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Integrated Feature-Based Modelling and Process Planning of Bending Operations in Progressive Die Design

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This paper describes an integrated modelling and process planning system developed for planning bending operations of progressive dies. The approach is feature- and rule-based. The paper presents a detailed description of the bending structure and its associated bending operations in the progressive die context. The geometrical bend mapping function for feature elements within individual bends, and the transformation matrix for connected sub-bends, are examined and formulated. The bend features of the part as well as their configuration and editing interfaces are defined. The paper also explains the algorithm used for determining the strip layout angle, and width and pitch. The system introduces, for the first time, a newly tabulated interface, which can satisfactorily represent the stations, operations, and their inter-relations for process planning. Configurable case-based reasoning algorithms for automatic operation planning are explored. The system was developed using C++ and ObjectARX of AutoCAD.

Keywords: Case-based reasoning; Feature-based modelling; Process planning; Progressive die design; Sheet metal bending; Strip layout

1. Introduction

In progressive die design, detailed strip layout is affected by the layout angle, the material width and pitch, the burr-side and forming direction, the number of stations, the operations in each station, the type and parameters of each operation, and the sequence of operations to produce each specified feature of the part. However, such design decisions require knowledge support of the tooling structures and of the performance of tedious and error-prone folding and unfolding calculations and drafting work.

Designers like to propose new ideas because this is creative and challenging. They dislike the tedious jobs of detailed calculation and drafting, which are both boring and time-consuming. Traditionally, strip layout is presented in a 2D drawing with sectional views to illustrate the forming sequence and the formed state of the bend structures. It is not easy for designers to visualise the 3D space-state and identify any occurrence of interference. Sometimes, they have to fold a paper mock-up (made by plotting the blank on paper, cutting out and folding up as required) to demonstrate their design feasibility when they discuss the planned strip layout with the other designers. There are several reasons why the strip layout may need to be modified after the first design:

- After discussion, there are usually inappropriate operating parameters or sequences to correct, and operations to add.
- The customer has modified the part structure, the material thickness, width, or pitch. In today's competitive environment, tooling is usually designed concurrently with the part.
- Mistakes are discovered when designing the detailed structure for each operation and station. The simplest example is that idle stations have to be added or adjusted to allow for either insufficient insert space or plate division.

If such modifications are major, it may be necessary to almost totally re-plan. Unfortunately, immediate action and fast results can be expected in most cases as companies are under tremendous pressure to reduce production lead-time.

The solution to this problem is to use computer-aided process planning (CAPP) software in the planning procedure. Over the last two decades, researchers have been trying to develop many systems at various levels to aid process planning of die design. However, most have achieved limited success because of the complexity of the progressive die design and the lack of the explicit knowledge about this field.

In the subsequent sections, we give an overview of the knowledge of bending structures, their properties, and the various bending operations, and the development of a feature-based modelling and process planning system for optimising the parameters and sequence of bending operations is presented. The bending structure of a part and its intermediate bending state can be displayed and updated in 3D wireframe on screen during the configuration, modification and planning stages. More generalised bending structures can be modelled, and

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a configurable case-based reasoning approach has also been developed in addition to the basic manual planning functions. This makes the system more effective and practical. The modelling and planning modules are integrated through ObjectARX within AutoCAD, which is one of the most widely used platforms for progressive die design.

2. Overview

2.1 Bending Structure and Bending Properties

Bends are the most common sheet metal structures of mechanical parts used in electric and electronic appliances. Parts such as chassis, frames, panels, covers, brackets, clips, plugs, and connectors, are examples of bending structures with some substructures (e.g. piercing holes, burring holes, embossments), attached to the base and bending walls. They can be produced quickly and cheaply by cutting and bending processes by progressive dies.

Bending normally refers to the forming process by which a flat metal sheet is transformed into a formed surface. Simple bend modelling systems usually ignore representation of the bending area and tend to suggest or imply the following restrictions:

- Minimum flat length for the bending wall by which the bending moment is applied directly.
- There are no other features (e.g. holes) across the bending area.
- The wall outline is perpendicular to the bending line for ease of modelling.

These rules exclude more general engineering bending cases as shown in Fig. 1:

- There is no flat area left unbent, as shown in Fig. 1(*a*).
- Relief holes and reinforced ribs can be present across the bending area as shown in Fig. 1(*b*).
- The outline is not perpendicular to the bending line, as shown in Fig. 1(*c*).

A practical feature modelling system should take such general cases into consideration.

There is a minimum bending radius for bending a specific material without cracks on the outer tensile surface. Some of the design rules governing bending radius are:

- It is in proportion to the material thickness, i.e. it is smaller for thinner material;
- It is smaller for ductile material, in some cases, even zero;
- It will be relatively larger when the burr-side is at the outer tensile surface;
- It will be smaller for bending lines which are perpendicular to the grain direction of rolled steel [1].

The rules for estimating springback are:

- The bend angle decreases and the radius of curvature increases when the load is released.
- Owing to the elastic recovery, springback will be greater for a higher yield stress, lower elastic modulus, and greater elastic strain.
- For a specified material, a larger bending radius results in a higher tendency to springback [2].

2.2 Bending Operations in Progressive Die Stamping

Using past design experience, a designer will develop a given part structure into a series of intermediate structures that can be produced by relatively simple and typical stamping operations. Some general knowledge about the development and the sequence of bending operations is discussed below:

- "L", "V", "Z", and "U" bending operations are frequently used bending types in progressive dies. Complex bend structures can always be completed by combining such typical bending operations with proven tooling structures. It is the so-called the "divide-and-conquer" method. A more detailed description of this method can be found in Section 4.3.
- Bending can be performed only after cutting off the outline to be bent. Although lancing is a special case, in which cutting and bending are combined into one single operation using the same punch, larger lancing angles or mixed bending shapes would normally require one more bending operation at the end of the process.
- Subfeatures such as piercing holes and deburring holes, can usually be completed before bending if they are not critically related in position to other bends.
- A bending radius of less than the limit can be achieved by normal bending at a reasonably small radius and be followed by coining at the bending area.

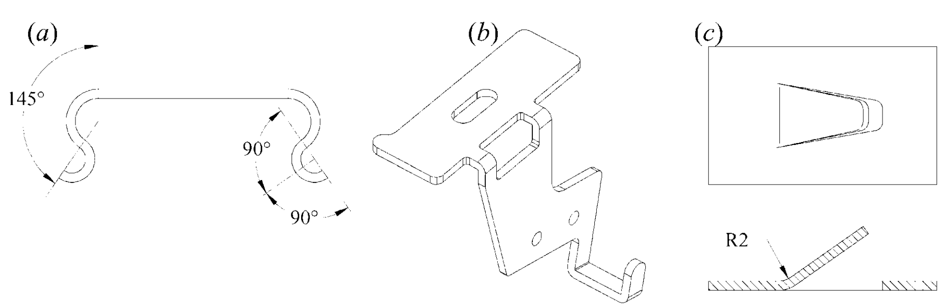


Fig. 1. Examples of bending structures.

- A common method to compensate for springback is to overbend to a smaller radius of curvature and a larger angle. In practice, the designer has only to estimate the maximum springback angle for use to modify the punch and die. The actual parameters will be fine-tuned by trial-and-error at the tooling test and verification stage when the bottom coining state controlled by the clearance between the punch and die is also an effective way to shorten the tuning time.

Bending operations in progressive die design are further limited by factors such as feeding requirements, piloting methods, and press direction, thus they are more complicated and difficult to plan than single die and press-brake design. Smooth feeding, which is the prerequisite for progressive die bending, has to be ensured for all stations. This can be achieved by checking the following:

- Appropriate bridges and tabs should be constructed as supplementary features on the part for holding and carrying purposes.
- The feeding height should be adequate for all up-bends to be completed before the strip reaches the die plate and for downward-bends to be lifted up after the operation.
- Movable (cam or rock) punches, stripper and die inserts should be set back after each operation to enable the bent structure to be lifted up or stripped down.
- Relief openings should be made accordingly in stripper and die plates so that the strip of partially formed parts can be lifted up and moved forward to the next station without hindrance.

Pilots and locators should be applied to selected holes (either newly constructed or existing) or formed structures, for precise repositioning for each operation station. A single slide press machine allows only vertical up and down press movements. Any bend, for which the absolute bending angle is greater than 90°, will normally have to be completed by more than one bending operation and have a cam or rock mechanism applied if it cannot be the second bend of a V or Z bend.

These requirements and considerations are basic evaluation rules for use in verifying the applicability of the planned layout.

2.3 System Architecture

The architecture of the system is shown in Fig. 2.

AutoCAD is selected as the working platform. Bends and part features are customised AutoCAD entities developed using ObjectARX [3] and C++ [4]. They are well integrated within AutoCAD, so that they can be handled like built-in entities for graphic representation and operated in the same manner as normal AutoCAD objects.

A bend feature defines the outline, bending properties, and any subfeatures of a bending wall. Part structures can be easily represented and queried in detail using the bend feature. The part feature is derived from the bend. This is achieved by adding more information and methods to represent the part with its name, number, material, and the operations required to produce the structures.

There are user friendly interfaces to make and edit the bend and part features and to perform process planning. They are all implemented using MFC [5].

Rules for the bends, the part and process planning, both geometrical and technological, have been implemented and integrated with the features and the interfaces using C++ and ObjectARX.

2.4 Related Work

State-of-the-art sheet metal part design systems focus mostly on the modelling of final part geometry with unfolding capability, and they are assembly oriented. Autodesk Inventor [6] and SPI-Sheetmetal [7] are good examples. They are suitable for performing the part assembly preview and are accurate enough in geometrical information for a downstream engineering FEM analysis. Although they have a high-quality solid rendering performance, they are not efficient for planning bending operations. One reason is that they do not have the capability of transforming the flat blank into a series of partial bending structures without the regeneration of excessive new surfaces or bodies, and doing so would consume large amounts of computer memory and storage. Another reason is that geometric reasoning based on the real 3D geometric representation would be difficult, though it is theoretically solvable. For example, to find whether two bends have the same structure using 3D geometric reasoning would be much more difficult and computer-intensive than checking whether their outlines have the same definition feature.

Only a few workers have investigated bend feature modelling and process planning. Wang and Bourne [8] classify a set of bend features to help determine the bending sequence of press-brakes effectively. The bend itself is defined simply by one bending line (contains other information such as bending radius, angle, and deduction) connecting two flat faces. This modelling is acceptable for press-brake bending applications. However, such a simplification is not practical for progressive die design, as partial bending is not editable, and some general structures as shown in Figs 1(*a*) and 1(*b*) cannot be modelled. Choi et al. [9] have developed an automated system to perform process planning and die design for cutting and bending operations. Detailed bending feature definition and how the bending process can be automatically planned are not mentioned and only simplified bending data and structures are illustrated.

Existing successful applications of bending process planning systems primarily focus on press-brakes. Gupta et al. [10] have developed a generative process planning system that can solve the bending sequence, tooling, grasping, and moving problems for robotic sheet metal bending press-brakes. Though the process-planning problem is conceptually similar for press-brake and progressive die bending, the constraints, bending types, and tooling structures are very much different. For example, press-brake bending can align the part at any desired orientation to apply effective "V" bending operations by using standard tooling components. On the other hand, the feeding and bending directions are fixed for bending in progressive dies, in which more bending

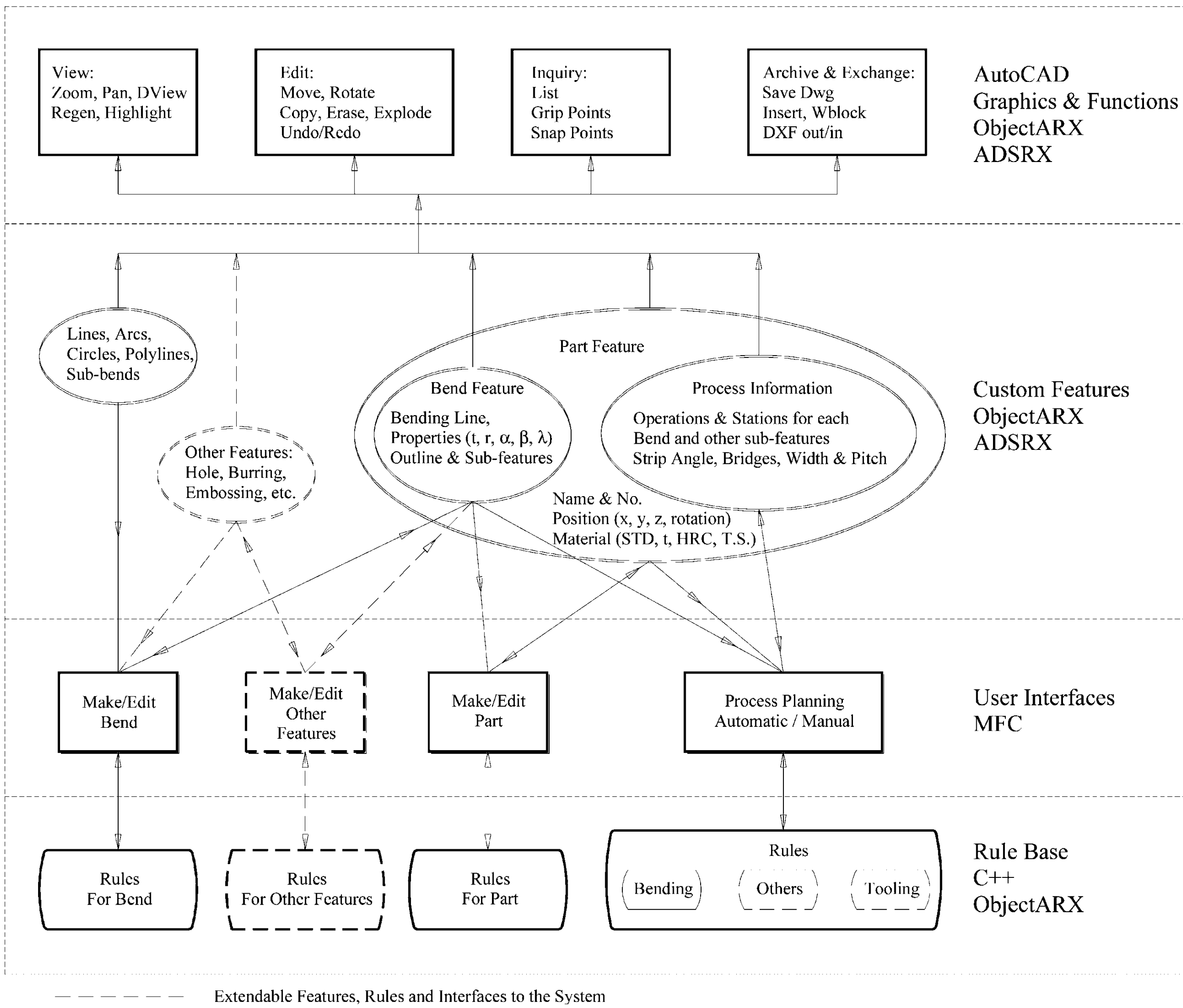


Fig. 2. System architecture.

types and partial bending operations can be applied and the tooling structure varies with local and neighbouring constraints.

3. Feature Modelling of Bend and Part

3.1 Definition of a Bend Feature

Bending can be regarded as the transformation of a flat metal-wall into a 3D shell with part of the cylindrical surface around bending axes which are parallel to a wall. The offset of the axis to the flat wall is the bending radius, and the including angle of the cylindrical surface is the bending angle. Bend feature definition and its associated rules should ideally represent a bending structure with full information, both geometrically and technologically, to meet the needs of identification and transformation, for the development of a process plan. Constructive definition and rules for bend features have been studied and are described as follows:

- *Outline.* This accepts coplanar lines, arcs, circle, polylines, and bends as elements. They should be able to form a closed loop which is continuous, derivative at the bending line, and not self-intersected.
- *Bending line.* A base point and end-point on the positive bending-axis are required to define the bending line. The positive direction is selected so that the bending area of the outline is always on the righthand side of the axis. The bending line of the sub-bend defines its position and orientation for the current bend and so is this current bend under its upper level coordinate system.
- *Bending attribute.* Bending radius, from-angle, to-angle, and neutral layer factor are attributes used to describe and control the bending. The radius should not be less than zero. From-angle and to-angle are first proposed here to represent the partial bending of a target bend. A positive angle means a bending up and negative means a bending down operation. Neutral layer factor relates to material thickness, bending radius, and material property, and the process-state can be determined by rules in a knowledge base or input by the user during configuration time.

3.2 Implementation of Bend Feature

The bend feature has been implemented and integrated within AutoCAD as a customised entity using C++ and ObjectARX. Notable considerations and the advantages can be summarised as follows:

- The outline of the bend is also constructed as a feature, represented by an AutoCAD anonymous block, such that more than one bend can refer to the same outline. This not only saves memory but also makes it more efficient and easier to implement geometric reasoning and outline modification. Two bends have the same geometry only if they refer to the same outline definition and have the same bending attributes. Multiple bends having the same outline can thus be modified at one time.
- It is simpler to represent the 3D wireframe bending area using AutoCAD display functionality and the curve tessellation technique. No splines need be created, and no simplification or restriction (i.e. the outline to be perpendicular with the bending line, no subfeatures across the bending area in some systems) has to be made. The tessellation is dynamic and automatic, so that the user can examine the feature from different viewpoints or view-ports, and can zoom to the finest resolution, as AutoCAD can do, for other curves. This capability uses only display memory without the extra expense of storage or the need to remodel the feature.
- Employing from-angle and to-angle attributes for the concept of partial bending makes it easy to transform a bend into any intermediate bending state (even total unfolding back to the flat blank), with the consistency of having the same bend definition.
- By integration with AutoCAD, the features can be edited using "move", "rotate", "copy", "erase", "undo", "redo", and "explode" commands and even by "grip points". "List" and "object snap" can also be used for inquiry and measurement purposes. The features, stored within the AutoCAD drawing database, can be exchanged using commands such as "insert", "wblock", "DXFIN", and "DFOUT".

3.3 Geometrical Mapping Equations for Folding and Unfolding of a Single Bend

Figure 3 illustrates the geometrical bending model. Suppose there is a bending feature as shown in Fig. 3(*c*), with the expected final bending angle range [0, *to*], and Fig. 3(*b*) is a pre-partial bending with the angle range [*from*, *to*] for this bend. Find the new point (x', y', z') on the partial bent structure with respect to the original point (x, y, z) on a flat blank as in Fig. 3(*a*), the equilibrium position is such that the material is neither compressed nor stretched in the so-called neutral layer:

Let:

$\alpha = from;\ \beta = to$	partial bending angle range
$\varphi = to - from = \beta - \alpha$	partial bending angle
$k = \varphi/\lvert\varphi\rvert$	direction: 1 up, −1 down
$\rho = r + \lambda t$	bending radius of neutral layer
$R = r$	point radius if bending up
$R = r + t$	point radius if bending down

where λ is the neutral factor and t is material thickness

Then:

for $x \le \rho\ |\alpha|$

$$\begin{cases} x' = x \\ y' = y \\ z' = z \end{cases}$$

for $\rho|\alpha| < x \le \rho|\beta|$

$$\begin{cases} x' = \rho|\alpha| + (R - kz)\sin(x/\rho - |\alpha|) \\ y' = y \\ z' = z + (R - kz)\,k(1 - \cos(x/\rho - |\alpha|)) \end{cases}$$

and for $x > \rho|\beta|$

$$\begin{cases} x' = \rho|\alpha| + (R - kz)\sin|\varphi| + (x - \rho|\beta|)\cos\varphi \\ y' = y \\ z' = z + (R - kz)\,k(1 - \cos\varphi) + (x - \rho|\beta|)\sin\varphi \end{cases}$$

These Eqs. are used as the geometrical mapping function to deal with the folding and unfolding transformations for the bending features.

3.4 Matrix Transformation for a Sub-Bend's Position and Orientation

The transformation matrix for sub-bends and other subfeatures on a current bend is used to transform such subfeatures to the same coordinate system (i.e. WCS) for display or geometrical reasoning.

Let A_c^w be the transformation matrix from the current bend to WCS, and A_s^c is the position and orientation of a sub-bend with respect to the current coordinate system, the bend mapping function of the current bend is B_c, then the absolute position and orientation of the sub-bend is A_s^w:

$$A_s^w = A_c^w\, B_c\, (A_s^c)$$

3.5 Interface for Bend Configuration and Modification

Figure 4 illustrates the MFC dialogue box to configure the bend feature. The user must select the outline and any contained sub-bends, to pick the bending line points and to set bending attributes for a valid bend feature. A bend, when successfully made, will be shown as an on the screen immediately in 3D wireframe. If the item "is to be bent" is unchecked, the bend will always be in the unfolded flat state where a base wall may be.

The same interface is also used to edit the bend and its sub-bends. The names of the bends are listed in the "outline/sub-bends" combo-box for selection in this case. When one of them is selected, its bending line points and attributes will be filled in the dialogue items, and the bending wall will be highlighted accordingly in AutoCAD view. The "OK" button becomes "Apply", and the "Clone outline" is enabled for use to make a copy of the outline for editing.

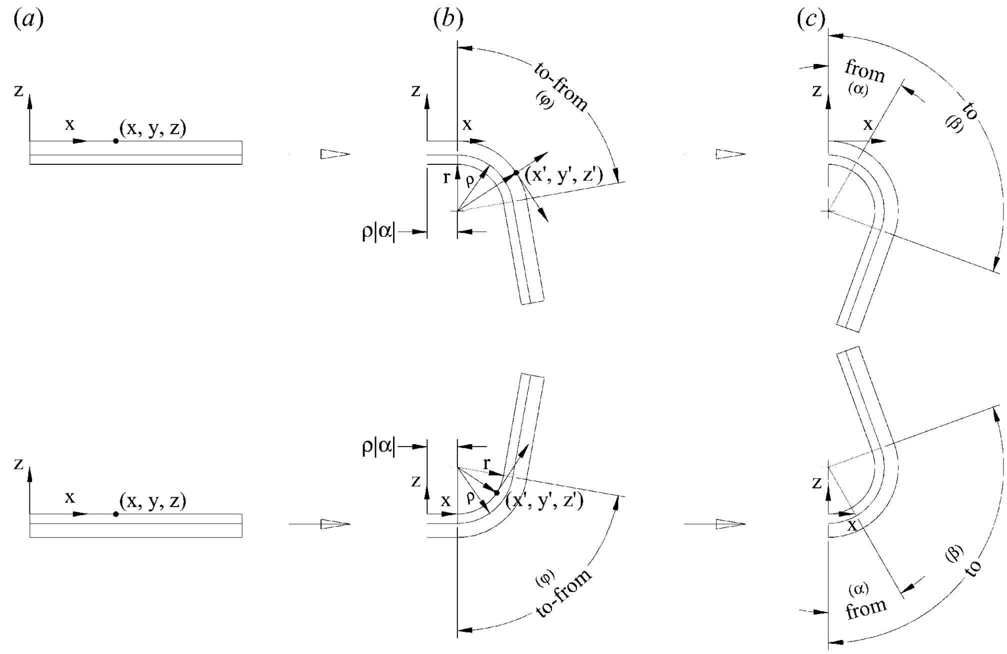


Fig. 3. Geometrical mapping of a bend.

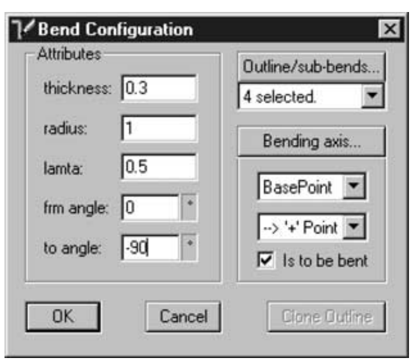


Fig. 4. A dialogue box to make and edit bend features.

3.6 Definition of a Part

The part feature is derived from the bend so that all the structural properties and capabilities are inherited. There are also more attributes defined and data attached for the part name, material, and the operations needed to produce the structures:

- Part name, and part number
- Material name, thickness, state, and strength
- Position and rotation angle
- Tilting angle and margins for the strip layout
- Operations and stations for each bend
- Current bending state of each bend for display

A part can be created in two steps. First, configure a bend with all the structures represented by sub-bends and other subfeatures; secondly, set attributes such as part name, number, material, and position to specify the part. Such a part model has enough information to perform the subsequent bending process planning, which also saves the resulting data in the part feature.

3.7 Interface to Edit Part General Information

General information of the part, such as part name and number, material name, thickness, state and strength, base-point and rotation, and the current bending state of each bend can be edited using the interface shown in Fig. 5. When the user picks any wall (bend) item, the long edit box will be replaced by four other edit boxes so that the user can view and edit the bending radius, from angle, to angle and the neutral layer factor for the current bending state of the bend. The selected bend of the part will be highlighted and updated accordingly.

Other information for process planning, such as layout angle, margins, operations, and stations for each bend is designed through the process planning interface.

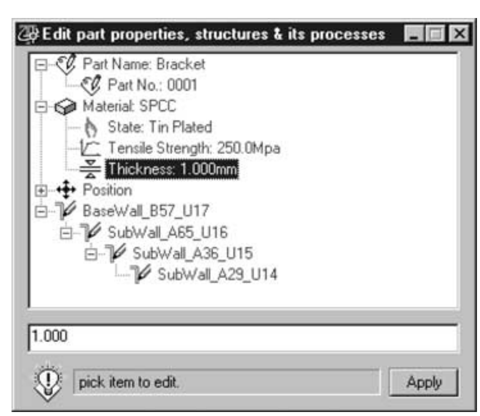


Fig. 5. A dialogue box to edit general information about the part.

4. Process Planning of Bending Operations

4.1 Feature-Tree Traversing and Information Retrieving

Using the bend and part feature definition and the transforming functions, detailed bending attributes, feature relationships, and spatial states can be retrieved and evaluated:

- Owner bends, sub-bends and sibling bends, if any, help to determine the bending sequence, e.g. normally, the owner bend should be bent after or with the sub-bends.
- Full information on bending properties (bending line, outline, radius, bending angles, etc.) for each bend, so that every pair of bends can be examined to see whether they are parallel or have the same outline and bending attributes.
- All the bending operations and stations planned for each bend, thus partial-bent state (up or down, convex or concave) and the last bending station number can be acquired before planning the current bending operation.

4.2 Determining Layout Angle, Width, Pitch, and Material Utilisation

Figure 6 shows an example of a strip where,

α	tilting angle
A	upper margin
B	lower margin
C	adjoining margin
H	height of tilted blank at angle α
Width	strip width
Pitch	layout pitch

The procedure to determine the optimised layout parameters is shown in Fig. 7:

- Set the upper, the lower, and the adjoining margins to accommodate the carriers, bridges and relief-piercing holes.
- Retrieve the flat blank outline from the part and calculate the area.
- Obtain enlarged blank outline offset by half of the adjoining margin (geometric degeneracy must be dealt with.

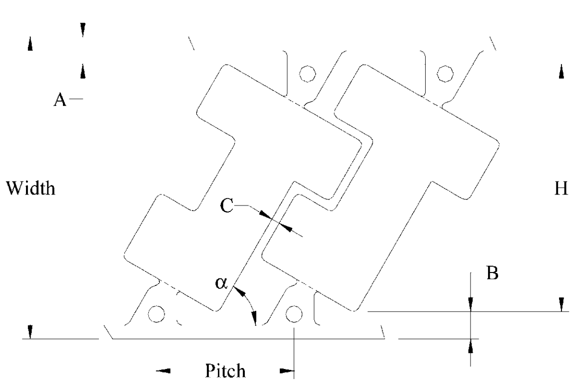


Fig. 6. Strip layout parameters.

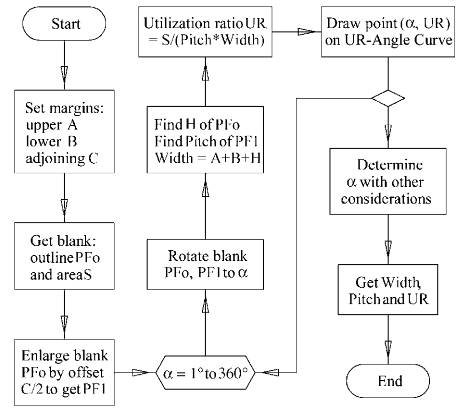


Fig. 7. The flowchart to determine layout parameters.

- Loop from 1° to 360°, rotate the blank outlines, obtain the width, pitch, and utilisation ratio to draw the utilisation rate (UR) – angle curve.
- Consider other aspects such as the anisotropy of bending ability and the smooth feeding requirement to select a tilting angle with an acceptable high utilisation of material, obtain the resulting width and pitch of the layout.

4.3 Typical Bending Operations in Progressive Die Stamping

Typical bending operations can be achieved with proven tooling structures and the knowledge about their precision control based on the experience of the toolmakers, thus they can be applied as elementary bending steps for all the bending structures in a progressive die design.

The common bending types are "L", "V", "Z", and "U" as given in Fig. 8. They can be used as solved cases for process reasoning and planning. The bending type "L $<$ 90° down" is the simplest and the most controllable; the "V down" is ranked second in terms of simplicity and controllability; and "Z down" is ranked third. Normally, a bending-up requires a pressure-pad to hold the material before the operation unless it can be planned as the sub-bend of a "V" or "Z" bending. "U" bending is the combination of two or more "L", "V", or "Z" operations at the same station with approximate symmetric geometry and the same bending parameters. As it is a balanced and stable process, "U" bending is always preferred in process planning.

4.4 Configuring User Preference for Bending Operations

There are different circumstances and considerations where the user may have different preferences for applying the bending types. Factors such as the limitation of each bending type, the constraints imposed by the completing direction for all the bends, and the springback compensation (shown in Fig. 9) may also require different preferences, as discussed below:

- Bending types to apply: "L", "V", "Z", and "U". Sometimes, a user would limit the use of "V" or "Z", or may prefer "V" rather than "Z".

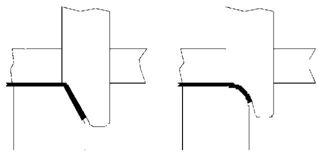
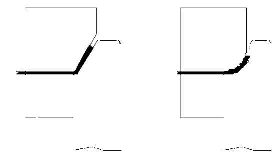
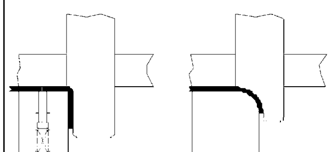
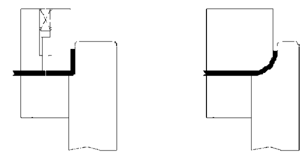
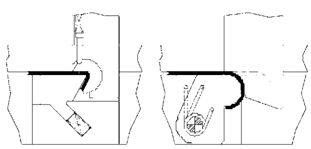
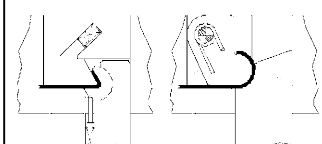
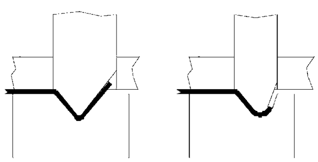
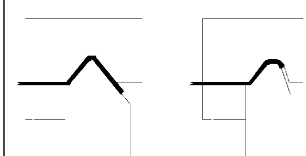
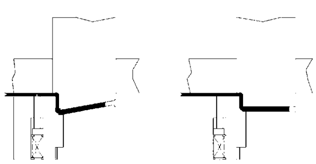
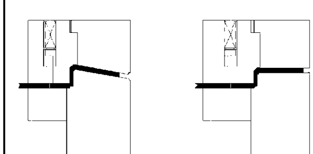
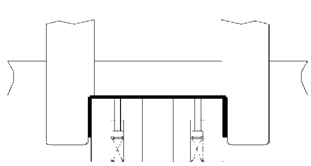
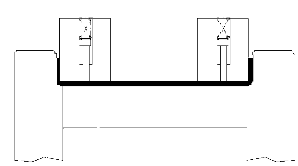
Bending Down	Description	Bending Up
	Type: "L" Angle: < 90° Tooling Structure: Down: Punch & Die insert Up: punch, pad & stripper insert Precision Control: Over-bending	
	Type: "L" Angle: = 90° Tooling Structure: Down: Punch & Die insert Up: punch, pad & stripper insert Ejector for bend with straight wall Precision Control: Coining	
	Type: "L" Angle: > 90° Tooling Structure: Down: Punch & Die insert Up: punch, pad & stripper insert Cam or rock insert Precision Control: Over-bending	
	Type: "V" Angle: $\alpha 1 < 90°$, $\alpha 2 < \alpha 1 + 90°$ Tooling Structure: Down: Punch & Die insert Up: punch, pad & stripper insert Precision Control: Coining, Over-bending	
	Type: "Z" Angle: $\alpha 1 = 90°$, R2 > Rmin Tooling Structure: Down: Punch & Die insert Up: punch, pad & stripper insert Ejector Precision Control: Coining, Over-bending	
	Type: "U" 2 or more concurrent "L", "V" or "Z" Angle: near equal Direction: same down or up Bending lines: 180° or near 180° Tooling Structure: as "L", "V" & "Z" Precision Control: as "L", "V" & "Z"	

Fig. 8. Typical bending types applied to progressive die design.

- Maximum "L" bending angle by a single operation. The default value is 90°. In the case of a material having a high springback tendency, some users would like to have a smaller bending angle allowance to ease the springback control for the larger over-bending angle and the work-hardening effect of multiple operations.
- The smallest draft angle of "V" or "Z" bending for the material to move into and to be lifted up from the die cavity.

Critical offset of two bending lines to force "V" or "Z" bending to be applied. When the offset is too small, the second punch would be too thin if two separate "L" bending operations are to be applied.

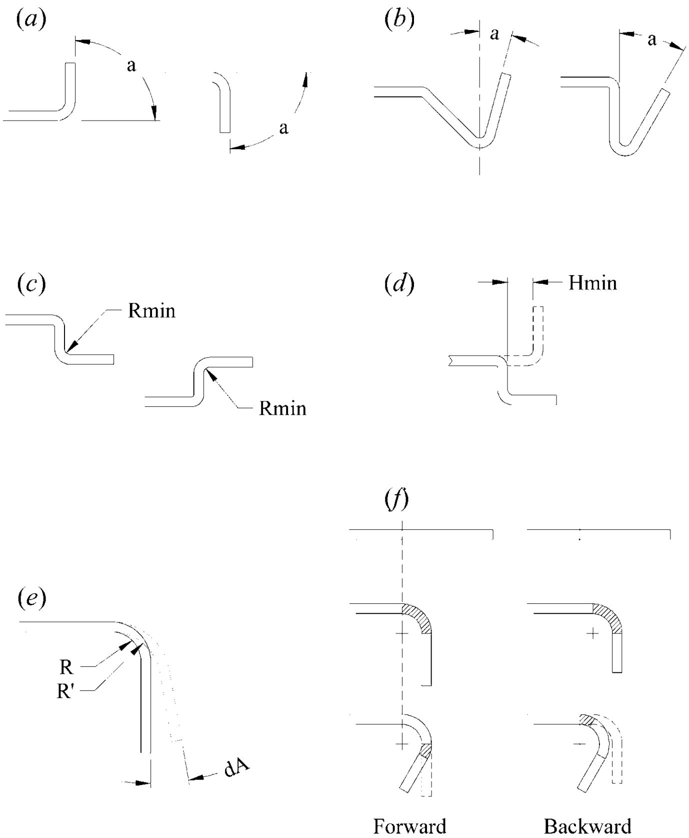


Fig. 9. Limitations, springback and completing direction. (*a*) Max L-bending angle. (*b*) Min V and Z draft angle. (*c*) Min Z punch radius. (*d*) Min offset not to apply Z or V. (*e*) Springback of angle and radius. (*f*) Bend completing direction.

- The smallest "Z" bending punch radius for the material to move smoothly along the punch head without scratching.
- The progressive completing direction for a bend must be decomposed into several partial-bending operations.
- Estimated springback angle loss and the compensation method. Springback results in both angle and radius changes and will be greater for a larger bending radius. Thus, radius compensation cannot be ignored involving large bending radius.

The preference-configuring interface has been implemented as shown in Fig. 10. The icons for each item can pop up a related illustration similar to those shown in Figs 8 and 9.

4.5 Case-Based Reasoning and Planning of Parameters and Sequence for the Bending Operations

The case-based reasoning (CBR) technique solves new problems by adapting previous successful solutions to similar problems. Over the last few years, CBR has increasingly been applied to more applications [11]. In this system, a part structure is modelled with a feature-tree so that it can be traversed and retrieved programmatically. The classified typical bending types are retained as solved cases, and the user configurations

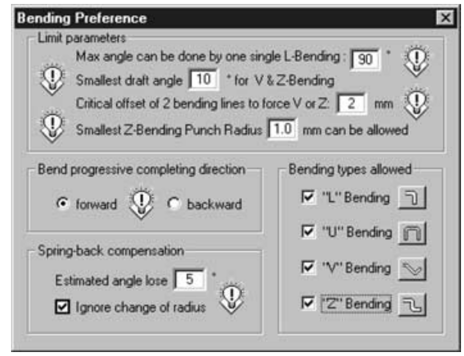


Fig. 10. Configure preference for bending operations.

have been formulated as adaptation rules. The reasoning and planning of bending operations for a specific bending part structure comprise:

- Matching possible bending types by checking the bending properties and bending states of current and owner bend (for "L", "V", and "Z") as well as other sibling bends (for "U").
- Verifying the bending type and adapting user-preferred bending parameters.
- Determining bending sequence and its station number.

Figure 11 shows the primary case matching and streaming flowchart. The essential module to plan the "V" and "Z" bending is shown in Fig. 12 in which, how the user-preferred parameters are applied, is elaborated in detail. The "L" bending planning module is relatively simple, and the "U" bending planning is actually to adjust the bending stations for the planned "L", "V", or "Z" bending operations.

An often-used example demonstrates that different results can be obtained using the CBR approach under respective user-preferences. In Fig. 13, the part can be planned using three possible methods:

1. When "U" and "Z" bending are preferred.
2. When "L" and "U" bending are preferred.
3. When "V" and "U" bending are preferred.

More plans can be made by setting the maximum "L" bending angle, the completing direction and the springback compensation.

4.6 Tabulated Interface for Planning Bending Operations

An interface for both manual and automatic planning of bending operations has been developed in a table form, as shown in Fig. 14. It can represent the parameters and sequence of bending operations as well as the bending state and bending types in stations for related bending structures of the part.

The first column displays the station numbers and can dynamically match and list all the bending types in each station when receiving user selections. Other column headings are filled with bend identifications (handle and outline name) and the desired bending attributes (radius r, from-angle α, to-angle β), while the subitems of columns can hold bending operations

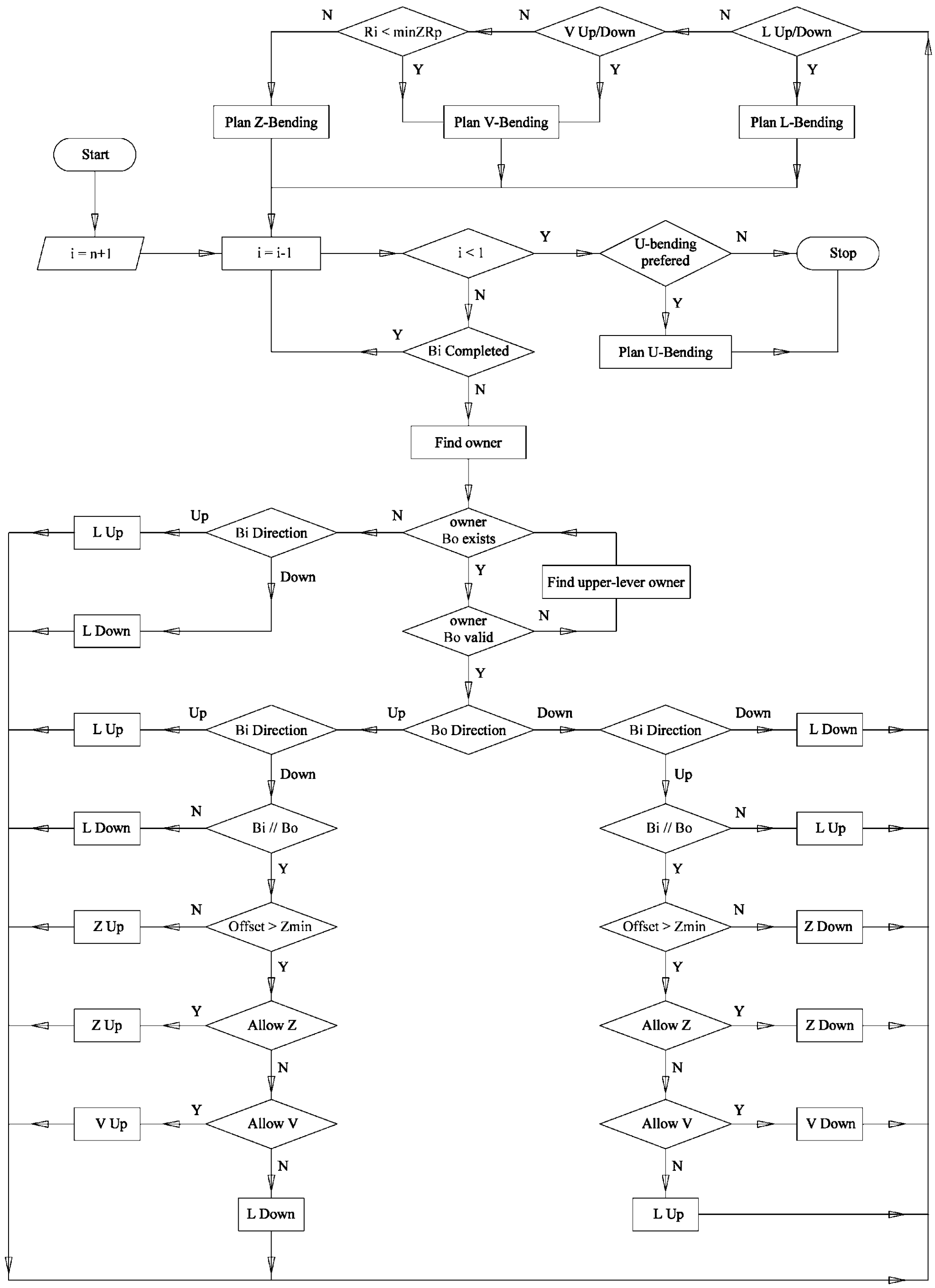


Fig. 11. Flowchart of primary bending-case matching and streaming algorithm.

which are also expressed by "radius, from-angle and to-angle" for precise partial bending representation. Using this format, all existing operations, and the sequence for a bend, can be located in the related column; and all the operations can be retrieved and bending types can be matched in each row of station.

All the commands, functions and configuring interfaces for the planning have been integrated in five pull-down menus:

- Planning –> *New empty*, *Restore from part*, *Knowledge-based auto*, *Save to part*, *Output 3D-layout and exit*.
- Edit station –> *Insert*, *append*, *and delete*.
- Move operation –> *Current up/down*, *current & following up/down*, *current & previous up/down*.
- Configure –> *Strip layout*, *Bending preference*, *Part to be updated by station selection*.
- Tools –> *Material utilisation curve*.

The strip-layout configuration interface can calculate the utilisation ratio accordingly when a user presets the estimated margins and the preferred tilting angle. The curve for material

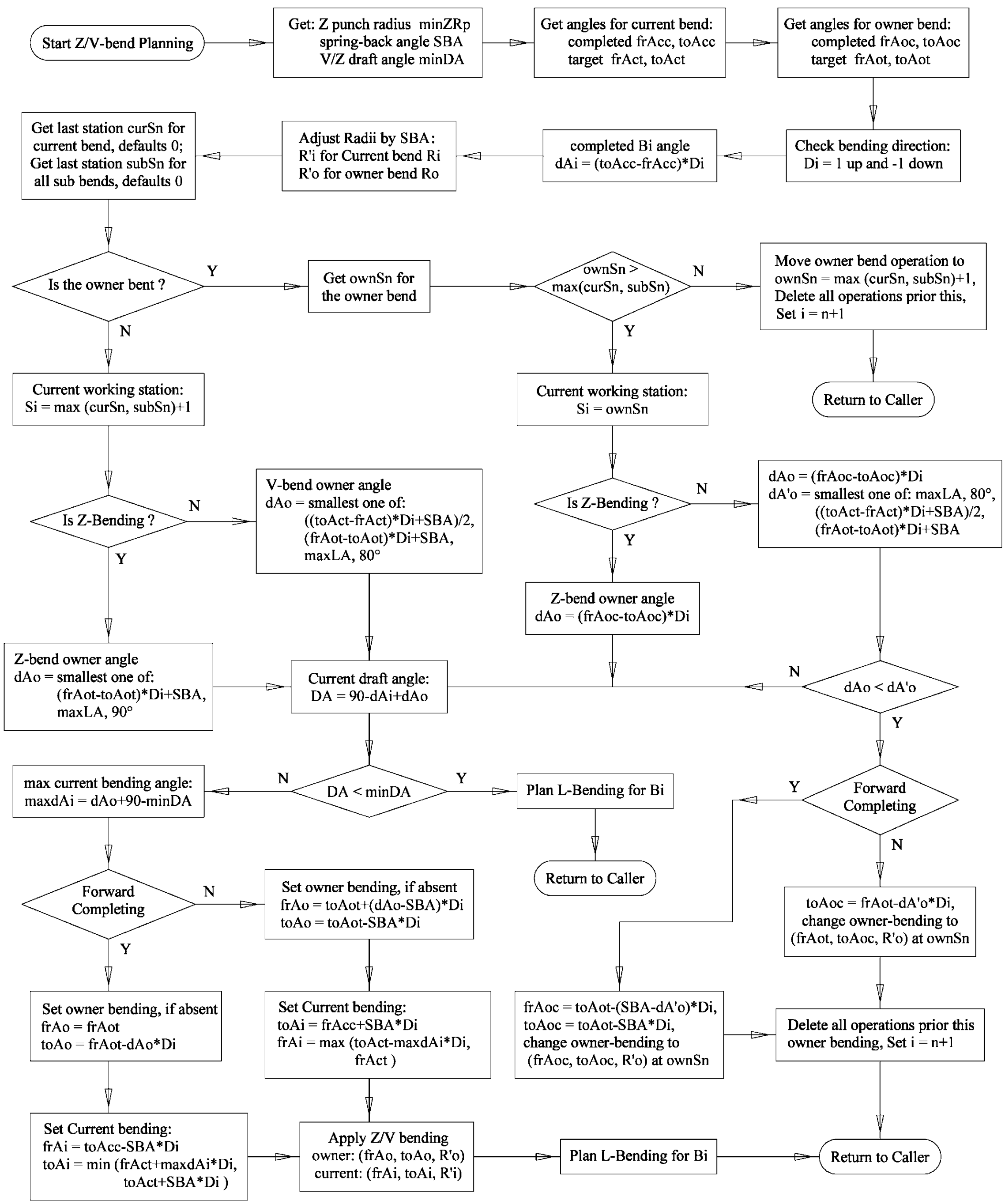


Fig. 12. Flowchart to match "V" and "Z" bending.

utilisation versus tilting angle (0°~360°) for the preset margins can be referenced by a user when deciding the final layout parameters.

The bending preference configuration interface described earlier has been integrated for use in the automatic operation reasoning and planning. Manual adjustment of the bending operations and stations can also be made by the user to meet his final design requirements. The subitems for operations can be edited *in situ* and navigated with arrow keys.

When the *Part to be updated by station selection* menu item is checked, the 3D wireframe part will be updated dynamically to reflect its bending state at the current station which the user has selected.

The current process plan can be cleared to start a new one, can be saved to and retrieved from the part. A 3D wireframe layout of partial bending parts at each station can also be generated. An example of the 3D layout is shown in Fig. 15, which represents the planned bending parameters and sequence shown in Fig. 14 with 10° springback angle compensation.

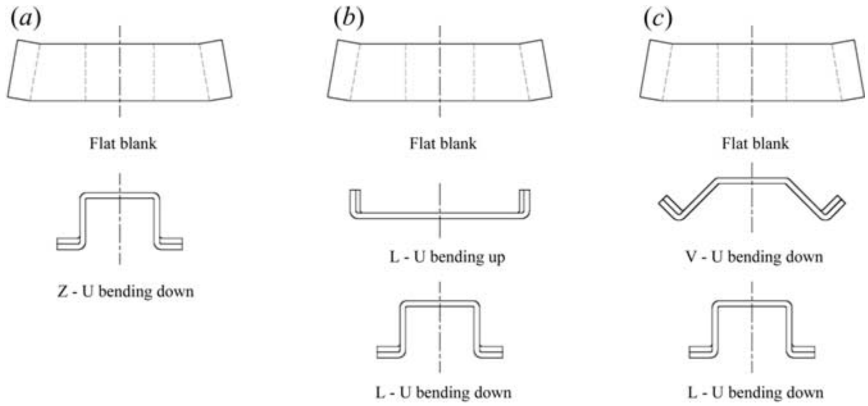


Fig. 13. Possible bending operations can be matched under different user preference. (*a*) Prefer "Z", "U". (*b*) Prefer "L", "U". (*c*) Prefer "V", "U".

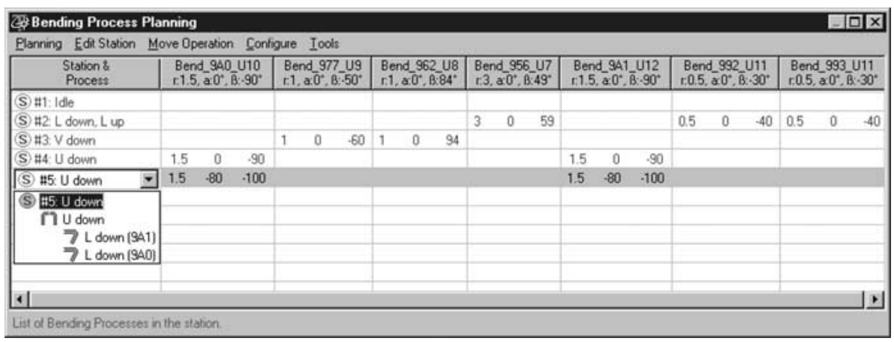


Fig. 14. Interface for planning bending operations.

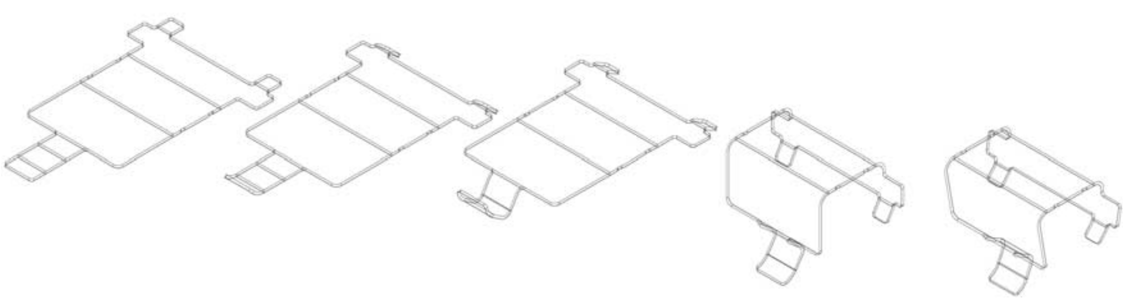


Fig. 15. 3D layout of planned bending operations.

5. Discussion and Conclusions

This paper describes an integrated feature-based modelling and process planning system for bending operations in progressive die design. Starting from an unfolded flat blank or the customer's part drawing, the user can produce the 3D wireframe bend structure, and edit or adjust any parameter afterwards. Once the bending structures and the part information are configured, the user can bring up the process planning interface and perform the process planning both automatically and manually. This system has the following advantages:

- The direct and natural definition of bend features enables the modelling of more generalised bending structures.
- The feature is represented consistently in its design life cycle from flat blank to partial bending states, and to the final structure. The geometry of the part is controlled only by bending parameters. There is no need for additional geometry elements or primitives generated for graphic representation. The data structure is compact and efficient.
- The system is fully integrated with AutoCAD, no switching into third-party packages is required for the modelling and planning. The working interfaces are user-friendly. Process planning, whether automatic or interactive, is under the total control of the user.

With the feature-based part and process representation and supporting rules, the human planner is encouraged to, and can easily, try out different solutions or make some refinements to obtain the optimum design solutions, without the time-consuming calculating and drafting work. This makes it possible for the planner to concentrate on the more creative aspects of the design task.

This system has been implemented in C++ using ObjectARX SDK 2.0 using AutoCAD R14 platform. The bend and part features have been developed as custom AutoCAD entities. Virtual functions for graphical representation of the bend and part have been implemented using the bend mapping function, geometric transformation matrix and curve tessellation techniques. All the interfaces are dynamically linked MFC dialogue boxes. All the data for the feature, the part, and the process are stored within the AutoCAD drawing file. The program has been fully tested under Win98 and NT4.0 operation systems for PCs.

By itself, the system is suitable for design work, however, the following extensions are suggested for future work:

- Addition of other sheet metal stamping subfeatures (e.g. extruded holes).
- Development and integration of tooling configuration and reasoning rules.
- 3D solid model representation of parts for better visualisation.

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