Generic Classification and Representation of Shape Features in Sheet-Metal Parts

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1 Introduction

Collaboration usually involves actors from different applications. These actors may be software, personnel of different disciplines and skill levels. These actors have to process data from different sources in different formats. Each actor has different need and interpretation of product information, e.g., for manufacturing operation, the information required is how to create the required shape which needs CAD model with shape information, tools, and manufacturing parameters for manufacturing the chosen shape. If the manufacturing operations involved are material removal only then the shape to be manufactured should be interpreted as negative features (classes of shapes representing subtraction of volumes only). For tolerance analysis, the information required is for performing tolerance studies and optimizing tolerance budgets, e.g., different types of dimensions (height, depth, radius, diameter, etc.), numerical tolerances on dimensions, geometrical tolerances with the whole range (form, profile, run-out, orientation, and location), surface finish values and types, multiple attributes to customize dimensions about a part.

Exchange of product data has undergone considerable evolution since the days of annotated engineering drawings (Owen 1997). At that point the focus was to

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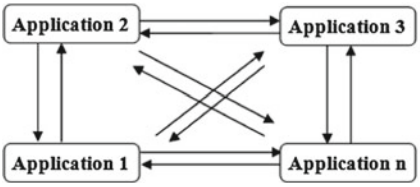
exchange primarily shape/geometric data between design and manufacturing. With the advent of computer-aided design and drafting systems, exchange of shape models between different CAD/CADD applications was required (Gupta and Gurumoorthy 2008a). Different approaches being used to handle the exchange of product model among applications of product development are: (i) a single CAD environment for all tasks, (ii) direct data transformation between different systems which requires '$(n * (n - 1))$' translators for 'n' applications (Fig. 1a) and, (iii) data exchange using neutral file formats (like IGES, STEP or STL) which requires '$(2 * n)$' translators for 'n' applications as depicted in Fig. 1b.

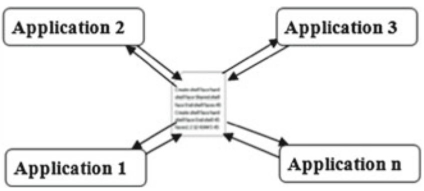
Use of neutral format therefore became the preferred framework to solve the data exchange problem. The Drawing Exchange Format (DXF) is the defacto neutral format used to exchange 2D drawing data across different drawing tools. Then, Initial Graphics Exchange Specification (IGES), another neutral format, was introduced for exchange of geometry information between dissimilar applications. IGES however, is capable of transferring only the geometry of the product; the nonfeature information and design intent are lost. Standard Exchange of Product data model (STEP, formally ISO 10303) evolved to interrelate all geometric and nongeometric data in a useful and meaningful way to represent product content model so that the complete description can be exchanged among CAD systems. STEP data is at present the most comprehensive standard to address the needs for exchange of geometric data.

Exchange of geometric and topological information through STEP, IGES, 3DXML, PLM-XML, and X3D does not have explicit definitions so it cannot be modified. The exchanged information with explicit definitions can be understood by receiving application and can be used and modified as it was developed in the receiving application. Part modeled in application 'A' (Fig. 2a) is exchanged using IGES to application 'B' (Fig. 2b). The exchanged model does not have feature labels and associated meanings. Whereas part model shown in Fig. 2c has feature labels and meanings so it can be modified when required.

Current art in exchange of product data is at the level of exchanging feature models. Feature-based product data exchange is emerging to accommodate design intent for data exchange. Features are capable of carrying constraints, parameters, and application attributes. In the product development cycle, several applications (engineering design, industrial design, manufacturing, supply chain, marketing,



(a) By Direct Translators



(b) By Neutral Format

Fig. 1 Product data exchange

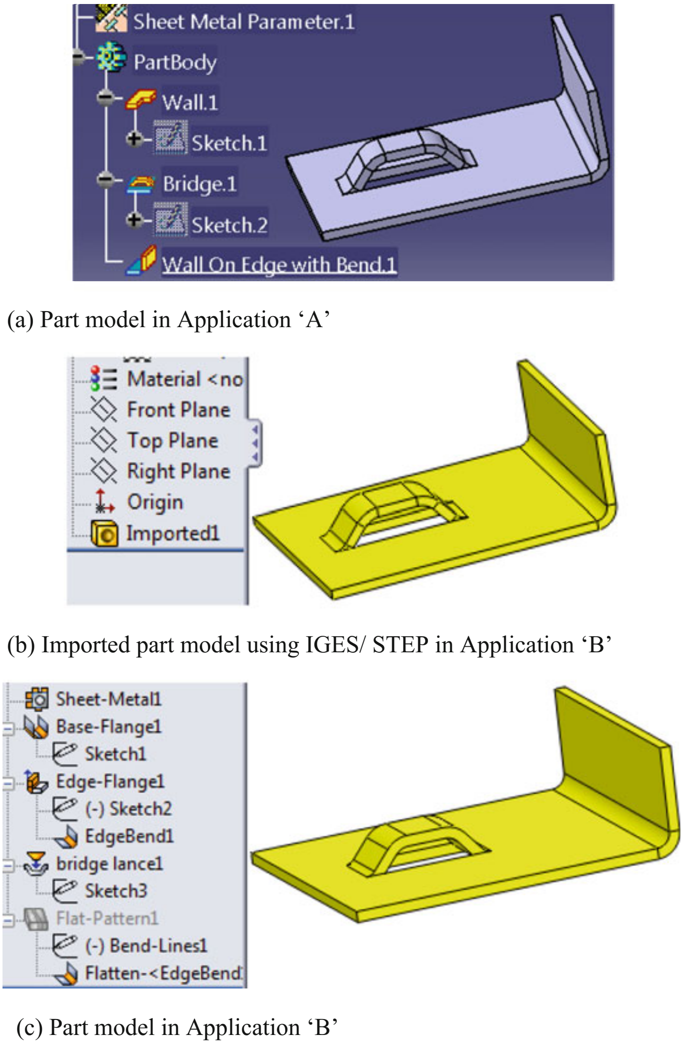


Fig. 2 Example of exchange of product information versus feature labels and meanings

maintenance, etc…) and different engineering domains (mechanical, electrical, electronic, etc…) require the ability to exchange product data with feature labels and their meaning. With product development happening in multiple locations with multiple tools/systems, the exchange of product information along with feature labels and their meaning between these tools/systems becomes more important.

Features are described by Shah (1991) as "Features encapsulate the engineering significance of portions of the geometry of a part or assembly, and, as such, are important in product design, product definition, and reasoning, for a variety of applications." In literature terms 'shape feature' (Falcidieno and Giannini 1989;

Sonthi et al. 1997; Brunetti and Grimm 2005) and 'form feature' (Coles et al. 1994; Nalluri 1994; Jha 1998; Subramani 2005) are used for features associated with addition or subtraction of volume to/from a base-solid. These are also defined as machining features (Kailash et al. 2001; Sunil and pande 2009) if features are associated with subtraction of material and can be realized using machining operations.

A feature is defined as the smallest building block that can be modified individually (Kulkarni and Deshpande 2008; Tickoo and Maini 2010). A part in a product is a combination of a number of individual features and each feature is related to other features directly or indirectly. These individual features are capable to carry constraints, parameters, and application attributes important for other applications. Generally, engineers/designers relate information to the features. Information necessary for other application can be attributed to these features and can be used when required. Hence, features are interfaces between shape models and applications (Wong and Leung 1995; Shah and Mäntylä 1995; Brunetti and Grimm 2005; Langerak and Vergeest 2007). The features can also be considered as interfaces for the construction of a shape model, its modification, and application-specific reasoning (Shah 1991).

Formal and unambiguous representations of shape features in a sheet-metal part model are required to exchange feature (feature label and meaning) among applications across product development life cycle. The representation should be unique and application independent so that multiple applications can work together using single representation of a sheet-metal part model. In general, the sheet-metal features in a part model are classified as follows:

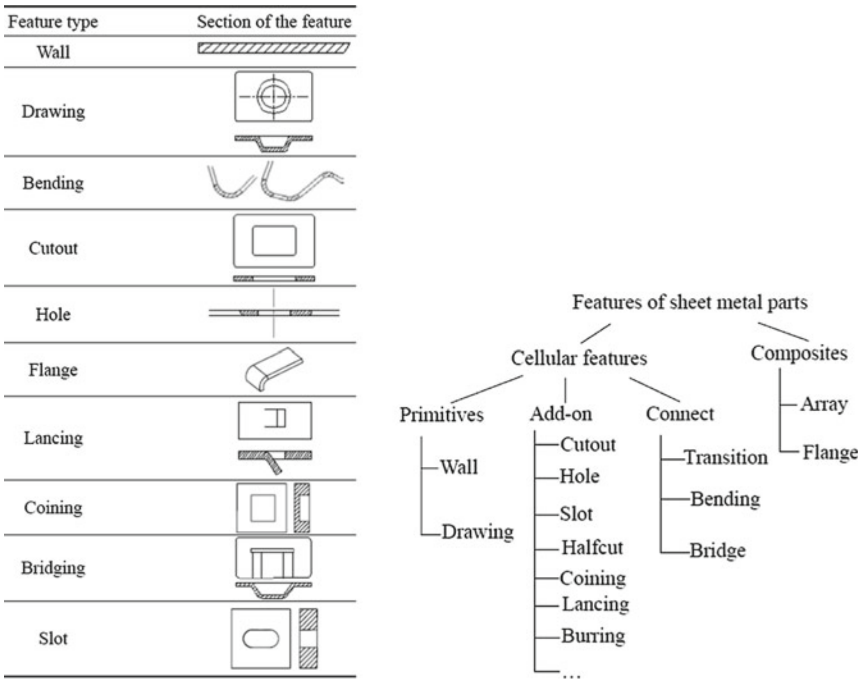
i. Volumetric sheet-metal features as a result of material removal operations on base-sheet (e.g., piercing/blanking operation);
ii. Deformation sheet-metal features as a result of deformation/modification of base-sheet or forming operation on base-sheet.

Researchers worldwide have focused on developing systems for classification and recognition of volumetric features from CAD models using techniques like rule-based (Henderson and Anderson 1984), syntactic pattern recognition (Prabhu and Pande 1999), graph-based (Venkataraman et al. 2001), volume decomposition-based (Woo 2003), hint-based (Vandenbrande and Requicha 1993), artificial neural Networks (ANN) (Shah et al. 2001; Babic et al. 2008; Sunil and pande 2009) and hybrid (Gao and Shah 1998). Comprehensive review of various volumetric feature recognition and classification techniques was reported in the literature (Shah et al. 2001; Babic et al. 2008). The feature classification proposed by Seo et al. (2005) is for feature modeling/construction available in existing commercial CAD systems for volumetric features.

Classification, representation, and extraction of deformation features in constant thickness part model such as sheet-metal have not received much attention in the literature. Many methods have been proposed for the recognition and representation of form features in solid models (Falcidieno and Giannini 1989; Nalluri 1994; Han 2010) but only a few techniques have been reported by researchers to recognize deformation features, based on solid model (Liu et al. 2004; Kannan and Shunmugam 2009) or surface model (Lipson and Shpitalni 1998; Joshi and Dutta 2003). In the stamping industry, the customers and suppliers often use different CAD tools which use different terms with different meanings and formats. The translation of a model results in a loss of the crucial engineering information for the downstream applications.

Liu et al. (2004) have classified features of sheet-metal parts into two categories —cellular features (basic features forming the sheet-metal part) and composites (features integrated as a whole by other kind of cellular features: Array, Flange). Cellular features are further categorized as Primitives (exist in sheet-metal part independently, e.g., Wall, Drawing), Add-ons (added to other features to form sheet-metal part, e.g., Cutout, Hole, Slot, Lancing, etc.), and Connects (acting as a bridge between different types of features, e.g., Bending, Bridge and Transition). This classification of shape features (Liu et al. 2004) along with the sections of these features in sheet-metal part is presented in Fig. 3.

Manufacturing feature classification for sheet-metal features has been presented by Kannan and Shunmugam (2009). The manufacturing features in sheet-metal parts are classified into four major classes: cut, stretched, drawn, and bent as



(a) Typical sheet-metal features (b) Classification scheme of sheet-metal features

Fig. 3 Classification of shape features in sheet-metal parts (Liu et al. 2004)

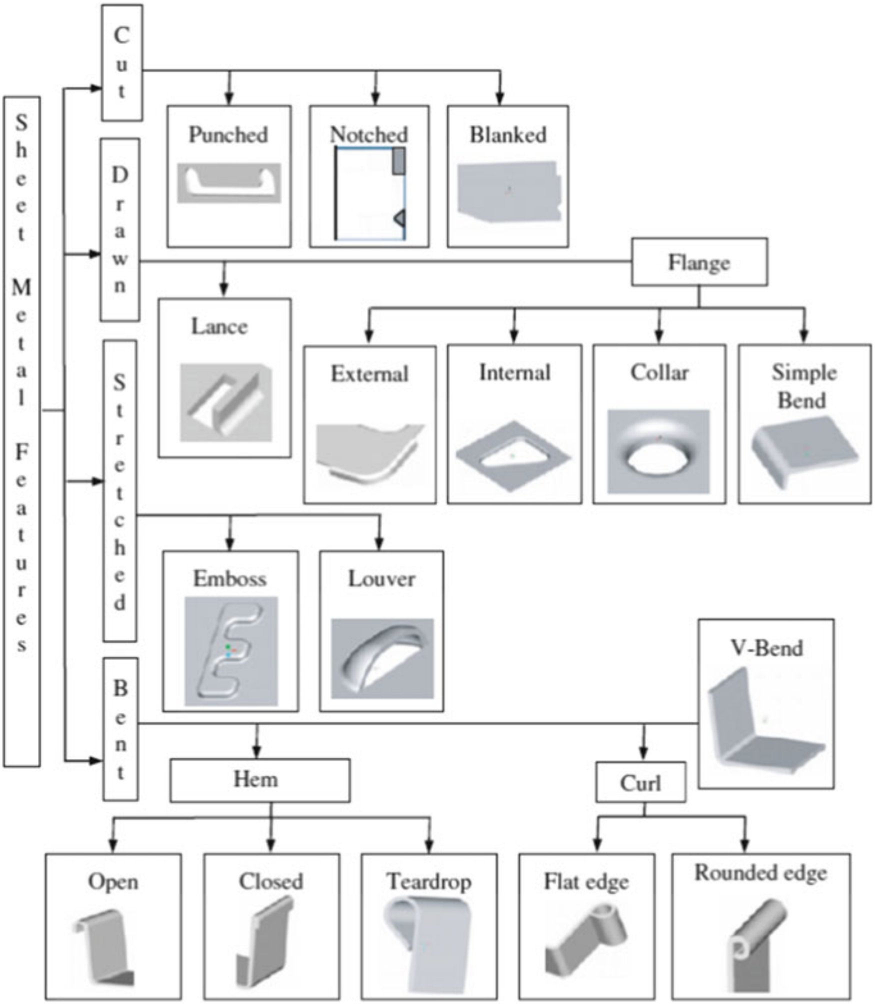


Fig. 4 Classification of manufacturing features in sheet-metal parts (Kannan and Shunmugam 2009)

presented in Fig. 4. The major difference between stretched and drawn features is that a change in sheet thickness occurs in the stretching operation whereas uniform sheet thickness is maintained in the case of a drawing operation. However, for the sake of convenience in modeling, a uniform sheet thickness is used by designers for both features. Bent and cut features involve pure bending and pure shear, respectively. Some features, like internal flanges, require a cut feature before flange is produced.

Sheet-metal feature recognition library (Geometric Limited 2012) operates on boundary representation (B-rep) of solid and surface models and is also available in commercial CAD modeling software. The algorithm in the recognition needs thickness of the sheet-metal part and a reference face to initiate the recognition. Unfolding and folding are used as intermediate step for the recognition of sheet-metal features. The recognized sheet-metal deformation features including Wall, Bend, Flange, and Stamp.

A generic classification scheme based on the classification proposed in literature (Liu et al. 2004; Kannan and Shunmugam 2009; Gupta and Gurumoorthy 2008b, 2013) and application domain (Geometric Limited 2012) is presented in this chapter for the shape features in a sheet-metal part model. DIFF (domain independent form feature) model proposed by earlier researches (Nalluri 1994; Subramani 2005; Gupta 2012) is adopted for representation, classification, and extraction of the sheet-metal features. The representation, classification, and extraction procedures of the sheet-metal features are based on topology and geometry. The definition presented for a feature is unambiguous and application independent and proposed to handle equivalences between feature labels and their representations among applications. The definition proposed for a feature can also be extended to include application-specific information.

2 Sheet-Metal Parts

Sheet-metal parts are created from a large rectangular sheet of constant thickness. The model of a sheet-metal part is first created in a CAD modeling software or on a paper sheet. Once the design is completed then it is sent to pattern-making department where master pattern is generated with different features available in the sheet-metal part and additional features required to achieve the part. After that the master pattern is sent to manufacture the sheet-metal part. Sheet-metal has applications in automobile, aircraft, shipbuilding, HVAC works, medical tables, architecture, farming, reactors, roofs for building, etc. The parts are designed and analyzed according to the application and then manufactured. There are some similarities and dissimilarities in creating sheet-metal parts with solid parts. Similarities, has base-feature, include sketched and placed features, features are created in sequence. Dissimilarities are, a sheet-metal part has a constant thickness, flat patterns created for manufacturing drawings, a feature can be added to a flat pattern that may not appear in the folded state.

3 Sheet-Metal Features

Sheet-metal can be cut and/or bent into a variety of shapes/features. Sheet-metal features are different from volumetric and surface features. These features can be considered as transition between volumetric and surface features. Many researchers consider sheet-metal features as solid models with constant thickness (Lipson and Shpitalni 1998; Liu et al. 2004). Researchers also consider sheet-metal features as surface models (Cavendish 1995; Joshi and Dutta 2003; Nyirenda and Bronsvoort 2008). But some sheet-metal features are created by removal of material, some are created by deforming the sheet-metal, and some are created by cutting partially and then deforming that partially cut portion of the sheet-metal.

Shape features in a sheet-metal part model can be associated with volume subtraction from base-sheet or deformation/modification of base-sheet (or base-surface) or forming of material of base-sheet. The shape features in a sheet-metal part model are classified as (i) Volumetric features, and (ii) Deformation features. These features are also classified as '2-dimensional (2D) features' (volumetric features) and '3-dimensional (3D) features' (deformation features) as a result of modification and forming of base-sheet. Examples of sheet-metal features in a sheet-metal part are presented in Fig. 5. This classification of sheet-metal features is based on volume subtraction and deformation of base-sheet. The volumetric and deformation features are further classified based on topology and geometric information present in the sheet-metal part model (Boundary Representation). Features in the classification are considered as generic features as the classification is independent of application-specific information. Features in sheet-metal parts can also be classified based on context/application information or refined geometric information and considered as nongeneric features. This classification is presented in Fig. 6. The generic classification and representation of volumetric and deformation features is explained in the following sections.

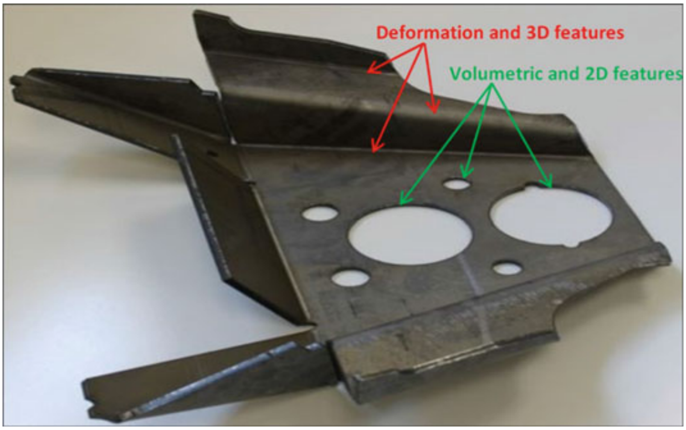


Fig. 5 Example of sheet-metal features in a sheet-metal part (Panghal et al. 2015)

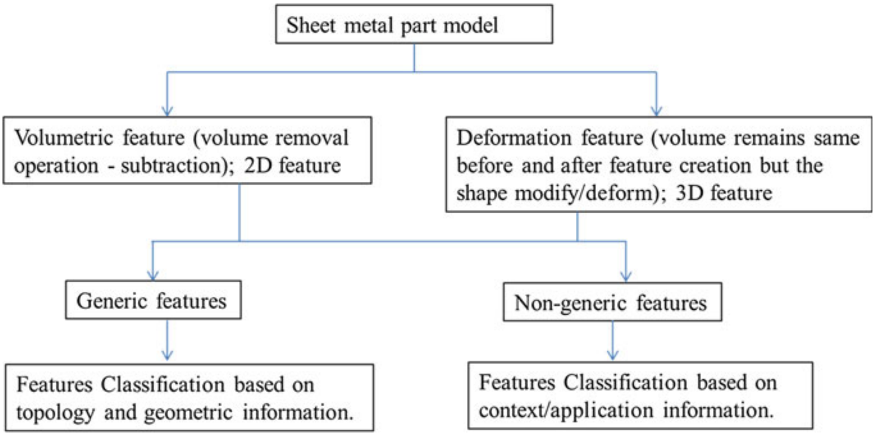


Fig. 6 Sheet-metal features based on volume subtraction and defamation

4 Volumetric Sheet-Metal Features

Sheet-metal piercing/blanking operations involve material removal/cut portion of sheet-metal to get the desired shape. So the result of piercing/blanking operation is negative volumetric feature. As the thickness of sheet-metal part is considered as constant throughout the part model and is also constant for the features so these features are also considered as 2D sheet-metal features. A sheet-metal part is first unfolded (flattened) to find out and mark stamping/blanking profile for the manufacturing. So the cut features has to be defined on the basis of the unfolded part model. If the cut is seen on a bend or bend-flat surfaces then also it will be identified on the unfolded part model.

Volumetric features in sheet-metal part model are results of material removal operations on base-sheet. These types of features are classified based on placement of the features in the part model and type of 2D profiles used in the material removal operations. Volumetric features such as hole, slot, cutout, chamfer, fillet, vent, notch, clip, etc., are created by material removal operations such as cutting, punching, stamping, shearing, nibbling, sniping, notching, clipping, blanking, etc. Examples of volumetric features in sheet-metal parts are depicted in Figs. 7 and 8. The volumetric feature thus created has (i) a 2D profile which is used for shearing operation, (ii) end faces which are shared by faces of the base-sheet and the created feature, these end faces are referred as Shared End Faces (SEFs), and (iii) newly created shell faces in the feature as a result of shearing operation are referred as Created Shell Faces (CSFs). The characteristic arrangements and type of '2D profile', 'SEFs', and 'CSFs' are used to classify generic classification of volumetric features in sheet-metal part model. The type of 2D profile, number, and arrangements of CSFs and SEFs can also be used to define nongeneric information for a volumetric feature.

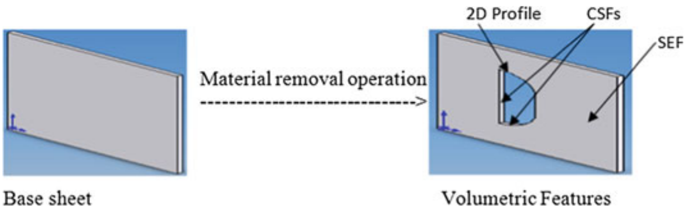


Fig. 7 Volumetric features in sheet-metal part

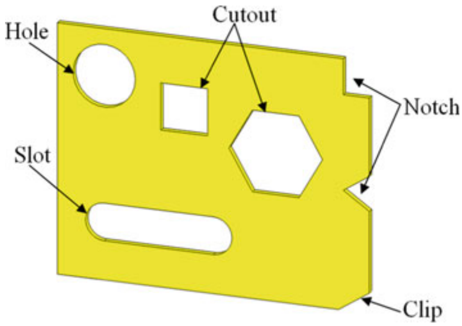


Fig. 8 Examples of volumetric features in sheet-metal part

4.1 Classification Based on Placement of 2D Profile

The classification based on placement of 2D profile presented in this subsection is considered as generic classification of volumetric features in sheet-metal part models. The placement of 2D profile with respect to the sheet-metal part model is used for classification of volumetric sheet-metal features as **Interior** and **Boundary**. This depends on the placement of feature's profile with reference to the part's outer boundary and can also be identified based on type of 2D profile. If the 2D profile is closed then the feature is Interior else the feature is Boundary.

Interior volumetric feature lies inside the part model. The feature profile is closed and completely inside the part's outer boundary. Example of the interior feature is presented in Fig. 9.

Boundary volumetric feature lies on the part's outer boundary. The feature profile is opened. The feature profile and part's outer boundary are interesting or some portion is common to the both. Example of the boundary feature is presented in Fig. 9.

4.2 Classification Based on Shape of the 2D Profile

The classifications based on shape of 2D profile presented in this subsection are considered as nongeneric classification of volumetric features in sheet-metal part

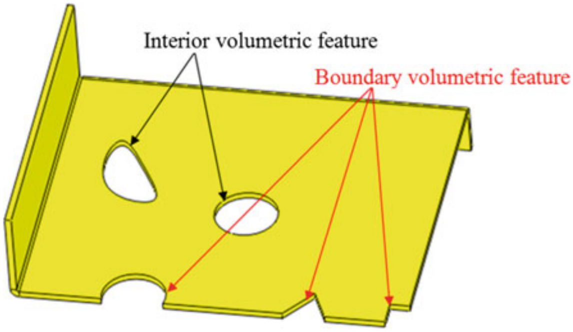
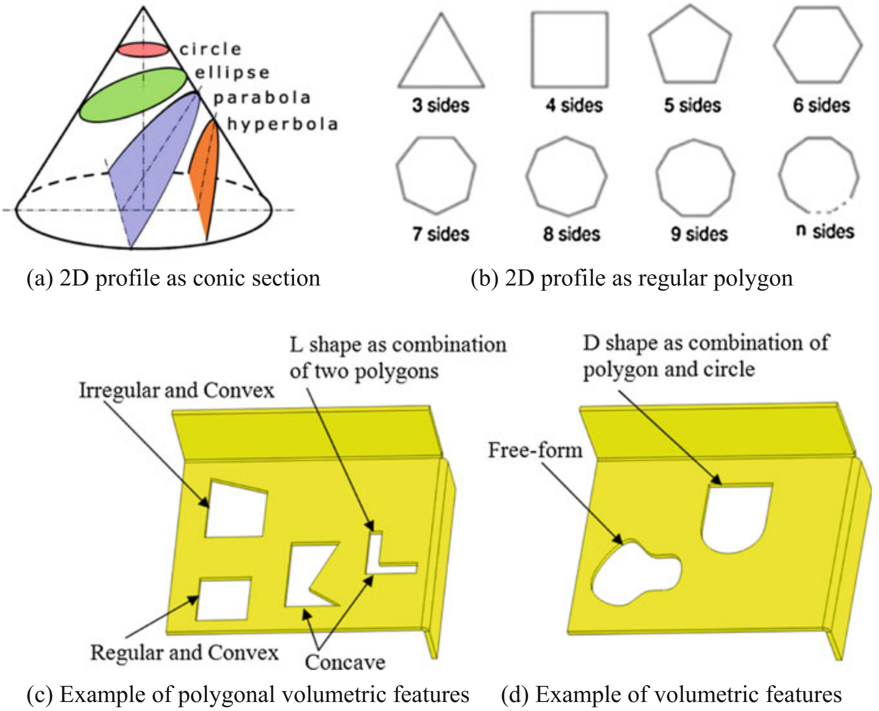


Fig. 9 Example of interior and boundary volumetric sheet-metal features

models. This is considered as nongeneric information as it is too specific to geometric information and can be required for specific application as opposed to the generic classification where the classified information is required for most of the applications considered. The classifications based on shape of 2D profile of a volumetric feature is considered as the classification based on 'number of edges', 'type of edges', and 'angle between two adjacent edges' in the 2D profile.

If shape of the 2D profile in a volumetric sheet-metal is a conic section (e.g., circle, ellipse, parabola or hyperbola as shown in Fig. 10a) then the volumetric feature is classified as circular, elliptical, parabolic, or hyperbolic volumetric feature, respectively. If shape of the 2D profile is a polygon (e.g., 3-sides, 4-sides, … n sides as shown in Fig. 10b) then the volumetric feature is classified as 3 sides, 4 sides, … n sides polygonal volumetric feature, respectively. The number of planar CSFs in the feature defines the type of polygonal volumetric feature in a sheet-metal part model. A polygonal volumetric feature is a regular polygonal volumetric feature if length of all edges in 2D profile is same and angle between adjacent edges is same else it is irregular polygonal volumetric feature. Examples of regular and irregular volumetric features are presented in Fig. 10c. 2D profile in a volumetric feature can be a combination of conic section(s) and/or polygon (s). For example, "L shape volumetric feature" as a combination of two rectangular polygons is shown in Fig. 10c and "D shape volumetric feature" as a combination of polygon and circle is shown in Fig. 10d. If angle between any two adjacent edges in a 2D profile of a volumetric feature is more than 180° then the volumetric feature is classified as concave else it is convex. Example of concave volumetric features and convex volumetric features are presented in Fig. 10c. If the 2D profile of a volumetric feature is not classified as conic section and/or polygonal, then the feature is a free-form volumetric feature (see Fig. 10d). Further classification based on nongeneric information, such as material information, actual dimensions, and application specific information, is not covered in this chapter. This nongeneric classification and information can be built as per the requirements.

The classification of volumetric features in sheet-metal parts is presented in Fig. 11. Each volumetric feature is classified uniquely based on the combination of four groups of factors presented in Fig. 11. This classification captures the geometric and topological variations in volumetric features.

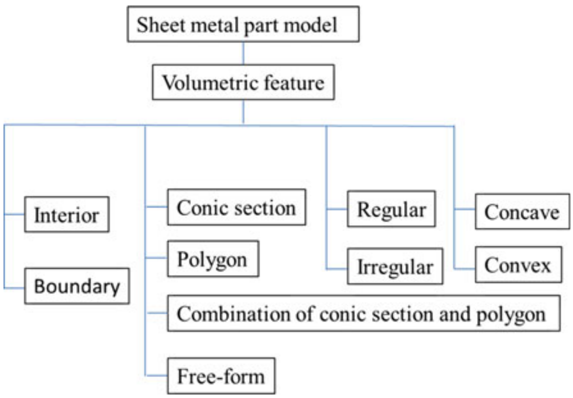


(a) 2D profile as conic section (b) 2D profile as regular polygon

(c) Example of polygonal volumetric features (d) Example of volumetric features

Fig. 10 Type of volumetric sheet-metal features based on shape of the 2D profile

Fig. 11 Classification of volumetric features in sheet-metal parts



5 Deformation Sheet-Metal Features

Deformation features in sheet-metal parts such as bend, flange, jog, hem, dimple, bead, crimp, ribs, embosses, louvers, lances, etc., are created by beading, bending, crimping, forming, folding, turning, joggling, embossing, lancing, louver operation, etc. Examples of deformation sheet-metal features are presented in Figs. 12 and 13.

Deformation features are created in constant thickness part models, for example, deformation of material (as in sheet-metal parts) or forming of material (as in injection molded parts of constant thickness) also referred as constant thickness features (Lipson and Shpitalni 1998; Liu et al. 2004; Gupta and Gurumoorthy 2008b; Geometric Limited 2012). The literature review for classification and extraction of deformation features in sheet-metal parts is presented in paper (Gupta and Gurumoorthy 2013). A classification scheme based on the classification proposed in literature (Liu et al. 2004; Kannan and Shunmugam 2009; Gupta and Gurumoorthy 2008b, 2013) has been presented for deformation features to realize their representation and extraction.

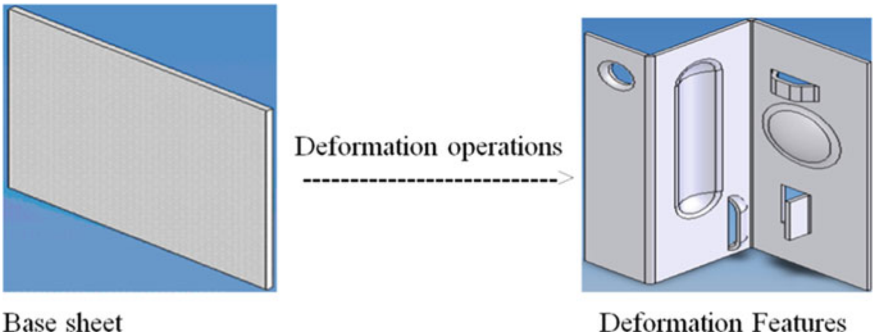


Fig. 12 Deformation features in sheet-metal part

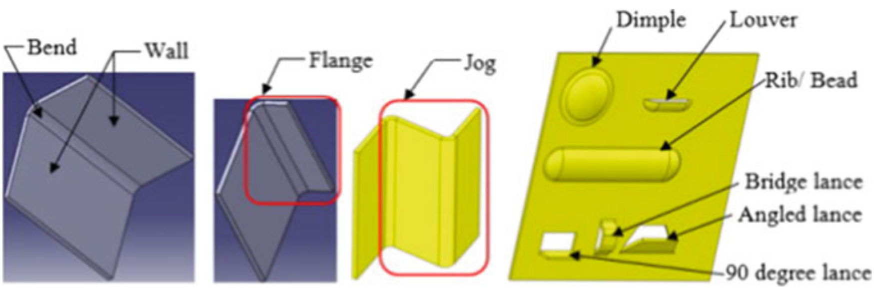


Fig. 13 Examples of deformation features in sheet-metal parts (Gupta and Gurumoorthy 2013)

The deformation features in sheet-metal part model are identified and represented in terms of faces and adjacency relationships between faces. Deformation of a base-sheet creates Bends and Walls with respect to the base-sheet which are referred as basic deformation features. Deformation features in sheet-metal part model are defined uniquely in terms of Basic Deformation Features Graph (BDFG) with characteristics of shell faces and bends. A deformation feature has certain number of Walls and Bends in particular sequence which is captured in BDFG (Gupta and Gurumoorthy 2013). The arrangement of Walls and Bends in the graph has information related to the classification of deformation features. Definition of Basic Deformation Features Graph (BDFG) and representation of deformation feature using BDFG can be referred in the work of Gupta and Gurumoorthy (2013). The classification of faces and features in sheet-metal parts related to deformation of base-sheet are described in the following sub sections. Some of the commonly used terms in the classification and representation are defined below:

Thickness It is constant for a sheet-metal part. It is the minimum of the shortest distances between pairs of two parallel faces of similar surface type (planar/cylindrical/conical/spherical/toroidal) which have normals in opposite directions as shown in Fig. 14 (Gupta and Gurumoorthy 2013).

It is found that a deformation sheet-metal feature has at least one pair of two concentric faces of similar surface type (as cylindrical/conical/spherical/toroidal) which have normals in opposite directions. The number of faces with surface type as cylindrical, conical, spherical, and toroidal is smaller than that of faces with surface type as planar. So, the thickness is identified as the minimum of the shortest distances between pairs of two concentric faces of similar surface type (cylindrical/conical/spherical/toroidal) which have normals in opposite directions as in Fig. 14b so that less number of surfaces are processed to find the thickness.

End face versus **Shell face** Faces along the thickness are classified as shell faces as shown in Fig. 14. Faces across the thickness are classified as end faces as shown in Fig. 14.

Wall versus **Bend** Two parallel end faces of similar type (Planar, cylindrical, conical, spherical, or toroidal) with normals in opposite directions and are at an equal distance to thickness are referred as end faces of a BDF (Wall/Bend). Shell faces joining these two end faces of the BDF are referred as shell faces of the BDF

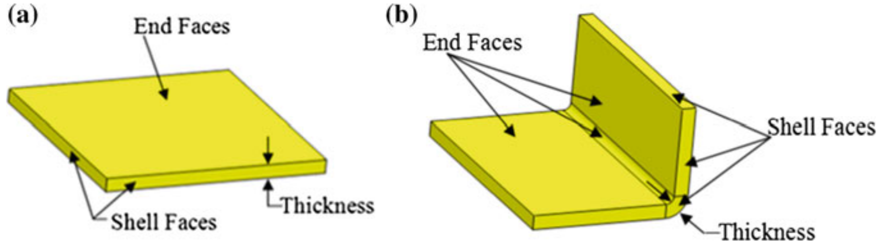


Fig. 14 Thickness, End faces, and Shell faces in sheet-metal part (Gupta and Gurumoorthy 2013)

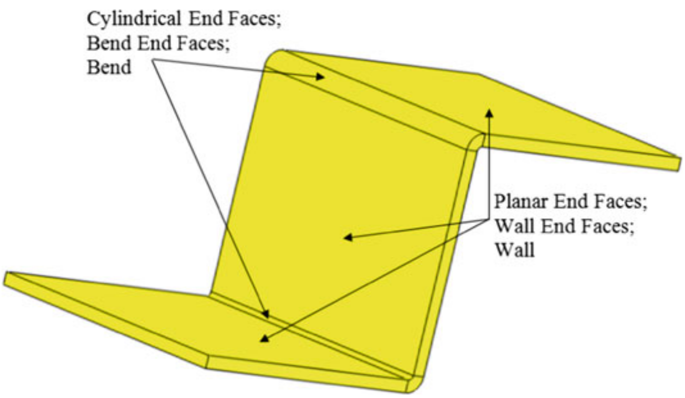


Fig. 15 End faces, wall and bend in sheet-metal part

(wall/Bend). If surface type of end faces of the BDF is cylindrical, conical, spherical, or toroidal then it is Bend, otherwise it is Wall as shown in Fig. 15.

Created Wall End Faces (CWEFs) versus **Created Bend End Faces (CBEFs)** End face is classified as Wall end face or Bend end face depending on the surface types. All end faces in a sheet-metal part are referred as created end faces and are classified as CWEFs or CBEFs depending on the surface type of the face. If the surface type of an end face is cylindrical, conical, spherical, or toroidal, then it is CBEF else it is CWEF (see Fig. 16).

Created Shell Faces versus **Shared Shell Faces** The adjacent faces of two or more contiguous basic deformation features in the deformed sheet which are in the same plane with their normals in the same direction are classified as shared face as shown in Fig. 16a. A face, shared by two or more contiguous basic deformation features in the deformed sheet, is also referred as shared face (Fig. 16b). A shell face of such type is classified as Shared shell face.

A face which is shared by only one basic deformation feature, and there is no adjacent faces which are in the same plane then the face is classified as created face

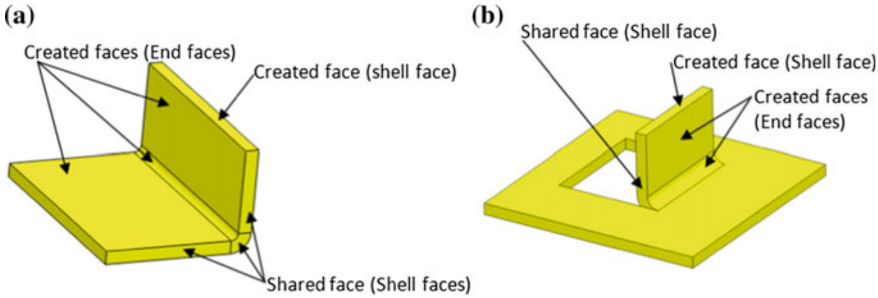


Fig. 16 Shared and created faces in sheet-metal part (Gupta and Gurumoorthy 2013)

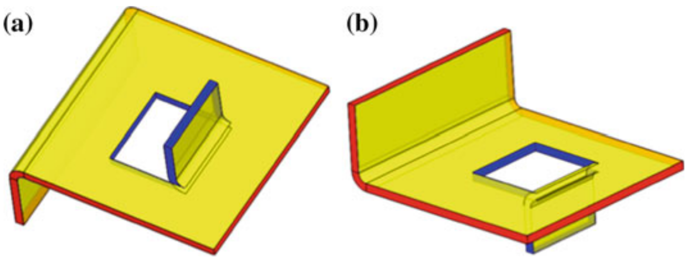


Fig. 17 Sheet-metal part's outer boundary shell faces and interior boundary shell faces

as shown in Fig. 16. A shell face of such type is classified as Created shell face (see Fig. 16b).

Part's outer boundary shell faces versus **Part's interior boundary shell faces** Shell face which has common edge with inner bound edge(s) of an end face is referred as part's interior boundary shell face. Shell face which is contiguous to part's interior boundary shell face is also referred as part's interior boundary shell face. Shell face which is not at inner bound edge(s) of an end face and also not contiguous to part's interior boundary shell face then the shell face is referred as part's outer boundary shell face. Blue color faces are part's interior boundary shell faces whereas red color faces are part's outer boundary shell face as shown in Fig. 17.

Feature's Boundary Shell Faces versus **Feature's Interior Shell Faces** Feature's shell face which is common to part's outer boundary shell face is referred as boundary shell face (Fig. 18a) else the feature's shell face is interior shell face as shown in Fig. 18b.

Base-feature BDF with maximum surface area of an end face is selected as base-feature.

Bend as SimpleBend and SBend in BDFG A bend is a SimpleBend when direction of this bend and previous bend in the graph is same or it is first bend in the graph. A bend is a SBend when direction of this bend and previous bend in the graph are opposite.

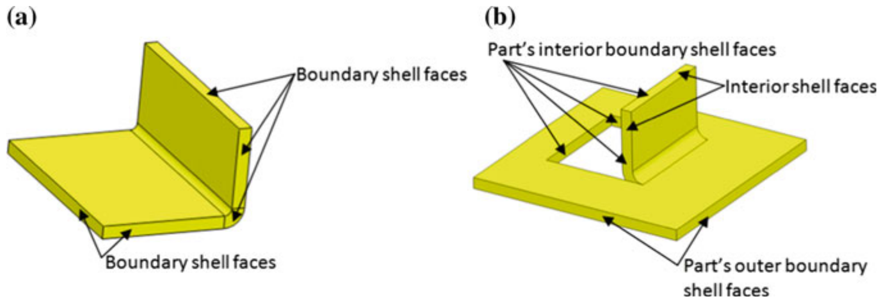


Fig. 18 Sheet-metal feature's boundary shell faces and interior shell faces

5.1 *Classification of Feature Faces for Deformation Sheet-Metal Features*

The faces in a sheet-metal part model associated with an individual "deformation feature" are classified as follows:

Created End Faces (CEFs)—Newly created faces in the base-sheet corresponding to the end faces of the created deformation feature in the deformed sheet. The CEFs are further classified as **Created Wall End Faces (CWEFs)** and **Created Bend End Faces (CBEFs)** depending on the basic deformation feature type as shown in Fig. 19a. Surface types of bend end faces are cylindrical, conical, spherical, or toroidal and are referred as CBEFs. Surface types of wall end faces are planar and are referred as CWEFs. Examples of CWEFs are 11, 14 (Fig. 20a) and 14, 16 (Fig. 20b), CBEFs are 10, 13 (Fig. 20a) and 13, 15(Fig. 20b).

Shared Shell Faces (SSFs)—If two or more adjacent shell faces in a deformation feature are lying in one plane and their normals are in same direction then these faces are classified as shared shell faces (SSFs) as shown in Fig. 19a. One shell face in a deformation feature which is shared by two or more contiguous basic deformation features then also the face is classified as shared shell face as shown in

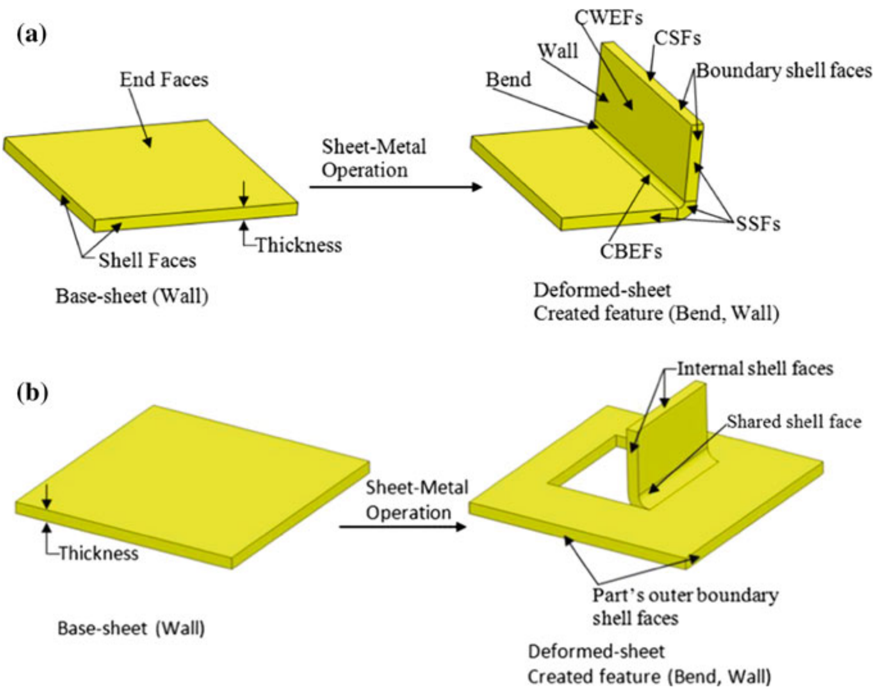
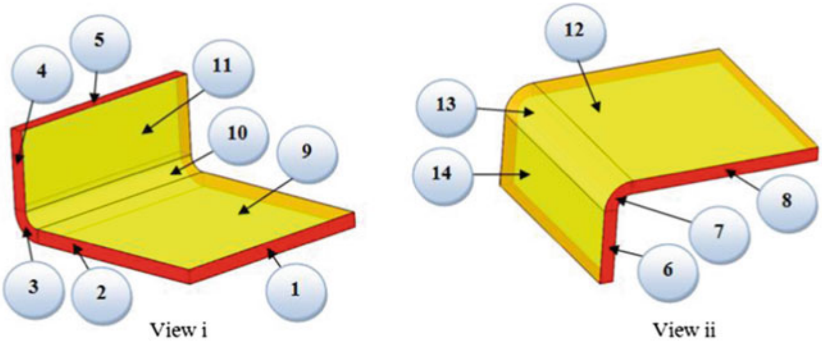
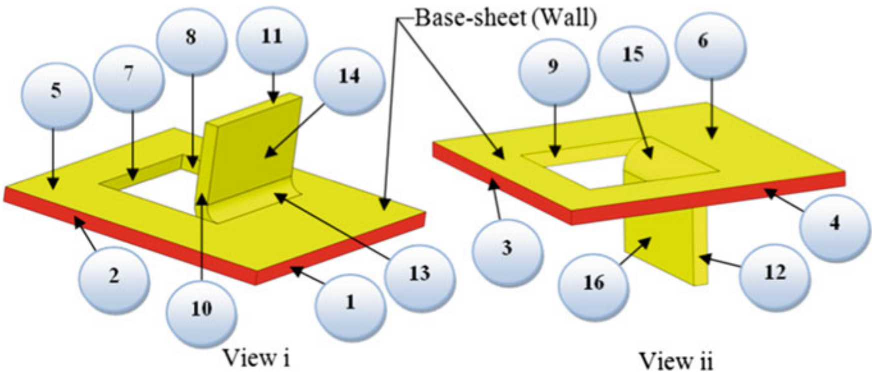


Fig. 19 Classification of feature faces for deformation features in sheet-metal parts (Gupta and Gurumoorthy 2013)



(a) Edge flange



(b) 90 degree lance

Fig. 20 Examples of faces in deformation sheet-metal features (Gupta and Gurumoorthy 2013)

Fig. 19b. The SSFs are further classified as **BSSFs** (Boundary SSFs) or **ISSFs** (Interior SSFs) based on whether the SSF of a deformation feature in sheet-metal part is coinciding with the outer boundary shell face of the part or not. Part's outer boundary shell faces are shown in red color in examples presented in Fig. 20. Examples of BSSFs are {3, 4}, {6, 7} in Fig. 20a, ISSFs are 10, 12 in Fig. 20b.

Created Shell Faces (CSFs)—A shell face in a deformation feature which is shared by only one basic deformation feature, and there is no adjacent shell faces which are in the same plane then the shell face is classified as created shell face (CSFs) as shown in Fig. 19a. The CSFs are further classified as **BCSFs** (Boundary CSFs) or **ICSFs** (Interior CSFs) based on whether the CSF of a deformation feature in sheet-metal part is coinciding with the outer boundary shell face of the part or not. Examples of BCSFs are 5 in Fig. 20a, ICSFs are 11 in Fig. 20b.

Since the deformation sheet-metal features are defined in terms of six types of faces (CBEFs, CWEFs, BSSFs, ISSFs, BCSFs, ICSFs), the feature definitions are consistent and amenable to automated reasoning. Hierarchical structure of classification of these faces in a deformation sheet-metal feature is shown in Fig. 21.

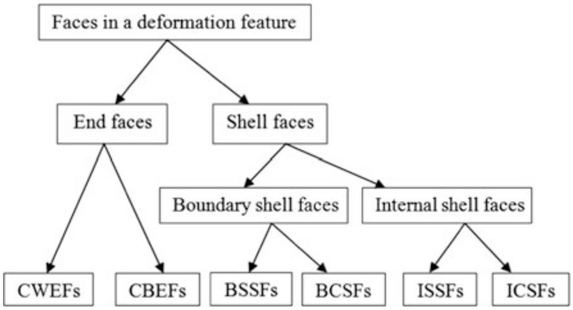


Fig. 21 Hierarchy of classification criteria in feature definition of deformation features (Gupta and Gurumoorthy 2013)

These six types of faces of each deformation feature along with face adjacency relationships are stored in the DIFF model (Gupta 2012).

5.2 *Classification of Deformation Sheet-Metal Features*

The definition of deformation sheet-metal feature separates the generic content from the nongeneric content. This is similar to the definitions proposed for volumetric sheet-metal features. The overall form and shape of a feature are separated into type and shape. The type of the feature is specified by the generic type and nature whereas the shape of the feature is specified by the actual values of the geometric entities such as angle of bend, length/height of flange, etc. The generic content of the deformation feature is defined in terms of basic deformation features (Wall and Bend) and their characteristics. The number and type of shell faces determines whether the identified feature is generated by partially cutting and subsequent deformation or generated by only deformation of the sheet. Deformation sheet-metal features are classified and represented based on the characteristics of the shell faces and bends. The six types of faces (CBEFs, CWEFs, ISSFs, BSSFs, ICSFs, BCSFs) and type of bends capture the feature form and the feature creation process.

The characteristics of the feature's shell faces and bends are used to classify the deformation sheet-metal features into classes based on three factors described in the following sub sections.

5.2.1 Number and Arrangement of Boundary Shell Faces

Feature's shell faces coincide with the sheet-metal part's outer boundary shell faces are referred as boundary shell faces. Based on this factor, deformation features are classified into four classes as defined below:

Interior These are the deformation features which do not coincide with the outer boundary shell faces of the part. This class of features does not have shell faces

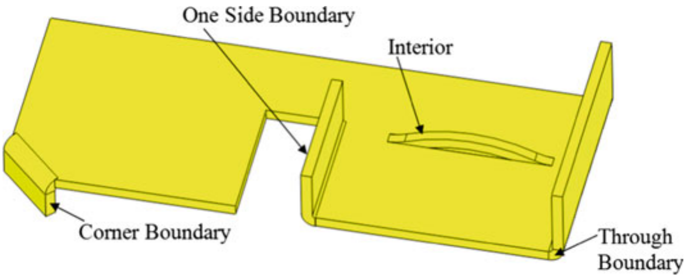


Fig. 22 Examples of type of defamation features based on 'number and arrangement of boundary shell faces'

which are common to the outer boundary shell faces of the part (means BSSFs = 0 and BCSFs = 0). This class of features is referred as *Interior* in the proposed classification. An example of this type of feature in a sheet-metal part is presented in Fig. 22.

One Side Boundary These features are at the outer boundary shell faces of a sheet-metal part. This class of deformation feature either has a coincidence of a single shared shell face of the deformation feature with the outer boundary shell face of the part which means BSSFs = 1 or has BCSFs without BSSFs (means BSSFs = 0 and BCSFs > 0). This class corresponds to a deformation feature referred to as *Boundary* in the classification. An example of the deformation feature, 'One Side Boundary', is presented in Fig. 22.

Corner Boundary This class of deformation feature is identified when any two adjacent shared shell faces of the deformation feature coincide with two adjacent outer boundary shell faces of the part which means this type of deformation feature has two adjacent BSSFs. Since two adjacent faces meet at a corner this class of deformation features is referred to as *CornerBoundary* in the proposed classification. Example of CornerBoundary feature is shown in Fig. 22.

Through Boundary This class of deformation features arises when two non-adjacent shared shell faces of the feature coincide with the outer boundary shell faces of the part and hence, there are two nonadjacent BSSFs. This class of deformation features is referred as *ThroughBoundary* in the classification. An example of this type of deformation feature in a sheet-metal part is presented in Fig. 22.

5.2.2 Number of Interior Shell Faces in a Deformation Feature

Each class based on the characteristics of boundary shell faces is further classified into two subclasses which captures the feature creation process. The classification is based on the number of ICSFs and ISSFs in the deformation feature. These two subclasses are described below.

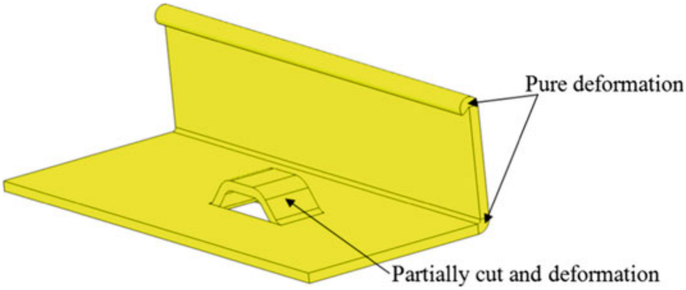


Fig. 23 Examples of type of defamation features based on 'number of interior shell faces in a feature'

Pure deformation This class of deformation features is generated by various stamping/forming processes. Features created by beading, bending, crimping, forming, folding, turning, joggling, embossing operations belong to this category, such as Dimple, Bead, emboss, Surface stamp, Curved stamp, Circular stamp, Stiffening rib(Dart), etc. Deformation features in this class have ISSFs = 0 and ICSFs = 0. This class of features is referred as *PureDeformation* in the classification. A PureDeformation feature can be either interior or boundary (one side, corner, through) based on the interactions of the deformation feature with the outer boundary shell faces of the part. Examples of PureDeformation features (Simple bend (Kannan and Shunmugam 2009), type of hem (Kannan and Shunmugam 2009) in a sheet-metal part are presented in Fig. 23.

Partially cut and deformation Features created by lancing and louver operations belong to this category. This class of deformation features are cut partially and then deformed the cut portion to get the desired shape. Deformation features in this class have one or more interior shell faces (means ISSFs > 0 and/or ICSFs > 0) which corresponds to the partially cutting and deformation of the cut portion to create a deformation feature in sheet-metal part so a deformation feature with ISSFs > 0 and/or ICSFs > 0 belongs to this class. This class of deformation features is referred as *PartiallyCutDeformation* feature in the proposed classification. If the identified feature has shell faces that coincide to the outer boundary shell faces of the sheet-metal part then the deformation feature is on the boundary else it is interior. An example of this type of feature (Bridging (Liu et al. 2004) or Bridge lance (Gupta 2012)) is shown in Fig. 23.

5.2.3 Type of Bends in a Deformation Feature

Each class of deformation sheet-metal features presented in Sects. 5.2.1 and 5.2.2 is further classified into subclasses based on the variations in curvature in the deformation feature. This factor captures the nature of the deformation features. The direction of curvature in a bend or a wall is same. It is different only when a

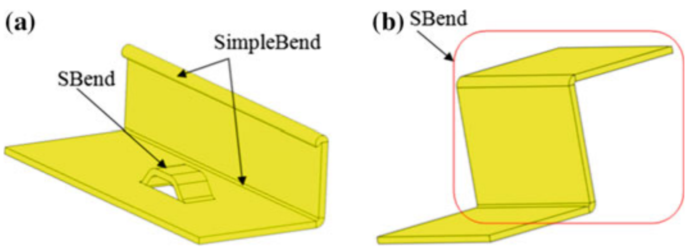


Fig. 24 Examples of type of defamation features based on 'type of bends in a feature'

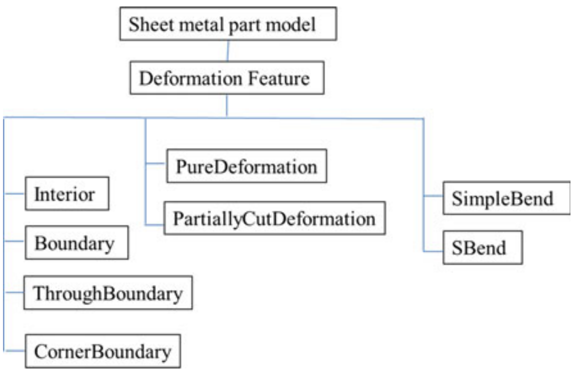
deformation feature has two or more bends and two bends are of opposite directions. These variations in curvature are captured by types of bends in a deformation feature.

Directions of curvature across the deformation feature are used to define feature nature. If the directions are same throughout the deformation feature then all bends in the feature have same type of curvatures (concave or convex) else different types of curvatures means some bends are concave and some bends are convex in nature.

These variations of curvatures in a deformation feature are captured as SimpleBend and SBend to define same type of curvatures and different type of curvatures, respectively, in the proposed classification. A deformation feature with SimpleBend means all bends in the feature have same type of curvature. A deformation feature with SBend means the deformation feature has at least one pair of bends with different type of curvature. These two types of bends create two subclasses as "**SimpleBend**" and "**SBend**" under each class of deformation features based on previous factors. Examples of features with SimpleBend are edge flange (Fig. 24a), hem flange (Fig. 24a), counter sink emboss, 90° lance and angled lance. Examples of features with SBend are jog (Fig. 24b), bead, dimple, louver, arc lance, bridge lance (Fig. 24a), etc.

The classification of deformation features in sheet-metal parts is presented in Fig. 25. Each deformation feature is classified uniquely based on the combination

Fig. 25 Classification of deformation features in sheet-metal parts



of above three factors. This classification captures the geometric and topological variations in deformation features in sheet-metal parts. Definition of Basic Deformation Features Graph (BDFG) and representation of deformation feature using BDFG can be referred in the work of Gupta and Gurumoorthy (2008b, 2013) and Gupta (2012). Complex deformation features (like jog, dimple, bead, rib, lance, and louver) can easily be expressed using BDFG.

6 Conclusion

Sheet-metal can be cut and/or bent into a variety of shapes/features. A sheet-metal part is a combination of a number of individual features and each feature is related to other directly or indirectly. Sheet-metal features are created by removing of material, deforming the sheet-metal, and cutting partially and then deforming that partially cut portion of the sheet-metal. The sheet-metal features are classified into two categories as volumetric and deformation. The generic classification of these features has been presented. The volumetric features in sheet-metal parts are classified based on placement of the feature in the part model and type of 2D profile present in volumetric feature and also used for the material removal operations. Deformation features are classified into type (placement of the feature in the part model and type of feature as pure deformation or deformation followed by partial shearing) and nature (type of bends) based on number, type, and arrangements of faces for a feature in a part model.

The features in sheet-metal parts are classified as generic features based on topology and shape information. These features are also classified based on geometric information and information specific to particular context as nongeneric. The generic information can be considered as common to all the applications involved and can also be used for development of common/shared understanding in the product design and development. The nongeneric information is application-/domain-specific so once a generic feature is identified then the nongeneric information can be built around the generic information for a particular application/domain.

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