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Automatically extracting sheet-metal features from solid model

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Abstract: With the development of modern industry, sheet-metal parts in mass production have been widely applied in mechanical, communication, electronics, and light industries in recent decades; but the advances in sheet-metal part design and manufacturing remain too slow compared with the increasing importance of sheet-metal parts in modern industry. This paper proposes a method for automatically extracting features from an arbitrary solid model of sheet-metal parts; whose characteristics are used for classification and graph-based representation of the sheet-metal features to extract the features embodied in a sheet-metal part. The extracting feature process can be divided for valid checking of the model geometry, feature matching, and feature relationship. Since the extracted features include abundant geometry and engineering information, they will be effective for downstream application such as feature rebuilding and stamping process planning.

Key words: Sheet-metal part, Feature extraction, Feature representation
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INTRODUCTION

With the development of modern industry, mass produced sheet-metal parts have been widely applied in mechanical, communication, electronics, and light industries in recent decades. Statistics showed that in the US, some 100 000 metal stampings could be found in the average American home in the 1980s (Cheok and Nee, 1998). In Singapore, the manufacturing sector contributes more than 25% to the GDP or a Total Gross Value of more than US$24 billion (Tan, 1993). In China, the Gross Value of electronic components and devices produced from sheet-metal parts totals to more than US$2 billion and the cost for importing sheet-metal part products will exceed US$100 million in 2005 (Ji, 2000). Nevertheless, the advances in sheet-metal part design and manufacturing remain too slow compared with the increasing importance of sheet-metal parts in modern industry. To satisfy the increasing requirement, the main technology that is adopted to improve competence of design and manufacturing for sheet-meal parts is CAD/CAM.

In recent decades, general computer aided design tools, such as Pro/Engineer, UG, CATIA, Ideas, Inventor, etc., are widely utilized in stamping industries to speed up stamping die design. Because of the specialty of stamping die design, these general CAD/CAM systems do not make any significant changes expected by stamping companies. Special designed CAD systems for sheet metal production are then developed based on those general CAD/CAM software packages. Striker System, UGS/Progressive Die Wizard, HMCAD, etc., to some extent, have gained approval from some stamping companies. All these software are built based on their special languages, known as sheet metal features, for describing the sheet metal products. In the stamping industry, the customers and suppliers often use different CAD tools which speak different languages. For the purpose of exchanging engineering information that can be passed to CAPP systems for the process planning between different CAD systems, neutral file formats such as STEP and IGES are employed. The translation from sheet metal feature model to neutral model results in the loss of all the engineering information crucial for the downstream design process.

How to deal with this neutral model and make it acceptable to those special CAD systems, manually rebuilding the model is an alternative solution, but the process is so time-consuming and expensive that it becomes the bottle-neck for those sheet metal feature based CAD software. Feature extraction is such a tool for extracting features from arbitrary solid model created with any types of CAD tools and rebuilding the feature model automatically and effectively. Nevertheless, feature extraction is still far from being used in sheet metal design.

The main objective of this paper is to reveal how sheet-metal features are extracted from solid model. To extract features, sheet-metal features are sorted, then represented with diagram structure. Extracted features can thus be used to rebuild the feature model directly.

In the next paragraph, works on feature extraction are reviewed. The algorithms of extracting features are discussed, and the implementation and case study is presented. The last chapter presents the conclusion reached and outlines the research prospect.

LITERATURE REVIEW

Since the seminal work of Kyprianou (1980), feature extraction has become the subject of research.

Woo (1982) developed a decreasing convex-hull-decomposition algorithm to extract removal volumes for machining from a 3D solid model. For the purpose of part classification and coding, Kyprianou (1980) developed a shape feature recognizer from a boundary representation of a solid model. Then Han and Aristides (1998) built an IF^2 system for generating machining feature models of mechanical parts, used information available in the nominal solid model of a part, design features, tolerances and attributes, and so forth. Liu and Liu (2002) proposed a methodology for abstracting features from a 3D solid model based on a detail-level metric method.

Gavankar and Henderson (1990) tried to isolate protrusions and depressions from boundary models; their work involved identification of faces with multiple edge loops as candidates for entrance faces of such features. The feature extracting method did not apply to blind holes and pockets which open up into more than one face. This is because such features do not exhibit a unique entrance face which can be identified as a cut node.

Der-Baau *et al.*(1990) proposed a method for automatically extracting the machining features from 3D CSG solid input. The method involved converting a part’s CSG tree representation into its equivalent DSG tree representation and then identifying the types of machinable features from the DSG tree.

Prabhakar and Henderson (1992) used the principles of neural networks to achieve form-feature recognition. They developed an algorithm for recognition using neural-net-based techniques, and a suitable net architecture, which is similar in function to the multiple player perception for whose implementation an algorithm was designed, but the domain of the recognizer is limited to features that can be defined in terms of one primary feature face and a set of secondary feature faces. Incorporation of conventional training algorithms such as back propagations still needs to be done.

Hlentz and Sowerby (1993) outlined an algorithm for the extraction of regions that have the properties of the general concave and convex features of a sheet-metal component from a CAD B-rep model.

Achievements in feature extraction researches are reported worldwide, but the main works are focused on machining features. Not much research on sheet-metal parts has been reported.

Agarwal and Waggenspack (1992) presented an algorithm for the automatic derivation of the surface topologies of a 3D volume from its wireframe representation of sheet-metal part. This fundamental approach overcomes the limitations of the currently known methods and it relaxed the restriction to manifold solids without holes. They decomposed the general wireframe model of sheet-metal parts into a set of simple wireframes with the use of a topology-based subdivision strategy.

Devarajan *et al*.(1997) presented an approach to extracting contour features in sheet-metal parts by generating the offset of the contour. They proposed a tool mapping algorithm based on medial axis transformation. Since stamping is assumed to be the method of manufacturing, feature-tool mapping involves identifying the punch which can stamp the feature.

Jagirdar *et al*.(2001) used a wireframe model to identify shearing features for 2-D sheet-metal components from the CAD database. They initially proposed a new classification system for press-working features and shearing operations. Based on this classification system, a set of principles was developed for identifying shearing features using set theory and diagram-based approach. Jagirdar *et al*.(2001) presented a new classification system for forming operations, and concepts for extracting forming features from the 3-D sheet-metal component created in a wireframe model.

Available literature revealed that researches in the area of extracting features for sheet-metal parts have not advanced significantly. Literature on feature extracting for sheet-metal components indicated that academicians and researchers used solid modeling for feature extraction; but that they converted the component into a foil type by neglecting their thickness, and then identified the pressworking features (Jagirdar *et al*., 2001). Besides, the result of feature extraction cannot be used in automatic feature rebuilding, which was the main reason why feature extraction system cannot be widely used in industry (Bridarrat *et al*., 1998).

FEATURES OF SHEET-METAL PARTS

The design and manufacture of sheet-metal parts generally involve feature modeling, stamping process planning, die design and stamping manufacturing in a single setup. Feature modeling is the first and basic stage, which is also the most important. Sheet-metal parts are different from other types of parts; and are generally fabricated by forming, bending, blanking, etc. A kind of stamping process can only form a class of specific shape sheet-metal part. Stamping process design should take into consideration the working procedure of features in sheet-metal parts. Therefore, sheet-metal parts should be analyzed and compared so that the shapes which are similar in geometry can be classified to automate the stamping process planning.

Classification of sheet-metal features

In order to provide meaningful information for stamping process planning of sheet-metal parts, the feature definition of sheet-metal parts is given below.

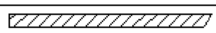
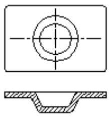
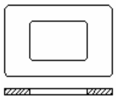
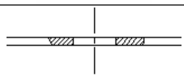
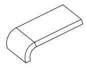
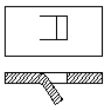
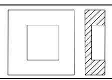
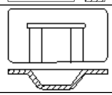
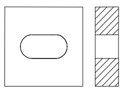
Definition 1 A sheet-metal feature is a 3D geometric shape that can be manufactured by one or more specific stamping operations.

From the definition, a feature should contain two kinds of information. One is engineering information related to the stamping processes. The other is the geometric description of feature shape, which includes all edges, faces and bodies.

Engineering information varies with different types of features. For example, a Hole feature should include the diameter, while a Drawing feature should include die radius, punch radius and taper angle. Some typical features based on the characteristics of sheet-metal parts are illustrated in Table 1.

For the benefit of managing the sheet-metal features and their relationships, a hierarchical structure is introduced to represent the sheet-metal parts. The features' classification scheme introduced here is based on how much information it should carry and what kind of information it carries. Hence features of sheet-metal parts are divided into two categories, cellular features and composites, as shown in Fig.1.

Table 1 Typical sheet-metal features

Feature type	Section of the feature
Wall	
Drawing	
Bending	
Cutout	
Hole	
Flange	
Lancing	
Coining	
Bridging	
Slot	

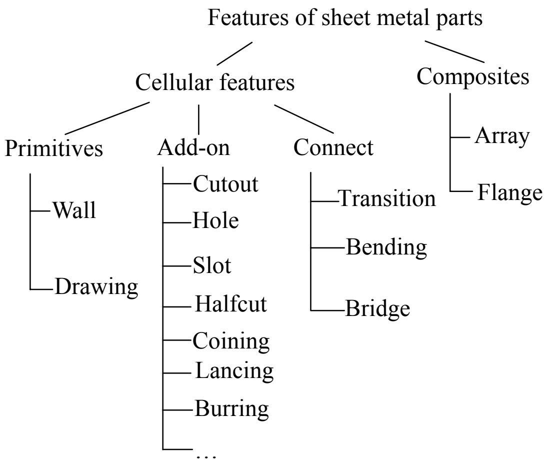


Fig.1 Classification scheme of sheet-metal features

Definition 2 Cellular feature is a 3D geometric shape that is associated with one (or more) shape class(es). In the feature model, the part could be seen as an assembly of volumetric quasi-disjoint cells (feature entities) other than a boundary represented solid (Li *et al*., 2001).

In terms of the definition, cellular features are basic features forming the sheet-metal part, while composites are features integrated as a whole by other kind of cellular features.

Cellular features can be further divided into three sub categories, Primitives, Add-ons and Connects. Primitives are features that can exist in sheet-metal part independently, Add-ons are features that must be added to other features to form sheet-metal part, Connects are features acting as a bridge between different types of features (Li *et al*., 2001).

Diagram-based representation

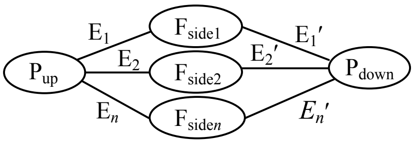
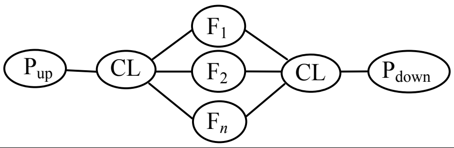
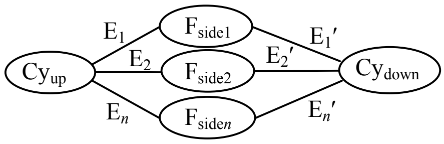
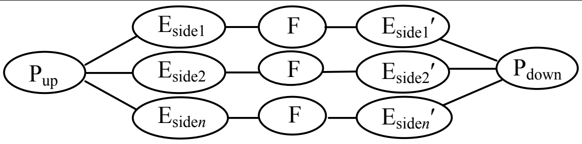
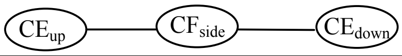
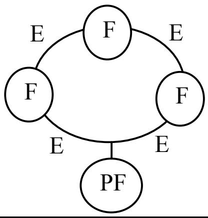
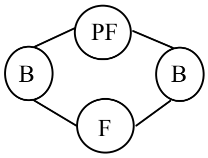
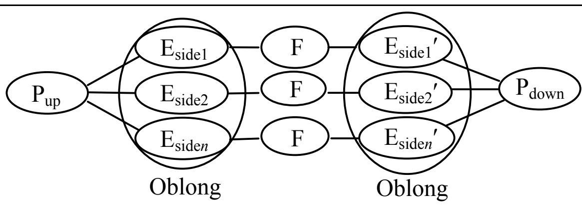
The procedure of extracting features is to match the geometry shapes of the sheet-metal part with the feature library. Therefore, features in the feature library should be pre-defined. In Table 2, sheet-metal features are described based on diagram. The purpose of this representation is to use the topological properties of a certain class of shapes to facilitate their extraction from a solid model.

Besides the above features, there are still some other features that cannot be described by one diagram. For example, if the Cutout feature gets across multiple features, the diagrammatic representation is different. As illustrated in Fig.2, P means Planar, B means Bending, F means adjacent face. In case 1, the Cutout feature gets across two Wall features and one Bending feature; and in case 2, the Cutout feature gets across one Wall feature and one Bending feature, therefore, their diagram representations are totally different.

EXTRACTING FEATURES FROM SOLID MODEL

To constitute a feature model, the user can either use the method of adding features one by one according to the given drawings or 3D model, or, automatically rebuild the feature model from the extracted features. Obviously, the method of feature extraction is more efficient. The feature extraction process can be divided to validity checking

Table 2 Diagrammatic representation of features

Feature type	Diagrammatic representation of feature	Meaning of parameters
Wall		E: Edge P: Planar face F_{side}: Side Face
Drawing		P: Planar face CL: Closed loop F: Face
Bend		E: Edge Cy: Cylinder face F_{side}: Side Face
Cutout in single feature		P: Wall feature E: Edge F: Face
Hole		CE: Circular edge CF: Cylinder face
Coin		E: Edge F: Face PF: Planar Wall
Bridging		F: Wall feature B: Bend PF: Planar face
Slot		P: Wall feature E: Edge F: Face

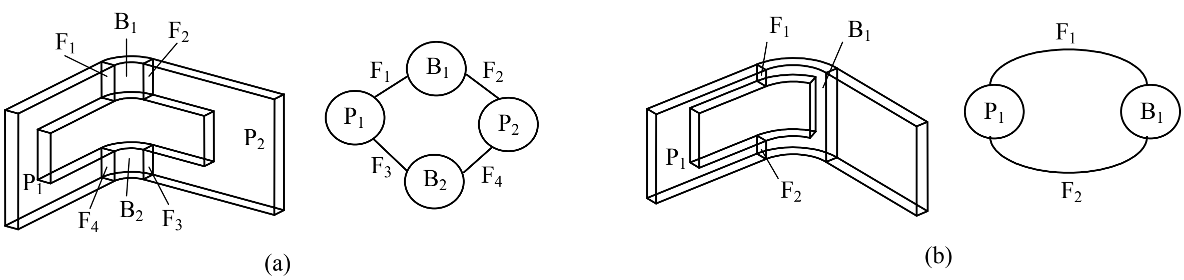


Fig.2 Special diagrammatic representations for Cutout (a) Case 1; (b) Case 2

for the geometry model, feature matching and constituting of the feature relationship diagram.

Validity checking for the solid model

Before feature extraction, the solid model should be checked to ensure it is valid. Sheet-metal parts are generally fabricated by forming, bending, blanking, etc. Therefore, features are jointed smartly, i.e. two Wall features must be connected by one Bending feature, otherwise, it is unacceptable to the stamping process planning. In some solid models, Wall and Wall, or Wall and Cutout are connected directly, as in Fig.3a. In this case, the solid model must be modified, as in Fig.3b.

When the solid model is transferred from other CAD model, isolated faces or edges may occur, as in Fig.4. In this case, the face or edge should be marked, so that it will not be wrongly extracted in feature extraction.

Matching sheet-metal features

Fig.5 presents a flow chart describing the feature extracting process. The input module can accept all kind of solid models that can be translated to IGES or STEP format.

To begin extracting features, a planar face on a Wall of the part should be pre-defined. From this face, its pair face belonging to the Wall feature is searched by comparing rules with the feature library. This Wall feature can also be named as Base feature. In the Wall feature that has been extracted, there may be some children features which satisfy the following conditions:

(a) $FE_i \cap FE_j = L_k$, and (b) $FE_i = \{F_i, E_i\}$

where FE is a feature, L is a closed loop, F is a face and E is an edge.

Different types of children features have different geometry shapes, a Hole can be determined as:

$$FE_{\mathrm{Hole}} = \{N_{\mathrm{L}}=1 \cap T_{\mathrm{L}}=CIRCLE \cap H_{\mathrm{L}}=H_{\mathrm{B}}\} \quad (1)$$

where N is the number of loop, T is the type of loop, and H is the thickness of the loop face.

And a Slot can be determined by:

$$FE_{\mathrm{Slot}} = \{N_{\mathrm{L}}=3 \cap T_{\mathrm{L}}=CIRCLE \cap H_{\mathrm{L}}=H_{\mathrm{B}}\} \quad (2)$$

If a feature does not satisfy Eqs.(1) and (2), but has the attribute:

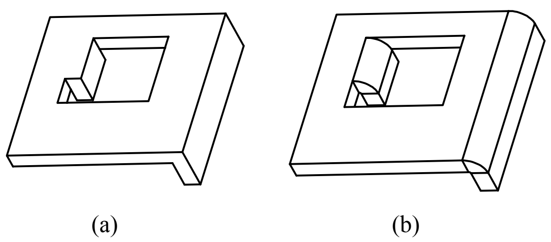


Fig.3 Model for sheet-metal part
(a) Invalid solid model; (b) Modified model

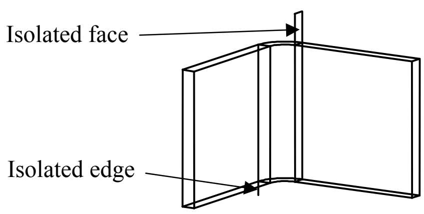


Fig.4 Isolated edge and face in solid model

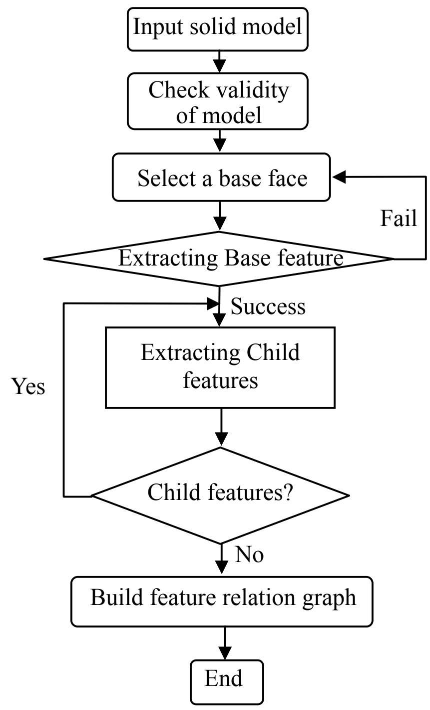


Fig.5 Flow chart describing the feature extracting process

$$FE_{\text{Cutout}}=\{N_L>1\cap T_L=CIRCLE\cap H_L=H_B\} \quad (3)$$

This feature can be classified as Cutout feature.

Bending feature can be adjacent to a Wall feature or a Cutout feature. If a feature satisfies the following conditions, we call it a Bending feature:

$$FE_{\text{Cutout}}=\{FE_i\cap FE_j=F_k,\ F_i//F_j,\ F_j=CYLINDER,\ R_{\text{inn}}>0\} \quad (4)$$

where R is radius.

By such matching and searching method, features in sheet-metal part can be extracted one by one.

During the extraction procedure, there may be some very complicated features that failed to be extracted. We consider these features as unrecognized feature. And they need to be extracted manually. In the automatic feature extracting model, 80% of the feature types can be extracted. Since the other 20% seldom existed in the sheet-metal part, the procedure of feature extraction system is relatively effective.

(1) Extracting algorithms of some typical features

In the procedure of feature extraction, different types of feature have different feature-matching algorithms. Extracting cellular features is relatively simple, while Composites extraction is much complex. Some cellular features like Cutouts' multiple features are also very complicated. Some typical features' extracting algorithms are discussed below. To record the engineering information of the features, User Define Object (UDO) is employed. UDO is an independent data structure existing in the feature model. Each feature has geometry and engineering information, which is connected by a CLASS_ID in the model data.

(a) Extracting Wall and Bending

Walls and Bendings are the basic features making up the sheet-metal part. Since the sheet-metal part is manifold, all the faces composing Walls and Bendings are connected smoothly. The extracting algorithm steps are:

i) Given a face F_1 (planar or cylinder face);

ii) Judge the type of F_1, if type=PLANAR, then add Wall attribute to it, else add BEND attribute to UDO list;

iii) Search F_1's pair face $F_1'=\{F|F$ is parallel with F_1 and $Ff(i)=-Df_1\}$, if it matches Wall or Bending rules, then add information of F_1' to UDO list;

iv) Record information of thickness, Bending's radius and location to UDO list.

(b) Extracting Hole, Slot and Cutout in single feature

Holes, Slots and Cutouts are local features which must be added to Wall, Bending, or Drawing. An algorithm consisting of the following steps is used to search the features:

i) Given an inner loop L_1 in a face;

ii) Judge the type and edge number of L_1, if number=1 and edge type is circle, then add HOLE to UDO list, else if the loop is like an oblong, then add SLOT to UDO list, else add CUTOUT to UDO list;

iii) Search faces including L_1, if the faces are connected to a closed loop, add faces information to UDO list;

iv) Record information of thickness, location, etc. in UDO list.

(c) Extracting Array

An Array is the concourse of two or more Holes, Slots or Cutouts, normally is located on a Wall feature. The extracting algorithm for array features consists of the following steps:

i) Given a group of Holes, Slots or Cutouts Group1 in one Wall;

ii) Check the relations among Group1, extract members of the Group1 that match array library, and add them to UDO list;

iii) Delete single member information from UDO list;

iv) Add ARRAY to UDO list.

(d) Extracting Cutout throughout multiple features

In sheet-metal part, there are probably some Cutouts with multiple basic features as shown in Fig.6.

Cutout2 passes through Base0, Bending1 and Wall3, so the three features constitute a closed loop.

According to the rule defining the Cutout feature, this loop is a Cutout feature, whose heuristic extracting algorithm is as follows:

i) Select a face F_1;

ii) Ask F_1's adjacent faces Adjacent_faces;

iii) Search its adjacent face $F_i=\{F_i|F_i$ is adjacent to F_1, and F_i is not member of $FE_b\}$;

iv) Select an F_2 from Adjacent_faces;

v) Repeat ii) and iii), add the faces to Adjacent_faces;

vi) Check the last searched face F_n, if $F_n \cap F_1 = Edge$, then add F_n to Adjacent_faces; and

vii) Add engineering information such as CUTOUT type of feature and father feature to UDO list.

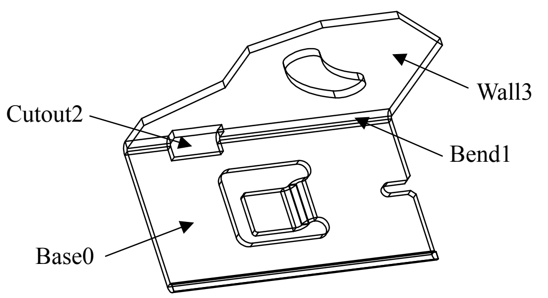


Fig.6 A sheet-metal part that has a Cutout throughout multiple features

(2) Feature merging and decomposing

During the feature extracting procedure, some features which are not acceptable to the following stamping process planning may be extracted. In this case, these features should be edited. In Fig.7, there are two sheet-metal parts.

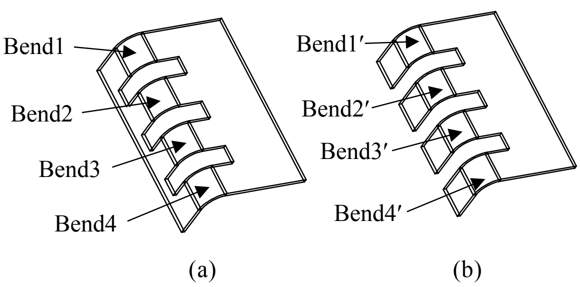


Fig.7 Case of feature merging and decomposing
(a) Bendings that should be merged;
(b) Bendings that should not be merged

In Fig.7a, four Bendings are extracted by the methods mentioned above, but obviously, in a real feature model, they constitute one Bending feature. In this case, we must merge the four Bendings.

Merging Bendings should satisfy:

i) $B_1 \cup B_2 \cup B_3 \cup \ldots = FE_{\mathrm{Wall}}$;

ii) $AXIS_1 = AXIS_2 = AXIS_3 = \ldots$;

iii) $DIR_1 = DIR_2 = DIR_3 = \ldots$;

iv) $B_1 \cap B_2 = CUTOUT_1$; $B_2 \cap B_3 = CUTOUT_2$; $B_3 \cap B_4 = CUTOUT_3$; …; and

v) $CHILD_{B1} = CHILD_{B2} = CHILD_{B3} = \ldots$.

where FE_{Wall} is a Wall feature, $AXIS$ is the Bend's axis, and $CHILD_{Bi}$ is the Bi's child feature.

According to the above conditions the four Bendings should be merged into one Bending, and the feature UDO list should also be modified. But in Fig.7b, if Bending$_1'$, Bending$_2'$, … are extracted as single Bending, the hollow parts among the Bending features may be erroneously extracted. In this case, the features should be decomposed. Bending feature that should be decomposed must satisfy the following conditions:

i) $CF_1 \cup CF_2 \cup CF_3 \cup \ldots = FE_{\mathrm{Bending}}$;

ii) $AXIS_1 = AXIS_2 = AXIS_3 = \ldots$;

iii) $R_{CF1} = R_{CF2} = R_{CF3} = \ldots$;

iv) $LR_B - (LR_1 + LR_2 + LR_3 + \ldots) = NULL$;

v) $B_1 \cap B_2 = NULL$; $B_2 \cap B_3 = NULL$; $B_3 \cap B_4 = NULL$; …; and

vi) $CHILD_{B1} = CHILD_{B2} = CHILD_{B3} = \ldots$.

where FE_{Bending} is the Bending feature, CF is cylinder face, R_{CFi} is radius of CF, LR is the length of each sub Bending.

Constituting feature relation diagram

To simplify the relationship among the features, we classify the relationships as parent-son, adjacent-on and array-on. Parent-son relation means that a feature is another feature's son feature, Adjacent-on means that a feature is adjacent to another feature, and Array-on means that some features that have the same geometry and engineering information are arrayed on one feature. In Fig.8a, Bending2 is adjacent to Base0, Wall4 is adjacent to Bending2, and Hole3 is Wall4's child feature.

The feature relationship is often described by a diagram structure, and we call this diagram structure as feature relationship diagram. The feature adjacency diagram is a diagram structure in which a node and an edge represent a feature instance and a feature relationship, respectively, as shown in Fig.8. In Fig.8b, a solid arrow represents a parent_son relation and a dotted arrow represents a feature adjacent-on relationship. If a feature F_i is positioned on the feature of F_j, F_i is a child of F_j. An adjacent relationship exists in the following two cases, where ∂F_i is the boundary set of F_i and $\cap^*$ is the regularized Boolean intersection:

(1) $F_i \cap^* F_j \neq \Phi$, or

(2) $F_i \cap^* F_j = \Phi$ and $\partial F_i \cap^* \partial F_j \neq \Phi$.

The first case is called volumetric interaction and the second is called adjacent interaction.

IMPLEMENTATION

The feature extracting system is implemented by using object-oriented modeling principles and C++ programming language based on the platform of UGNX2.0, as shown in Fig.9a. In the system, all extracted features are listed in the left item list, the correlative features (father, children, and array) are listed in the right item list. For instance, Hole1 has eight array features (Hole2, Hole3, …) and one parent feature Base0. The parent of Bend13 is Base0, and its children, Wall16. Buttons in the bottom part can be used to edit the extracted features. All the extracted features can be directly applied to downstream feature rebuilding. In the part shown in Fig.9b, all features can be extracted automatically. But in some special cases, features may be extracted manually.

CONCLUSION

The significance of this research is in the development of a methodology for feature extraction. The C++ Programming language based on the platform of UGNX2.0 is used as a tool to test all algorithms. The main contributions of this research include:

(a) Arbitrary 3-D solid model of sheet-metal parts can be input to the feature extraction system;

(b) According to the characteristic of the sheet-metal part, sheet-metal features are classified, and feature types are represented graphically.

(c) With the methodology of automatically extracting features, almost all the sheet-metal features can be extracted, which makes it possible to apply this feature extraction system into industry.

Our future work will focus on extracting more abundant engineering information on complex sheet-metal features to enhance the performance of automatic feature extraction.

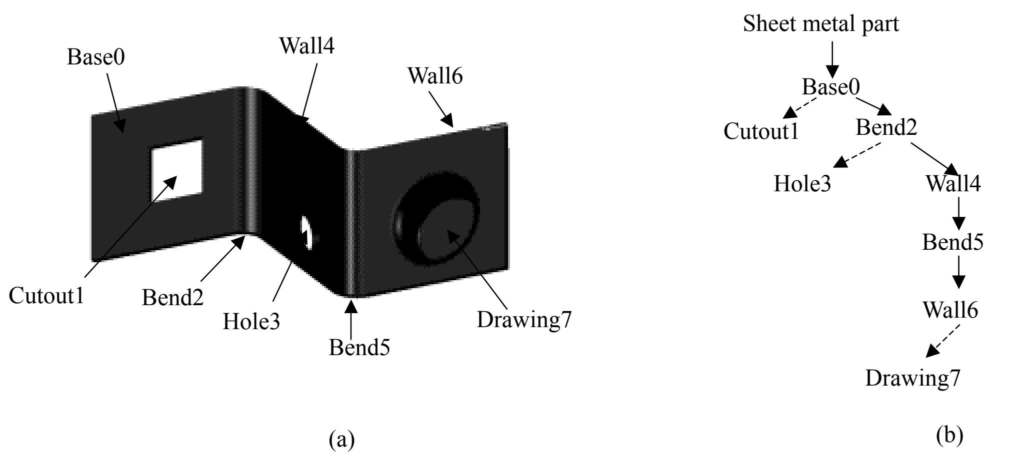


Fig.8 Information on feature relations
(a) Sheet-metal part; (b) Feature relation diagram

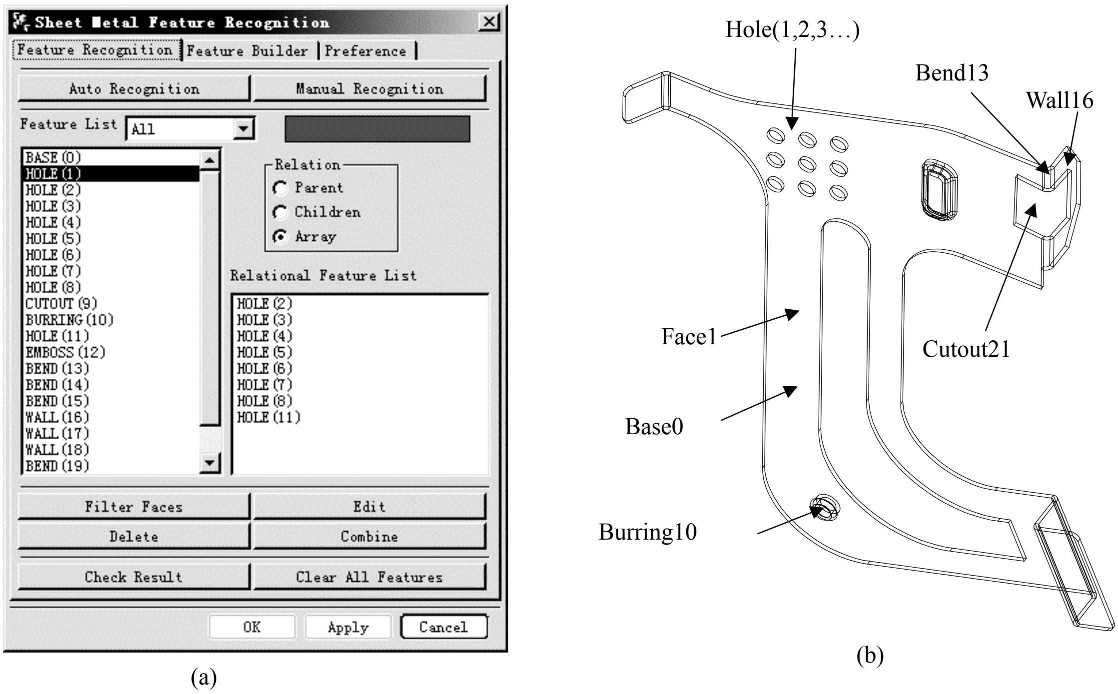


Fig.9 Example of feature extracting
(a) The interface of feature extracting; (b) The sheet-metal part

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