



A feature-based flat pattern development system for sheet metal parts

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Sheet metal fabrication requires flat pattern development to determine blank shapes and sizes. For a 2D design, bend allowances resulting from metal stretching at bends must be accommodated. In addition to bend allowances, flat patterning for a 3D design involves unfolding of walls and mapping of features such as slots, cutouts, etc., onto unfolded walls. Manual determination of flat patterns is time-consuming and error-prone, especially for intricate parts. Integrated CAD/CAM packages for sheet metalworking that incorporate flat patterning modules can significantly shorten the design cycle. However, these packages are often supported on expensive systems and only concentrate on geometry processing, overlooking design and production rules that can cause fabrication failures.

We developed a PC-based flat patterning system that runs on AutoCAD. The system includes a high-level design module that allows parametric design and modification of parts using standard features. Unfolding and folding are performed in a progressive manner, i.e., bend-by-bend. As design and flat patterning proceed, possible fabrication failures are checked against using geometric reasoning. After unfolding, mould lines and bend lines are displayed for manual dimensioning. The flat pattern data can be generated in the formats of DXF and IGES for integration with software that perform other operations such as nesting, cutting and bending.

1. INTRODUCTION

For many decades, the design and flat pattern development of sheet metal parts have been performed manually or using conventional CAD geometrical procedures. A great deal of knowledge is necessary when determining blank shapes and accounting bend allowances for blank sizes. The common approach is to take the end views of a part and superimpose the geometry at different stages with the calculated bend allowances. Hours of drawing and calculation are required and sometimes hardware tryout is inevitable, especially for parts with complex geometry.

To cope with the rapid changes in production requirements, advanced CAD/CAM tools that incorporate 2D/3D modelling, flat pattern development and other multitudes of operations, have been taken on board. Most of the systems are supported on workstations or mainframes. These systems, like Parametric Technology Corp.'s PROSHEETMETAL [1], Integrgraph's Flat Pattern and Nesting [2] and many others are very effective with their high processing speed, bulk storage capacities and sophisticated operating system, but generally

are too expensive for smaller companies to acquire. Therefore, the advent of hardware development for personal computers (PC's) has made them the natural targets for low cost CAD/CAM systems.

Realising this trend, many PC-based systems dedicated to sheet metal industry have been developed. Auto-trol Technology (UK) Ltd. has developed a series of software that cater for sheet metal design, stress analysis, flat pattern development, nesting and punching [3]. Hagerman & Company has developed an AutoCAD-based unfolding package for 3D wireframe models [4]. 4D Engineering offers a stand-alone PC-based system called Mastercam Fabrix [5]. It is a 3D CAD/CAM package for sheet metal punching and profiling; plasma, water jet and laser cutting; automatic folding and unfolding; and, tool path editing.

Even though some of the existing PC-based systems are rather inexpensive, the application may run across the following problems:

- (1) The in-house drafting package of a company may have to be abandoned if the software incorporates an in-built graphic modeller.

- (2) The operations of some packages require switching between drafting mode and other functional programs such as flat pattern development, nesting, etc.; this is inconvenient for design modification.
- (3) Most of the packages are used primarily for fast geometry processing, but lack the ability to assist inexperienced designers in evaluating the manufacturability of designs.

In view of this, the present work aims to:

- (1) Develop a flexible system using a widely used CAD package as the development platform.
- (2) Provide a convenient design environment, quick and precise flat pattern development methodology and, readiness for integration with any existing systems that use the same platform or accept Drawing Interchange File (DXF) or Initial Graphics Exchange Specification (IGES) format.
- (3) Include in the system the design heuristics which can be the accumulated expert experience and the widely used standards.

The system described herein uses Autodesk's AutoCAD drafting package as the development platform and comprises two main modules: design and flat patterning.

In this paper, the system's concepts for the input and modification of design, capture of part definition, flat patterning methodologies as well as the design heuristics considered are presented.

2. SYSTEM CONFIGURATION

The system runs on an IBM 386, 486 or compatibles, with at least 4 MB RAM and 40 MB hard disk. The hardware configuration involves a VGA display, a keyboard for data entry, a mouse for easy menu selection and a printer/plotter for graphical output. The graphic platform of the system is Autodesk's AutoCAD that runs in Microsoft DOS or Windows environment and the programming language used is AutoLISP.

3. DESIGN MODULE

The system adopts the domain-specific design-with-features approach for design input and focuses on parts constituted by flat plates and linear bends. The approach provides a convenient design environment and enables important design definitions to be captured during the design stage.

3.1. Graphic modeller and representation

A design, in its 2D or 3D configuration, is input in a customised drawing editor. Along with the drafting facilities provided by AutoCAD, a feature library and a design editing library have been embedded in the pull-down menus of the drawing editor. To minimise computing time, the feature geometry is generated in wireframe representation. The thickness of the part is neglected and bends are represented as sharp corners.

3.2. Part modelling

The feature library consists of a set of commonly used sheet metal features which can be divided into two groups according to their characteristics:

- (1) Macro features -- features that form the major shapes of a part. Examples are bends, walls, hems, etc.
- (2) Co-features -- add-ons or inclusions to the macro-features such as holes, slots, etc.

Generally, feature instantiation involves parametric input of feature classes, shapes, orientations, origins and attributes. Feature classes are the names of the features such as "Wall", "Bend", etc. Feature shapes are the outer profiles of features such as rectangular, circular, etc. The system allows design of features with any shape constituted by lines, arcs and circles. Feature orientations are the spatial relationships between plates such as angles between planes and bend angles. Feature origins represent the reference points of the feature topologies. For example, the origin of a polygonal plate is a vertex of the plate, the origin of a circular hole is the centre of the hole, etc. Feature attributes are numerical values that define the sizes and orientations of features. Examples are lengths and angles.

3.2.1. Defining a bend

A bend can be seen as the connector of two straight sections. Figure 1 shows the nomenclature used for a bend [6]. When defining a bend, the user needs to specify the bend angle, bend radius and the sections' measurement methods. After creating a bend, a new plate must be attached to the bend to form a complete connection.

There are three section measurement methods used in the system: "Outer", "Inner" and "Straight". Figure 2 shows the three measurement methods.

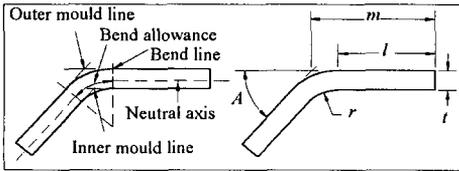


Figure 1. Bending nomenclature: r = bend radius, t = stock thickness, l = length of straight section, m = mould line dimension and, A = bend angle.

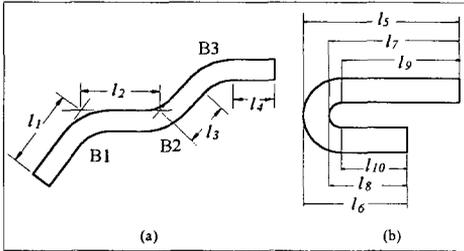


Figure 2 (a) Part measurements (except for a 180-degree bend). "Outer" (l_1 and l_2) for bend "B1"; "Inner" (l_2 and l_3) for bend "B2" and; "Straight" (l_3 and l_4) for bend "B3".
 (b) Part measurements for a 180-degree bend. "Outer" (l_5 and l_6); "Inner" (l_7 and l_8) and; "Straight" (l_9 and l_{10}).

3.2.2. Defining a plate

Before creating a new plate, a bend needs to be defined on an edge of an existing plate. The origin of the new plate can then be specified along, or, on the extent of, the bend edge. In both the 2D and 3D design modes, nominal dimensions are used to specify the sizes of plates, i.e., the user needs not include bend compensations during design.

3.2.3. Defining a co-feature

When adding a co-feature, the user needs to indicate the parent feature and input the attributes in a reference plane of the parent feature. For co-features that change the outer profiles of the parent plate, such as slots, notches, etc., necessary profile updates are made automatically by the program. For example, after defining a slot, the selected edge will be split for the slot opening as shown in Figure 3(a).

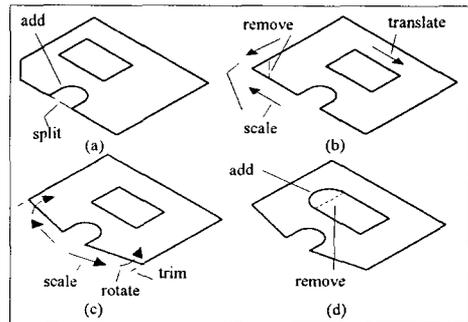


Figure 3. Some examples of design amendments made at the feature level ((a) and (b)) and the feature entity level ((c) and (d)).

3.3. Design modification

Design modifications can be divided into two levels: feature and feature entity. At the feature level, modifications of a feature will automatically be propagated, if necessary, to the related features. As shown in Figure 3(b), after deleting the chamfer, the corresponding plate will automatically be closed. To provide greater design flexibility, the system allows design changes at the feature entity level. As shown in Figure 3, feature entities can be translated, rotated, scaled, trimmed, added and removed. After performing modifications at the feature entity level, the program will check to ensure the closure of close loop features such as plates and holes.

As bends are represented as sharp corners, the bend geometry cannot be visualised graphically. However, the program allows interactive checking and modification of bend attributes. After selecting a bend, the specified bend attributes will be displayed and modifications can be made for the bend angle, bend radius and the sections' measurement method.

Since material thickness is graphically represented as paper thin, the modification only requires re-specification of its value, i.e., no regeneration of geometry is required. This permits a created part to be copied and used for other design with minimal modifications.

3.4. Internal Representation

A textual file, called the part definition file (PDF), is created to store the design data during design stage. The stored information includes part identity, measurement unit, material specifications, feature identities, handles of geometric entities and feature relations.

The user can select required materials and heat treatment conditions from a material database and specify the material thickness. To minimise data storage space and processing time of the PDF, only the feature identity (Wall 1, Bend 1, etc.) and the entity handles (Edge 1, Arc 8, etc.) that constitute a feature are recorded. However, when needed, the program can extract other geometric data such as vertices, normal vectors, etc., using the recorded entity handles. Feature relations are divided into relations between plates ("CNT-TO" -- connected to) and relations of add-ons and their parent features ("PRT-OF" -- part of).

Figure 4(a) shows a sample part created in the design module and Figure 4(b) is the data structure of the feature definitions and feature relations recorded in the PDF.

6(a) shows that wall "W1" has been chosen as the reference plane for unfolding bend "B1".

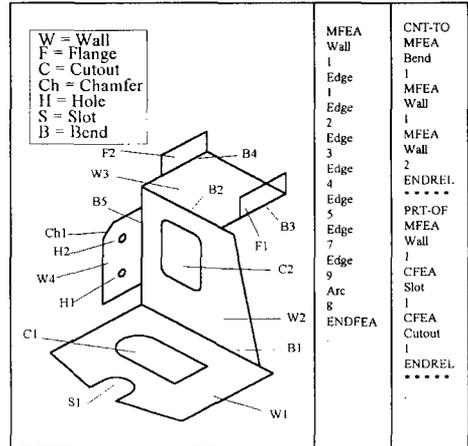


Figure 4 (a) A sample part. (b) A portion of the part definition data.

4. FLAT PATTERNING MODULE

The flat pattern development program is integrated with the design module -- the user does not need to quit the design mode before running the flat patterning program, and design modification is allowed during or upon the completion of the flat pattern development. During flat patterning, the part definition data captured in the design stage are further adapted for determining the blank shapes and sizes.

4.1. Unfolding a 3D design

Figure 5 shows the flowchart of the unfolding algorithm. The sample part shown in Figure 4(a) will be used to illustrate the algorithm.

4.1.1. Selection of bend and reference plane

The module adopts an interactive approach in which a part is unfolded bend-by-bend. After a bend is specified by the user, the program will first set a reference (target) plane (into which the connected features will be unfolded) on one of the connected plates. The user can select this plane or toggle the reference plane to the other connected plate. Figure

4.1.2. Bend allowance and bend compensation

The system uses Sach's rule [7] for the bend allowance calculation because it is commonly used in the industry. In the empirical equation, the bend allowance (*B.A.*) is given as $B.A. = \theta (r + kt)$, where θ is the bend angle measured in radians, r is the inner radius of bend, k is an empirical constant and t is the stock thickness. Material thinning during bending is ignored in the calculation. The constant k , which varies from 0.2 to 0.5 depending on material type, hardness, inner radius of bend and stock thickness, is extracted from a database of the system. The user can edit the database or change the selected k value.

Some recent research has found that Sach's model fails to predict the variations of bend allowance as a function of tooling geometry and material properties [8, 9]. Thus, to provide alternatives for more accurate blank size determination, the present system allows user-defined bend allowances. The user can override the program-calculated bend allowances by other standards or values based on his experience with the material specifications and bending parameters.

A bend compensation (B.C.) is the length to be subtracted from the specified lengths of two connected sections when calculating the blank length. For example, in Figure 2(a), the blank length for the sections with lengths l_1 and l_2 is

$$\text{blank length} = l_1 + l_2 - B.C.$$

"Inner" -- $B.C. = 2 r \tan (\theta / 2) - B.A.$
 "Straight" -- $B.C. = -B.A.$

For a 180-degree bend:

"Outer" -- $B.C. = 2 (r + t) - B.A.$
 "Inner" -- $B.C. = 2 r - B.A.$
 "Straight" -- $B.C. = -B.A.$

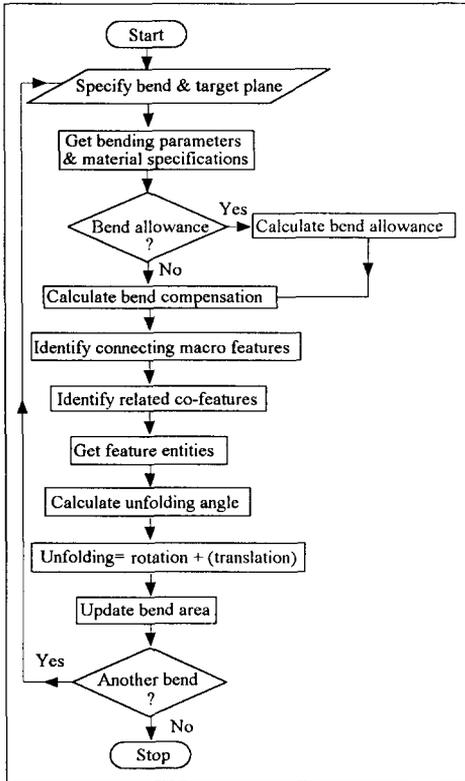


Figure 5. The flowchart of the unfolding algorithm

Bend compensations are calculated based on the bend allowances and specified section measurement methods. The bend compensation equations of the three types of measurement are summarised as follows (refer to Figure 2):

For a non-180-degree bend:

$$\text{"Outer" -- } B.C. = 2 (r + t) \tan (\theta / 2) - B.A.$$

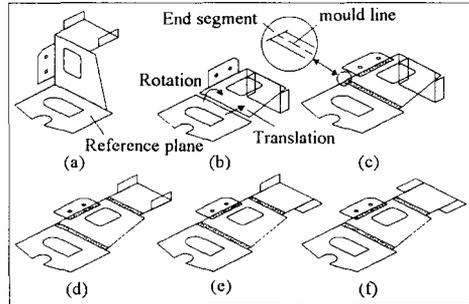


Figure 6. The unfolding steps for the sample part.

4.1.3. Determination of connected features

Based on the feature relations that stored in the PDF, the flat patterning program performs a depth-first search for the connected macro features. After obtaining all the connected macro features, their co-features are obtained. Then, the geometric entities that constitute these features are searched. To avoid repetition in the entity search, co-features that form part of the outer profiles of the parent plates are not considered in the searching algorithm. This is because the entities of the co-features have also been included in the parent features. For example, in Figure 4(a), chamfer "Ch1" is not considered in the searching program since its geometric entity has been included in wall "W4". Figure 7 shows a macro features and co-features trees constructed when unfolding bend "B1".

4.1.4. Calculation of unfolding angle

The entity handles of the connected features are used to extract the entities' in-process positions and orientations, which are in turn used for unfolding angle calculations.

4.1.5. Unfolding

After obtaining the bend compensation and unfolding angle, the geometric entities of the connected features are unfolded. Where a bend compensation is needed, the unfolding process involves two spatial transformations: rotation and translation. For unfolding with zero bend compensation, only rotation is performed.

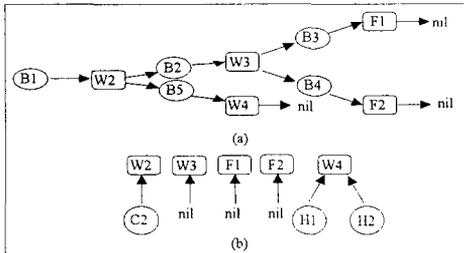


Figure 7(a) The connected macro feature tree for bend "B1"; (b) The related co-feature tree.

The rotation is performed about the selected bend edge for the calculated unfolding angle. The rotated entities are then translated in the direction perpendicular to the bend edge in the magnitude of the calculated bend compensation.

4.1.6. Update of bend area

The mould line, which indicates the location for the bending tool placement, is generated automatically after unfolding. The location of the mould line is parallel to, and, one half of the calculated bend compensation away from, the bend lines. For a negative bend compensation, i.e., where the connected features are translated away from the selected reference plate, a gap is produced after the translation as shown in Figure 6(b). In such a case, the program will generate two end segments to connect the plate. Figure 6(c) depicts the updated bend "B1".

Figures 6(d)-(f) show the subsequent unfolding steps of the sample part. After flat patterning, the user can add dimensions to the drawing to obtain the actual blank size. In Figure 8, some of the dimensions are specified for the 3D configuration and the flat pattern of the part to illustrate the significance of bend compensations on the blank sizes.

4.2. Flat pattern development of a 2D design

Where a design is input in 2D, the flat pattern can be determined in a similar way as unfolding a 3D design except that no spatial rotation of geometric entities is involved; the connected features will only be translated for bend compensations.

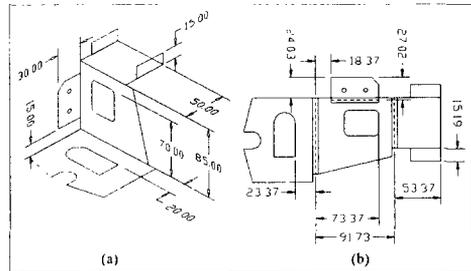


Figure 8. Partially dimensioned 3D configuration and flat pattern of the part.

4.3. Folding up an unfolded part and a 2D design

All unfolded plates can be interactively or automatically re-folded. When folding a bend, the connected features are first translated (for the bend compensation) and then rotated. The folding angle (bend angle) is obtained from the PDF.

Folding of a 2D design allows its 3D configuration to be viewed and any overlapping error can be rectified. Since nominal dimensions are used for a 2D design, the folding will not involve any bend compensation. After all of the bends are folded, the user can unfold them to obtain the actual blank shape and size. In addition to the method discussed in section 4.2, this serves as an alternative approach for determining the flat pattern of a 2D design.

5. DESIGN HEURISTICS

Some design heuristics, which focus on constraints imposed by materials and design parameters, are embedded in the system in the form of production rules. They are discussed in the following:

5.1. Minimum bend radii

The minimum bend radius is the smallest allowable radius that can be bent without material failures such as cracking along bend and end

splitting. A minimum bend radius is dependent upon the material type, stock thickness and heat treatment condition, etc.

When specifying a bend, the minimum bend radius based on the material specifications will be extracted by the program from a database and indicated to the user to serve as a design guide.

5.2. High stress area

High stress areas usually occur at the ends of a bend and possible material failures, like tearing and fracture, can easily propagate from these areas. Also, buckling may occur at the ends of a bend, especially for thick material. The system performs simple geometric reasoning to detect bends with high stress areas and corners that require modification for successful bending. Modification suggestions are provided for alleviating the problems.

5.3. Minimum spacing

A minimum spacing between perforations and bends must be maintained to avoid possible distortion during bending. The system performs such a minimum spacing checking and highlights perforations that violate the heuristics. Re-location of perforations or re-design of plates to provide enough flat material around the perforations will be recommended where necessary.

6. INTEGRATION WITH OTHER SYSTEMS

The generated flat pattern of a part can be used for other process planning operations in sheet metalworking such as nesting, nibbling and laser cutting and bending. The present system can generate the flat patterning results in the DXF and IGES formats for interfacing with the existing CAD/CAM systems that accept the data exchange formats.

7. SUMMARY AND CONCLUSIONS

A flexible design and flat pattern development system for sheet metalworking has been presented. By adding specific design functions and using standard design procedures on a widely used CAD package, the system provides convenient design input environment and readiness for re-design and modification. Necessary design information is captured during design with minimal user

interaction. This information, when used by the system to perform flat pattern development, drastically reduces the tedium of the process as encountered in the conventional approach. Design heuristics are embedded in the system to aid the designer to check against possible material failures and manufacturability constraints thereby reducing, if not eliminating, tedious and costly hardware tryouts. The generated flat patterns can be represented in two standard data exchange formats which are commonly acceptable by the existing CAD/CAM systems. This makes the system a possible platform for an integrated CAD/CAM package for sheet metalworking.

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