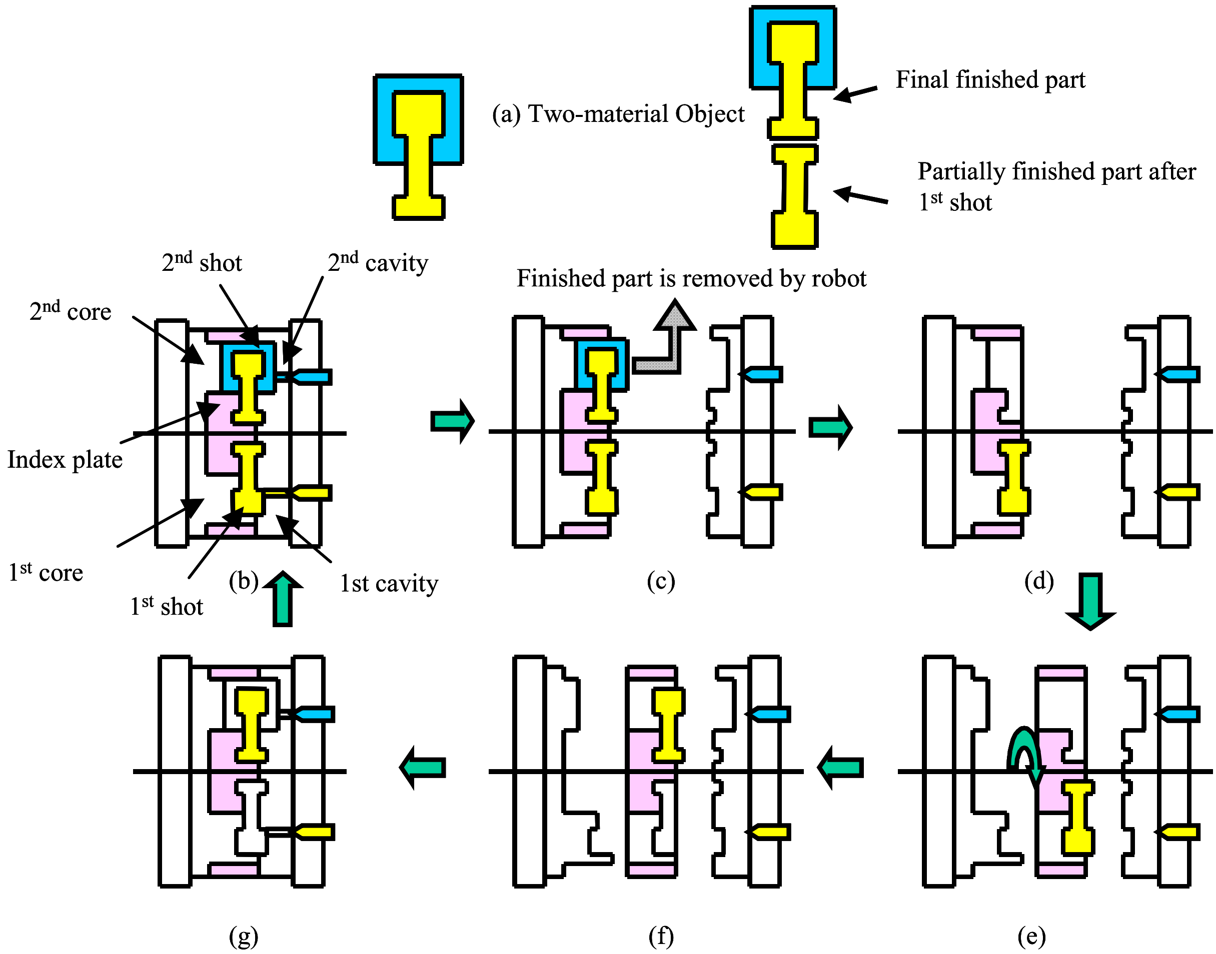


Figure 2 Index-plate two-shot injection molding process

Multi-material objects are modeled as an assembly of homogenous components. Each component l^i of the object assembly is represented as a solid model, which can have one or more lumps, and has a material attribute m_i associated with it. The material attribute m_i defines the material type of each homogenous component.

Output: Mold-stage sequence $T = \{t_1, t_2\}$, where each t_i is defined by:

1. The mold assembly used in the stage t_i, which includes: core M_{coi}, cavity M_{cai}, index-plate M_{idx} and set of side cores R.
2. O_i: the resulting object after the mold-stage t_i.

Output Requirements:

1. The final object is the desired object O.
2. Mold pieces in each stage t_i do not intersect with each other.
3. There is one common mold opening direction d for all the stages.
4. For each stage t_i, the core M_{coi} and cavity M_{cai} can be disassembled from each other and the partially finished (or final) object along mold-opening direction d.
5. The index-plate M_{idx} is common for both stages. The partially finished object O_i will stay with the index-plate after every mold stage and finally get removed by a robot after the last mold stage.
6. If a set of side cores R is used, it should be the same for every stage and can be removed before removing the core M_{coi} and cavity M_{cai}. The sliding direction for each of the side core should be perpendicular to the mold opening direction d. (Using different side cores in different stages or using side cores with moving directions not perpendicular to d will

greatly increase the manufacturing cost, thus is not preferred in industry. Therefore, only the side core satisfying this requirement is considered in our algorithm.)

Input Restrictions:

1. The object should have only two different materials.
2. The gross object should not have any internal shell.
3. Two components should not intersect with each other.
4. The gross object should be moldable by a mold consisting of two main pieces and zero or more side cores.

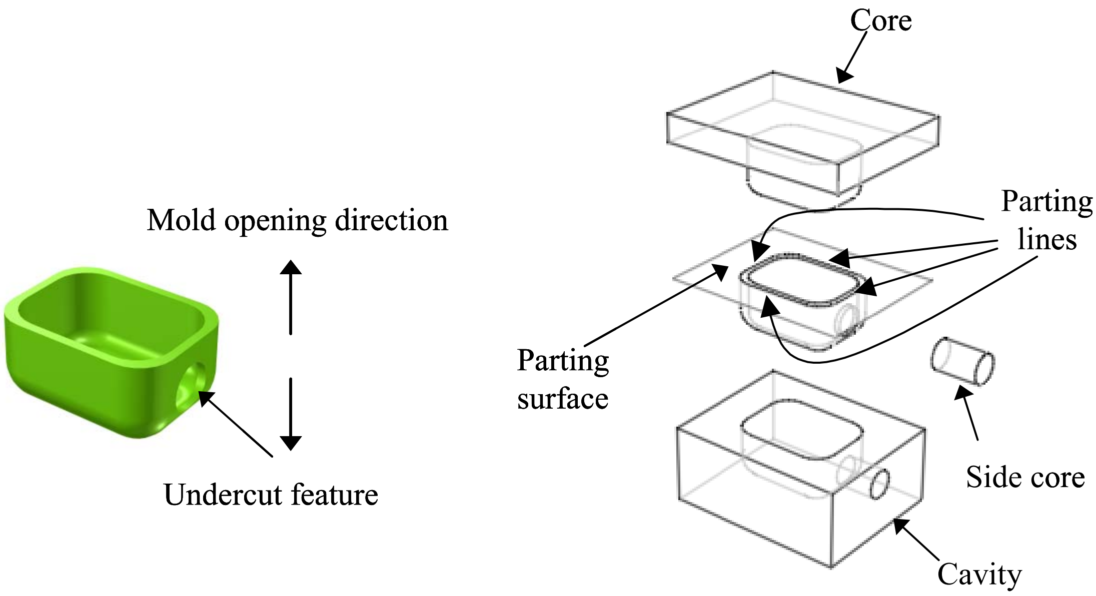
2.2. Overview of Approach

The index-plate mold design algorithm consists of the following two main steps:

1. *Manufacturing sequence and mold opening direction determination:* Based on the index-plate process constraints, we determine if the given multi-material object is moldable by index-plate process by analyzing the geometry and interface of the object. If the object can be made, then the manufacturing sequence and mold opening direction are determined.
2. *Mold stages generation:* In this step, the mold pieces for the gross object and the mold pieces for the first component are generated. The second component can be decomposed into two pieces, which will be used for generating the mold pieces for each stage. Based on the geometry of all of these mold pieces and decomposed components, the final mold pieces for each stage are generated, which accounts for the constraints associated with the index-platen molding process.

3. MOLD PIECE GENERATION FOR SINGLE MATERIAL COMPONENT

The algorithms for index-plate mold design described in Section 4 need to call an algorithm for designing mold pieces for single material components that compose the multi-material object. The traditional mold design for a single-material component, involves determination of the parting direction, parting lines, parting surface and



(a) Single material component to be molded

(b) Mold with side core

Figure 3 Example of a single material component and the mold pieces with side core mold pieces generation. Figure 3 shows a single material component and a mold to produce it. Several different approaches have been developed for finding a parting direction. Examples include work by Chen et al. (1993), Weinstein et al. (1996), Chen and Rosen (2001), Chen and Rosen (2002), and Priyadarshi and Gupta (2004). Many of the approaches are based on the notion of visibility maps. The concave regions on a component restrict the directions along which the mold halves can be separated. The convex hull of the component is used to decompose the component geometry into concave and convex regions. A visibility map is then constructed for each concave region to determine the possible mold opening directions. In contrast to the visibility map based approaches, Priyadarshi and Gupta (2003) have developed an approach based on global accessibility analysis.

In the area of finding parting lines, parting surfaces, and generating mold pieces, there are approaches based on silhouette and slicing methods, for example approach by Ravi et al. (1990). Some of these approaches such as Majhi et al. (1999) can only work on convex polyhedron. For complex polyhedral geometries, Tan et al. (1988) proposed a method to find parting lines. The parting surface is generated by extending the parting lines outward and used to get the mold pieces.

Most of these mold piece generation algorithms for single material component work on polyhedral components. If the component geometry includes curved faces, a polyhedral approximation is used to generate mold pieces. In many situations, faceting a component with high accuracy results in an acceptable solution for these algorithms. However, for index-plate mold design problems, these algorithms may have difficulties in certain cases because the mold cavities may include gaps or extra material due to faceting errors. This causes undesired geometries at the interfaces in multi-material objects. Complex interfaces are more prone to such errors. Therefore, the previous algorithms cannot be used in index-plate mold design.

The algorithm described in Section 4 uses algorithm FIND-PARTING-DIRECTIONS (or FIND-PARTING-DIRECTIONS-WSC) to get the mold opening direction set for a component, and call algorithm GENERATE-MOLD-PIECES (or GENERATE-MOLD-PIECES-WSC) to generate the mold pieces for a component. These algorithms are minor modifications of the algorithms developed by Li and Gupta (2003). Algorithms FIND-PARTING-DIRECTIONS and FIND-PARTING-DIRECTIONS-WSC described in Li and Gupta (2003) allow each material to have only one lump. To handle objects in which each material can have two or more lumps, we have extended the two algorithms using the following approach. First, if one material has two or more lumps, then the gross mold for the whole component is divided into several sub-gross molds by planes, which are parallel to the mold opening direction, such that each lump is in a different sub-gross mold. Next, the mold piece generation algorithm GENERATE-MOLD-PIECES (or GENERATE-MOLD-PIECES-WSC) described in Li and Gupta (2003) can be used for each lump based on its own sub-gross mold to obtain the mold pieces. Then, the mold pieces for all the lumps can be combined to form the two mold pieces for manufacturing the multi-lump component. The precondition for this method is that there is a common mold opening direction for all the lumps. The final mold for the multi-lump component will be a multi-cavity mold, by which all the lumps can be made simultaneously.

The algorithm FIND-PARTING-DIRECTIONS described in Li and Gupta (2003) for finding the mold opening direction set is based on a global accessibility analysis for each facet of the component. First, the global accessibility cone of each facet is computed. Direction *d* will be one of the parting directions if all the facets of the component are accessible along either +*d* or -*d*. A facet is globally accessible along unit vector *v*, if *v* is contained in the global accessibility cone of the facet. In presence of side cores, a similar algorithm FIND-PARTING-DIRECTIONS-WSC described in Li and Gupta (2003) is used.

The basic idea behind the algorithm GENERATE-MOLD-PIECES (or GENERATE-MOLD-PIECES-WSC) described in Li and Gupta (2003) is as following. First, a set of surfaces, including necessary and spare surfaces, is determined based on the position of the approximate parting lines and the exact geometry of the faces of the component. Then, these necessary surfaces are used to decompose the gross mold into a set of solids. Spare surfaces will also be used if needed. All the solids are classified into several categories based on their disassemblability characteristics from the component to be molded. Those solids that cannot be disassembled are further decomposed. Finally, mold pieces are generated by combining different solids together. In presence of side cores, preprocessing is needed as described in Li and Gupta (2003).

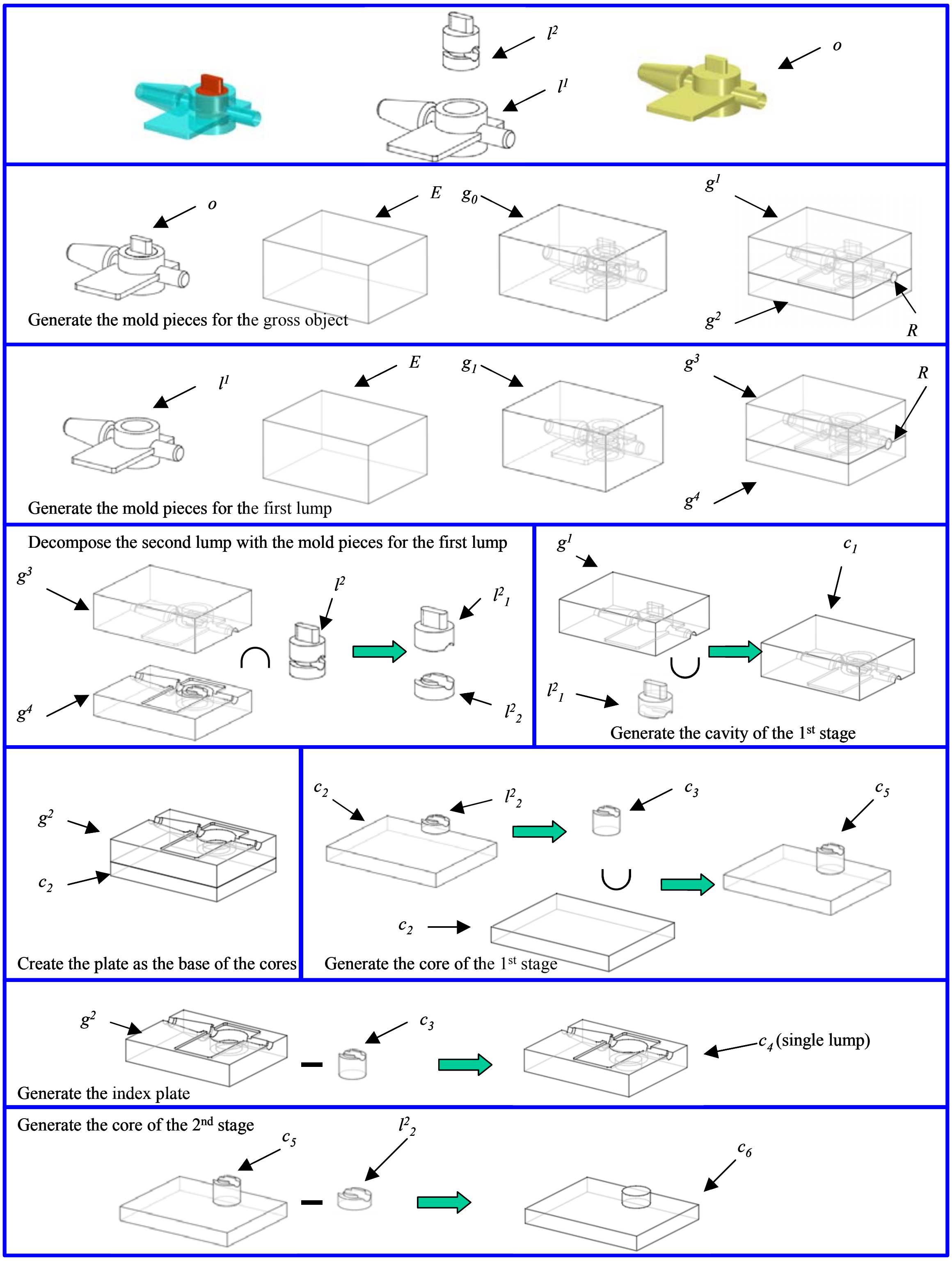


Figure 4 Illustration of the algorithm INDEX-PLATE-MOLD-DESIGN

4. INDEX-PLATE MULTI-SHOT MOLD DESIGN ALGORITHM

This section describes the algorithms for index-plate mold design. The algorithm INDEX-PLATE-MOLD-DESIGN is the top-level algorithm. This algorithm has two main steps. The first step determines the manufacturing sequence and the mold opening direction by calling another algorithm DETERMINE-SEQUENCE-AND-DIRECTION. The second step generates the mold stages by calling algorithm GENERATE-INDEX-PLATE-MOLD-STAGES.

Algorithm INDEX-PLATE-MOLD-DESIGN is described below.

Algorithm INDEX-PLATE-MOLD-DESIGN

Input: Object assembly of two components: l^a and l^b

Output: A mold stage sequence T

Steps:

1. Determine manufacturing sequence (l^1 and l^2), and the mold opening direction d.

   This step determines if the object can be made by the index-plate process or not. If the object can be made by the index-plate process, then the manufacturing sequence and the mold opening direction are determined. This step is performed by calling the algorithm DETERMINE-SEQUENCE-AND-DIRECTION.

2. Generate mold stage sequence T.

   This step generates the mold stage sequence T based on the manufacturing sequence and the mold opening direction determined in the first step. This step is performed by calling the algorithm GENERATE-INDEX-PLATE-MOLD-STAGES.

Based on the constraints associated with index-plate multi-shot process, the algorithm DETERMINE-SEQUENCE-AND-DIRECTION determines if the object can be produced by the index-plate process or not. If the object can be made by the index-plate process, then the manufacturing sequence and the mold opening direction are determined. The algorithm DETERMINE-SEQUENCE-AND-DIRECTION is described below.

Algorithm DETERMINE-SEQUENCE-AND-DIRECTION

Input: Object assembly of two components: l^a and l^b

Output:

1. Manufacturing sequence of two components: l^1 and l^2
2. Mold opening direction d

Steps:

1. Create gross object $o = l^a \cup l^b$.
2. Find mold opening direction set D_o for the gross object o by calling FIND-PARTING-DIRECTIONS (If this fails, call FIND-PARTING-DIRECTIONS-WSC).
3. Find mold opening direction set D_a for l^a by calling FIND-PARTING-DIRECTIONS (If this fails, call FIND-PARTING-DIRECTIONS-WSC).
4. Compute $D = D_o \cap D_a$.
5. If $D \neq \emptyset$, then

   If both o and l^a need side cores, and common side cores can be used, then $l^1 = l^a$, $l^2 = l^b$, and go to Step 8.

   Else, Find mold opening direction set D_b for l^b by calling FIND-PARTING-DIRECTIONS (If this fails, call FIND-PARTING-DIRECTIONS-WSC).
6. Compute $D = D_o \cap D_b$.
7. If $D \neq \emptyset$, then

   If both o and l^b need side cores, and common side cores can be used, then $l^1 = l^b$, $l^2 = l^a$.

   Else, the object cannot be produced by index-plate process; exit.
8. Select d from D along which the projected area of the gross object is the largest. d will be the mold opening direction.
9. Output l^1, l^2 and d.

Based on the manufacturing sequence and the mold opening direction determined by the algorithm DETERMINE-SEQUENCE-AND-DIRECTION, the algorithm GENERATE-INDEX-PLATE-MOLD-STAGES generates the mold pieces for each of the mold stages, including the cavities, the cores, and the index-plate. The algorithm GENERATE-INDEX-PLATE-MOLD-STAGES is described below.

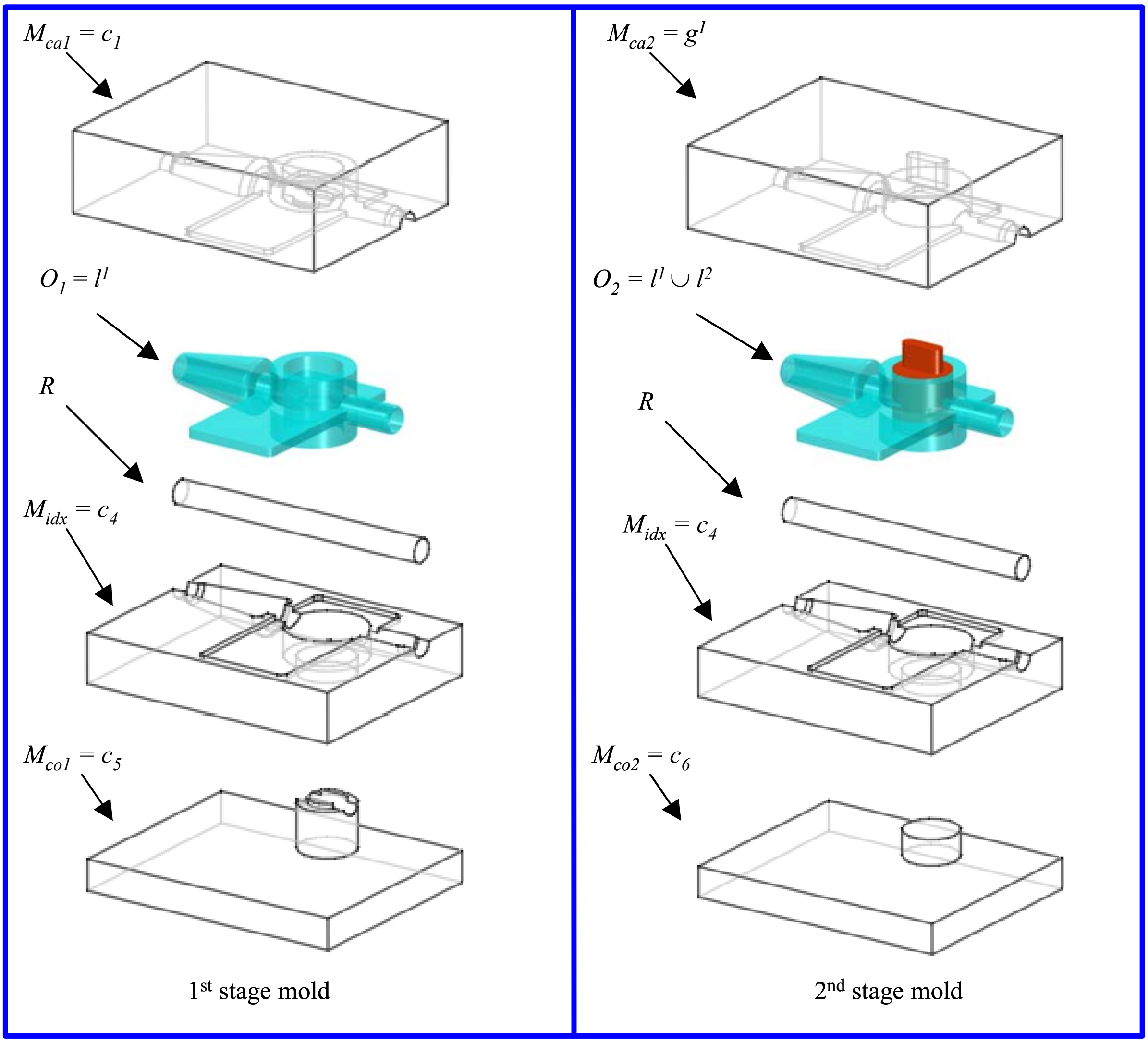


Figure 5 Index-plate mold generated by the algorithm INDEX-PLATE-MOLD-DESIGN

Algorithm GENERATE-INDEX-PLATE-MOLD-STAGES

Input:

1. Manufacturing sequence of two components: l^1 and l^2
2. Mold opening direction d

Output: A mold stage sequence T

Steps:

1. Create gross object $o = l^1 \cup l^2$.
2. Create mold enclosure E based on gross object o and orient it along d.
3. Create gross mold g_o for gross object o by subtracting o from E. Create gross mold g_m for l^1 by subtracting l^1 from E.
4. Generate mold pieces (g^1, g^2, R) for the gross object o by calling GENERATE-MOLD-PIECES or GENERATE-MOLD-PIECES-WSC ($R = \varnothing$ if no side core is needed).
5. Generate mold pieces (g^3, g^4, R) for l^1 by calling GENERATE-MOLD-PIECES or GENERATE-MOLD-PIECES-WSC (If $R \neq \varnothing$, then R is the same with the side cores generated for the gross object o. This is ensured by the algorithm DETERMINE-SEQUENCE-AND-DIRECTION).

6. Create the following solids:

$$l^2{}_1 = g^3 \cap l^2;\ l^2{}_2 = g^4 \cap l^2;\ c_1 = g^1 \cup l^2{}_1.$$

7. Suppose face f is the bottom face of E, create solid c_2 by sweeping f along direction $-d$ by a certain distance.

8. Create solid c_3 by sweeping $l^2{}_2$ along direction $-d$ to the top face of c_2 (which is also f).

9. Create the following solids:

$$c_4 = g^2 - c_3;\ c_5 = c_2 \cup c_3;\ c_6 = c_5 - l^2{}_2.$$

10. If c_4 has only one lump, then

    i. Get final mold pieces:

    $M_{co1}= c_5$; $M_{ca1}=c_1$; $M_{idx}=c_4$; $M_{co2}=c_6$; $M_{ca2}=g^1$.

    ii. Generate mold stage: $T = \{t_1, t_2\}$

    t_1: $M_{co1}, M_{ca1}, M_{idx}, R, O_1=\{l^1\}$.

    t_2: $M_{co2}, M_{ca2}, M_{idx}, R, O_2=\{l^1, l^2\}$.

11. Else if c_4 has more than one lump, then

    i. Project l^2 to a plane e perpendicular to d. The projection of l^2 separates e into two or more disconnected regions.

    ii. Find one or more 2D sections Q on the projection area of l^2, such that if Q is removed, those disconnected regions will form a connected region. Q can be found by the following method: (1) For two disconnected regions, find two points in each region, and the four points will form a polygon. (2) The intersection of the polygon with the projection area of l^2 can be a section in Q. (3) Repeat (1) and (2) until all the regions form a connected region.

    iii. Create solid w by sweeping Q along $+d$ and $-d$ by a distance greater than the extent of l^2.

    iv. Compute intersection $i_s = l^2 \cap w$. If the projections of i_s and l^1 on the plane perpendicular to d have in intersection,

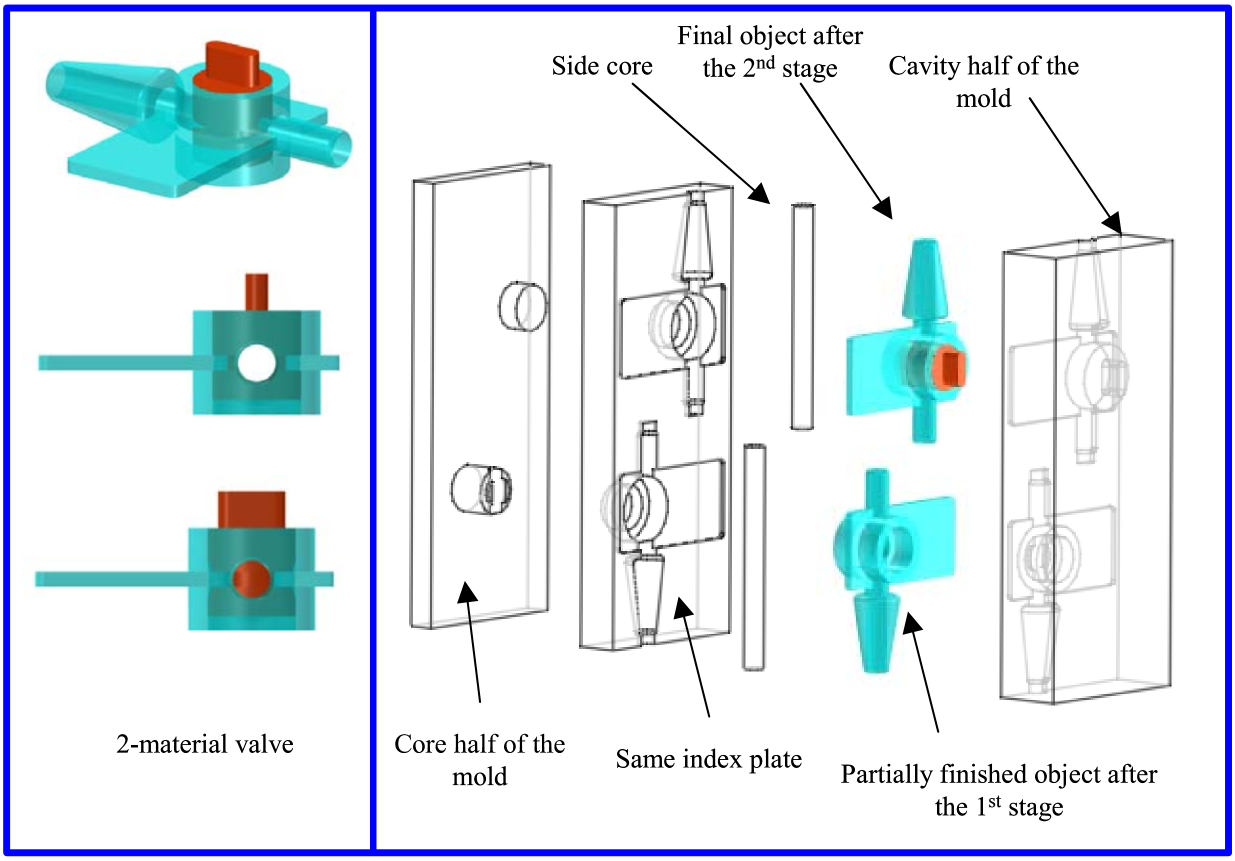


Figure 6 Final mold consisting of core, index-plate, cavity, and side cores

then repeat steps ii, iii and iv, until no intersection exists between the projection of i_s and l^1. If Q cannot be found, then the object cannot be made by index-plate process; and exit.

v. Create c_7 by sweeping i_s along direction $-d$ to the top face of plate c_2.

vi. Create following solids:

$c_8 = c_7 - i_s$; $M_{co1} = c_5 - c_7$; $M_{ca1} = c_1 \cup i_s$;

$M_{idx} = c_4 \cup c_8$; $M_{co2} = c_6 - c_7$; $M_{ca2} = g^1$.

vii. Generate mold stage: $T = \{t_1, t_2\}$

t_1: M_{co1}, M_{ca1}, M_{idx}, R, $O_1=\{l^1\}$.

t_2: M_{co2}, M_{ca2}, M_{idx}, R, $O_2=\{l^1, l^2\}$.

12. Output T.

The final mold pieces generated by the algorithms cannot be directly used on industrial index-plate multi-shot machines. There is an additional step needed to combine the mold pieces together to form the final mold halves. The method is as following. The final cavity half of the mold is obtained by combining the two separate cavities for two stages together to form a single piece. Similarly, the final core half of the mold is obtained by combing the two separate cores for the two stages together to form a single piece. The final index-plate is obtained by combining two identical index-plates together to form a single piece. Since two different stages are realized by rotating the index-plate, before combining the mold pieces of the two-stages together to form the final mold halves, the mold pieces of the first stage or the second stage need to be first rotated by 180 degrees.

5. IMPLEMENTATION AND EXAMPLES

A prototype system has been developed based on the algorithms described in Section 4 for designing index-plate type molds. The system was developed using VC++, MFC and ACIS geometric kernel. All computational experiments were done on a 2.1

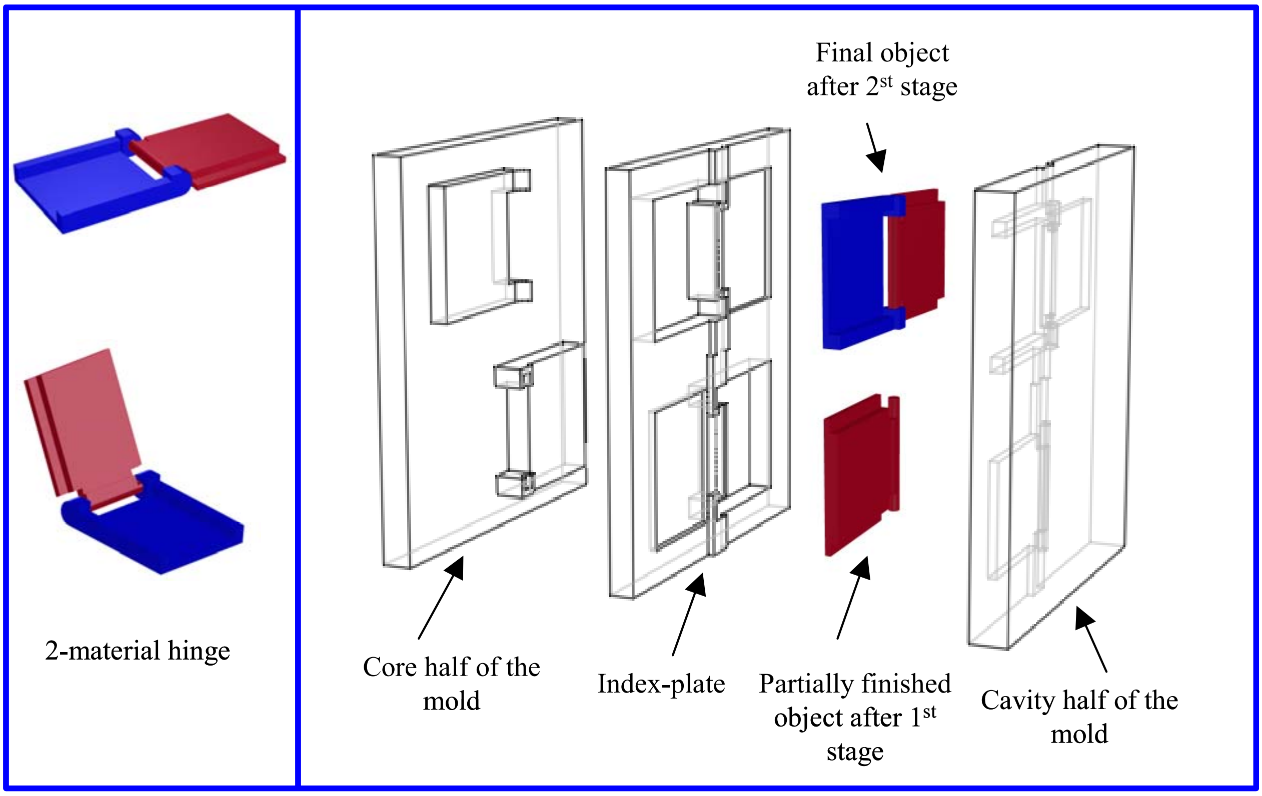


Figure 7 Two-material hinge and the index-plate mold generated by the algorithm INDEX-PLATE-MOLD-DESIGN

GHz Pentium 4 machine with 1GB RAM.

Figure 4 shows the process for designing the index-plate mold based on the algorithm INDEX-PLATE-MOLD-DESIGN for the two-material object shown in Figure 4(a). For this object, solid c_4 generated in Step 9 is a single lump solid, therefore c_4 becomes the index-plate and Step 10 is used to generate the final two-stage index-plate mold, shown in Figure 5. Figure 6 shows the final mold generated by combining the mold pieces for two individual stages. The computation time for generating the mold stages for this object is 2.5 minutes.

Figure 7 shows an additional example of multi-material object, and the final index-plate mold generated by using the algorithm INDEX-PLATE-MOLD-DESIGN. The computation time for generating the mold stages for the object in Figure 7 is 3.5 minutes.

6. DISCUSSION AND CONCLUSIONS

This paper describes a geometric algorithm for generating mold-stages for index-plate type multi-shot process. The new algorithm is a significant improvement over algorithms described in Gupta et al. (2002), Kumar and Gupta (2002), and Li and Gupta (2003) by considering the constraints for index-plate process in generating molding stages, such that the generated mold can be used in an industrial process. In addition, the soundness of the algorithm has been proved. For the sake of brevity the soundness proof is omitted from this paper.

We expect that the algorithm described in this paper will provide the necessary foundations for automating the design of index-plate molds and therefore will help in significantly reducing the mold manufacturing lead-time associated with these types of molds.

Our current algorithm for index-platen process has the following limitations:

- The types of material in the object cannot be more than two. We are planning to extend the algorithm to handle objects that are made of three materials, by developing three stage index-plate molds.
- The mold-pieces generated by our algorithm may not have the optimal shape. For example, it is desirable to have mold pieces that minimize the mold opening distance. We plan to develop algorithms to optimize the shape of mold-pieces.
- We have not considered the feasibility of addition of sprues in the mold shapes.

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