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A novel approach of automatically designing EDM electrodes for machining uncut regions

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ABSTRACT

With the restriction of the diameter and feed direction of the cutting tool in milling process, electric discharge machining (EDM) is the only effective machining technology for the uncut regions with internal sharp corner. Automatic design of the electrode is of great significance for the CAD/CAM integration of EDM technology. In current CAD/CAM system the electrode design is done manually by technologists based on experience and knowledge. The procedure is tedious and time-consuming. In this paper, a novel approach is proposed to automatically generate the electrode CAD model taking the topological vertices of uncut region as the hint. The hint feature points are innovatively defined and classified into three types: internal-sharp points, cutting-into points and interacting points. Based on this, our approach firstly determines the faces and the type of uncut region. Secondly, the interacting region is decomposed into the isolated region by reconstructing the topological structure, patching the split face and partitioning the shared face. Thirdly, the modeling parameters are extracted from the isolated region. Finally, the electrode CAD model is created by executing a set of generic modeling operations. The electrode CAD model can be directly used in the process planning, so as to promote the integration of CAD and CAM.

KEYWORDS

EDM; Uncut region; Hint feature point; Region recognition; Region decomposition; Electrode CAD model; Design automation

1. Introduction

Uncut region with internal sharp corners exist widely in the mold components, as shown in Fig. 1. With the restriction of cutter radius and feeding direction, EDM is the only effective machining technology for such region [1, 3]. As a non-traditional machining method, EDM is low efficiency [16], and need the complicated electrode design [14, 9].

The automatic design of electrode is of high importance to EDM [8–21]. But the related research is still little. Mahajan et al. [12] presented the basic rules for the automatic design of electrode to improve the electrode design process. However, these rules were presented in the form of high-level description, and the automatic design of electrode cannot be achieved. Ding et al. [4] developed an algorithm of detecting sharp corner uncut region for electrode design. The created electrode CAD model has the correct shape. But, as the interaction of delta volume was not considered, the machinability of the designed electrode cannot be ensured. The intelligent CAD tool developed by Lee et al. [10] took convex edges in the machining region as the hints of splitting electrode. When all of the initial regions were split into the valid sub-regions, the CAD model of sub-region electrode was constructed through a set of CAD modeling operations. With the tool, the automaticity of electrode generation was raised at least a 50% improvement. However, the uncut region was partly recognized through the interactive selection. The algorithm proposed by Zhou et al. [21] took the convex edge as hint for the volume decomposition, so as to assure the machinability of the designed electrode. But their method assumed that all the uncut regions had been identified.

In summary, the previous researches cannot achieve the electrode automatic design. Fundamentally, the feature recognition is a prelude to the electrode generation. Over the past decades, the extensive methods on feature recognition have been proposed, such as graph-based [6–15,17], hint-based [15,17] and volume decomposition-based approaches [19]and so on. Therefore we propose an approach based on feature recognition to automatically generate the electrode CAD model for machining uncut regions.

The remainder of this paper is organized as follows. Section 2 introduces technical definitions. Section 3 outlines the approach proposed here. Section 4 details the

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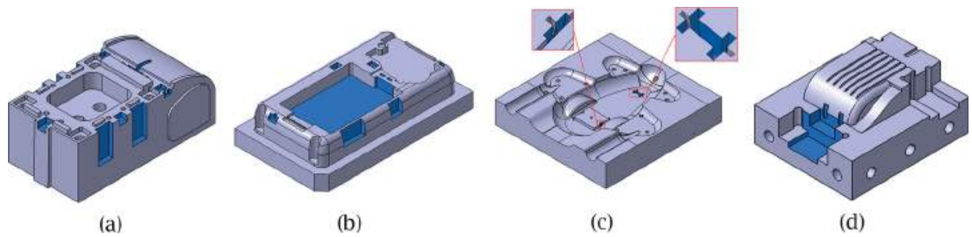

Figure 1. Mold components: (a) Distributor box core, (b) Phone cover core, (c) Toy plane core (d) Razor core.

approach. Section 5 illustrates the algorithm analysis and experiment results, and, finally, Section 6 concludes this paper and discusses future work.

2. Technical definition

The region only via EDM technology must be recognized and decomposed in order to ensure the validity and machinability of the electrodes. The related technical definitions are discussed in this section.

2.1. Uncut region

Uncut region is a cavity that contains the internal sharp corner. With the restriction of cuter radius and cutter feeding direction, the uncut region is machined only via EDM technology.

2.1.1 The classification of uncut region

The interacting region has the common topological elements [17–20]. According to whether the uncut region shares the common topological elements with another region, the uncut regions can be classied into two types: **isolated regions** and **interacting regions**. **The isolated region** does not share the common elements with another region, as *R* in Fig. 2.

The interacting regions share the common topological elements. According to the difference of common elements, the interacting uncut regions are classified into **adjacent-interacting regions** and **bridge-interacting regions**.

If two regions share a group of successive convex edges, they are adjacent-interacting. For example, in Fig. 3, $e^1 \sim e^3$ are the successive convex edges shared by R^1 and $R^{2,}$ so R^1 and R^2 are adjacent-interacting.

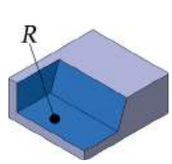

Figure 2. Isolated region.

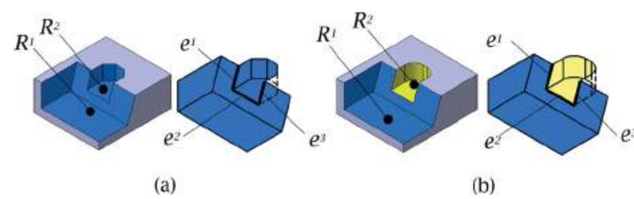

Figure 3. Adjacent-interacting regions: (a) Two uncut regions, (b) Uncut region and Milling region.

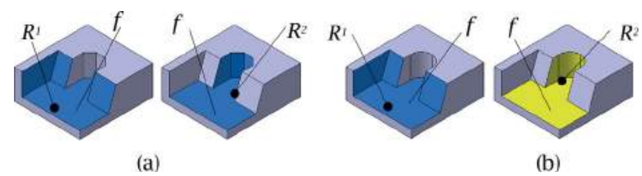

Figure 4. Bridge-interacting regions: (a) Two uncut regions, (b) The uncut region and the milling region.

The adjacent-interacting can be the interaction between two uncut regions or the interaction between uncut region and milling region, as showed in Fig. 3.

When two regions have the common face, they are bridge-interacting. For example, in Fig. 4, *f* is the face shared by R^1 and R^2, so R^1 is bridge-interacting with $R^{2.}$

The bridge-interaction can also be the interaction between two uncut regions or the interaction between uncut region and milling region. In Fig. 4a, R^1 and R^2 are uncut features; in Fig. 4b R^1 is uncut feature, and R^2 is milling feature.

2.2. Hint feature point

The topological, geometrical and heuristic information about the part can be used as the hints of presence of a certain form feature [2]. The choice and utilization of the hint is a key and difficult problem in handling interacting machining feature. The vertex has several adjacent edges, and their convex-concave configuration contains the substantial information on the process planning. Therefore, the vertex is innovatively used as the hints for handling the uncut region in this paper. The vertices of uncut region are termed as **the hint feature point**, which

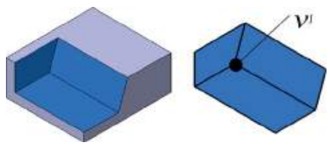

Figure 5. Internal-sharp point.

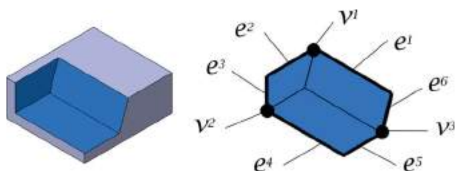

Figure 6. Cutting-into points and Cutting-into edges.

are classified into three types: **internal-sharp points**, **cutting-into points** and **interacting points**.

The internal-sharp point is the hint for extracting the region faces. If the vertex meets the following conditions, then it is termed as **the internal-sharp point.**

- It has at least three adjacent concave edges and no adjacent convex edge;
- The two adjacent edges on any topological face are not continuously differentiable (C1);

For example, in Fig. 5, the vertex v^1 is the internal-sharp point.

The cutting-into point suggests the cutter wedging. If the vertex meets the following conditions, then it termed as **the cutting-into point**.

- It has two adjacent convex edges and one or more than one adjacent concave edges;
- Another endpoint of all the adjacent concave edges is the internal-sharp point;
- The two adjacent edges on any topological face are not continuously differentiable (C1);

As the adjacent convex edges of the cutting-into point are on the cutting-into face of electrode, the edges are termed as the cutting-into edge. For example, In Fig. 6, the vertices $v^1 \sim v^3$ are the cutting-into point, and their adjacent convex edges, $e^1 \sim e^6$, are the cutting-into edge.

The interacting point is formed by the intersection of machining operation, and so its adjacent edges belong to different regions. The ownership relation of an edge is defined as follows.

- If a convex edge is the boundary of one face, then it belongs to the region which the face belong to;

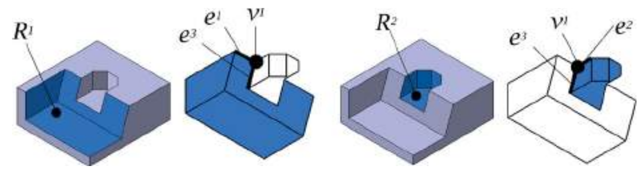

Figure 7. Interacting points.

- If a concave edge is the boundary of two adjacent faces, then it belongs to the region which the two faces belong to;

If the vertex meets the following conditions, then it termed as **the interacting point**.

- Not all the adjacent edges belong to the region;
- The two edges on any topological face are not continuously dif ferentiable (C1);

Fig. 7 shows an example of the interacting point, where e^1 and e^3 belong to R^1, and e^2 and e^3 belong to R^2. So v^1 is the interacting feature point of R^1 and $R^{2.}$

The hint feature points contain the subtantial information on the process planning, so we dig up information from the hint feature points for the recognition and decompostion of uncut regions.

3. Overview of the approach

The recognition and decomposition of uncut region is the key of the automatic electrode design. The topological, geometrical and heuristic information on part CAD model is called as hints, which indicates the need for one type of processing technology. Therefore, Hint-based approaches intrinsically show better performance in resolving the problem of region interaction than other approaches [18–7]. Hint selection is the key in the hint-based approach. Our approach innovatively takes the topological vertices as hints. The proposed approach automatically generates the electrode CAD model. The main steps are as follows, the result of each step is shown in Fig. 8.

Step1: Identify the uncut region in section 4.1;
Step2: Decompose the interacting region into the isolated region in section 4.2;
Step3: Extract the parameters for generating the electrode CAD model in section 4.3.1;
Step4: Build the electrode CAD models in section 4.3.2;

Among the above stages, the first three stages are the innovative work of this paper.

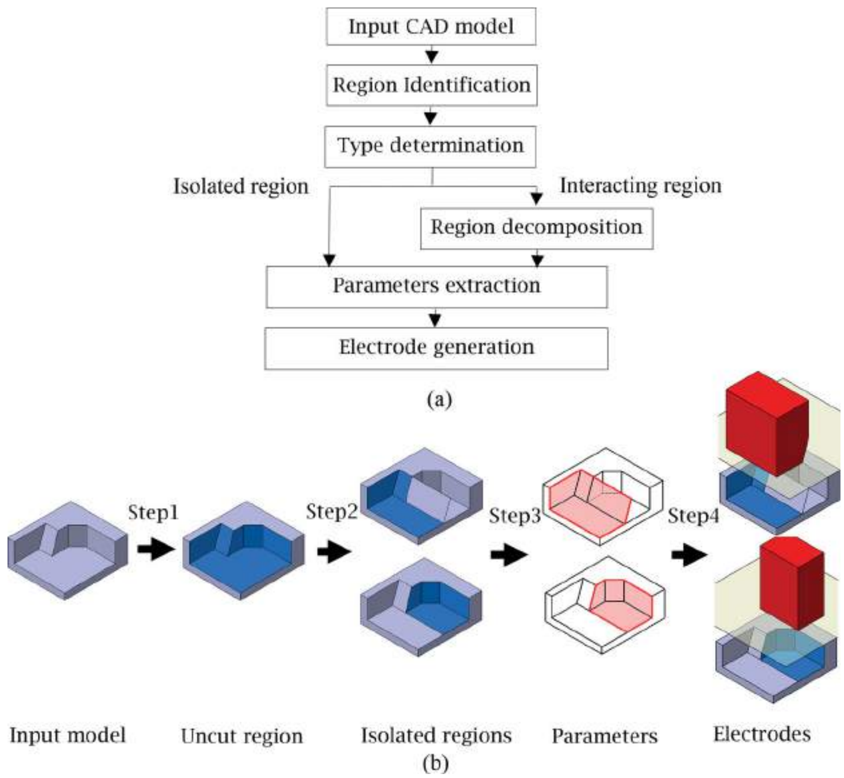

Figure 8. Flowchart and illustration of the approach: (a) Flowchart, (b) Illustration of flowchart.

4. Details on the overall steps

In this section, the overall steps are described in greater details.

4.1. Identification of uncut region

In this section, the faces of uncut region and its type are identified successively.

4.1.1 Extract the topological faces of uncut region

The basic idea is to extract the regional faces by using the adjacent relation of topological elements with internal-sharp points as the hint. So the internal-sharp points are firstly extracted from all vertices in B-rep model of the part, as shown in Fig. 9.

Next, the concave edges of each region are searched. For the bridge-interacting regions there may be geometrically co-defined edges, and so the search scope includes both the topologically adjacent edges and geometrically co-defined edges. The concrete steps are as follows.

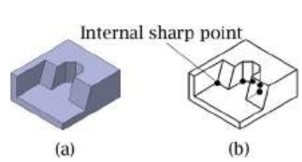

Figure 9. Internal sharp points: (a) Input model, (b) Internal sharp points.

Step1: Visit the first unvisited internal sharp point;

Step2: Search other internal-sharp points along the adjacent concave edge until there is no the internal-sharp point available. Once an internal sharp point is searched, perform the following steps;

- Step 2.1: Uniquely store the adjacent concave edges of the internal sharp point;
- Step 2.2: if another endpoint of current edge is an interacting point, that is, there may be the co-defined edge with the current edge, then search and store such edge;

The above steps are performed repeatedly until all the internal-sharp points are visited, so that the concave edges of each region are stored into their respective list.

Finally, the regional faces are extracted with the extracted edges as input. Fig. 10 shows an example where the concave edges and the faces of the region are extracted respectively.

4.1.2 Determine the region type

The region type is determined based on the edge or face shared by regions. So the convex edges are firstly

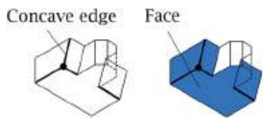

Figure 10. Extraction of regional faces.

extracted, and then the following steps are performed to determine the region type.

Step1: Execute the matching of faces to identify the bridge-interacting regions, which have the common face;
Step2: Tag the common edge of the bridge-interacting region as matched;
Step2: Execute the matching of convex edges to identify the adjacent-interacting regions, which satisfies the following condition:

- The cutting-into edges of one uncut or milling region belong to the face of another uncut region;

Step3: Tag the surplus as the isolated region.

4.2. Decomposition of interacting uncut region

The region interaction causes the defect and merging of interacting regional faces, which hamper the electrode generation and the generated electrode machinability. Therefore, the interacting uncut region must be decomposed into the isolated regions. So the structure of interacting region must be topologically reconstructed. The methods of PATCH and SWEEP are designed. In this section, we will discuss the corresponding methods for two types of interacting regions.

4.2.1 Decomposition of the adjacent-interacting regions

The adjacent-interacting regions have the common convex edges. There are the cutting-into points on the common edges. The cutting-into points suggest the cutter wedging. So the region to which the cutting-into points belong is tagged as Interacting Region (**IR**), and another is tagged as Be Interacted Region (**BIR**). The face of BIR where the cutting-into points is on is tagged as **the split face**. The adjacent edge of interacting point belonging exclusively to **BIR** is tagged as **the split edge**, which contains the boundary information of the split face.

For example, in Fig. 11b, v^1 and v^2 are the cutting-into points of R^2 on the common edges, and so R^2 is **IR**, R^1 is **BIR**, f is the split face; in Fig. 11c, e^1 and e^2 belong exclusively to R^1, and so they are the split edges.

In Fig. 11, the cutting-into points only belong to one region. But the cutting-into points may belong respectively to two adjacent-interacting regions. For example, in Fig. 12b, $v^1 \sim v^2$ are the cutting-into points of R^1; in Fig. 12c, v^3 is the cutting-into point of R^2. In this case, there are two groups of the split faces need to be repaired.

Given both situations mentioned above, the methods PATCH and SWEEP are designed and selectively performed. The associated flowchart is shown in Fig. 13.

The method PATCH includes two operators: REPAIR-EDGE and FILL-FACE. The associated flowchart is shown in Fig. 14.

When the common convex edges form a closed loop, the split face can be directly repaired. Conversely, the REPAIR-EDGE operator constructs the edge to make the unclosed common edges closed based on the geometrical configuration of the split edges. The specific situations are as follows.

- Case1: The split edges are geometrically co-defined
  Step1: Built the connecting edge of two split edges;
  Step2: Set the new edge to be continuous curvature with the split edges;
- Case2: The split edges are geometrically intersecting

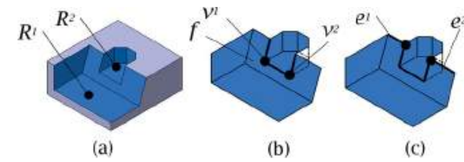

Figure 11. Hints of decomposing the adjacent–interacting regions: (a) Interacting regions, (b) and (c) Hints.

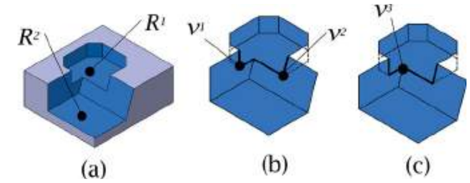

Figure 12. Interacting points of two regions: (a) Interacting regions, (b) and (c) Interacting point.

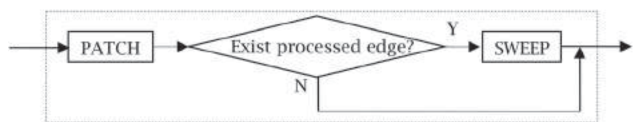

Figure 13. Flowchart of the decomposition of adjacent-interacting region.

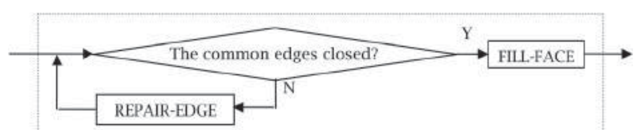

Figure 14. Flowchart of the method PATCH.

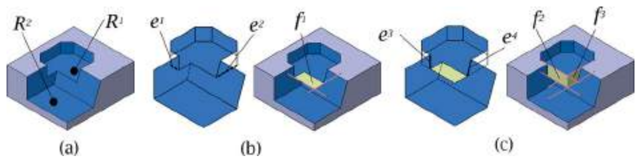

Figure 15. Decomposition of adjacent-bridge regions: (a) Interacting regions, (b) and (c) Region decomposition.

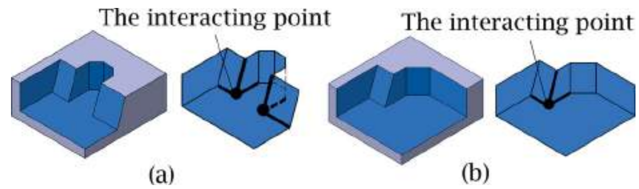

Figure 16. Interacting points on the shared face: (a) A pair of interacting points, (b) A single interacting point.

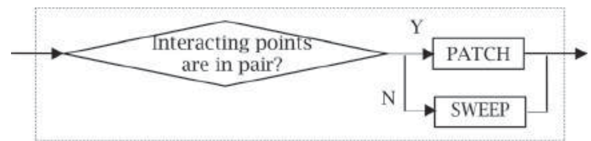

Figure 17. Flowchart of the adjacent-interacting region decomposition.

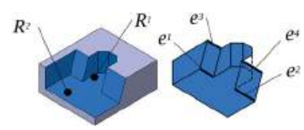

Figure 18. Split edges in bridge-interacting regions.

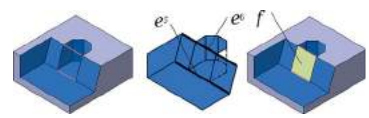

Figure 19. Performance of the method PATCH.

Step1: Extend the split edges from the respective interacting points;
Step2: Set the extended edges to be continuous curvature with the respective split edges

The FILL-FACE operator is to repair the split face. The concrete steps are as follow.

Step1: Fill the loop formed by the repaired edges and the common edges to build a face;

Step2: Set the geometry type of the new face to be the same as the split face.

If there are some common convex edges not being processed, which denote that the split face is not completely repaired, then the method SWEEP is executed. The concrete steps are as follow.

Step1: Extend the split edges being coplanar with the remaining edge from the interacting points;

Step2: Build the swept face with the remaining edge as silhouette and the extended edges as the leading curves;

Step3: Split the swept faces with each other and retain the inside partitions;

Fig. 15 shows an example of the adjacent-interacting region decomposition. In Fig. 15b, the split edges, e^1 and e^2, are geometrically interacting, and the face f^1 is built by performing the method PATCH. As the edges e^3 and e^4 are unprocessed, the method SWEEP is executed to build the faces f^2 and f^3.

4.2.2 Decomposition of the bridge-interacting region

The bridge-interacting region decomposition includes both repairing split face and partitioning shared face.

4.2.2.1 Repair the split face

The interacting points on the shared face may be alone or in pairs, as shown in Fig. 16.

Based on whether the interacting points are in pair, the methods of PATCH and SWEEP are selectively performed. The associated flowchart is shown in Fig. 17.

- Case1: The interacting points is a pair

In this case, there are two pairs of co-defined edges. These edges are formed by the wedging of cutter, so and they are the split edge. The region to which the split edge belongs is **BIR**, another is **IR**. For example, in Fig. 18, e^1 and e^2, e^3 and e^4 are two pairs of split edges, and R_2 is **BIR**, R_1 is **IR**.

The method PATCH is as follows.

Step1: Build the connecting edges of the co-defined split edges;

Step2: Set two new edges to be continuous curvature with the respective split edges;

Step3: Fill the loop formed by the new edges and the common convex edges to build a face;

Step4: Set the geometry type of the new face to be the same as the split face;

Fig. 19 shows the PATCH execution process, where e^5 and e^6 are the connecting edges, and f is the repaired face.

- Case2: The interacting point is not a pair

The method Sweep is as follows.

Step1: Extend the two coplanar split edges;

Step2: Build the swept face with the convex edge of the interacting point as silhouette and the extended edges as the leading curves to the closest element;

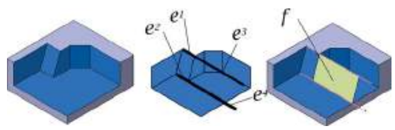

Figure 20. Performance of the Sweep method.

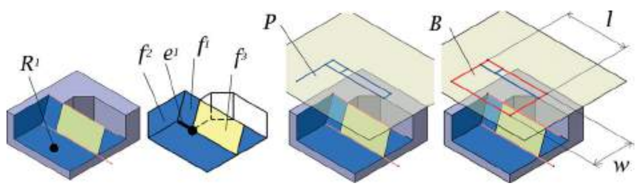

Figure 21. Calculation of rigidity coefficient.

Step3: Set the geometry type of the new face the same as the split face;

Fig. 20 shows the method Sweep executions, where e^3 and e^4 are the extended edges, and f is the repaired face.

The interacting feature point has two adjacent concave edges on the shared face. The choices should achieve the optimal decomposition to promote the machining efficiency and quality. For the bridge-interaction between uncut region and milling region, the concave edge of the milling region is chosen as the leading directions, thus promoting the machining efficiency.

For the bridge-interaction between two uncut regions, the electrode rigidity is considered to promote the machining quality. To evaluate the rigidity of electrode, the following steps are executed to calculate the rigidity coefficient (***RC***).

Step1: Project the pre-decomposed region faces besides the shared face onto the plane perpendicular to z axis;
Step2: Create the smallest quadrangle encasing box of the projection;
Step3: Calculate $\boldsymbol{RC} = w/l$, where w is the width of the box, l is the length of the box;

Fig. 21 shows the ***RC*** calculation of the pre-decomposed region R^1 with the edge e^1 as the leading directions, where ***P*** is the projection of the faces $f^1 \sim f^3$, ***B*** is the smallest quadrangle encasing box.

To achieve the optimal decomposition, we firstly calculate the ***RC*** of all pre-decomposed regions in two leading directions, and then choose the adjacent concave edge, whose ***RC*** has no extreme value, as leading direction. This way avoids the decomposed region electrode to be too thin.

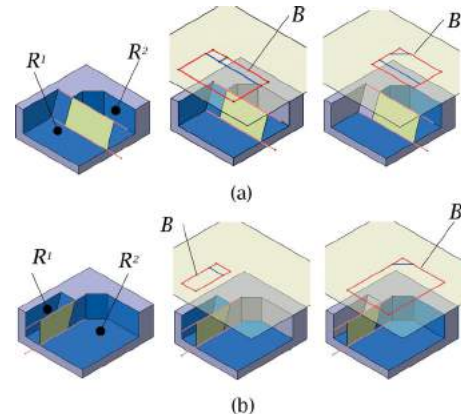

Figure 22. Two kinds of decomposition: (a) Better decomposition, (b) Bad decomposition.

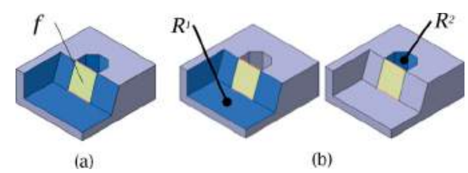

Figure 23. Partition of shared face: (a) Interacting regions with adjacent face, (b) Two isolated regions

Fig. 22 shows two groups of pre-decomposed regions. In Fig. 22b, as the ***RC***s contain the extreme value in two groups of ***RC***s, the decomposition causes the region R^1 electrode to be too thin. So the decomposition is better in Fig. 22a.

4.2.2.2 Partition the shared face

The shared face partition is simple. Namely, by cutting the shared face with the reconstructed face the shared face is partitioned into the two separate regions. Fig. 23a shows the region with the newly created patch face, and Fig. 23b shows the two isolated regions R^1 and R^2.

4.3. Generation of electrode CAD model

In this section, we firstly discuss the extraction of the parameters for generating electrode CAD models.

4.3.1 Extract the parameters for generating electrode CAD models

The region faces and the boundary loop formed by the convex edges are used as the parameters for the electrode CAD model generation. The extraction is different for the isolated region and interacting region.

For the isolated region, its structure is intact. So the region faces have been extracted in section 4.1, and the

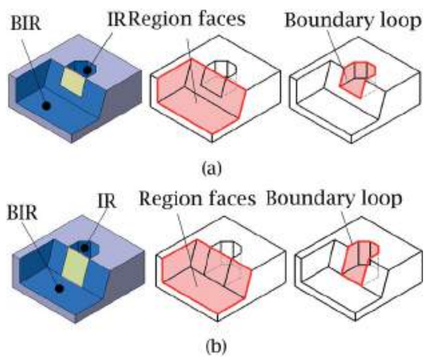

Figure 24. Parameters for generating electrode: (a) Adjacent-interacting regions, (b) Bridge-interacting regions.

boundary loop is directly extracted by searching the convex edge of the region based on Depth First Search Principles.

For the interacting region, the repaired face is added into the BIR face list. The edge of repaired face only having one adjacent face belongs to **BIR**, and the other edges belongs to **IR**. So in addition to the original edges, the above two types of edges are also added to the edge list. Fig. 24 shows an example of the above parameters for the adjacent-interacting region and the bridge-interacting region.

4.3.2 Generate the electrode CAD model

The recognition and decomposition of the uncut region and the parameters extraction are the innovations of this paper. Based on above works, a set of modeling operations are executed to create a group of electrode CAD models for different EDM machining steps.

(1) Build the initial electrodeWith the extracted parameters the following modeling operations are executed to generate the initial electrode.
 Step1: Project the boundary loop onto the plane above the part orthographically;
 Step2: Extrude the projected boundary loop along +z to obtain the solid body;
 Step3: Trim the solid body with the formed faces;

The generation of the initial electrode CAD model is shown in Fig. 25.

(2) Refine the initial electrodeThe refinement of the initial electrode includes the following steps.
 Step1: The trimmed faces of the initial electrode are offset inward according to the different sparking gaps, as show in Fig. 26a, to obtain a group of electrodes for the different EDM machining steps;
 Step2: The untrimmed faces are offset outward to avoid the burrs on the fringe of region, as show in Fig. 26b;

5. Experiments and analysis

The methodology and algorithms discussed above were implemented by using "Visual Studio 2005" integrated with the "CAA and RADE" toolkit for the application development of CATIA v5 R21. All of the tested samples are from industry.

5.1. Experiment 1: corrective analysis

Experiment 1 was performed for the purpose of validating each stage of our approach.

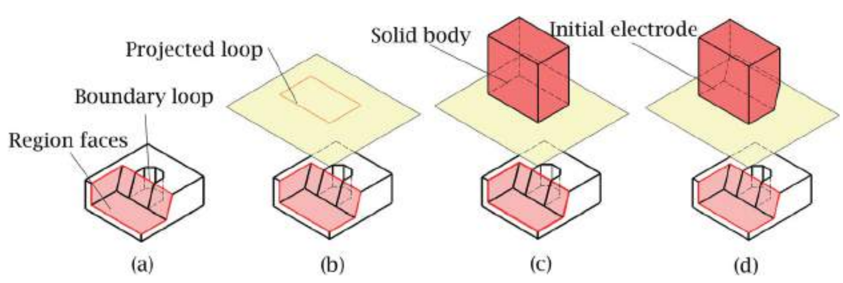

Figure 25. Generation of initial electrode: (a) The extracted parameter, (b) The projected boundary loop, (c) The extruded body, (d) The initial electrode.

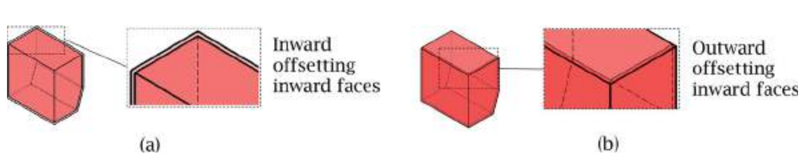

Figure 26. Initialization of refined electrode: (a) Offsetting of trimmed faces inward, (b) Offsetting of untrimmed faces. Outward.

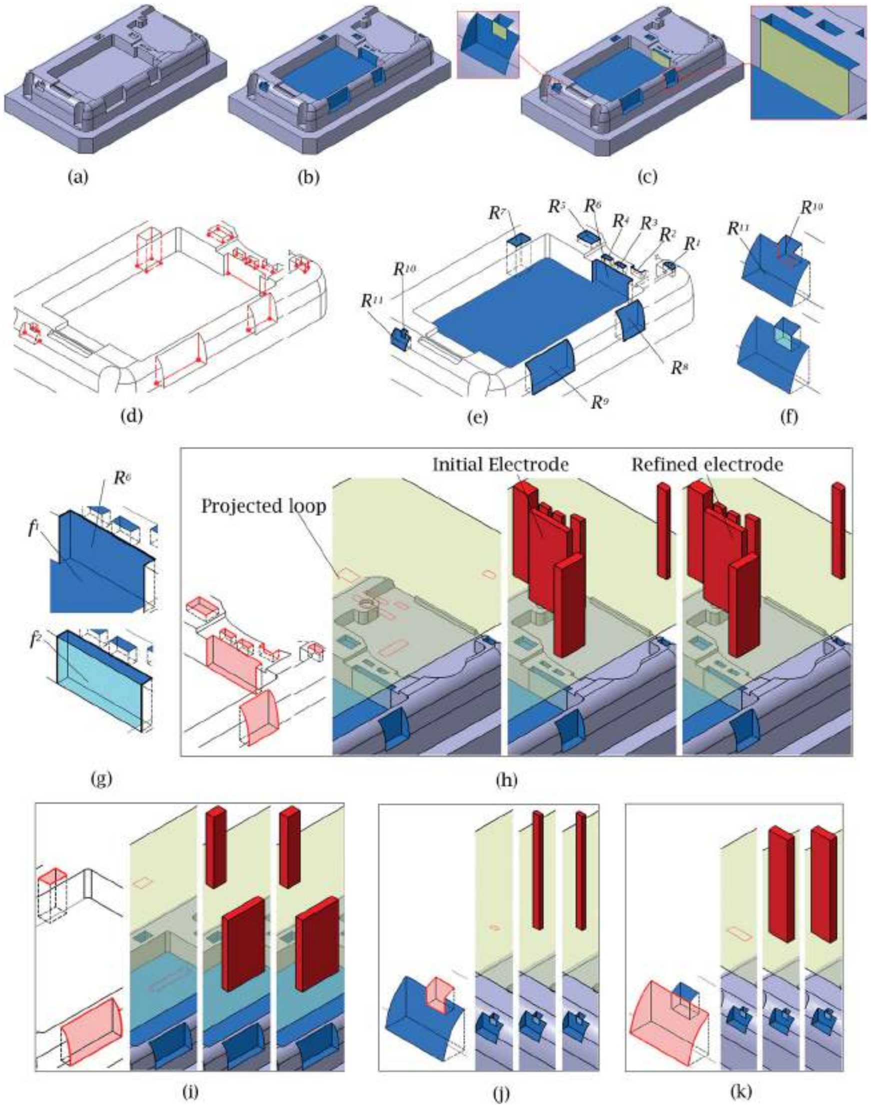

Figure 27. Phone cover mould: (a) Input model, (b) Region recognition, (c) Region decomposition, (d) Internal-sharp points and concave edges, (e) Region face, (f) Adjacent-interacting regions, (g) Bridge-interacting regions, (h) ∼ (k) Generation of electrodes CAD model.

The case part is the core of phone cover. The number of its faces, edges and vertices is 145, 397 and 261 respectively. The input model is shown in Fig. 27a. The result of recognition and decomposition are shown in Fig. 27b and Fig. 27c respectively.

The analysis of recognition and decomposition are shown as a wireframe in Fig. 27d ∼ 27g. All the internal-sharp points and the concave edges are shown in Fig. 27d. The region faces are shown in Fig. 27e. The core contains 11 uncut regions. As the cutting-into edges of R^{10} are partly on the face of R^{11}, R^{10} is adjacent-interacting with R^{11}. By performing the method PATCH in section 4.2.1, the split face of R^{11} is repaired, as shown in Fig. 27f. As R^7 share the common face f^1 with one milling region, R^6 is bridge-interacting with the milling region. After performing the method PATCH in section 4.2.2, the face f^2 is created and the face f^1 is partitioned, as shown in Fig. 27g.

The procession of electrode generation are divided into four groups, and shown in Fig. 27h ∼ 27k respectively. The extracted parameters are shown in the first column. The generations of electrode CAD models are shown in the last three columns.

5.2. Experiment 2: robustness and efficiency test

To test the robustness and efficiency of our method, the electrodes of some parts have been automatically generated. Fig. 28 shows the experimental results of four parts, where the models through the processing of region recognition, decomposition and electrode generation are shown from left to right in each row.

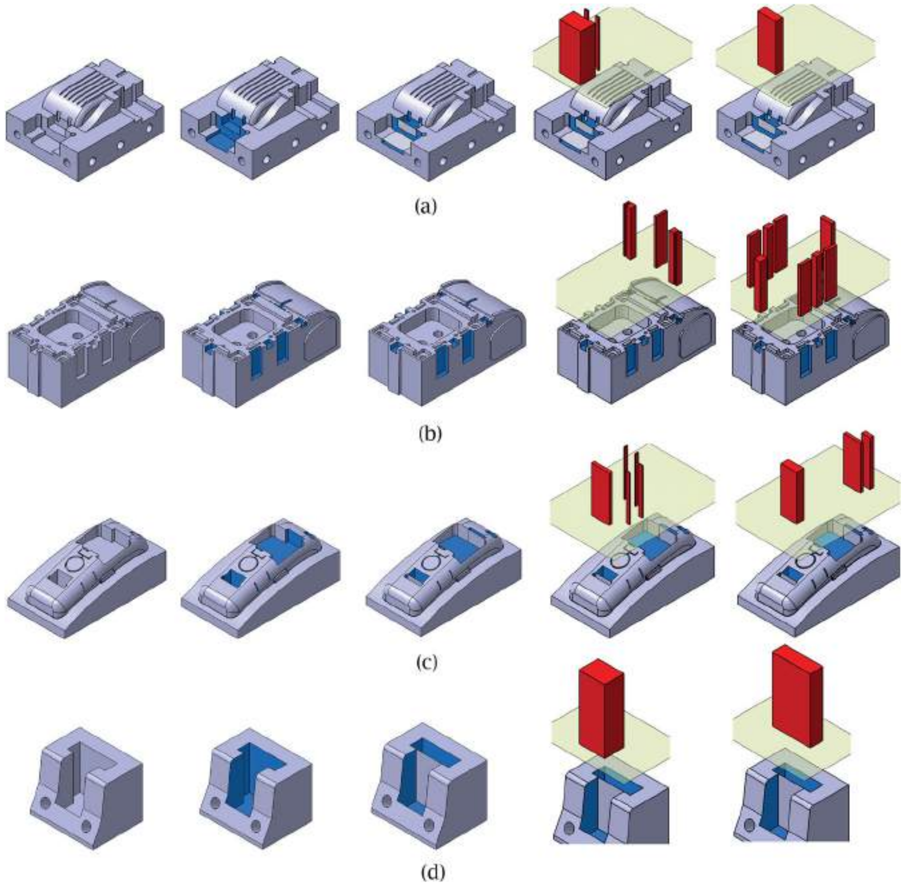

Figure 28. Examples: (a) Razor core, (b) Distributor box core, (c) Phone cover core, (d) Holder.

Table 1. Model complexity and executing time

	Model complexity			Executing time (ms)			
No	*NF*	*NE*	*NV*	*TRR*	*TDR*	*TGE*	*NGE*
a	110	307	204	2023	118	209	4
b	204	551	367	3647	207	380	13
c	135	339	233	2322	139	243	8
d	26	66	44	439	29	49	2

The complexity of model and the execution time of each stage are listed in Table 1, where *NF*, *NE* and *NV* indicate the number of faces, edges, vertices in the model, *TRR* (Time of Region Recognition), *TRD* (Time of Region Decomposition Region), and *TEG* (Time of Electrode Generation) indicate the time of the recognition and decomposition of uncut regions and the time of the electrodes generation, *NGE* (Time of Generated Electrode) indicates the number of generated electrodes.

The following conclusion can be drawn from the experiments.

(1) The CAD model of the electrode can automatically be created without any user interaction;
(2) The generated electrode not only has correct shape but also contains no uncut region.
(3) The recognition of region for the core parts need about three to four seconds. This is because the extraction of internal-sharp points is from all the vertices of B-rep model of the core which has high complexity, other stages are completed in less than a second.

6. Conclusions and future work

Automatic design of electrode is of great significance for the CAD/CAM integration of EDM technology. In this research, a novel approach has been proposed to automate the electrode design. The innovative work is concluded as follows.

1. According to the characteristics of EDM process, the hint feature points of uncut region are defined and classified into the three types: internal-sharp points, cutting-into points and interacting points. Based on this, a set of heuristic rules are proposed to rapidly identify the uncut region and its types.
2. By using various geometric reasoning-based algorithms, the interacting regions are optimally decomposed into the isolated regions so as to ensure the

reasonability and machinability of corresponding electrodes.
3. The parameters for generating the electrode CAD models are rapidly extracted via edges searching and face updating based on the ownership relation of topological elements.

Our approach proves to be highly efficient in automatically generating the electrode CAD model. Still, our future work should focus on the following two aspects.

1. The optimal selection between milling and EDM technology.
2. The optimal combination of electrode tools.

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