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ORIGINAL ARTICLE

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Development of a process sequence determination technique by fuzzy set theory for an electric product with piercing and bending operation

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Abstract This paper describes a research work to develop a computer-aided design of a product with bending and piercing operations for progressive working. The approach to the system is based on knowledge-based rules. Knowledge for the system is formulated from plasticity theories, experimental results and the empirical knowledge of experts in the field. The system has been written in AutoLISP with AutoCAD on a personal computer and is composed of three main modules: input and shape treatment, flat pattern layout, and strip layout modules. The system is designed by considering several factors, such as piercing and bending sequence by fuzzy set theory, complexities of blank geometry, punch profiles, and the availability of press equipment. The strip layout module generates the 3D strip layout drawing with the punch profiles for the external area of a product according to the results of the FVM set. The system could serve as a valuable system for experts and as a dependable training aid for beginners.

Keywords Piercing and bending sequence · Flat pattern layout · Fuzzy set theory · Knowledge based rules · Strip layout

1 Introduction

Experience and intuitive decisions have mostly guided strip layout for forming by bending and piercing. In order to solve this manufacturing problem, workers have reported the automation of computer-aided process planning for the design of products by formulizing the experience of skilled engineers [1–7]. Fogg and Jaimson developed an improved PDDC [1]. Shibata and Kuni-tomo followed them by developing a CAD system which produces a screen-output for blank- and die-layout [2]. Nakahara introduced a system for a progressive die design [3]. Wang and Chang studied determination of the bending sequence in progressive die design [4], and Nee et al. developed a system for feature-based flat patterns [5]. Choi et al. developed an automated process planning and die design for blanking or piercing of irregular shaped sheet metal product [6, 7]. Also, Ong et al. [8] and Aomura and Koguchi [9] developed an automated process planning theory for bending sequences by an intelligent inference system.

In this study, the system developed organizes the design rules of piercing and bending operations and determines the sequencing process by considering several piercing and bending factors and adopting a fuzzy set theory. It constructs a fuzzy matrix for calculating fuzzy relationship values and determines the optimum based on combining several rules with fuzzy reasoning. The strip layout module of the system is able to carry out bending and piercing operations for a 3D electric product. The results obtained using the modules enable the manufacturer to be more efficient by progressive working of electric products.

2 Configuration of the system

The system is composed of three modules: input and shape treatment, flat pattern layout and strip layout modules. It is accomplished without interruption while processing, as each module holds rules and a database in common. It is easy to use, as the dialogues are user-friendly with appropriate prompting statements for the various data required. The configuration of the system can be seen in Fig. 1.

For an electric product requiring piercing and bending operations, a user inputs the items in the input and shape treatment module. The items are the shape of the product,

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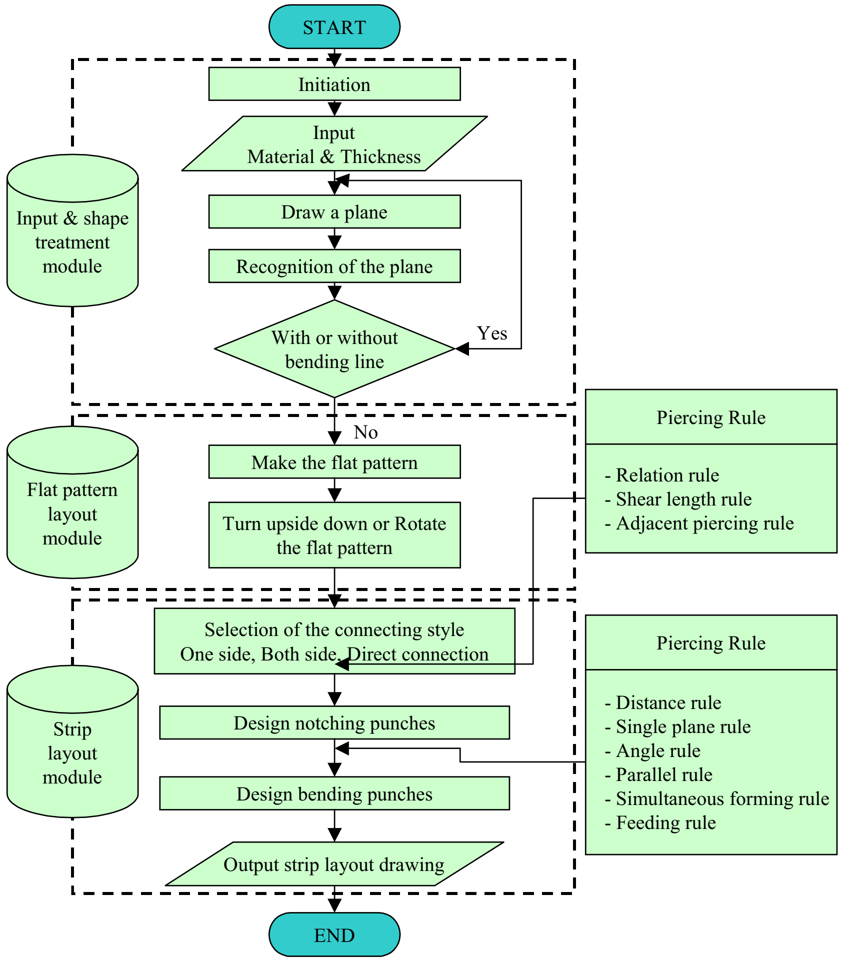


Fig. 1 Configuration of the system for progressive working

bend angle, and bend radius required. Then, the system carries out the recognition process of these data and transfers the results of the shape treatment into the flat pattern layout module. A flat pattern layout drawing considering bend allowances is generated in this module and the results are transferred into the strip layout module to carry out strip layout automatically. A functional description of the system modules is presented as follows.

2.1 Input and shape treatment module

The input and shape treatment module is divided into submodules, which are then the input and shape treatment submodules. If a user inputs material type, thickness, width, heat treatment condition, and the shape of a product to generate an AutoCAD drawing by hand, or outputs a drawing file on the screen, the input submodule auto-

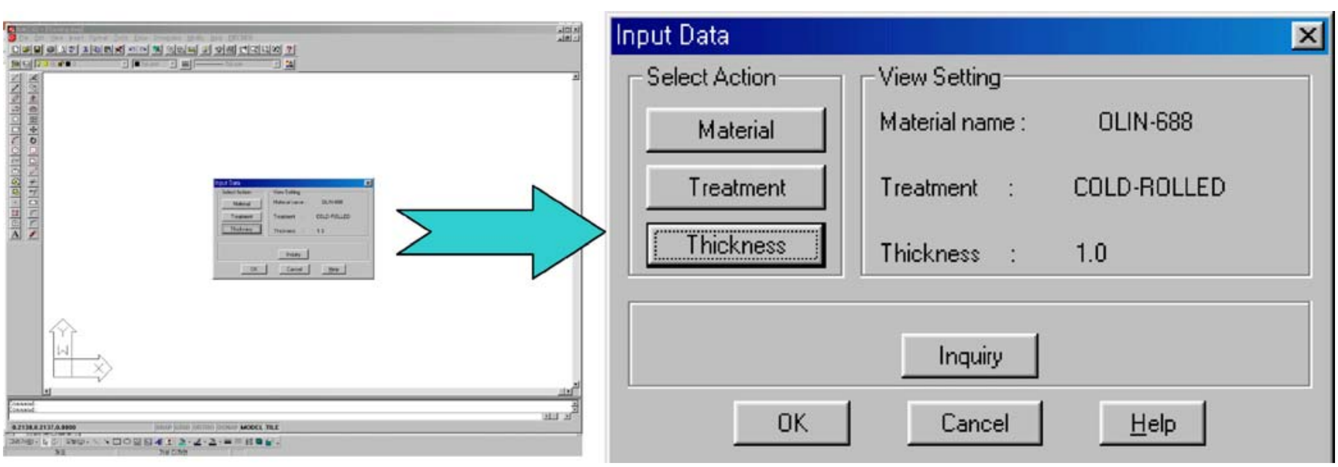


Fig. 2 Input of material condition of a product

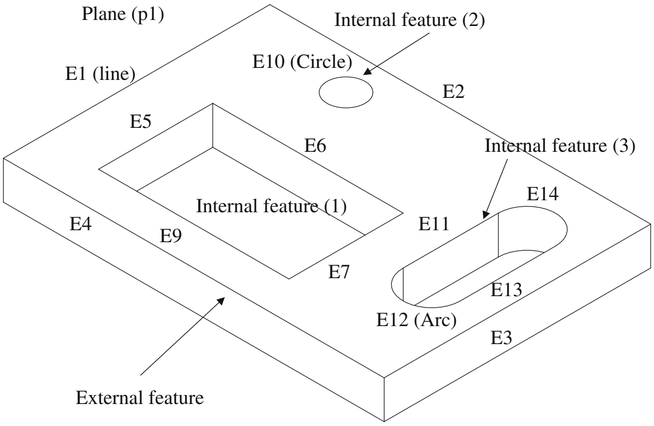


Fig. 3 Constitution of the list for recognizing the shape of a plane

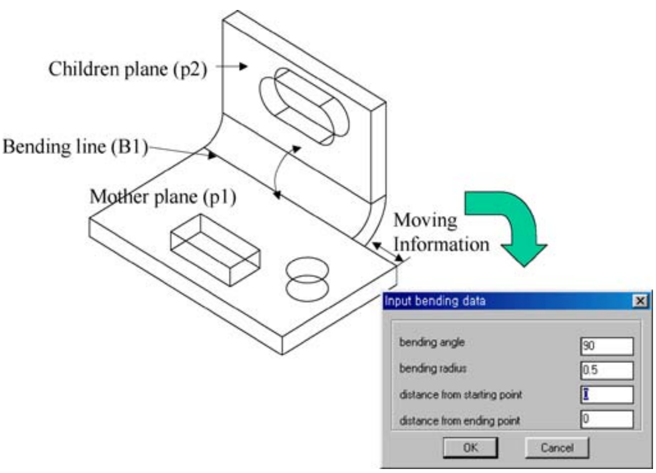


Fig. 4 Constitution of the list for recognizing the bending part of a product

matically reads the information about the mechanical properties of the material from the database. The shape treatment submodule converts the shape data into numerical data for recognizing a 3D shape product. Figure 2 shows input of the material condition of a product.

2.1.1 Shape list of plane

Assembling planes divided by bends constitutes a product. Each plane is composed of an outer shape, inner hole, and slot. The entities of a product drawing organize the list into lines and arcs or circles. Figure 3 shows the constitution of entities for recognizing inner shapes of a plane.

- List representation constituted by lines and arcs (0.0 (S_p E_p) (S_p E_p) ………… (S_p E_p C_p) (S_p E_p C_p) ……….…..)
- List representation constituted by circles (0.0 (C_p R) (C_p R) (C_p R) …………………………….)

where "S_p E_p" is a line of the drawing entity, " S_p E_p C_p" is an arc, "C_p R" is a circle, "$S_p(X_s\ Y_s\ Z_s)$" is a starting point, "$E_p(X_e\ Y_e\ Z_e)$" is an endpoint, "$C_p(X_p\ Y_p\ Z_p)$" is a center point, and "R" is a radius.

In order to recognize the shape of a drawing, the list of lines and arcs reorganizes drawing entities as closed loops.

(0.0 ((P_1 P_2) (P_2 P_3 P_{c1})(P_3 P_4) ……..($P_{n\text{-}1}$ P_n P_{cn}) (P_n P_1))

((q_1 q_2)(q_2 q_3)(q_3 q_4 q_{c1})……..($q_{n\text{-}1}$ q_n q_{cn})(q_n q_1))

In "($P_{n\text{-}1}$ P_n P_{cn}) (P_n P_1)" , "P_n" is the endpoint of "$P_{n\text{-}1}P_n$ P_{cn}" and the starting point of "P_n P_1", and " P_{cn} " is the center point of an arc.

In "$P_1(X_1Y_1Z_1)$", X_1 has the smallest x-coordinate in the closed loop of "P" type. Based on the point "P_1", the closed loop of "P" type has the entities in the clockwise direction.

Each internal and external shape composed of the closed loops is listed in one plane. By assembling these plane lists, the shape lists of a product are organized as follows.

("P_1" (external feature internal feature(1) internal feature (2) ……..internal feature(n)))

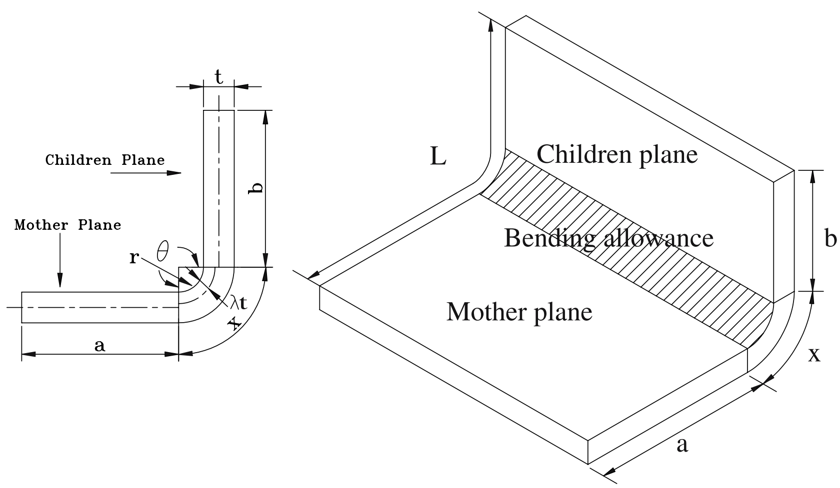
("P_2"(external feature internal feature(1) internal feature (2) ……..internal feature(n)))

("P_n" (external feature internal feature(1) internal feature (2) ……..internal feature(n)))

2.1.2 Bend list of a product

Information detailing bend angle and line and the relationship of planes connected to one another should be defined for

Fig. 5 Calculation of the bending allowance between the mother plane and children planes



a product involving bending and piercing operations. The information for a bending operation is composed of the entities of bend line, bend angle, bend radius, and the movement of bend line. The information of a plane is composed of a list of a mother plane and a rotated children plane.

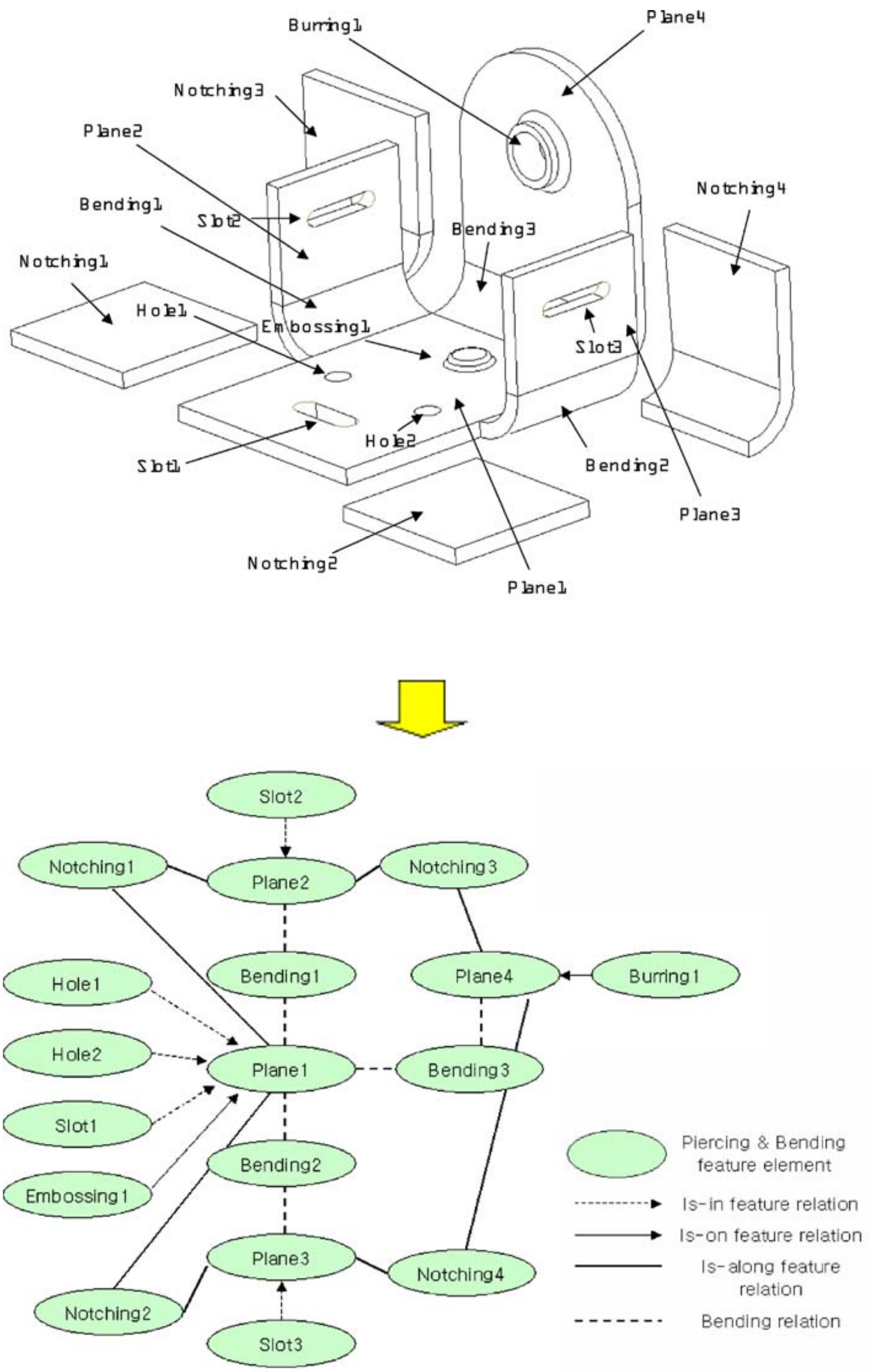
(“B_1” (information bending line) bending line, bending radius, information of bending line movement, referenced plane, rotated plane)

(“B_2” (information bending line) bending line, bending radius, information of bending line movement, referenced plane, rotated plane)

(“B_n” (information bending line) bending line, bending radius, information of bending line movement, referenced plane, rotated plane)

Figure 4 shows the dialogue box for recognizing the bends of a product.

Fig. 6 Explanation of relation rule with feature model



2.2 Flat pattern layout module

The flat pattern layout module calculates bend allowances with bend radius, bend angle extracted from the bend list recognized in the shape treatment module, and coefficients according to material type read from the database. Figure 5 shows the bend allowance between a mother plane and the children plane. The unfolded length of a flat pattern layout is calculated as follows.

$$L = a + b + x, \quad x = \frac{\theta}{360} 2\pi(r + \lambda t) \qquad (1)$$

where λ is the coefficient obtained from the database according to r/t.

When the bending lines are unfolded from the bends one by one in the reverse order of folding them, the planes associated with the bends are automatically compensated by the bending allowances calculated.

2.3 Strip layout module

The strip layout module automatically decides the shapes of the punch profiles for the external area of a product and carries out piercing and bending. The module also determines the order of the process, which is capable of progressive working based on the rules, influencing the strip layout of the electric product. The rules are as follows.

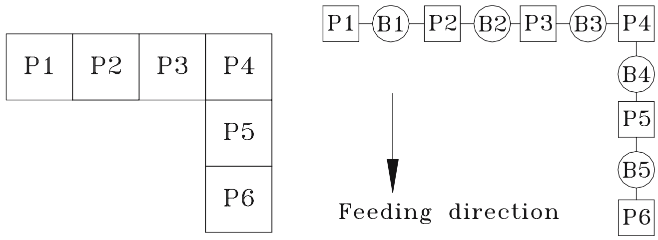


Fig. 8 The product structure of a flat pattern. **a** Flat pattern. **b** Product structure

2.3.1 Process planning rules for piercing process

The rule and the database as process variables are derived from plasticity theories, relevant references and the empirical know-how of experts in the blanking or piercing industries. The fuzzy set theory constructs a fuzzy matrix for calculating fuzzy relationship values and determines the optimum notch shape by combining several rules with fuzzy reasoning. As the design procedure and experience of field experts are quantified, even a novice is able to obtain results comparable with those of a skilled engineer.

1) Relation rule

Three types of relations among stamping features, i.e. is-in, is-on, and is-along are represented in the relation rule. Hole and slot in the plane are defined as the “is-in” relation; embossing, burring and knurling on the plane as the “in-on” relation; and notching, and piercing of the outer feature along the plane as the “is-along” relation. Each feature

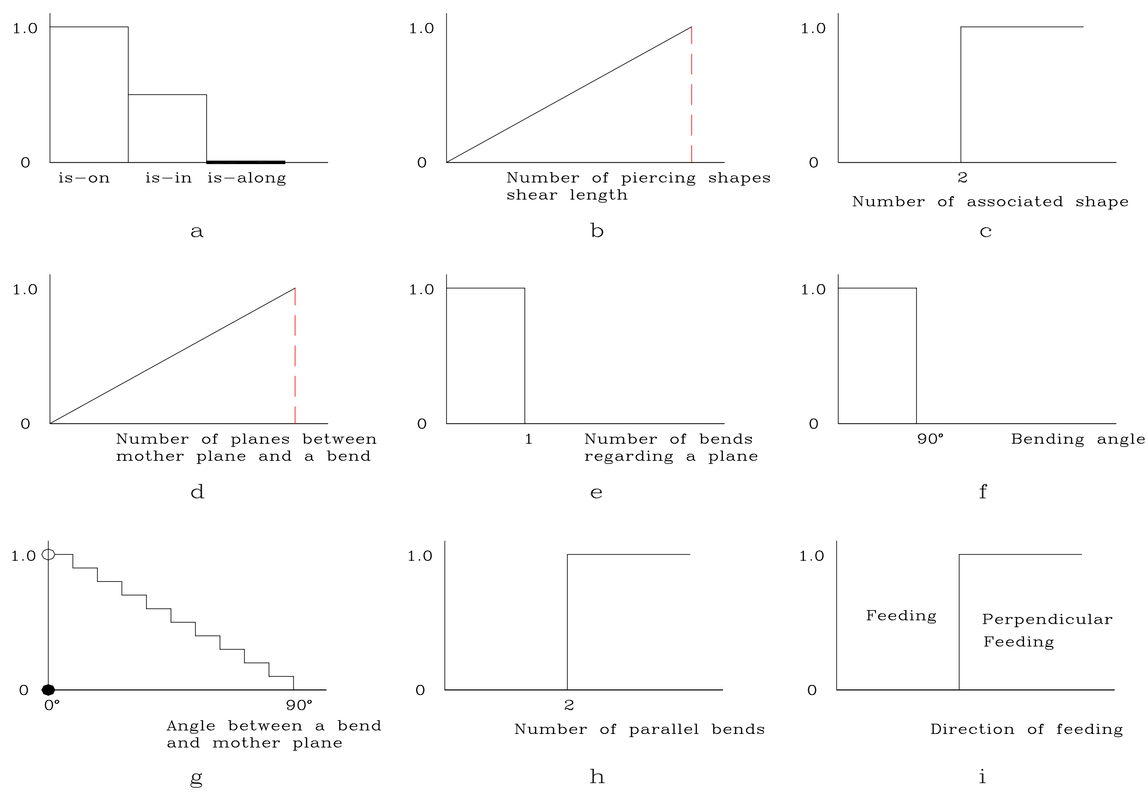


Fig. 7 Fuzzy membership functions

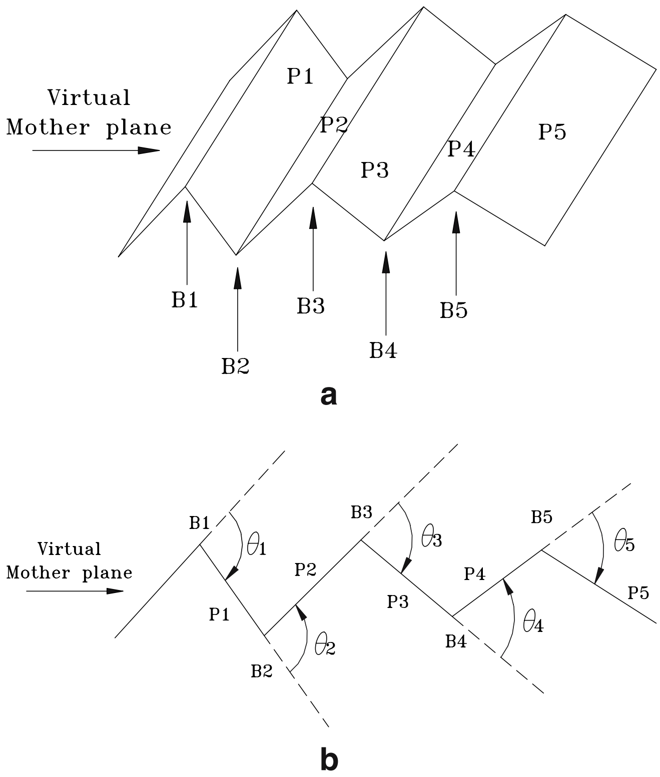


Fig. 9 Determination of the virtual mother plane

relation is schematically shown in Fig. 6, and the fuzzy membership function of this rule is shown in Fig. 7a.

2) Shear length rule

This rule determines the priority order of the process as the size of shear length of the shape to be pierced, and the fuzzy membership function is shown in Fig. 7b.

3) Adjacent piercing rule

This rule is applied to adjacent shapes to be pierced because they are neighboring so that the piercing is possible with the united punch shape, and the fuzzy membership function is shown in Fig. 7c.

2.3.2 Process planning rules for bending process

The rule and the database as process variables are derived from plasticity theories, relevant references and the empirical know-how of experts in the bending industries. The fuzzy set theory constructs a fuzzy matrix for calculating fuzzy relationship values and determines the optimum bend by combining several rules with fuzzy reasoning.

A “mother plane” is the fixed plane that does not rotate for all bending operations. The rotating plane is called a “children plane”. The definition of a “mother plane” is as follows:

1. A plane surrounded by other planes.
2. A plane located at the center of a product.
3. The largest plane in an area.

When the determination of a mother plane is not clear from the above, it is determined by the minimum number of bends between a plane and the plane in the central plane. Planes on the periphery of a product structure (Fig. 8), i.e. planes that are connected to the part with only one bend, are called “single planes”.

In this module, the handling rules and criteria required for determining the bend sequence are discussed. These rules deal with the selection of the next bend for bending. Each of these rules establishes the relationships between pairs of bends. A high membership grade indicated for a particular rule means that the bend is a good selection to bend next, according to the rules. These relationships between the bending and the criteria are represented as fuzzy relations, and the membership grades of these fuzzy relations are determined through a fuzzy membership function, as shown in Fig. 7d–i.

1) Distance rule

This rule is to determine the fuzzy relationship value of a fuzzy function according to the number of planes between a bend and the mother plane. The number of planes from the mother plane to a bend is calculated; the fuzzy relationship value of the largest number is unity and that for other numbers decreases proportionally. When a bend is further from the mother plane, the grade of the relationship will be higher and this can be bent first. The grades of fuzzy relationship values that are formed as a result of this rule are determined using the function in Fig. 7d.

2) Single plane rule

As mentioned above, a single plane is connected with only one bend to the part. On average, this bend has only a minor influence on the overall geometry of the part. Therefore, “single plane” bends can be bent at an early stage, without causing problems for the processing of the other bends. It is preferred that a bend that has fewer bends

Table 1 A fuzzy matrix [**V**]

	Rule 1(r_1)	Rule 2(r_2)	Rule 3(r_3)	Rule 4(r_4)	Rule 5(r_5)	Rule 6(r_6)	Rule 7(r_7)	Rule 8(r_8)	Rule 9(r_9)
p_1	$v_{RA}(p_1,r_1)$	$v_{SL}(p_1,r_2)$	$v_{Sp}(p_1,r_3)$	0	0	0	0	0	0
p_2	$v_{RA}(p_2,r_1)$	$v_{SL}(p_2,r_2)$	$v_{Sp}(p_2,r_3)$	0	0	0	0	0	0
…	………	………	………	………	………	………	………	………	………
p_n	$v_{RA}(p_n,r_1)$	$v_{SL}(p_n,r_2)$	$v_{Sp}(p_n,r_3)$	0	0	0	0	0	0
b_1	0	0	0	$v_{MD}(b_1,r_4)$	$v_{SP}(b_1,r_5)$	$v_{Ag}(b_1,r_6)$	$v_{PB}(b_1,r_7)$	$v_{So}(b_1,r_8)$	$v_{Fd}(b_1,r_9)$
b_2	0	0	0	$v_{MD}(b_2,r_4)$	$v_{SP}(b_2,r_5)$	$v_{Ag}(b_2,r_6)$	$v_{PB}(b_2,r_7)$	$v_{So}(b_2,r_8)$	$v_{Fd}(b_2,r_9)$
…	………	………	………	………	………	………	………	………	………
b_n	0	0	0	$v_{MD}(b_n,r_4)$	$v_{SP}(b_n,r_5)$	$v_{Ag}(b_n,r_6)$	$v_{PB}(b_n,r_7)$	$v_{So}(b_n,r_8)$	$v_{Fd}(b_n,r_9)$

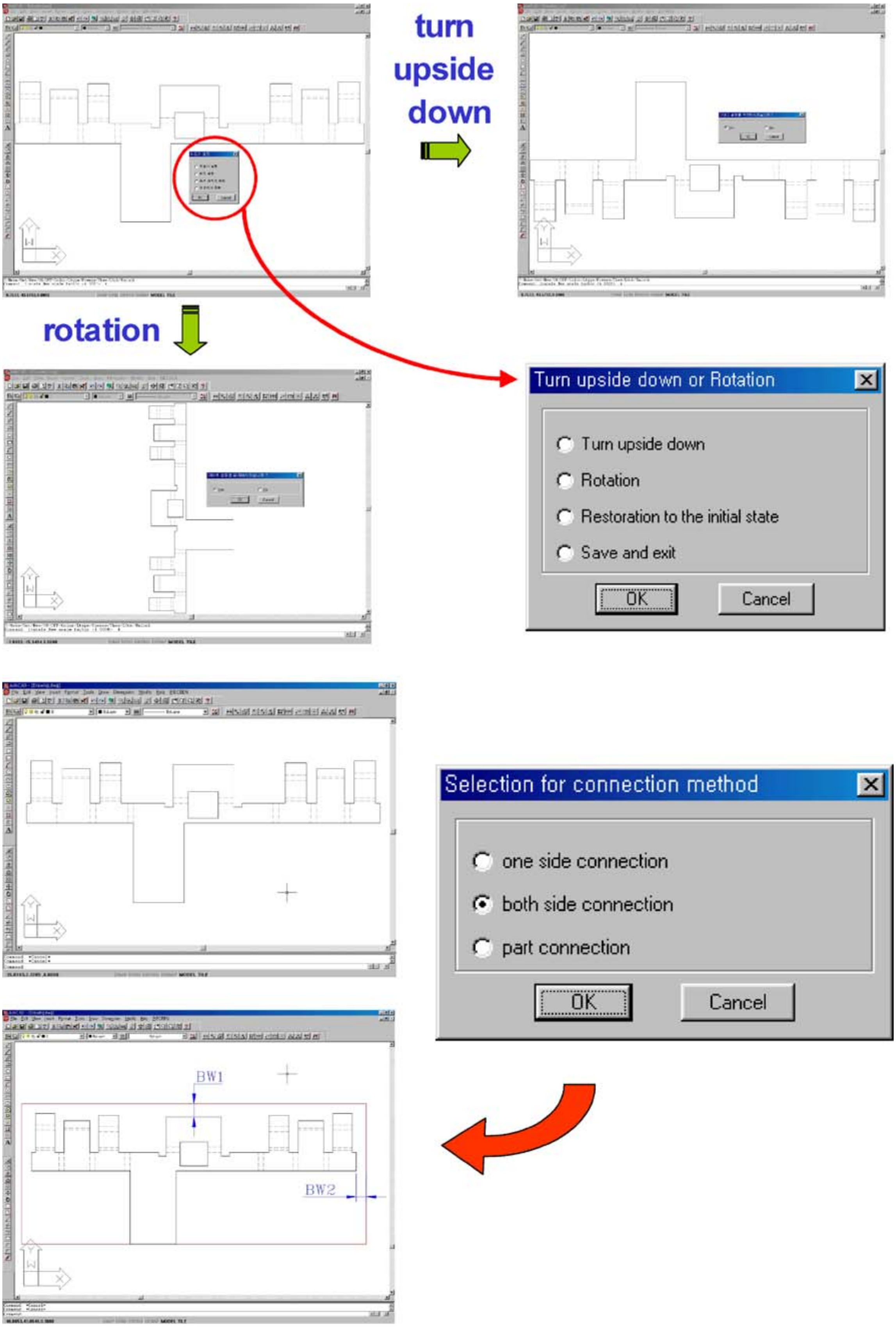


Fig. 10 The rotation and connection method of a flat pattern layout drawing for progressive working

connected to its adjacent planes is bent first or unfolded last, as illustrated in Fig. 7e.

3) Angle rule

This rule is to determine the fuzzy relationship value of a fuzzy function according to the bend angle between the mother plane and the rotation plane.

If the bend angle is greater than 90°, the bending process is divided into one or more processes. The fuzzy relationship value is unity in the case of a bend angle greater than 90°. These relationships according to bend angles are represented as fuzzy functions as shown in Fig. 7f.

4) Parallel bends rule

This rule is formulated as follows: after a bend is made, proceed with the nearest parallel bend when this bend is situated on the same side of the central plane. "On the same side" means that there is a connection between the first bend to the other bend in the product structure that does not contain the central plane. The membership function in Fig. 7g for this rule is formulated such that if there are fewer bends between the bend that has just been made and the bend that is being considered next for bending, the relationships based on this criterion would have a lower value than when there are more bends (on the same side of the central plane).

The definition of "parallel" is as follows.

$$VP = BLU_i \bullet BLU_j \geq 0.707 \tag{2}$$

where VP is the inner product of the direction vector of the unit vector, BLU_i is the unit direction vector of the ith bend, and BLU_j is the unit direction vector of the jth bend.

The bend angle relative to the virtual mother plane is calculated as follows and is shown in Fig. 9.

$$\theta_{n,\,sum} = ABS\left(\sum_{i=k}^{n} \theta_i\right) \tag{3}$$

5) Simultaneous forming rule

This rule is applied for vector bends in the same direction. They can be performed at the same time if interference of the punch and die does not occur. Therefore, if more than two same direction bends exist, they are performed in advance. When there are more than two bends in the same direction, the fuzzy relationship value is unity, and zero otherwise. The relationships that are formed as a result of this rule are illustrated in Fig. 7h.

6) Feeding rule

This rule is to determine the fuzzy relationship value of a fuzzy function according to whether or not the bend is in the feeding direction. After bending, an escape space is necessary in either the stripper plate of the upper die or the die plate of the lower die. The escape space should be at a minimum considering the die strength, the part to be fixed,

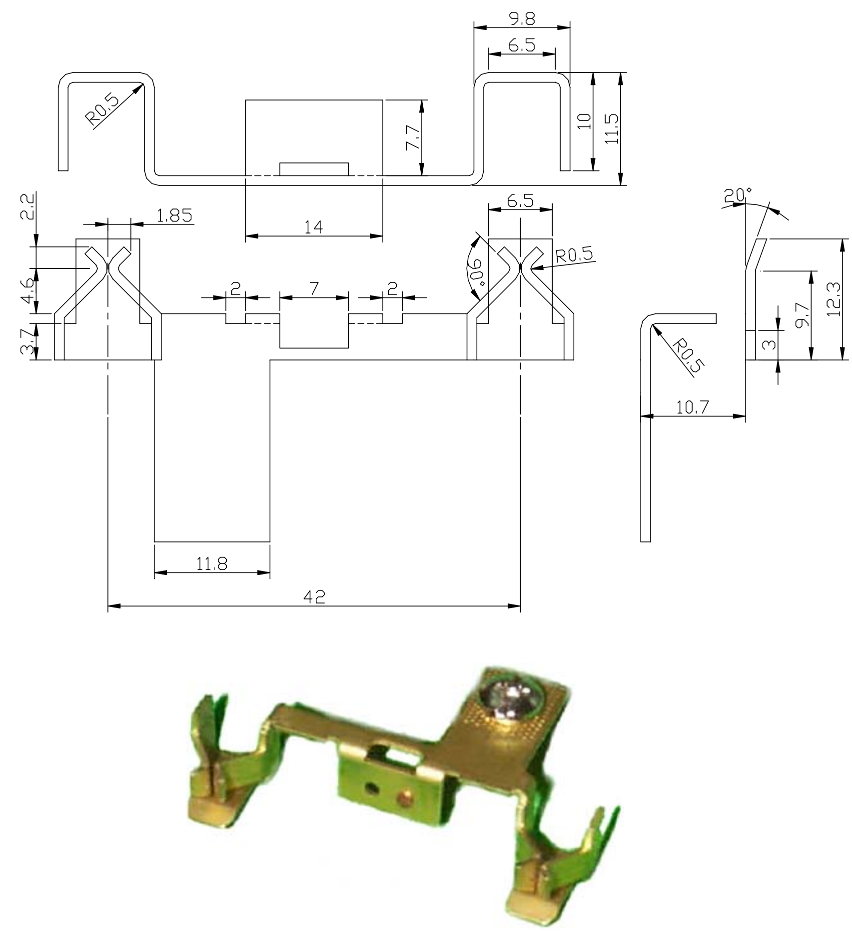


Fig. 11 A sample of electric product

the loss of die material, and the manufacturing time. Bending processes requiring a large escape space should be performed later to minimize the escape space. Because a bend perpendicular to the feeding direction requires a smaller escape space than a bend in the feeding direction, the former precedes the latter. The membership value for the perpendicular feeding direction is unity, and zero otherwise. The fuzzy membership function for this rule is shown in Fig. 7i.

2.3.3 Fuzzy set based evaluation

Rules are used to establish the relationships between a bend that has just been bent and the remaining bends that are being considered for bending, taking into consideration the handling criteria. The selection of a bend from the remaining bends will satisfy a particular criterion to some extent. Hence, the degrees of satisfaction of the criteria are evaluated with respect to each criterion, for each of the remaining bends. These relationships are represented as fuzzy relations.

1) Fuzzy matrix for piercing

Let $P=\{p_i| i=1, 2, \ldots\ldots , n\}$ represent the set consisting of all the remaining shapes to be pierced that are being considered for piecing, where p_i is one of the shapes to be pierced.

Let $R=\{r_j \mid j=1, 2, 3\}$ represent the set of three criteria in the handling rules, where r_j represents one of the criteria.

The grade, $(v_{ij})_p$, is expressed as follows.

$$(v_{ij})_p = f(p_i, r_j) \tag{4}$$

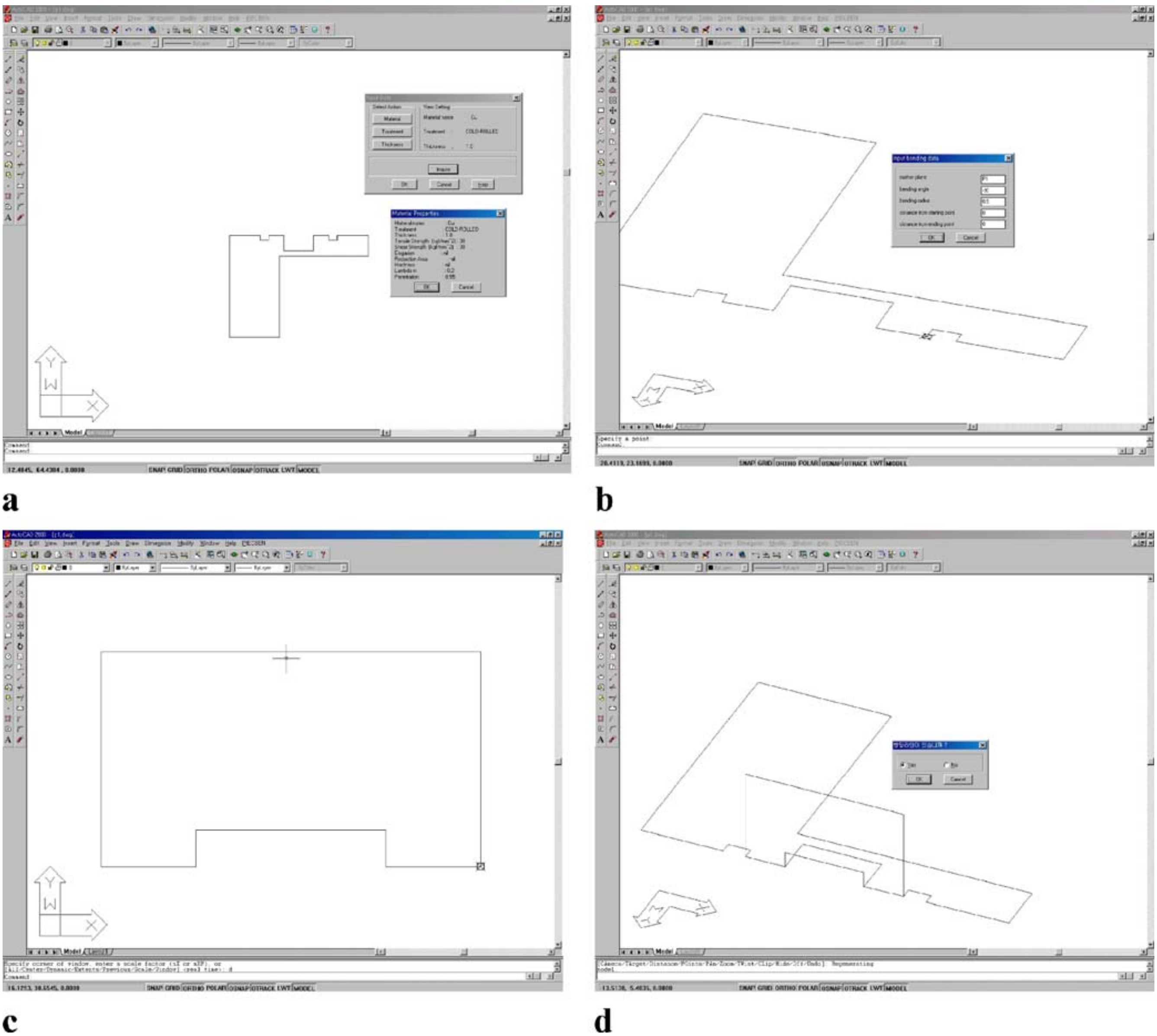


Fig. 12 Inputting shape data of each plane

Table 2 List for shape of parts and bending line

1) shape list of plane
(("P1" ((((0.0 0.0 0.0) (1.13276e–015 18.5 0.0)) ((1.13276e–015 18.5 0.0) (1.13276e–015 23.2 0.0))((1.42054e–015 23.2 0.0) (7.3 23.2 0.0)) ((7.3 23.2 0.0) (7.3 22.2 0.0)) ((7.3 22.2 0.0) (9.3 22.2 0.0)) ((9.3 22.2 0.0)(9.3 23.2 0.0)) ((9.3 23.2 0.0) (12.8 23.2 0.0)) ((12.8 23.2 0.0) (12.8 19.7 0.0)) ((12.8 19.7 0.0) (19.8 19.7 0.0))((19.8 19.7 0.0) (19.8 23.2 0.0)) ((19.8 23.2 0.0) (23.3 23.2 0.0)) ((23.3 23.2 0.0) (23.3 22.2 0.0)) ((23.3 22.2 0.0) (25.3 22.2 0.0)) ((25.3 22.2 0.0) (25.3 23.2 0.0)) ((25.3 23.2 0.0) (32.6 23.2 0.0)) ((32.6 23.2 0.0) (32.6 18.5 0.0)) ((32.6 18.5 0.0) (11.8 18.5 0.0)) ((11.8 18.5 0.0) (11.8 0.0 0.0)) ((11.8 0.0 0.0) (0.0 0.0 0.0)))))
…… an omission ……
("P18" ((((-23.927 30.2435 -4.36074e-015) (-23.927 33.0715 -3.47256e-015)) ((-23.927 33.0715 -3.47256e-015) (-18.927 33.0715 -8.08028e-016)) ((-18.927 33.0715 -8.08028e-016) (-18.927 30.2435 -3.47256e-015))((-18.927 30.2435 -3.47256e-015) (-23.927 30.2435 -4.36074e-015))))))
2) bending list
(("B1" (((23.3 23.2 0.0) (19.8 23.2 0.0)) ((12.8 23.2 0.0) (9.3 23.2 0.0))) -90.0 0.5 0.0 0.0 “P1” "P2") ("B2" (((32.6 23.2 0.0) (32.6 18.5 0.0))) 90.0 0.5 0.0 0.0 “P1” "P3")
…… an omission ……
("B16" (((-6.5 23.7 6.5) (-6.5 23.7 1.5))) 45.0 0.5 0.0 0.0 “P16” "P17") ("B17" (((-3.26145 26.9385 6.5) (-3.26145 26.9385 1.5))) -90.0 0.5 0.0 0.0 “P17” "P18"))

The determination of the grade, which may vary anywhere between zero and unity, is based on the strip layout rules. The fuzzy relationship is composed of a fuzzy matrix [**V**] and is shown in Table 1.

2) Fuzzy matrix for bending

Let $B=\{b_i \mid i=1, 2, \ldots\ldots, n\}$ represent the set consisting of all the remaining bends that are being considered for bending, where b_i is one of the bends.

Let $R=\{r_j \mid j=1, 2, 3, 4, 5, 6\}$ represent the set of three criteria in the handling rules, where r_j represents one of the criteria.

The grade, $(v_{ij})_b$, is expressed as follows.

$$\left(v_{ij}\right)_b = f\left(b_i, r_j\right) \quad (5)$$

The determination of the grade, which may vary anywhere between zero and unity, is based on the strip layout rules. The fuzzy relationship is composed of a fuzzy matrix [**V**] and is shown in Table 1.

3) Determination of FVM (final value matrix) set

FVM is a fuzzy set consisting of bends that are being considered for the next bending and of the shapes to be pierced for the next piercing. The grades of the bends and the shapes to be pierced in this set indicate how well the criteria of handling are satisfied when these bends and the shapes to be pierced are selected.

The following rules have been found to give fair results in the operations of piercing: relation rule, shear length rule, adjacent piercing rule.

A higher value means that the particular bend is the preferred one to be bent next, as compared to a bend with a lower value. The relative importance of the handling rules is different. The following rules have been found to give fair results in the operation of bending: distance rule, single plane rule, angle rule, parallel rule, simultaneous forming rule, feeding rule.

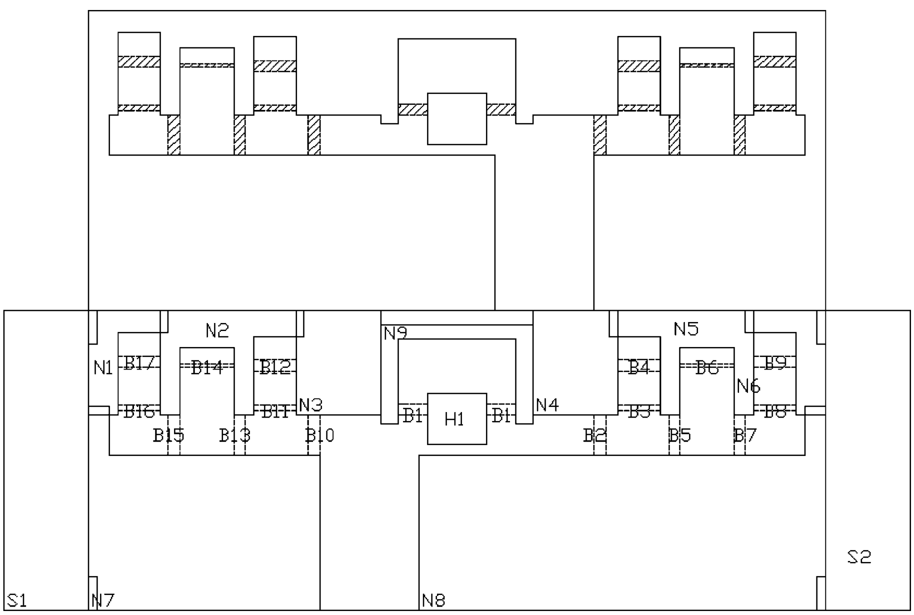


Fig. 13 The results generated in the flat pattern layout module

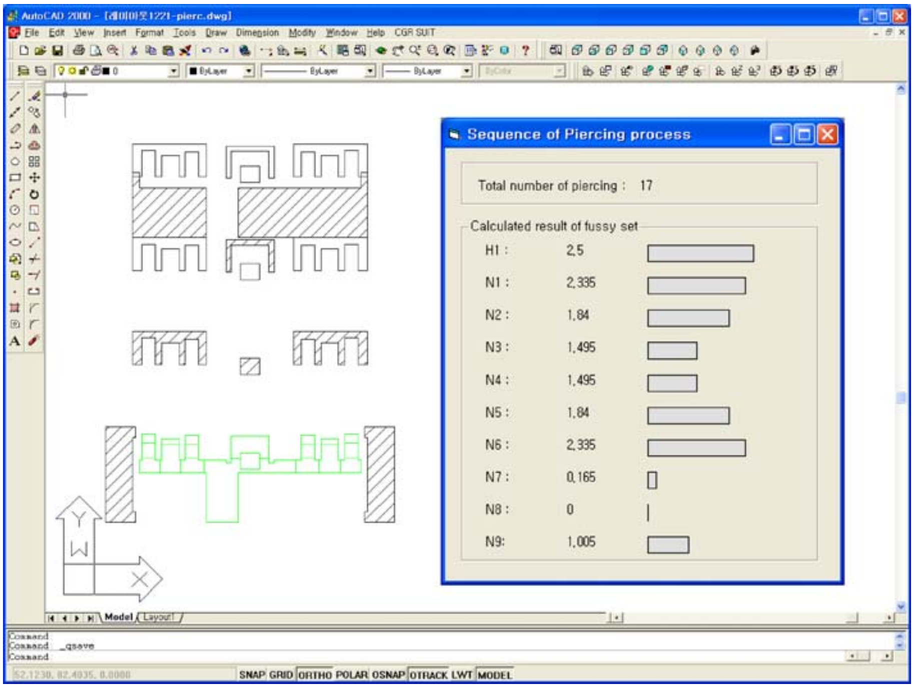


Fig. 14 Final fuzzy value of the product in Fig. 11 for the piercing process

The relative importance of the rules is represented as a fuzzy set $W[R]$, as shown in Eqs. 6 and 7.

$$W_p[R] = \{r1\times2.0,\ r2\times1.5,\ r3\times1.0\} \tag{6}$$

$$W_b[R] = \{r1\times1.2,\ r2\times1.0,\ r3\times0.8,\ r4\times0.6,\ r5\times0.4,\ r6\times0.2\} \tag{7}$$

The relative importance of these rules can now be taken into account in selecting the next bend and the next shapes to be pierced. This is achieved by multiplying the respective column vector of this W set with the fuzzy matrix [**V**] to give a column vector containing the values of the bends and the parts to be pierced in the FVM set. From Eqs. 6 and 7, the best bend to bend next, and the best shape to pierce next can be found.

$$\begin{aligned} FVM &= [V_p]\times W_p(R) + [V_b]\times W_b(R) \\ FVM(p) &= \begin{bmatrix} v_p(1,1) & v_p(1,2) & v_p(1,3) \\ v_p(2,1) & v_p(2,2) & v_p(2,3) \\ \cdots & \cdots & \cdots \\ v_p(n,1) & v_p(n,2) & v_p(n,3) \end{bmatrix} \begin{bmatrix} W(p_1) \\ W(p_2) \\ \cdots \\ W(p_n) \end{bmatrix} \\ FVM(b) &= \begin{bmatrix} v_b(1,1) & v_b(1,2) & v_b(1,3) & v_b(1,4) & v_b(1,5) & v_b(1,6) \\ v_b(2,1) & v_b(2,2) & v_b(2,3) & v_b(2,4) & v_b(2,5) & v_b(2,6) \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ v_b(n,1) & v_b(n,2) & v_b(n,3) & v_b(n,4) & v_b(n,5) & v_b(n,6) \end{bmatrix} \begin{bmatrix} W(b_1) \\ W(b_2) \\ \cdots \\ W(b_n) \end{bmatrix} \end{aligned} \tag{8}$$

2.3.4 Piercing and bending force

The strip layout module also chooses the connection method by the users through the dialogue box. After checking the constraints on bending operations, as shown in Fig. 10, it automatically generates a 3D strip layout drawing.

After considering material utilization, the rolling direction of a strip, the positional relations of the bend, and the connection method, this module permits rotation and turning upside down. Connection methods are as follows:

1. One side connection method

Table 3 Fuzzy matrix [$\mathbf{V}_p$] for piercing

	*R*1	*R*2	*R*3
*H*1	0.5	1	0
*N*1	0	0.89	1
*N*2	0	0.56	1
*N*3	0	0.33	1
*N*4	0	0.33	1
*N*5	0	0.56	1
*N*6	0	0.89	1
*N*7	0	0.11	0
*N*8	0	0	0
*N*9	0	0.67	0

2. Product connection method. The bends exist in both sides of a product so that connection is accomplished by the middle part of the product.
3. Both sides connection method. The bends exist in both sides of a product so that connection is accomplished on both sides of the product

Piercing of force is calculated as follows.

$$P = \tau t l \tag{9}$$

where P is the force of blanking or piercing (kg$_f$), τ is the shear stress (kg$_f$/mm^2), t is the thickness of the workpiece (mm), and l is the shear length (mm).

Bending of force is calculated as follows.

$$F = k\frac{bt^2(1.5 + \varepsilon_r)\sigma_r}{6l} \tag{10}$$

where F is the force of bending (kgf), k is the coefficient of correction for bending, b is the length of the bending line (mm), ε_r is the strain by bending, σ_r is the shear strength (kgf/mm2), and l is the length of the bending arm (mm).

3 Application and results of the system

When a component requiring piercing and intricate bending operations is applied to the system, the study considers the results carried out in each module. The electric product used as a sample is shown in Fig. 11.

3.1 Application to the input and shape treatment module

After the user inputs the items demanded, i.e. the type of material, the heat treatment condition, and the thickness of the electric product shown in Fig. 12a, the shape data for each plane are input. A system capable of inputting planes in the *X*-*Y* coordinates is formulated for the user's convenience. After the shape data of one plane is recognized, this module chooses the bend as shown in Fig. 12b. The user inputs the bend angle, the bend radius, and the information about the starting point of the bend. After inputting these, only the bend is redrawn in order to input another plane. The second plane is input as shown in Fig. 12c and this module automatically recognizes it and outputs the shape. The results produced by these procedures are shown in Fig. 12d. The shapes and the bend list of the electric product, automatically recognized, are shown in Table 2.

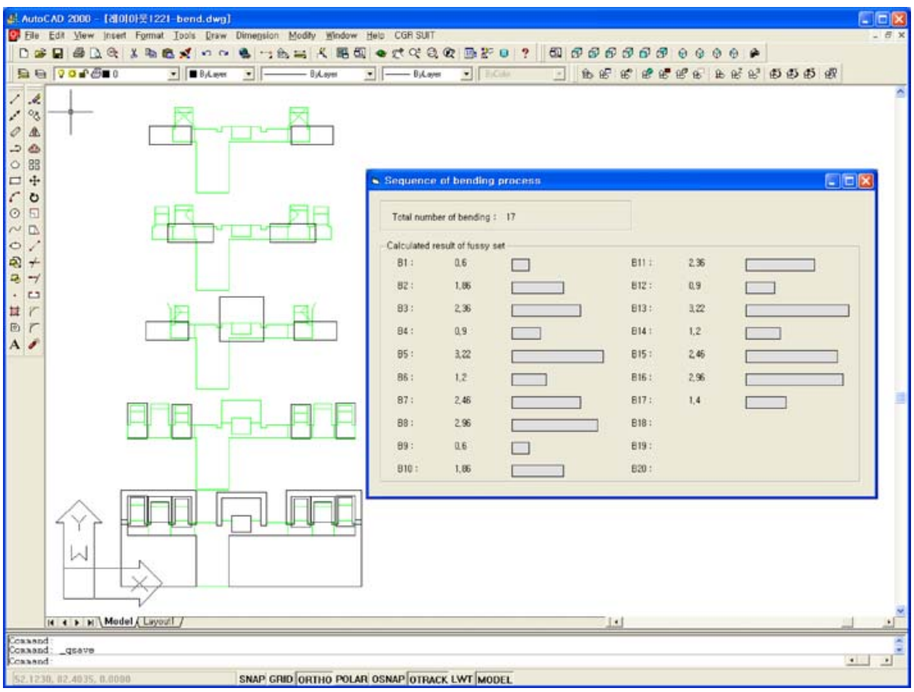


Fig. 15 Final fuzzy value of the product in Fig. 11 for the bending process

Table 4 Fuzzy matrix [$\mathbf{V}_b$] for bending

	*R*1	*R*2	*R*3	*R*4	*R*5	*R*6
*B*1	0	0	0	1	0	1
*B*2	0.25	0	1	0.6	1	0
*B*3	0.5	1	0	0.6	1	0
*B*4	0.25	0	0	0	1	1
*B*5	0.5	1	1	0.7	1	0
*B*6	0.5	0	0	0	1	1
*B*7	0.75	0	1	0.6	1	0
*B*8	1	1	0	0.6	1	0
*B*9	0	0	0	0	1	1
*B*10	0.25	0	1	0.6	1	0
*B*11	0.5	1	0	0.6	1	0
*B*12	0.25	0	0	0	1	1
*B*13	0.5	1	1	0.7	1	0
*B*14	0.5	0	0	0	1	1
*B*15	0.75	0	1	0.6	1	0
*B*16	1	1	0	0.6	1	0
*B*17	0	1	0	0	1	0

3.2 Application to the flat pattern layout module

Using the shapes and the bend list automatically recognized in the input and shape treatment module, the flat pattern layout drawing is output in this module. The bend allowances are calculated from the bend radius and the bend angle extracted from the bend list and the coefficient obtained from the database according to the product material. After the system automatically searches for the planes associated with the bend and rotates the nodes on the plane, the planes associated with the bend automatically move by the calculated bend allowances. Repeating these procedures, the flat pattern layout drawing is output as shown in Fig. 13. The hatched parts represent the amount of bending allowances.

3.3 Application to the strip layout module

Figure 14 shows the ten types of shapes: one inner slot and nine notches to be pierced. When they are applied to the rules of the strip layout module, the fuzzy matrix [$\mathbf{V}_p$] of the piercing operations and the FVM(p) obtained by multiplying the respective column vector of this W_p set with the fuzzy matrix [$\mathbf{V}_p$] are shown respectively in Tables 3 and 5. The value of FVM for indicating the final

Table 5 Fuzzy set matrix [**V**]×*W*(*R*)

	*R*1	*R*2	*R*3	*R*4	*R*5	*R*6	*R*7	*R*8	*R*9	Total
*H*1	1	1.5	0	0	0	0	0	0	0	2.5
*N*1	0	1.335	1	0	0	0	0	0	0	2.335
*N*2	0	0.84	1	0	0	0	0	0	0	1.84
*N*3	0	0.495	1	0	0	0	0	0	0	1.495
*N*4	0	0.495	1	0	0	0	0	0	0	1.495
*N*5	0	0.84	1	0	0	0	0	0	0	1.84
*N*6	0	1.335	1	0	0	0	0	0	0	2.335
*N*7	0	0.165	0	0	0	0	0	0	0	0.165
*N*8	0	0	0	0	0	0	0	0	0	0
*N*9	0	1.005	0	0	0	0	0	0	0	1.005
*B*1	0	0	0	0	0	0	0.6	0	0	0.6
*B*2	0	0	0	0.3	0	0.8	0.36	0.4	0	1.86
*B*3	0	0	0	0.6	1	0	0.36	0.4	0	2.36
*B*4	0	0	0	0.3	0	0	0	0.4	0.2	0.9
*B*5	0	0	0	0.6	1	0.8	0.42	0.4	0	3.22
*B*6	0	0	0	0.6	0	0	0	0.4	0.2	1.2
*B*7	0	0	0	0.9	0	0.8	0.36	0.4	0	2.46
*B*8	0	0	0	1.2	1	0	0.36	0.4	0	2.96
*B*9	0	0	0	0	0	0	0	0.4	0.2	0.6
*B*10	0	0	0	0.3	0	0.8	0.36	0.4	0	1.86
*B*11	0	0	0	0.6	1	0	0.36	0.4	0	2.36
*B*12	0	0	0	0.3	0	0	0	0.4	0.2	0.9
*B*13	0	0	0	0.6	1	0.8	0.42	0.4	0	3.22
*B*14	0	0	0	0.6	0	0	0	0.4	0.2	1.2
*B*15	0	0	0	0.9	0	0.8	0.36	0.4	0	2.46
*B*16	0	0	0	1.2	1	0	0.36	0.4	0	2.96
*B*17	0	0	0	0	1	0	0	0.4	0	1.4

fuzzy relationship value for each notch is shown in Fig. 15. The shape, $H1$, has a 0.5 value by the relation rule because it exists in the inner plane. All notches, $N1$ and $N2$, …, and $N9$, have a zero fuzzy relationship value by the relation rule. All the shapes to be pierced, $H1$ and $N1$~$N9$, have a fuzzy relationship value in the order of the size of shear length by the shear length rule. The shapes, $N1$ and $N2$ and $N3$, have a unit fuzzy relationship value by the adjacent rule because they are simultaneously to be pierced. Also, the notches, $N4$ and $N5$, $N6$, have the same fuzzy relationship value.

The fuzzy matrix $[\mathbf{V}_b]$ of the bending operations and the FVM(b) obtained by multiplying the respective column vector of this W_b set with the fuzzy matrix $[\mathbf{V}_b]$ are shown respectively in Tables 4 and 5. The value of FVM for indicating the final fuzzy relationship value for each bend is shown in Fig. 15. When the bend, $B1$, is performed, it needs a larger escape space in the die set because the size of the planes left to the right of the bend, $B1$, is too large. Therefore the bends, $B4$ and $B1$ and $B6$, are performed after checking the constraints on the bending operations. Among the bending operations perpendicular to the feeding direction, the bending in the middle part is preferentially carried out to prevent interference.

It preferentially carries out notching and piercing in the outer region, before the bending operations. The outer shape,

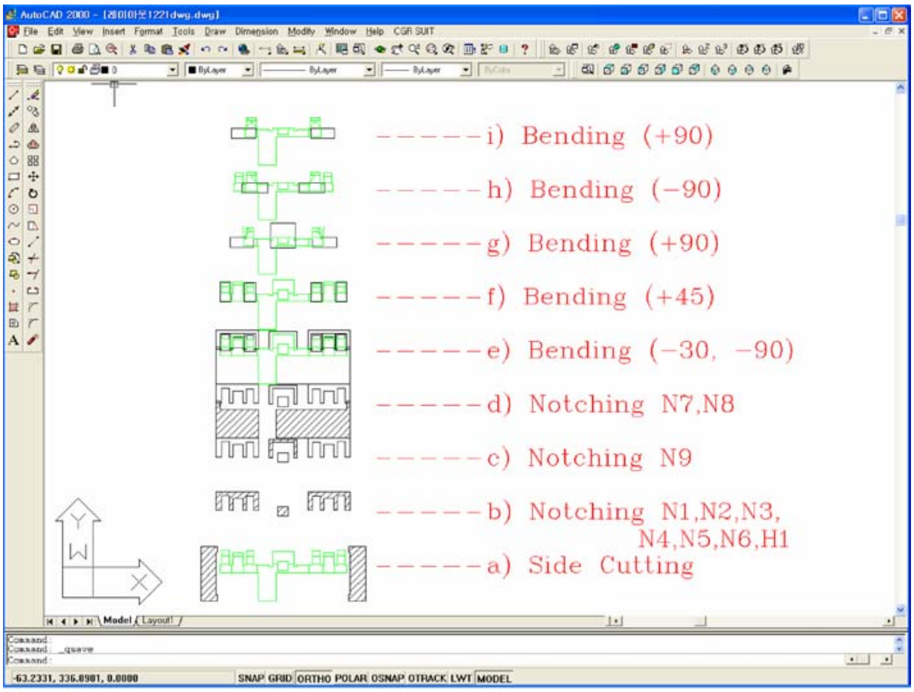


Fig. 16 A drawing of the strip layout generated in the strip layout module

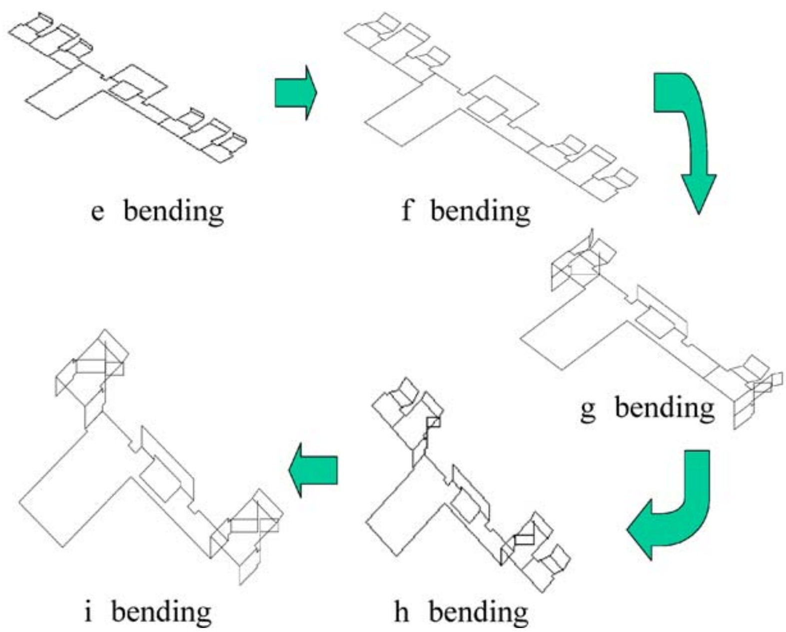


Table 6 The results of force and shear length calculated in each stage

Stage	Shear length (mm)	Blanking force (kg)	Bending force (kg)	Total force (kg)
1stage	190.286	5,708.58	0	5,708.58
2stage	268.311	8,049.33	0	8,049.33
3stage	80.036	2,401.08	0	2,401.08
4stage	206.508	6,195.24	0	6,195.24
5stage	0	0	963.63	963.63
6stage	0	0	208.58	208.58
7stage	0	0	156.432	156.432
8stage	0	0	83.43	83.43
9stage	0	0	83.43	83.43
Total	745.141	22,354.23	1,495.502	23,849.732

using the dialogue, designs the shapes of the notching punches, which is user-friendly, having the appropriate prompting statements for the various data required.

The strip layout module determines the order of the process as the above procedure and generates the strip layout drawing shown in Fig. 16. In Fig. 16a the side cutting process, which cuts off both ends of the strip, is carried out in order to reduce feeding error and standardize the shape of the strip. This module carries out the notching and piercing operations in the outer region as shown in Fig. 16b. Also, it performs the piercing operations for the shape, *N*1, as shown in Fig. 16c and for the shapes, *N*8 and *N*9, as shown in Fig. 16d. Two types of bending (the bending to the feeding direction occurs in the middle part, and the bending perpendicular to the feeding direction occurs in both ends of the strip) are carried out and are shown in Fig. 16g. These are six bending operations perpendicular to the feeding direction, three at each side. According to the design rule, the bending operations are carried out and are shown in Fig. 16h,i. Finally, it generates the 3D strip layout drawing, as shown in Fig. 16. The piercing and bending forces of each stage are shown in Table 6 after calculating them according to the relevant rules.

4 Conclusion

The study developed an automated design system capable of generating a 3D strip layout drawing for an electric product involving piercing and bending operations for progressive working operations; the system has the following features.

1. The system recognizes 3D shapes and performs process planning according to sequences determined in the strip layout module, with information of shape data obtained by the shape recognition method.
2. The flat pattern layout module can generate the flat pattern layout drawing with the information given in the shape and treatment module.
3. The strip layout drawings of the products with intricate bending operations are the same as those of an actual workshop using the values of the FVM set.
4. It has the advantage that a novice who may have only some knowledge of tool design can use it and the design and working time for each part is reduced by making use of the results generated in this system.

This system quantifies techniques and experience needed in designing strip layout and standardizes design rules for formulating design procedures. By developing an automated process planning system on AutoCAD, the system, linked with other CAM software, can generate NC data automatically which is suitable for working operations, so a CAD/CAM system for electric product requiring piercing and bending operations may soon be developed.

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