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Knowledge-Based Engineering Supporting Die Face Design of Automotive Panels

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1. Introduction

Sheet metal is commonly used in the automotive industry. The requirements for developing approaches for manufacturing automotive panels have become increasingly important as carmakers seek to shorten their time to market. However, designing and manufacturing mold dies for automotive sheet metal panels is time-consuming as several processes use the trial-and-error method. The die design period for one sheet metal panel is usually a few months to up to one year.

Along with advances in Computer-Aided Design (CAD), simulation of interference checking can be conducted using a three-dimensional solid model, and Computer-Aided Engineering (CAE) software can be used to simulate and analyze die face to accelerate the design process (Fig. 1).

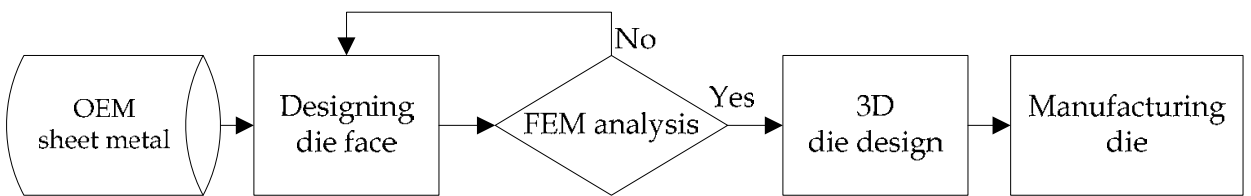


Fig. 1. Design process of die design

Cold dies are used for drawing, trimming, restriking and piercing when manufacturing sheet metal (Fig. 2).

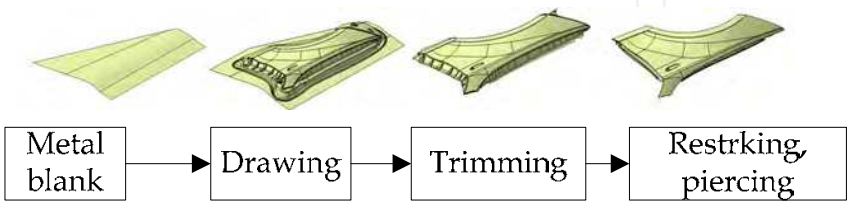


Fig. 2. Manufacturing process of automobile sheet metal

1. Drawing (DR) mold

Drawing is the first operation in a manufacturing process in which a metal blank is drawn without wrinkles or cracks.

2. Trimming (TR) mold

A trimming mold is used to cut sheet metal into an appropriate size and shape, such that the restriking mold can bend. During this operation, the most essential factor is trim cutter and scrap cutter position in a combination that enables sheet metal scrap to automatically drop and be removed after trimming.

3. Restriking (RST) mold

Restriking is an operation in which sheet metal is molded into a desired shape. The main activities in this process are flanging and restriking. Flanging refers to the process of folding edges at a 90° angle, while restriking refers to folding at any angle and is usually driven by a cam for wide areas. When designing a mold for restriking, one should compensate for springback, which can be determined based on raw material characteristics.

4. Piercing (PI) mold

Piercing is typically the last operation. When piercing is done prior to restriking, the position of a hole can move or hole shape can deform during shaping.

2. Die face

The die face plays a crucial role in drawing operations as it determines operation quality (Makinouchi, 1996). Not only does the design have to prevent sheet metal from cracking, wrinkling, offset of the characteristic line, it also has to take the following factors into consideration including compensation of springback, and whether the trimming mold should use normal cams or suspended cams, whether the restriking mold should use a convex hull, and piercing direction. Designers usually search for previous successful cases as references when designing a new die face. This design process is explained in Section 2.2.

2.1 Introduction to the die face

Fig. 3 lists the factors that should be considered when designing a die face for an automotive fender.

1. Product-in face: The part of a sheet metal that would be shaped during the drawing operation (excluding the areas that would be folded afterwards).
2. Binder: The binder is the area that a piston presses against on an upper mold to ensure the metal blank remains stationary during drawing.
3. Drawbead: The drawbead controls tension resistance of a metal blank during drawing.
4. Convex hull: The convex hull stores prepared materials to avoid sheet metal cracking while folding.
5. Stamp mark: A stamp mark is used when determining whether the upper mold and lower mold are in full contact.
6. Parting line: The parting line is a line separating the lower mold and piston.
7. Trimming line: The trimming line is a rough profile of the boundary of a piece of sheet metal. During trimming, the sheet metal is trimmed along this line to facilitate restriking.

Die face design can be divided into three parts—product-in face, product-out face, and binder. Fig. 4 shows a die face cross section. A sheet metal surface generally has two parts—product-in face and product-out face. Product-out face is the largest boundary that must be restriking because it can only be shaped after drawing, and is not included in the die face.

Product-in face is the outside of a sheet metal piece that can be seen after being assembled in an automobile and is shaped during drawing and, thus, is included in the die face.

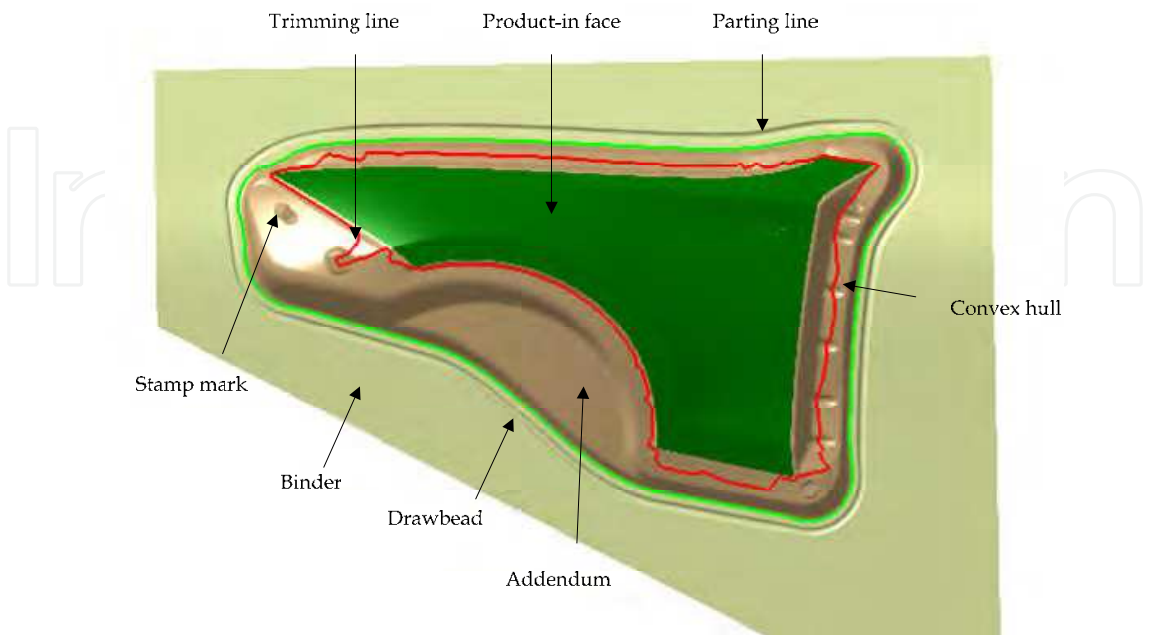


Fig. 3. Features on fender design

Addendum is the surplus area outside the product-in face that facilitates drawing operations; thus, when designing an addendum, the quality and strength of a sheet metal piece after drawing must be considered.

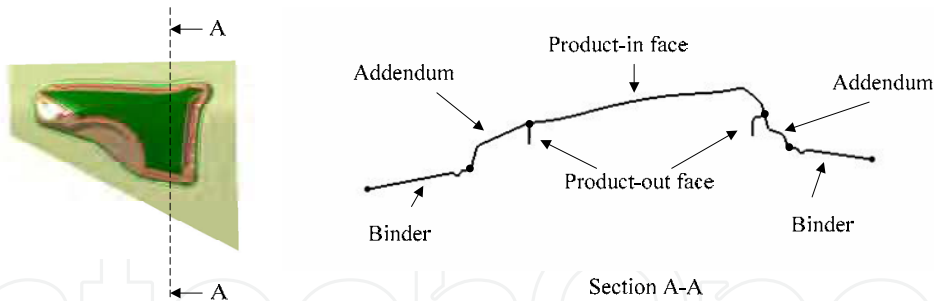


Fig. 4. Divisions on die face

Normally when designing a die face, except for such parts as product-in face, the addendum, and binder—the three main parts—other features like drawbead and the stamp mark during the drawing operation, trimming line during the trimming operation, and convex hull during the restriking operation are also included in die face to facilitate those operations.

2.2 Designing a die face

Fig. 5 shows the design process for a die face. When stamping a piece of sheet metal, no area should be unable to be pressed; that is, undercut (Fig. 6). The upper mold and lower mold should be fully pressed against each other during drawing and all areas that must be drawn should be drawn at one time; therefore, avoiding an undercut is the first priority when designing a die face.

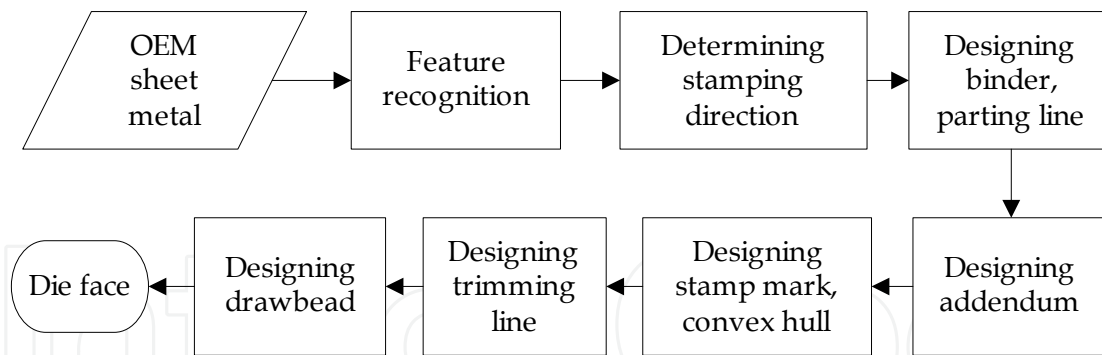


Fig. 5. Design process of die face

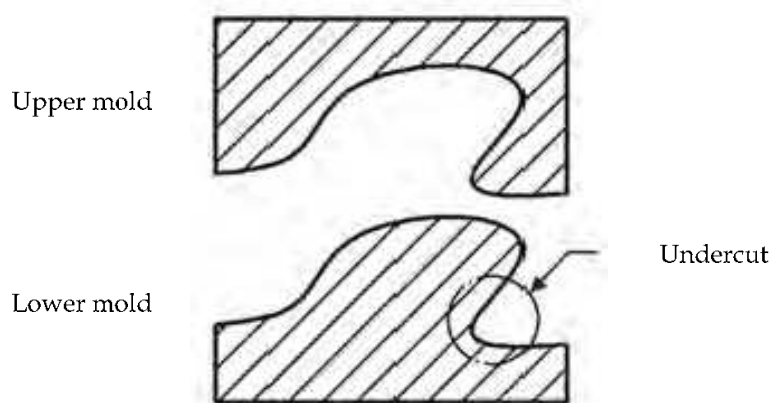


Fig. 6. Undercut

2.2.1 Feature recognition

The first step in designing molds for sheet metal automotive panels is to determine the stamping angle, such that subsequent operations can be successful. Typically, the outer appearance of a panel should be included in the product-in face and be formed during the first operation to yield the highest surface quality with the largest stamping force among all the operations.

A die face can be divided into two parts. One is product-in face and, when designing it, its face cannot have an undercut, and radius of chamfer should be $>3\text{mm}$ to prevent cracking while drawing. If these requirements cannot be met, an addendum can be added, such that some tasks can be done in later operations.

The area of a sheet metal outside of a product-in face is called product-out face, which is divided into connecting features and corners (Fig. 7). The design of a product-out face focuses on how to facilitate restriking and bending operations. A product-out face can be divided into several parts and cams can be used to shape each part.

The case in this study considers product-out face as a feature (Fig. 8), and is adopted from the previous works (Tor et al., 2003; Zheng & Wang, 2007).

Factors are considered when designing a die face and cams are the existence of an undercut, area and length of the line connecting the product-out face to the product-in face, and the angle between the product-in face and the product-out face. Thus, this study uses these features to describe the product-out face. In some cases, undercut surfaces may be blocked

by the product-in face during stamping (Fig. 9). In such cases, cams should be utilized to change the direction of stamping forces to horizontal to form surfaces that are undercut.

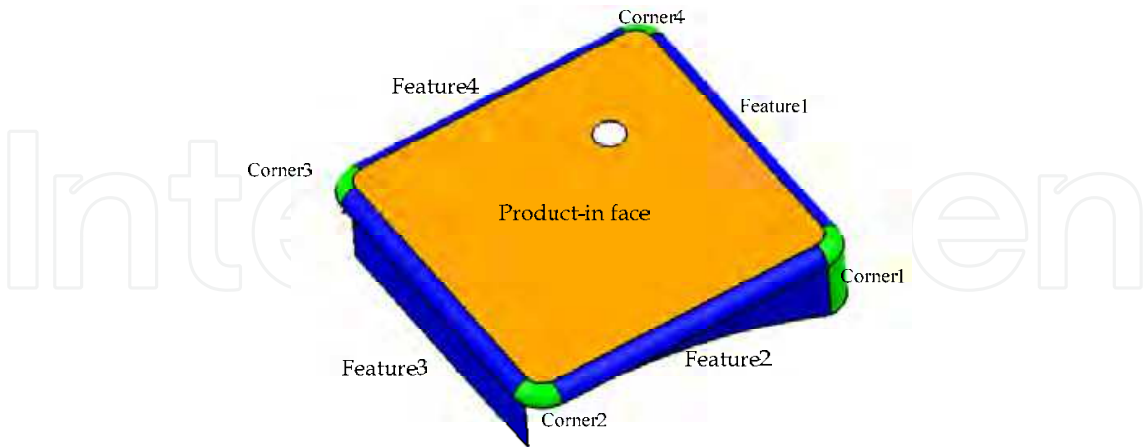


Fig. 7. Surface features on sheet metal

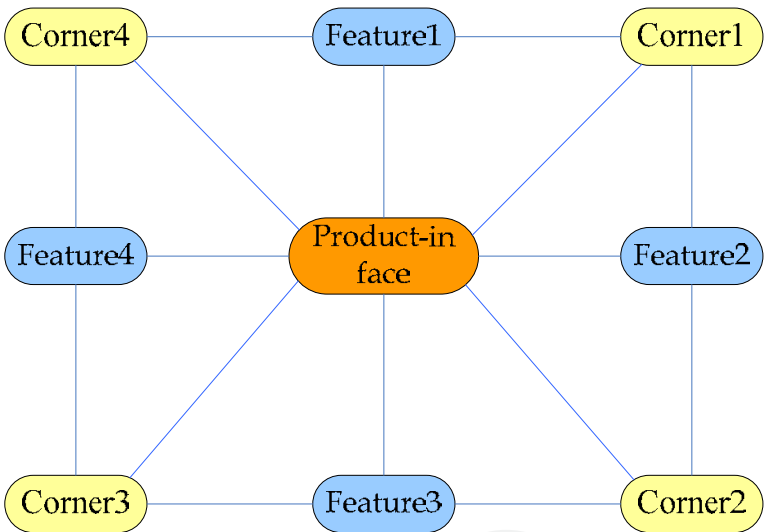


Fig. 8. Feature graph of sheet metal

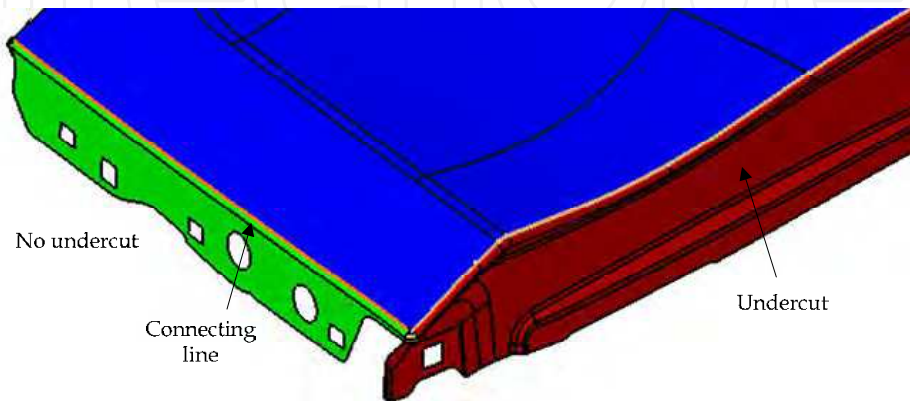


Fig. 9. Features on product-out face

2.2.2 Analysis of stamping direction

The most important drawing goal is to draw a raw metal piece into a desired high-quality shape. This quality is markedly affected by the orientation of stamping when the sheet metal panel is punched and is based on symmetry, equal-angle, and equal-depth not exceeding an appropriate value.

2.2.3 Binder design

To prevent sliding and wrinkling during drawing operations, a binder is used to hold the piston and upper mold. A binder should be the same height as the product-out face and be smooth and simple in terms of geometry. A binder has a straight line, a curved section, and different types of boundaries.

2.2.4 Addendum design

The shape of a sheet metal automobile panel is typically complex and irregular, resulting in difficulty achieving uniform forces on the die face during drawing operations. To solve this problem, an addendum is introduced that uses various section curves (Fig. 10) to make forces uniform. Additionally, the convenience of subsequent operations is also a concern and can affect the choice of section type.

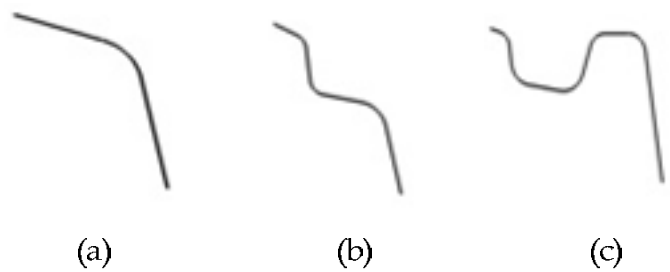


Fig. 10. Common section types

The design of an addendum requires determination of the trimming position, section type, and its size. Fig. 11 provides a detailed explanation of Fig. 10(b). A 3–5mm line is usually extended from the product-in face to avoid cracks from bending. An addendum is typically shaped like stairs to facilitate trimming. The bending angle of an addendum should be as small as possible.

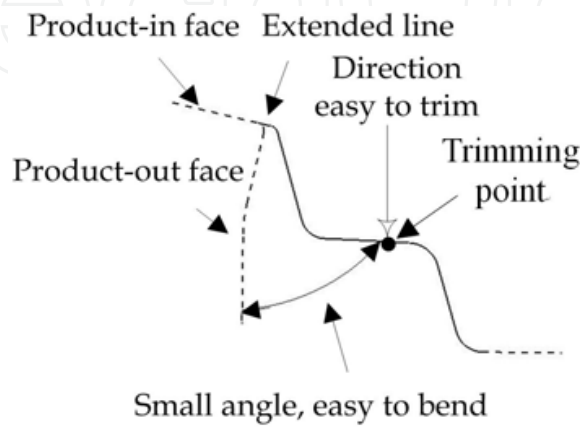


Fig. 11. Stair-like section curve

2.2.5 Addendum construction

Designers first construct the parting line as a limitation in subsequent design steps (Fig. 12). The addendum surface is then designed, which is composed of a section curve and connecting curve (Dy et al., 2008). The section curve determines how the addendum is shaped and is a concern for subsequent operations. The connecting curve connects section curves to produce a smooth surface. Finally, chamfer at the parting line.

When using programs to construct an addendum, the trimming point should lie on the trimming face and a connected curve along the shape of the sheet metal panel should be used to make its surface smooth. The design platform in this study is based on the SpringSolid system developed by the Solid Model Laboratory, National Taiwan University and written in Java.

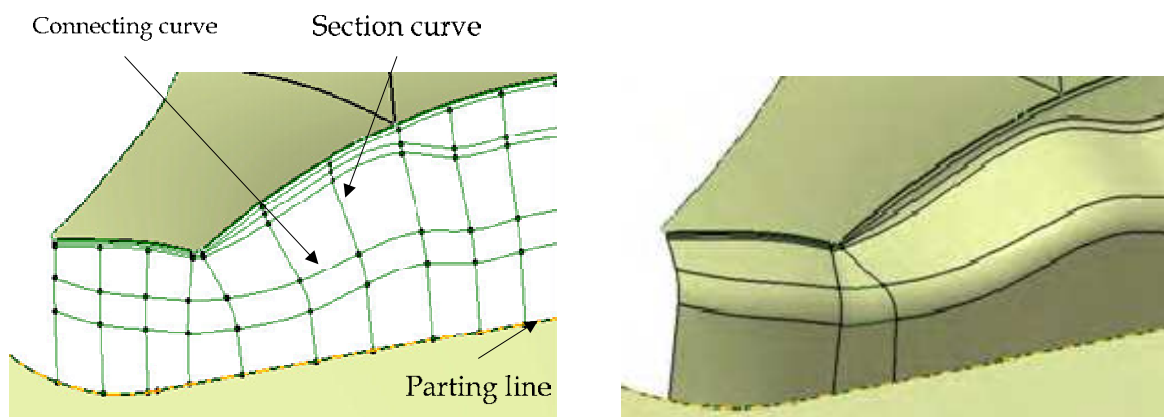


Fig. 12. Addendum construction

3. Knowledge-based engineering

Knowledge-based engineering (KBE) refers to the concept of a knowledge database applied in engineering that can be regarded as an intelligent system in a specific engineering field in which experts modularize product information and design processes to assist in product design. The design process is then stored for knowledge management. KBE is also combined widely with CAD/CAE/Computer-Aided Manufacturing (CAM) software for design, analysis, and manufacturing, respectively.

The KBE system is composed of a database and reasoning engine; the database stores related knowledge and assists in design via the reasoning engine.

Retrieval and case representation of knowledge are two crucial elements of a knowledge database. First, KBE engineers retrieve related knowledge from books, experts, and other resources, and record this knowledge using an appropriate knowledge representation. A representation should be able to store related knowledge in that field to enable a system to read and show that knowledge such that the knowledge can be provided to the reasoning engine.

3.1 Case-based reasoning

Fig. 13 shows case-based reasoning (CBR) operations. CBR compares cases in an analogue way. First, CBR compares a new case with cases in a case database and searches for the most similar case.

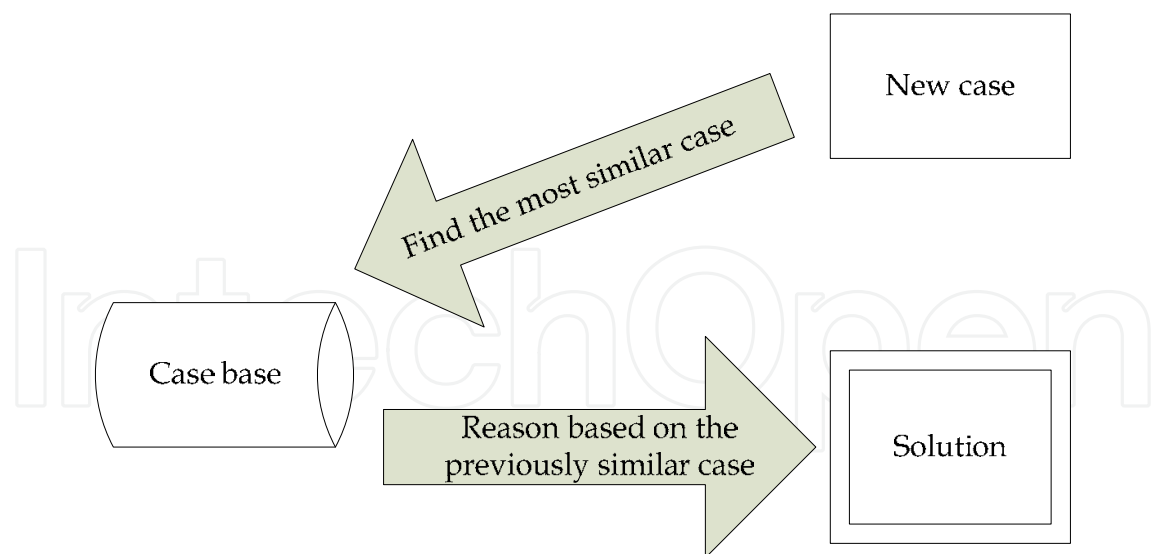


Fig. 13. Reasoning process of case-based reasoning

Typically, CBR has the following four procedures (4R) (Fig. 14):

- 1. Retrieve: After feature recognition of an automotive sheet metal panel, CBR compares the features with those in the case database, assesses the similarity among cases, and retrieves the most similar case as a reference for the design process.
- 2. Reuse: Designers can decide whether a retrieved case is appropriate for reuse and which manufacturing method should be a reference.

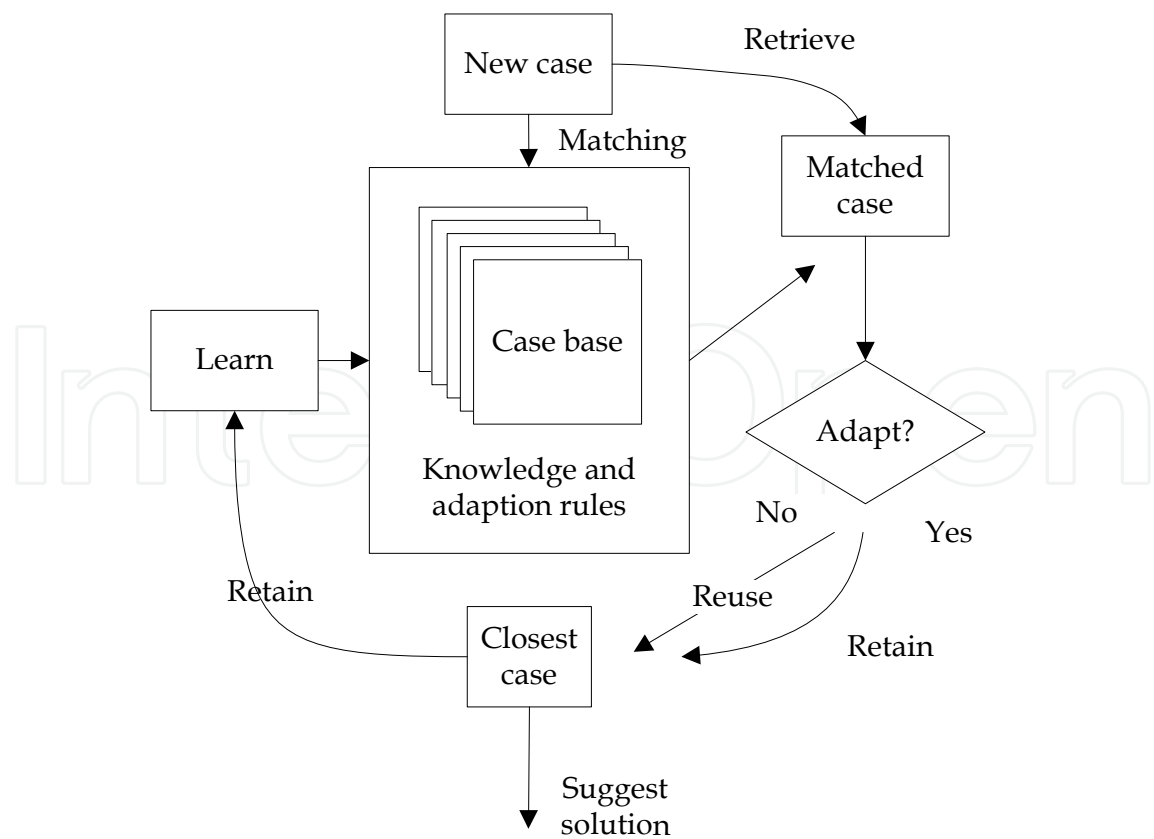


Fig. 14. The CBR cycle (Kendal & Green, 2007)

3. Revise: Based on the reuse assessment, designers revise the proposed solution when necessary.
4. Retain: The final assessment result for a stamping die design for an automotive sheet metal part for future reference is stored and reference cases are recorded.

Differing from rule-based reasoning, CBR does not require a set of explicitly defined mathematical models, rules, or logic. Thus, CBR is suitable for problems with general rules that cannot be systemized.

When comparing cases, algorithms (Watson & Marir, 1994; Tor et al., 2003) are used to assess similarity among cases, and CBR uses significant features to describe a case (Fig. 15), compares each case with given weights, and finally determines total similarity.

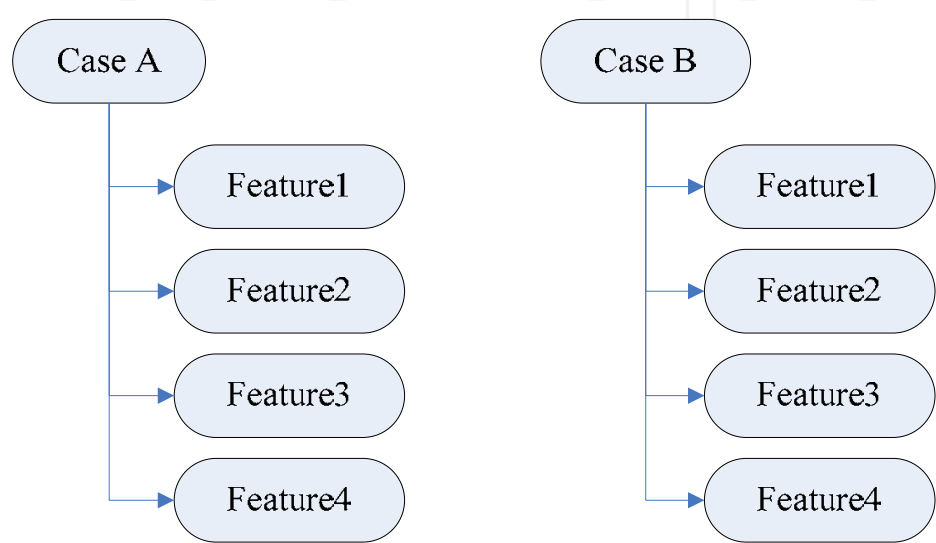


Fig. 15. Data structure of feature recognition

The algorithm for determines similarity is
$$S = \frac{\sum_{i=1}^n w_i \times s(f_i^A, f_i^B)}{\sum_{i=1}^n w_i}.$$

S : similarity between case A and case B, $0 \leq S \leq 1$

w_i : weight of each feature

f_i^A : the i^{th} feature of case A

$s(f_i^A, f_i^B)$: similarity between features f_i^A and f_i^B , $0 \leq s(f_i^A, f_i^B) \leq 1$

When features are represented numerically, the similarity between features f_i^A and f_i^B

would be
$$s(f_i^A, f_i^B) = 1 - \left| \frac{f_i^A - f_i^B}{\max(f_i^A - f_i^B)} \right|.$$

When features are represented non-numerically (e.g., Boolean value or textual description), similarity between feature f_i^A and f_i^B is $s(f_i^A, f_i^B) = 1$ if $f_i^A = f_i^B$; otherwise, $s(f_i^A, f_i^B) = 0$ if $f_i^A \neq f_i^B$.

3.2 Determining similarity of sheet metal panels

In this study, KBE and CBR are combined to provide designers with guidance from similar panels when designing a new panel.

Before comparisons, one should first define “similar” for two sheet metal parts. One approach (Tor et al., 2003) is to use part features, geometries, topologies, and materials to describe panels, meaning that this method compares the “appearance” of sheet metal parts. However, in this study, locating sheet metal panels that are similar in terms of manufacturing processes is more important than locating those with similar appearances. This is because sheet metal parts that have a similar appearance may be made with different manufacturing processes and, on the other hand, sheet metal parts that have different appearances may have similar manufacturing processes. For instance, two significantly different product-in face parts may have been shaped by the same drawing operation, meaning these differences do not guarantee differences in the manufacturing process. When comparing two sheet metal parts, the product-in face part should not be considered because it does not significantly affect manufacturing processes. However, the product-out face part significantly affects manufacturing processes. Thus, this study compares product-out face sheet metal parts to locate cases with similar manufacturing processes. The parts are compared using a cross-reference method to calculate similarity.

1. Cross reference

Each sheet metal part has uncertain number of product-out face areas. Take sheet metal parts A and B as an example; this study first cross-references each product-out face part (Fig. 16).

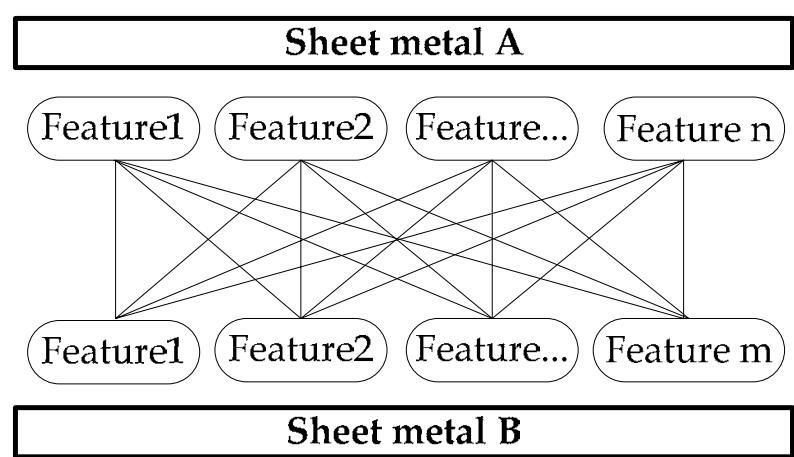


Fig. 16. Cross-reference between sheet metal A and B

Here, S_{ij} is defined as the similarity between the i_{th} product-out face area of panel A and the j_{th} product-out face area of panel B and $\begin{cases} 1 \leq i \leq n \\ 1 \leq j \leq m \end{cases}$. An $n \times m$ matrix can be derived as

$$\begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1m} \\ S_{21} & S_{22} & \cdots & S_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nm} \end{bmatrix}.$$

The maximum entry S_{ab} is then found and marked as S_1 and then $S_{a1}, S_{a2}, \dots, S_{am}$ and $S_{1b}, S_{2b}, \dots, S_{nb}$ are removed.

Next, the maximum entry S_{cd} among the $n-1$ pieces of product-out face parts of each sheet metal is found and marked as S_2 ; the entries that are similar to the c_{th} product-out face of A and those that compared with the d_{th} product-out face of B are removed. Eventually, each feature of product-out face A that matched those of product-out face B are found (Fig. 17)

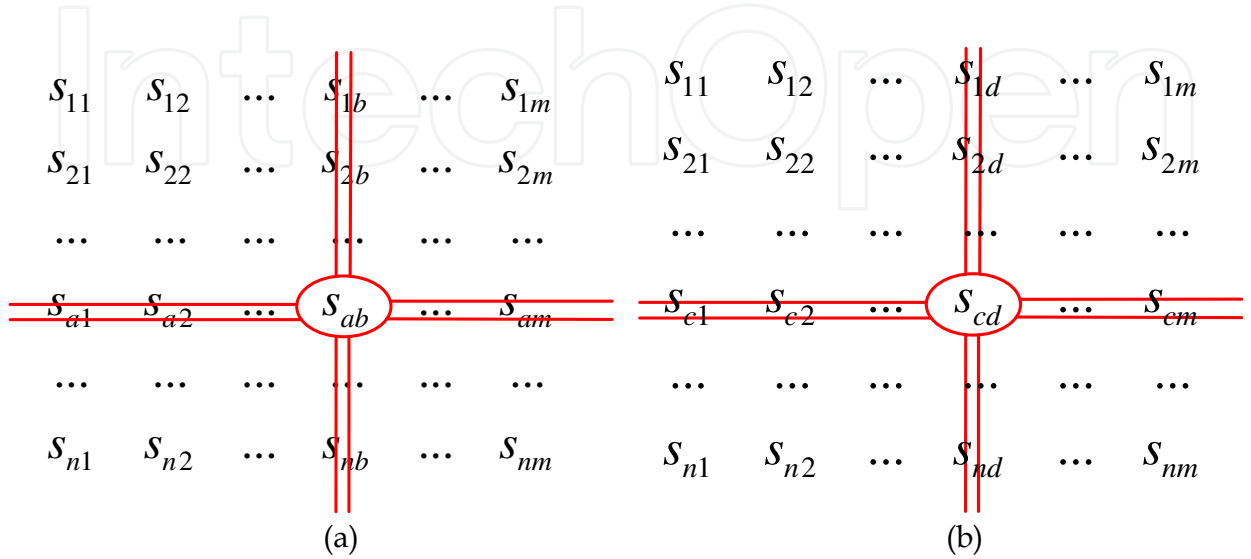


Fig. 17. Accessing similarities between features of A and that of B

This comparison is repeated, such that, S_3, S_4, \dots, S_m ($n \geq m$) can be derived and, finally,

the similarity between sheet metal A and B can be determined as $S = \frac{1}{n} \sum_{k=1}^m S_k$.

In this approach, when the numbers of product-out face areas differ ($n > m$) between sheet metal parts A and B, the maximum similarity is $\frac{m}{n}$. As the difference between n and m increases, the similarity between parts A and B decreases. If A and B have the same number of product-out face areas, maximum similarity is 1.

2. Similarities between product-out face areas

Table 1 shows the similarities between product-out face areas. In this table, f_1 is a non-numerical item representing the existence of undercuts. If both sheet metals parts have an undercut, then $s(f_1^A, f_1^B) = 1$; otherwise, $s(f_1^A, f_1^B) = 0$. Items f_2, f_3, \dots, f_6 are numerical ones

and their similarity is defined as $s(f_i^A, f_i^B) = 1 - \left| \frac{f_i^A - f_i^B}{\max(f_i^A - f_i^B)} \right|$. If one calculates the similarity

between each item with weights, overall similarity between two sheet metal parts is

$$S = \frac{\sum_{i=1}^n w_i \times s(f_i^A, f_i^B)}{\sum_{i=1}^n w_i}.$$

Similarity	Compared item	Data Type	Weight
$s(f_1^A, f_1^B)$	f_1 : the existence of undercut	Boolean	3
$s(f_2^A, f_2^B)$	f_2 : area ratio (product-out face to product-in face)	float	1
$s(f_3^A, f_3^B)$	f_3 : connecting line (the line that connect product-out face and product-in face)	float	1
$s(f_4^A, f_4^B)$	f_4 : angle (between product-out face and product-in face)	float	1

Table 1. Similarity of items of product-out face

3.3 Application of designing with case-based reasoning

Designing a die face is an art; that is, it is difficult to systemize. However, some sheet metal parts share common features, enabling reuse of similar cases to reduce design time.

Among all procedures when designing a die face, the most difficult task is designing the addendum part, which affects all operations and involves choosing an appropriate section type and size, and determining the position of trim points. All these tasks require tacit knowledge (Polanyi, 1958) and, thus, design time is considerable. Therefore, this study applies CBR to locate a similar case (Schenk & Hillmann, 2004) to accelerate design time.

This study combines CBR when designing a die face for a sheet metal panel with KBE (Fig. 18). To make the system flexible, the scale of reuse can be based on the degree of similarity between two sheet metal parts. If only a few features are shared, then only those features would be adopted; this is called local reuse. Conversely, if many similarities exist, then reuse can involve the entire addendum design; this is called global reuse.

The area or items that can be reused from previous cases are those that are difficult to design and their design is time-consuming. For a die face, only the addendum meets this criterion. The product-in face and product-out face parts are relatively easy to design and are not reused.

Two examples are used to demonstrate how local reuse and global reuse operate.

Fender B is an example of local reuse. After constructing its binder and the parting line of the die face, CBR is applied and the design of the addendum of, say, fender A is used to reduce design time. Due to the shape complexity of fender B, similarity is only for relatively small parts and, thus, only a small portion of the previous design is reused.

The procedures for reusing the design of fender A for fender B are listed as follows.

- Step 1.** Locate the most similar case – fender A (Fig. 19).
- Step 2.** Select a portion of the boundary of fender B that is similar to that of fender A (Fig. 20).
- Step 3.** Select the corresponding boundary of fender A (Fig. 19) and then apply it to the design of fender B. In this case, only the radius of chamfer, draft angle, and addendum design are reused. Other parts, such as the trimming line, are designed all over again.
- Step 4.** After reusing the design of fender A, a user can decide whether to adopt the reused design. The final reuse result is stored in a database for future reuse.

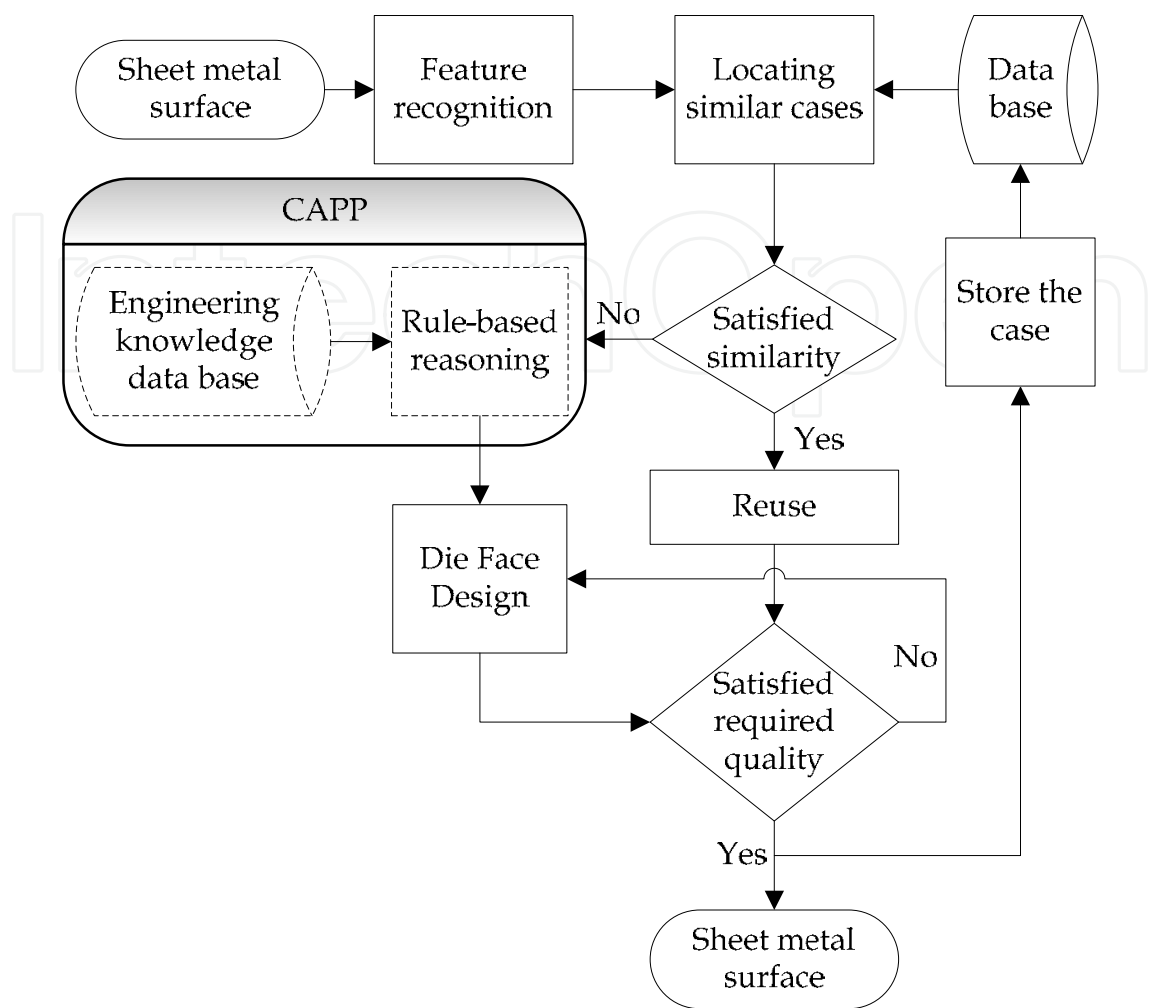


Fig. 18. Design process integrated with case-based reasoning

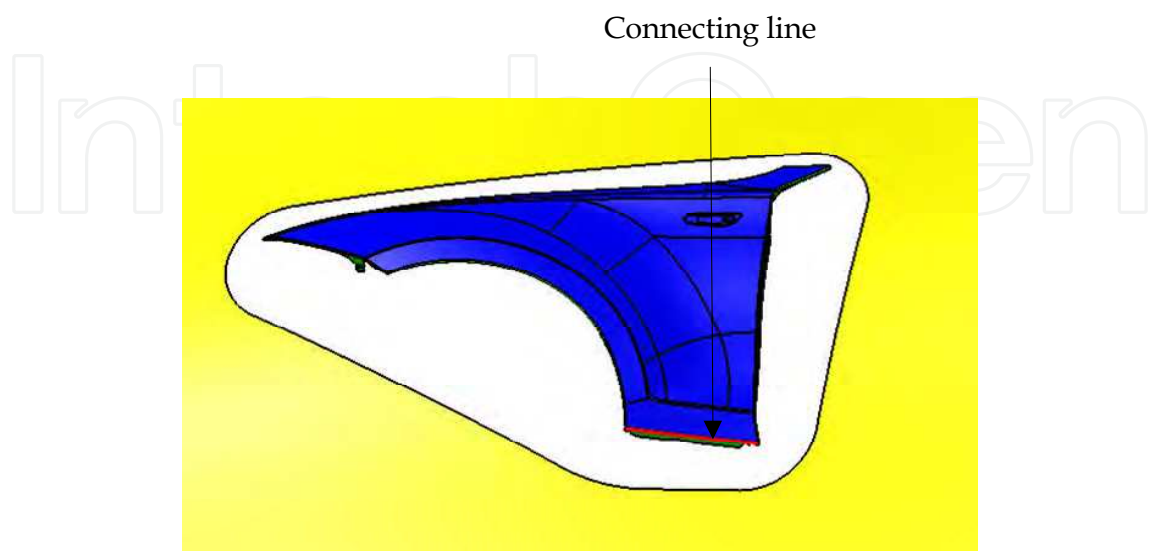


Fig. 19. Fender A

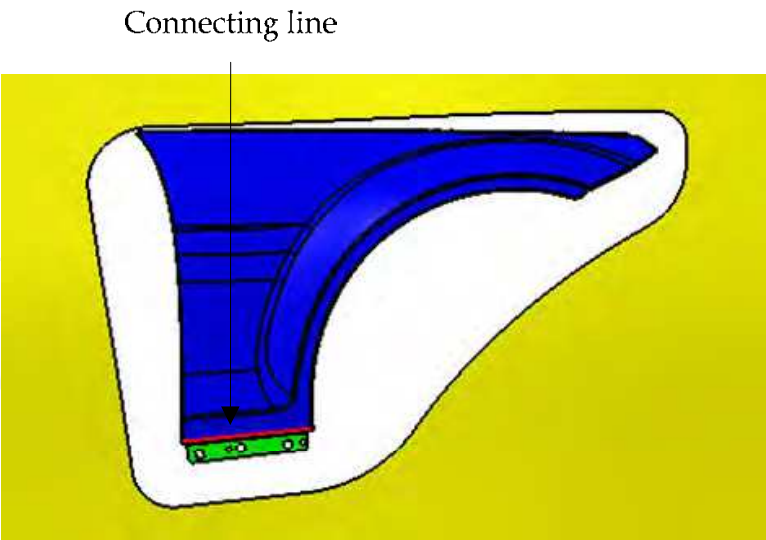


Fig. 20. Fender B

Fig. 21 shows the detailed explanation of addendum A. The reused parameters (Fig. 22) include the radius of section curve and the draft angle (Fig. 23); other parameters of, such as the addendum and trimming line, are new designs.

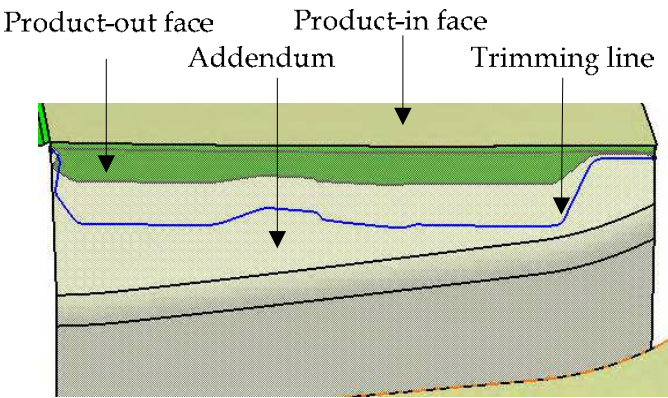


Fig. 21. Addendum of fender A

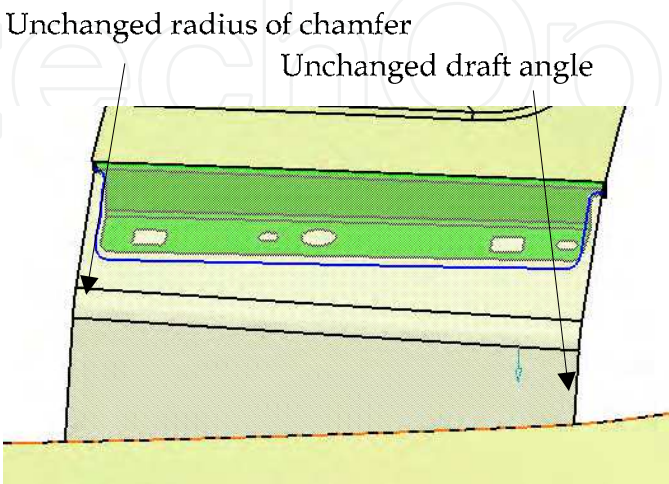


Fig. 22. Addendum of fender B that reused parameters of fender A

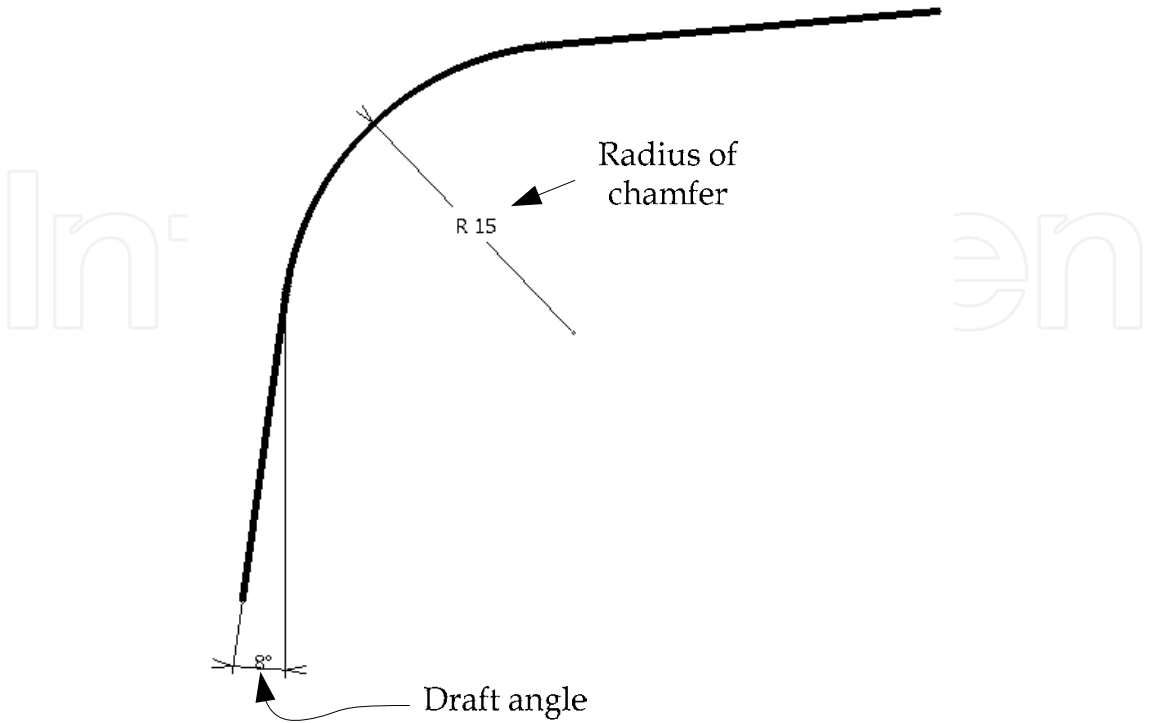


Fig. 23. The features that reused parameters of previous case

Take hood B as a global reuse example. Fig. 24-Fig. 27 show hood A and hood B and their section views. Considerable similarity exists between hood B and hood A; thus, many parameters of hood A are adopted for hood B such as type of the section curve, radius of chamfer, draft angle, addendum design, and trimming angle (Fig. 28).

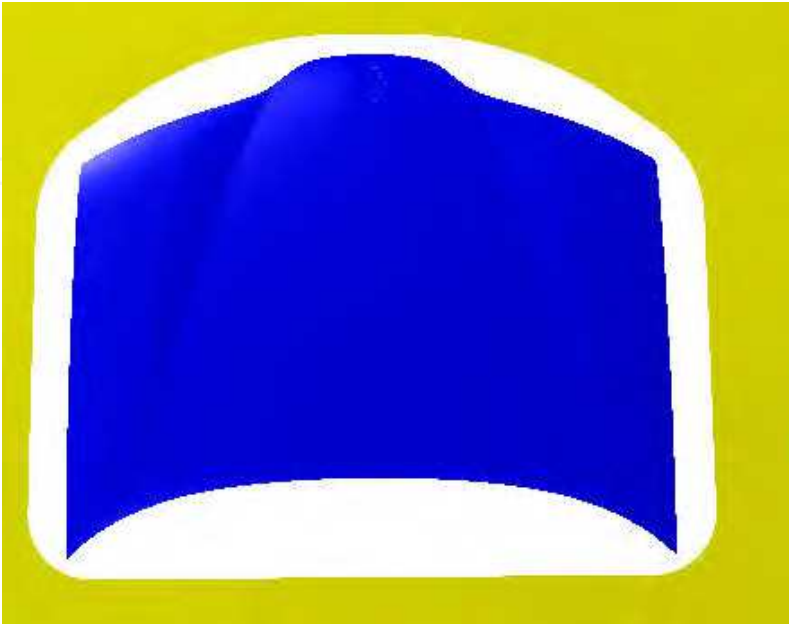


Fig. 24. Hood A

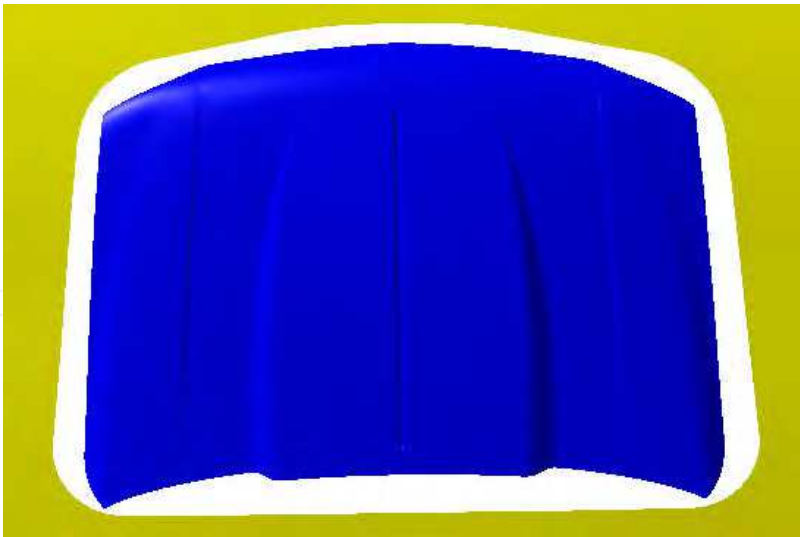


Fig. 25. Hood B

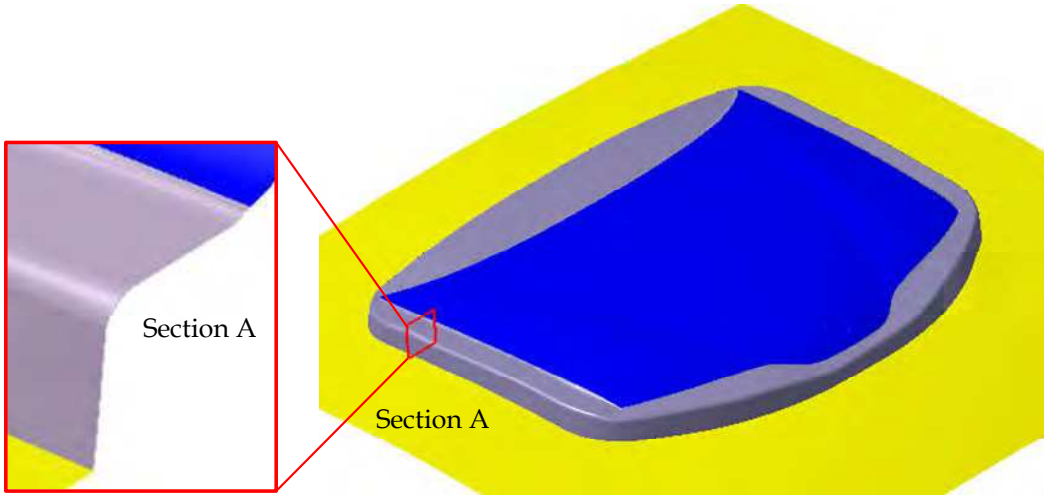


Fig. 26. Section view of addendum of hood A

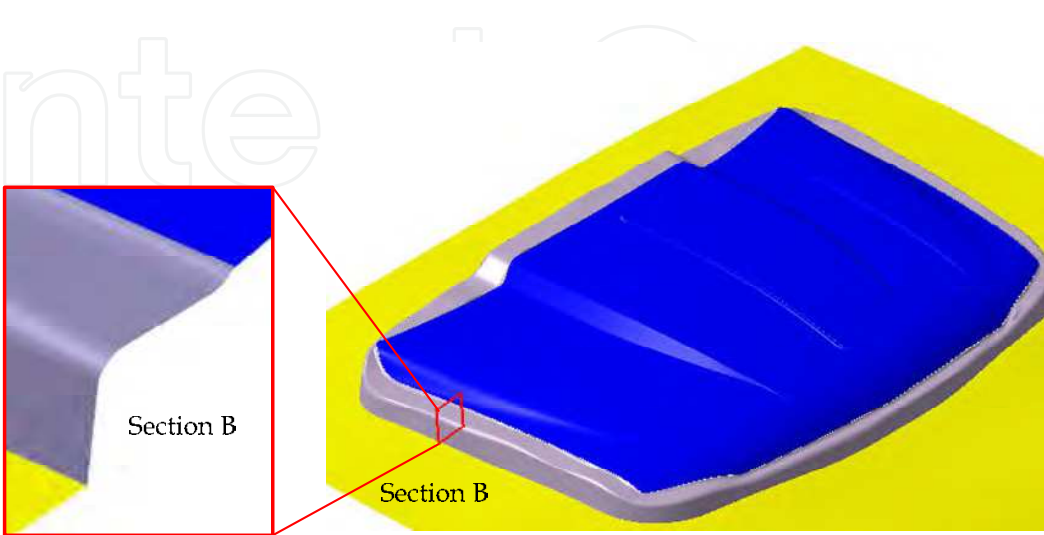


Fig. 27. Section view of addendum of hood B that reused parameters of hood A

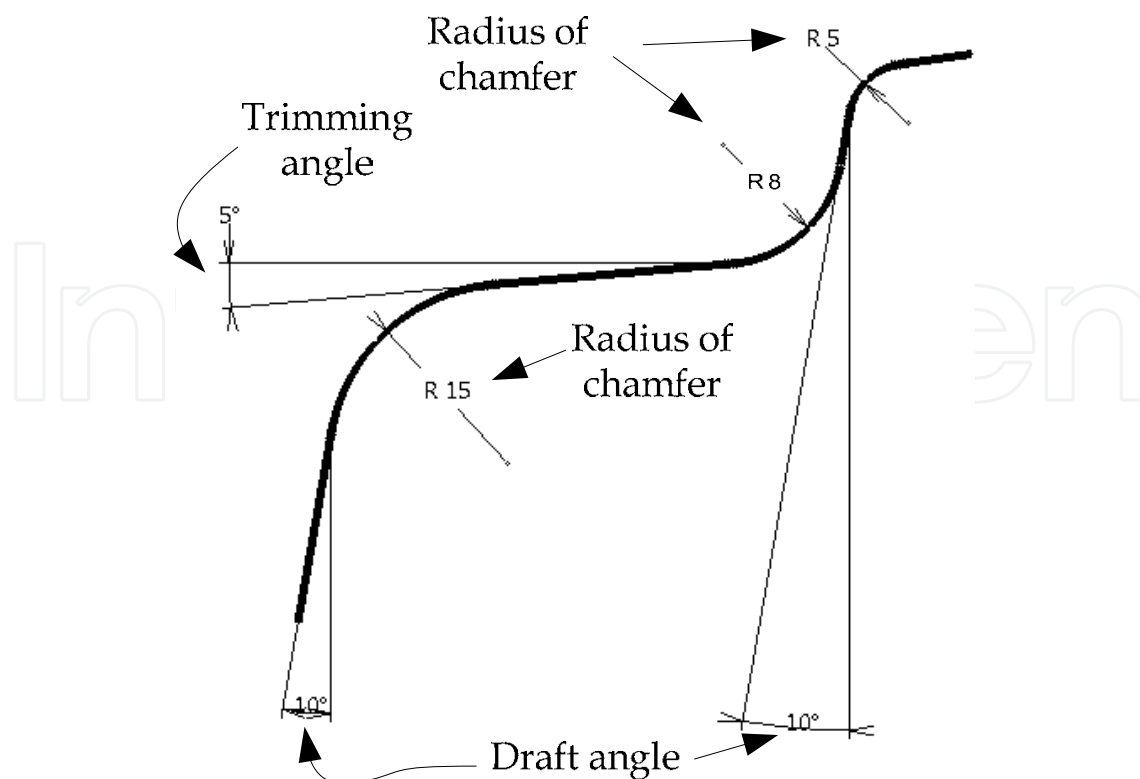


Fig. 28. The features that reused parameters of previous case

4. Conclusion and discussion

This study developed a framework in which KBE replaces the conventional method of designing a die face that relies heavily on designer experience and repeated trial and error, especially for addendum design due to the unpredictability of metal blank flow. With KBE techniques, designers can apply parameters from similar cases to a new case. In this study, feature recognition and case representation use features to describe cases and CBR compares features to determine their similarity.

The questions faced after integrating KBE into the design process of a die face is that, due to the geometric complexity of a die face, reuse may not be successful. Additionally, reuse relies heavily on retrieved cases from a case database, meaning that if previous cases are poor or the case database is biased, reuse is not desirable.

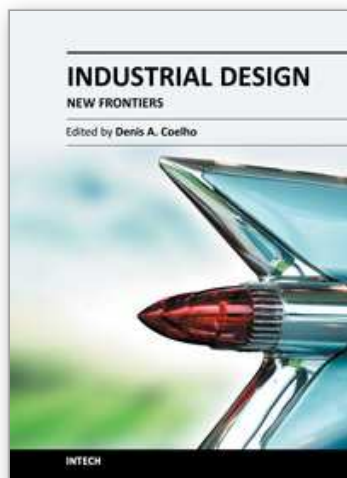
In the future, as the number of cases in the case database increases, CBR can search among an increasing number of possibilities to find the most similar case, resulting in desirable reuse. Furthermore, the reuse concept can be extended to the entire die design process, such that convenience for die designers can be increased.

5. Acknowledgement

The authors would like to thank the engineers of Gordon Auto Body Parts Co., Ltd. for their technical supports. Ted Knoy is appreciated for his editorial assistance. The authors would like to thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research under Contract No. NSC-100-2221-E-002-061-MY2.

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Industrial Design - New Frontiers

Edited by Prof. Denis Coelho

ISBN 978-953-307-622-5

Hard cover, 190 pages

Publisher InTech

Published online 09, November, 2011

Published in print edition November, 2011

A new breed of modern designers is on the way. These non-traditional industrial designers work across disciplines, understand human beings, as well as business and technology thus bridging the gap between customer needs and technological advancement of tomorrow. This book uncovers prospective designer techniques and methods of a new age of industrial design, whose practitioners strive to construct simple and yet complex products of the future. The novel frontiers of a new era of industrial design are exposed, in what concerns the design process, in illustrating the use of new technologies in design and in terms of the advancement of culturally inspired design. The diverse perspectives taken by the authors of this book ensure stimulating reading and will assist readers in leaping forward in their own practice of industrial design, and in preparing new research that is relevant and aligned with the current challenges of this fascinating field.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Chun-Fong You, Yu-Hsuan Yang and Da-Kun Wang (2011). Knowledge-Based Engineering Supporting Die Face Design of Automotive Panels, Industrial Design - New Frontiers, Prof. Denis Coelho (Ed.), ISBN: 978-953-307-622-5, InTech, Available from: <http://www.intechopen.com/books/industrial-design-new-frontiers/knowledge-based-engineering-supporting-die-face-design-of-automotive-panels>

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