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Development of a System for Progressive Working of an Electric Product by Using Fuzzy Set Theory

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This paper describes the development of a computer-aided design for a product with intricate 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 and AutoCAD on a personal computer. It is composed of four main modules, which are input and shape treatment, flat pattern layout, strip layout, and die layout modules. The system is designed considering several factors, such as bending sequence by fuzzy set theory, complexities of blank geometry, punch profiles, and the availability of press equipment and standard parts. The strip layout and die layout drawings, which are automatically generated by formulisation and quantification of experimental technology, will minimise trial and error and reduce the period for developing new products. The system could serve as a valuable system for experts and as a dependable training aid for beginners.

Keywords: Bending sequence; Die layout; Flat pattern layout; Fuzzy set theory; Knowledge based rules; Strip layout

1. Introduction

Standardisation of design is required because of the trends of miniaturisation, weight reduction, and speed in today's industry. Shear forming, by which parts with a desired shape are manufactured from sheet metal using a punch and a die, especially requires this kind of standardisation to achieve compatibility and accuracy of components. Experience and intuitive decisions have mostly guided strip layout and die layout for forming by piercing and bending. In order to solve this manufacturing problem, workers have reported the automation of computer-aided process planning for the design of products by formulising the experience of skilled engineers [1–8].

Fogg and Jaimeson developed an improved PDDC [2]. Shibata and Kunitomo followed them by developing a CAD system which produces a screen-output for blank- and die-layout [3]. Nakahara et al. introduced a system for a progressive die design [4]. Wang and Chang studied the determination of the bending sequence in progressive die design [5], and Nee et al. developed a system for feature-based flat patterns [6]. Also, Choi et al. developed an automated process planning and die design system for blanking or piercing of irregular shaped sheet metal products [7-8]. In this study, the system developed decides the sequencing process of an electric product involving intricate piercing and bending operations by considering several bending factors and adopting a fuzzy set theory. It constructs a fuzzy matrix for calculating fuzzy relationship values and determines the optimum bend by 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. Using the data of the strip layout, the die layout

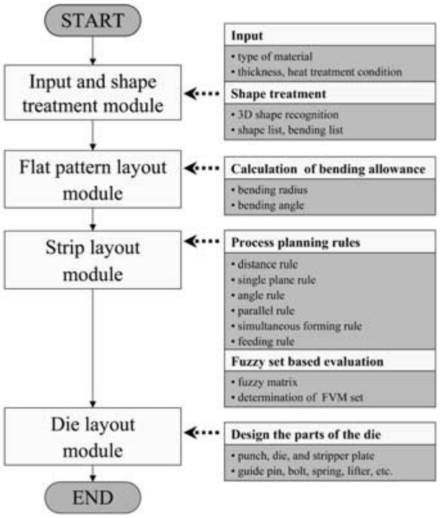

Fig. 1. Configuration of the system for progressive working.

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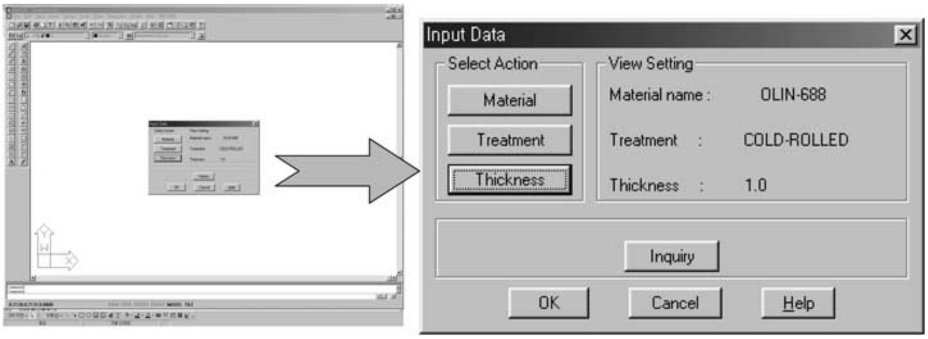


Material name : OLIN-688

Treatment : COLD-ROLLED

Thickness : 1.0

Fig. 2. Input of the material condition of a product.

module generates the parts of a die, i.e. punch, die, die plate, punch plate, stripper plate, guide plate, guide pin, spring, fastener, dowel pin, and lifter. The results obtained using the modules enable the manufacturer by progressive working of electric products to be more efficient.

2. Configuration of the System

The system is composed of four modules, which are input and shape treatment, flat pattern layout, strip layout, and die 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 product, the bend angle, and the 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. The results of the strip layout module are transferred to the die layout module to generate parts and an assembly of the die set. The functional description of the modules of the system is presented as follows.

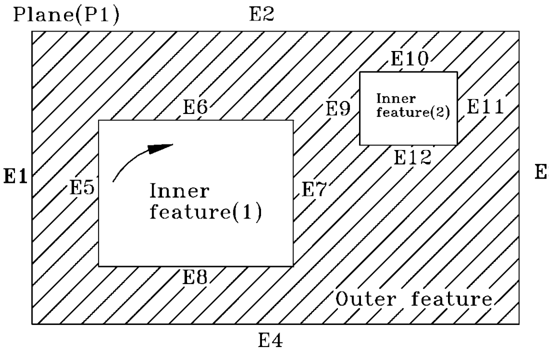
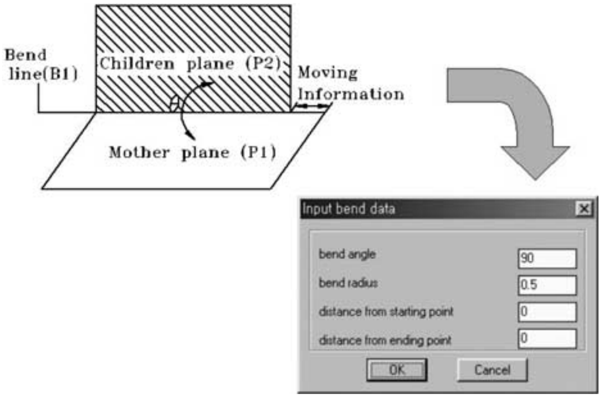


Fig. 3. Constitution of the list for recognising the shape of a plane.



bend angle 90

bend radius 0.5

distance from starting point 0

distance from ending point 0

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

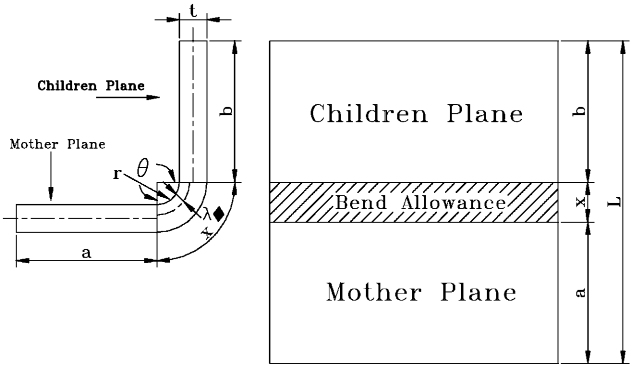


Fig. 5. Calculation of the bend allowance between the mother and children planes.

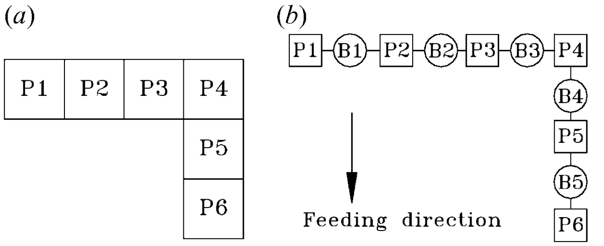


Fig. 6. The product structire of a flat pattern. (*a*) Flat pattern. (*b*) Product structure.

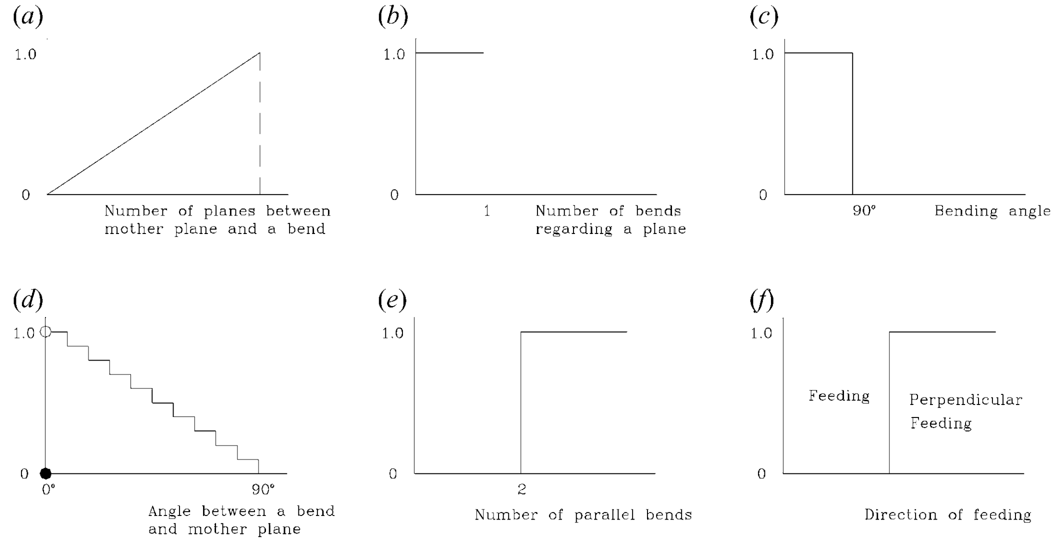


Fig. 7. Fuzzy membership functions.

2.1 Input and Shape Treatment Module

The input and shape treatment module is divided into submodules, which are 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 automatically 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 recognising a 3D shape product. Figure 2 shows input of the material condition of a product.

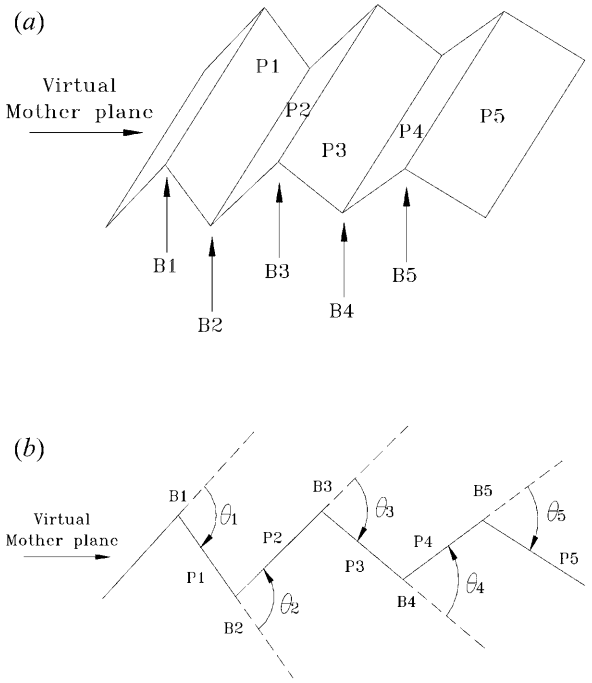


Fig. 8. Determination of the virtual mother plane.

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 organise the list into lines and arcs or circles. Figure 3 shows the constitution of entities for recognising inner shapes of a plane.

List representation constituted by lines and arcs

$$(0.0\ (S_p\ E_p)\ (S_p\ E_p)\ \cdots\ (S_p\ E_p\ C_p)\ (S_p\ E_p\ C_p)\ldots)$$

List representation constituted by circles

$$(0.0\ (C_p\ R)\ (C_P\ R)\ (C_p\ R)\ldots)$$

Where "$S_p\ E_p$" is the line of drawing entity, "$S_p\ E_p\ C_p$" is the arc, "$C_p\ R$" is the circle, "$S_p(X_s\ Y_s\ Z_s)$" is the starting point, "$E_p(X_e\ Y_e\ Z_e)$" is the endpoint, "$C_p(X_c\ Y_c\ Z_c)$" is the centre point, "R" is the radius.

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

$$(0.0\ ((P_1\ P_2)\ (P_2\ P_3\ P_{c1})(P_3\ P_4)\ \cdots\ (P_{n-1}\ P_n\ P_{cn})\ (P_n\ P_1))$$
$$((q_1\ q_2)(q_2\ q_3)(q_3\ q_4\ q_{c1})\ \cdots\ (q_{n-1}\ q_n\ q_{cn})(q_n\ q_1))$$

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

In "$P_1(X_1\ Y_1\ Z_1)$", 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 organised 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)))

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)
b_1	v_{MD} (b_1, r_1)	v_{SP} (b_1, r_2)	v_{Ag} (b_1, r_3)	V_{PB} (b_1, r_4)	V_{So} (b_1, r_5)	v_{Fd} (b_1, r_6)
b_2	v_{MD} (b_2, r_1)	v_{SP} (b_2, r_2)	v_{Ag} (b_2, r_3)	v_{PB} (b_2, r_4)	v_{So} (b_2, r_5)	v_{Fd} (b_2, r_6)
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
b_n	v_{MD} (b_n, r_1)	v_{SP} (b_n, r_2)	v_{Ag} (b_n, r_3)	V_{Pb} (b_n, r_4)	V_{So} (b_n, r_5)	V_{Fd} (b_n, r_6)

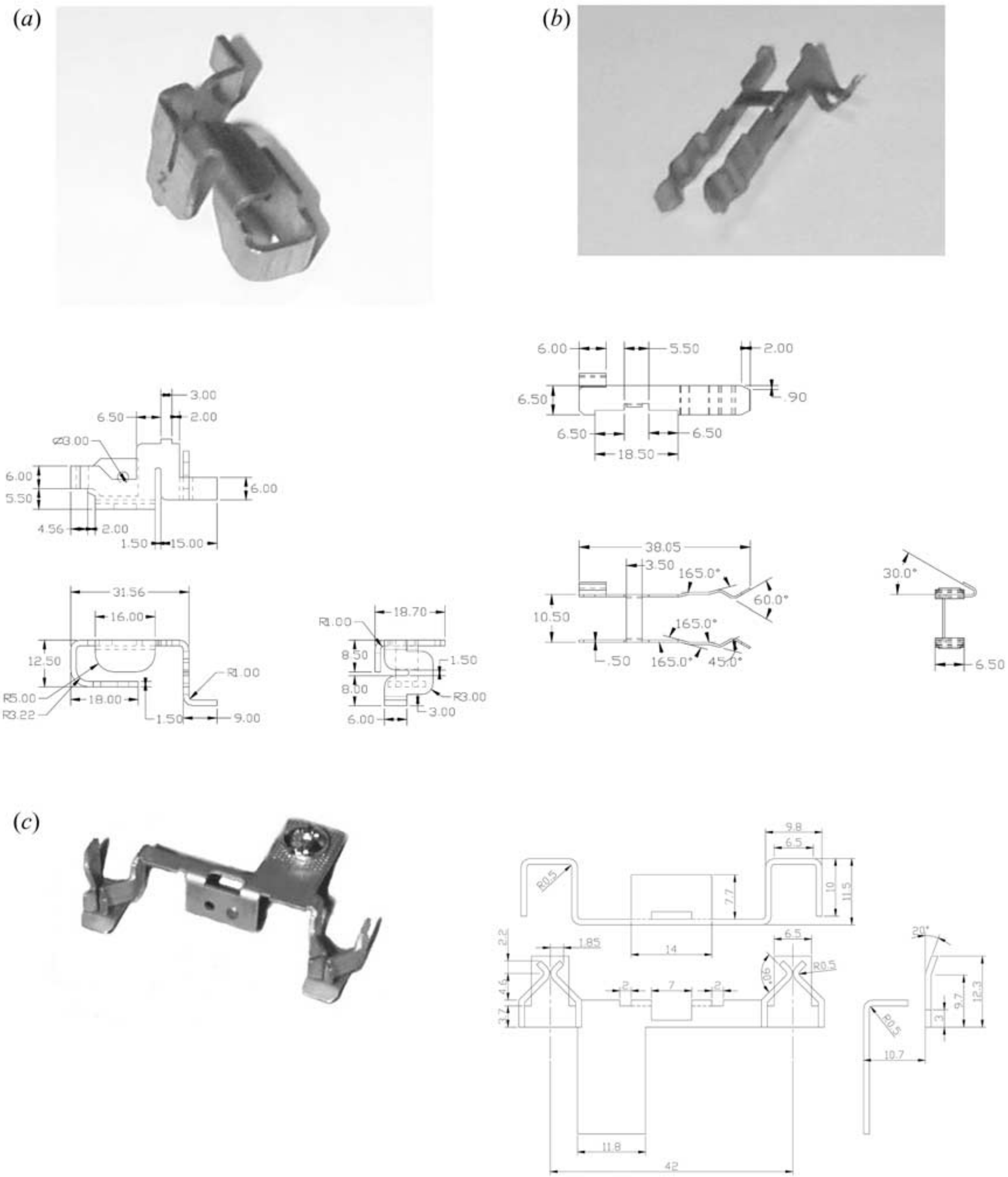


Fig. 9. Samples of electric products.

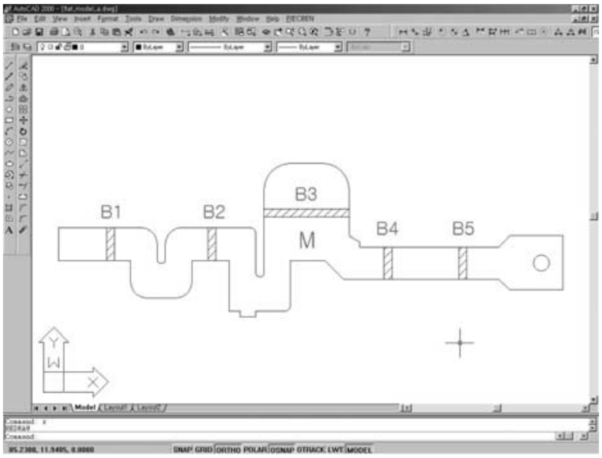


Fig. 10. The development figure of the product shown in Fig. 9(*a*), generated in the flat pattern layout module.

Table 2. Fuzzy set matrix [*V*] (Fig. 9(*a*)).

	R1	R2	R3	R4	R5	R6
B1	1	1	0	0	1	1
B2	0	0	0	0	1	1
B3	0	1	0	0	0	0
B4	0	0	0	0	1	1
B5	1	1	0	0	1	1

Table 3. Fuzzy set matrix [*V*] × *W*(*R*) (Fig. 9(*a*)).

	R1	R2	R3	R4	R5	R6	Total
B1	1.2	1	0	0	0.4	0.2	2.8
B2	0	0	0	0	0.4	0.2	0.6
B3	0	1	0	0	0	0	1
B4	0	0	0	0	0.4	0.2	0.6
B5	1.2	1	0	0	0.4	0.2	2.8

2.1.2 Bend List of a Product

Information of bend angle and line and the relationship of planes connected to one another should be defined for 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 list of a mother plane and a rotated children plane.

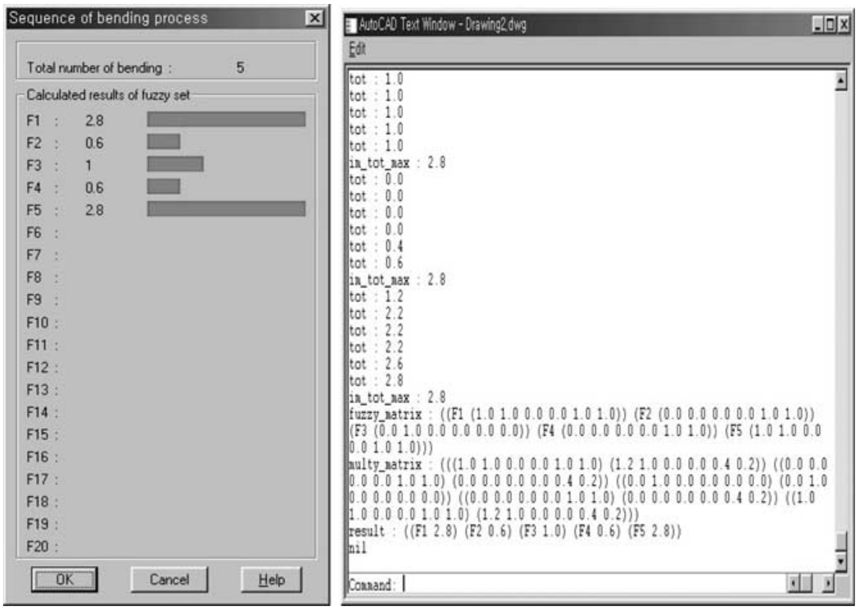
((“B1” (information bend line) bend line, bend radius, information of bend line movement, referenced plane, rotated plane)
(“B2” (information bend line) bend line, bend radius, information of bend line movement, referenced plane, rotated plane)
⋮
(“Bn” (information bend line) bend line, bend radius, information of bend line movement, referenced plane, rotated plane))

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

2.2 Flat Pattern Layout Module

The flat pattern layout module calculates bend allowances with bend radius, bend angle extracted from the bend list recognised 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.

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



Total number of bending : 5

Calculated results of fuzzy set

F1 : 2.8
F2 : 0.6
F3 : 1
F4 : 0.6
F5 : 2.8
F6 :
F7 :
F8 :
F9 :
F10 :
F11 :
F12 :
F13 :
F14 :
F15 :
F16 :
F17 :
F18 :
F19 :
F20 :

```
tot : 1.0
tot : 1.0
tot : 1.0
tot : 1.0
tot : 1.0
im_tot_max : 2.8
tot : 0.0
tot : 0.0
tot : 0.0
tot : 0.0
tot : 0.4
tot : 0.6
im_tot_max : 2.8
tot : 1.2
tot : 2.2
tot : 2.2
tot : 2.2
tot : 2.6
tot : 2.8
im_tot_max : 2.8
fuzzy_matrix : ((F1 (1.0 1.0 0.0 0.0 1.0 1.0)) (F2 (0.0 0.0 0.0 0.0 1.0 1.0))
(F3 (0.0 1.0 0.0 0.0 0.0 0.0)) (F4 (0.0 0.0 0.0 0.0 1.0 1.0)) (F5 (1.0 1.0 0.0
0.0 1.0 1.0)))
multy_matrix : (((1.0 1.0 0.0 0.0 1.0 1.0) (1.2 1.0 0.0 0.0 0.4 0.2)) ((0.0 0.0
0.0 0.0 1.0 1.0) (0.0 0.0 0.0 0.0 0.4 0.2)) ((0.0 1.0 0.0 0.0 0.0 0.0) (0.0 1.0
0.0 0.0 0.0 0.0)) ((0.0 0.0 0.0 0.0 1.0 1.0) (0.0 0.0 0.0 0.0 0.4 0.2)) ((1.0
1.0 0.0 0.0 1.0 1.0) (1.2 1.0 0.0 0.0 0.4 0.2)))
result : ((F1 2.8) (F2 0.6) (F3 1.0) (F4 0.6) (F5 2.8))
nil
Command:
```

Fig. 11. Final fuzzy value of the product in Fig. 9(*a*).

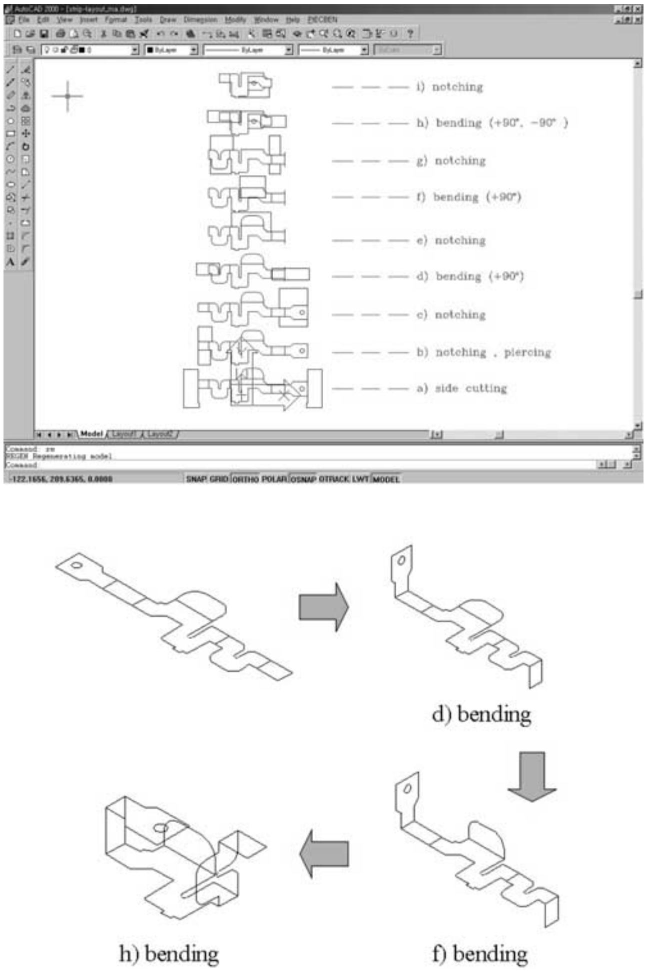


Fig. 12. A drawing of the strip layout generated in the strip layout module.

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

When it unfolds the bends one by one in the reverse order of folding them, the planes associated with the bends are automatically compensated by the bend 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. The module also decides the order of the process, which is capable of progressive working based on the rules, influencing the strip layout of electric product. The rules are as follows.

2.3.1 Strip Layout

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:

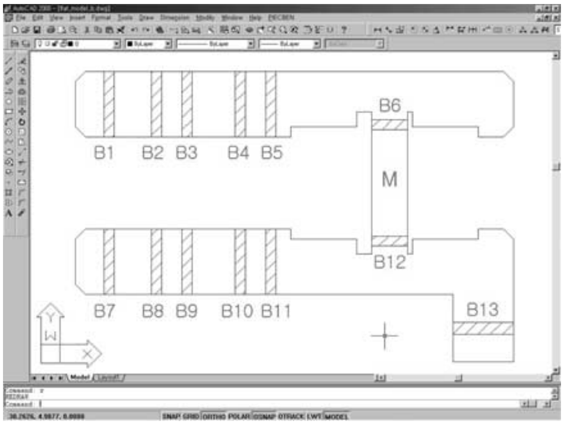
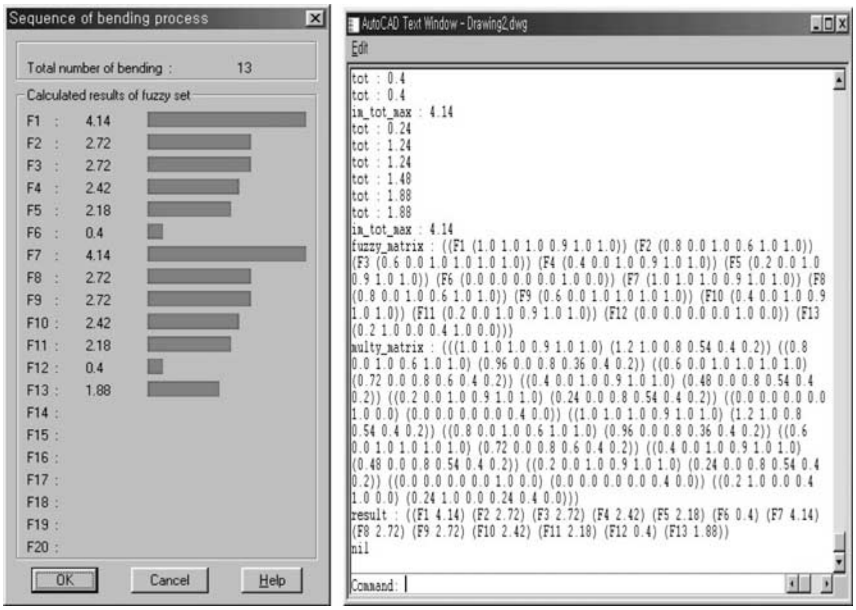


Fig. 13. The development figure of the product in Fig. 9(*b*), generated in the flat pattern layout module.



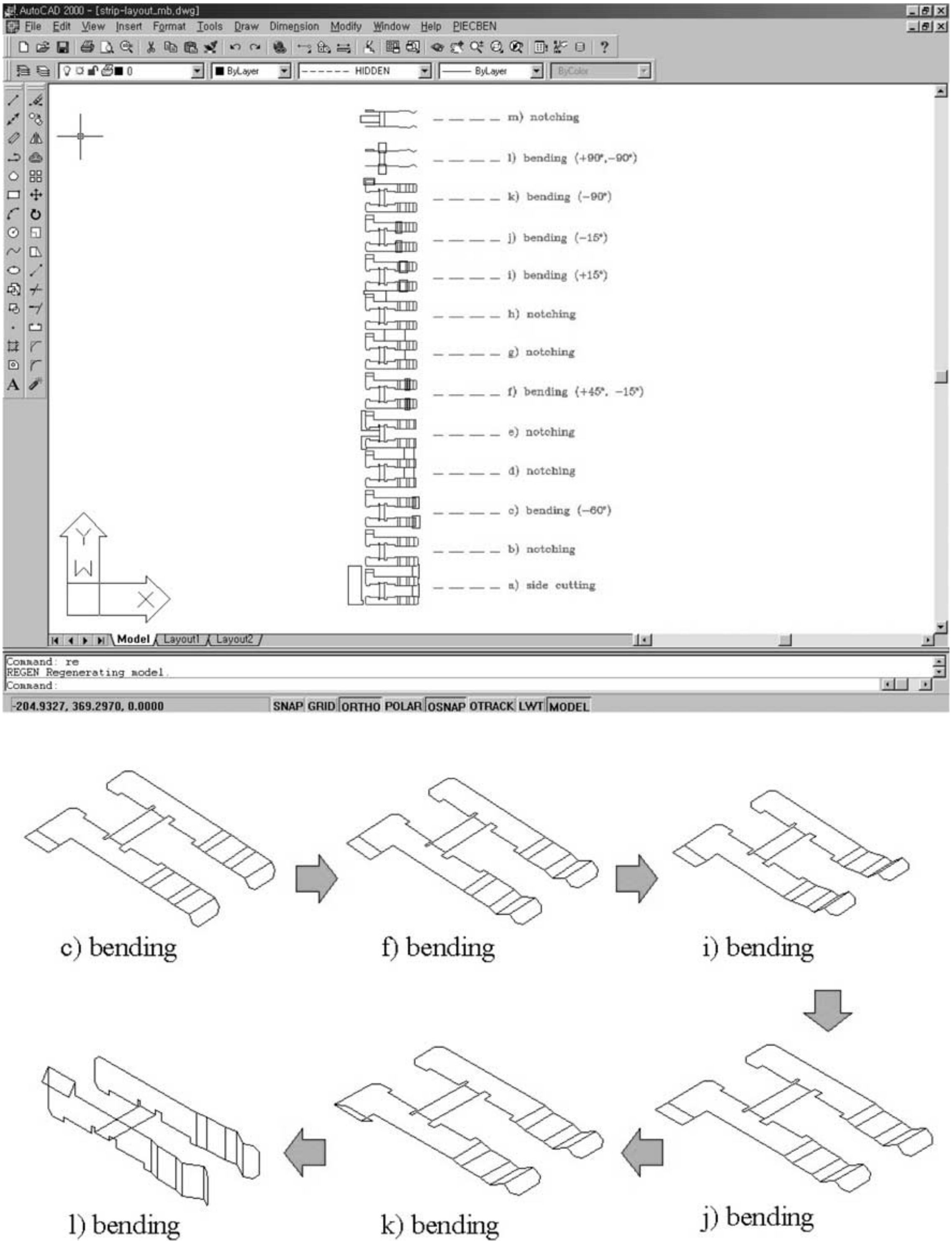
Total number of bending : 13

Calculated results of fuzzy set

F1 : 4.14
F2 : 2.72
F3 : 2.72
F4 : 2.42
F5 : 2.18
F6 : 0.4
F7 : 4.14
F8 : 2.72
F9 : 2.72
F10 : 2.42
F11 : 2.18
F12 : 0.4
F13 : 1.88
F14 :
F15 :
F16 :
F17 :
F18 :
F19 :
F20 :

```
tot : 0.4
tot : 0.4
im_tot_max : 4.14
tot : 0.24
tot : 1.24
tot : 1.24
tot : 1.48
tot : 1.88
tot : 1.88
im_tot_max : 4.14
fuzzy_matrix : ((F1 (1.0 1.0 1.0 0.9 1.0 1.0)) (F2 (0.8 0.0 1.0 0.6 1.0 1.0))
(F3 (0.6 0.0 1.0 1.0 1.0 1.0)) (F4 (0.4 0.0 1.0 0.9 1.0 1.0)) (F5 (0.2 0.0 1.0
0.9 1.0 1.0)) (F6 (0.0 0.0 0.0 0.0 1.0 0.0)) (F7 (1.0 1.0 1.0 0.9 1.0 1.0)) (F8
(0.8 0.0 1.0 0.6 1.0 1.0)) (F9 (0.6 0.0 1.0 1.0 1.0 1.0)) (F10 (0.4 0.0 1.0 0.9
1.0 1.0)) (F11 (0.2 0.0 1.0 0.9 1.0 1.0)) (F12 (0.0 0.0 0.0 0.0 1.0 0.0)) (F13
(0.2 1.0 0.0 0.4 1.0 0.0)))
multy_matrix : (((1.0 1.0 1.0 0.9 1.0 1.0) (1.2 1.0 0.8 0.54 0.4 0.2)) ((0.8
0.0 1.0 0.6 1.0 1.0) (0.96 0.0 0.8 0.36 0.4 0.2)) ((0.6 0.0 1.0 1.0 1.0 1.0)
(0.72 0.0 0.8 0.6 0.4 0.2)) ((0.4 0.0 1.0 0.9 1.0 1.0) (0.48 0.0 0.8 0.54 0.4
0.2)) ((0.2 0.0 1.0 0.9 1.0 1.0) (0.24 0.0 0.8 0.54 0.4 0.2)) ((0.0 0.0 0.0 0.0
1.0 0.0) (0.0 0.0 0.0 0.0 0.4 0.0)) ((1.0 1.0 1.0 0.9 1.0 1.0) (1.2 1.0 0.8
0.54 0.4 0.2)) ((0.8 0.0 1.0 0.6 1.0 1.0) (0.96 0.0 0.8 0.36 0.4 0.2)) ((0.6
0.0 1.0 1.0 1.0 1.0) (0.72 0.0 0.8 0.6 0.4 0.2)) ((0.4 0.0 1.0 0.9 1.0 1.0)
(0.48 0.0 0.8 0.54 0.4 0.2)) ((0.2 0.0 1.0 0.9 1.0 1.0) (0.24 0.0 0.8 0.54 0.4
0.2)) ((0.0 0.0 0.0 0.0 1.0 0.0) (0.0 0.0 0.0 0.0 0.4 0.0)) ((0.2 1.0 0.0 0.4
1.0 0.0) (0.24 1.0 0.0 0.0 0.24 0.4 0.0)))
result : ((F1 4.14) (F2 2.72) (F3 2.72) (F4 2.42) (F5 2.18) (F6 0.4) (F7 4.14)
(F8 2.72) (F9 2.72) (F10 2.42) (F11 2.18) (F12 0.4) (F13 1.88))
nil
Command:
```

Fig. 14. Final fuzzy value of the product in Fig. 9(*b*).



```
Command: re
REGEN Regenerating model.
Command:
```

Fig. 15. A drawing of the strip layout generated in the strip layout module.

1. A plane surrounded by other planes.
2. A plane located at the centre 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 in Fig. 6, 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

Table 4. Fuzzy set matrix [*V*] (Fig. 9(*b*)).

	R1	R2	R3	R4	R5	R6
B1	1	1	1	0.9	1	1
B2	0.8	0	1	0.6	1	1
B3	0.6	0	1	1	1	1
B4	0.4	0	1	0.9	1	1
B5	0.2	0	1	0.9	1	1
B6	0	0	0	0	1	0
B7	1	1	1	0.9	1	1
B8	0.8	0	1	0.6	1	1
B9	0.6	0	1	1	1	1
B10	0.4	0	1	0.9	1	1
B11	0.2	0	1	0.9	1	1
B12	0	0	0	0	1	0
B13	0.2	1	0	0.4	1	0

Table 5. Fuzzy set matrix [*V*] × *W*(*R*) (Fig. 9(*b*)).

	R1	R2	R3	R4	R5	R6	Total
B1	1.2	1	0.8	0.54	0.4	0.2	4.14
B2	0.96	0	0.8	0.36	0.4	0.2	2.72
B3	0.72	0	0.8	0.6	0.4	0.2	2.72
B4	0.48	0	0.8	0.54	0.4	0.2	2.42
B5	0.24	0	0.8	0.54	0.4	0.2	2.18
B6	0	0	0	0	0.4	0	0.4
B7	1.2	1	0.8	0.54	0.4	0.2	4.14
B8	0.96	0	0.8	0.36	0.4	0.2	2.72
B9	0.72	0	0.8	0.6	0.4	0.2	2.72
B10	0.48	0	0.8	0.54	0.4	0.2	2.42
B11	0.24	0	0.8	0.54	0.4	0.2	2.18
B12	0	0	0	0	0.4	0	0.4
B13	0.24	1	0	0.24	0.4	0	1.88

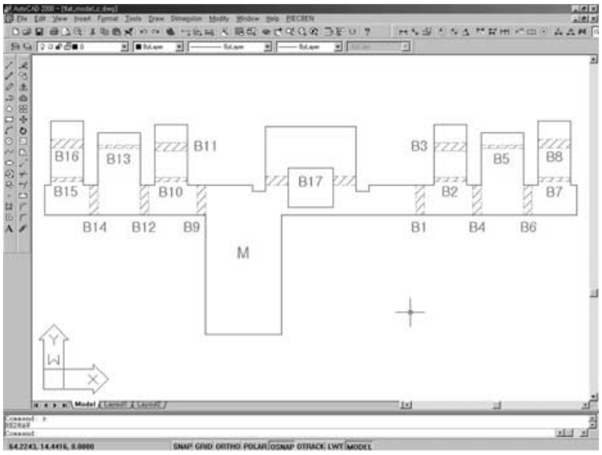
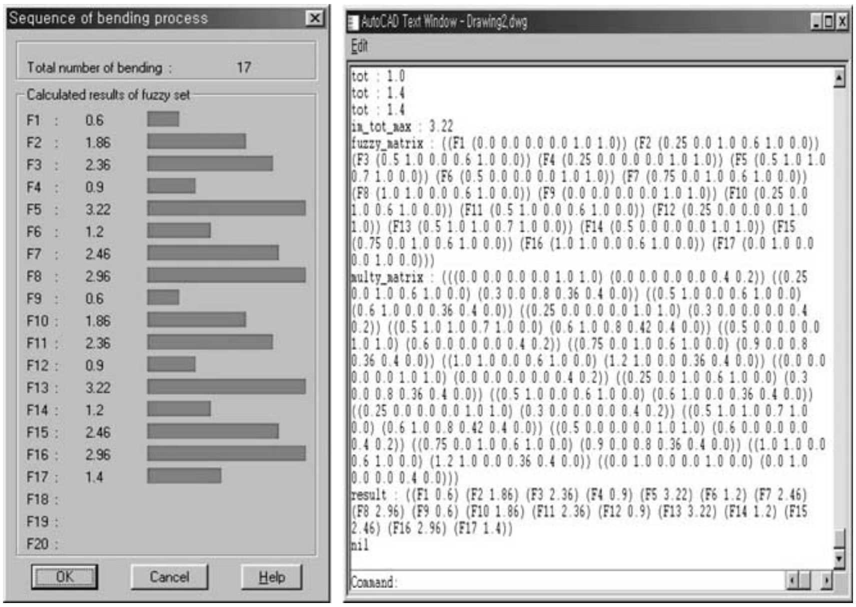


Fig. 16. The development figure of the product in Fig. 9(*c*), generated in the flat pattern layout module.

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. 7.

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. 7(*a*).



Total number of bending : 17

Calculated results of fuzzy set

F1 : 0.6
F2 : 1.86
F3 : 2.36
F4 : 0.9
F5 : 3.22
F6 : 1.2
F7 : 2.46
F8 : 2.96
F9 : 0.6
F10 : 1.86
F11 : 2.36
F12 : 0.9
F13 : 3.22
F14 : 1.2
F15 : 2.46
F16 : 2.96
F17 : 1.4
F18 :
F19 :
F20 :

```
tot : 1.0
tot : 1.4
tot : 1.4
im_tot_max : 3.22
fuzzy_matrix : ((F1 (0.0 0.0 0.0 0.0 1.0 1.0)) (F2 (0.25 0.0 1.0 0.6 1.0 0.0))
(F3 (0.5 1.0 0.0 0.6 1.0 0.0)) (F4 (0.25 0.0 0.0 0.0 1.0 1.0)) (F5 (0.5 1.0 1.0
0.7 1.0 0.0)) (F6 (0.5 0.0 0.0 0.0 1.0 1.0)) (F7 (0.75 0.0 1.0 0.6 1.0 0.0))
(F8 (1.0 1.0 0.0 0.6 1.0 0.0)) (F9 (0.0 0.0 0.0 0.0 1.0 1.0)) (F10 (0.25 0.0
1.0 0.6 1.0 0.0)) (F11 (0.5 1.0 0.0 0.6 1.0 0.0)) (F12 (0.25 0.0 0.0 0.0 1.0
1.0)) (F13 (0.5 1.0 1.0 0.7 1.0 0.0)) (F14 (0.5 0.0 0.0 0.0 1.0 1.0)) (F15
(0.75 0.0 1.0 0.6 1.0 0.0)) (F16 (1.0 1.0 0.0 0.6 1.0 0.0)) (F17 (0.0 1.0 0.0
0.0 1.0 0.0)))
multy_matrix : (((0.0 0.0 0.0 0.0 1.0 1.0) (0.0 0.0 0.0 0.0 0.4 0.2)) ((0.25
0.0 1.0 0.6 1.0 0.0) (0.3 0.0 0.8 0.36 0.4 0.0)) ((0.5 1.0 0.0 0.6 1.0 0.0)
(0.6 1.0 0.0 0.36 0.4 0.0)) ((0.25 0.0 0.0 0.0 1.0 1.0) (0.3 0.0 0.0 0.0 0.4
0.2)) ((0.5 1.0 1.0 0.7 1.0 0.0) (0.6 1.0 0.8 0.42 0.4 0.0)) ((0.5 0.0 0.0 0.0
1.0 1.0) (0.6 0.0 0.0 0.0 0.4 0.2)) ((0.75 0.0 1.0 0.6 1.0 0.0) (0.9 0.0 0.8
0.36 0.4 0.0)) ((1.0 1.0 0.0 0.6 1.0 0.0) (1.2 1.0 0.0 0.36 0.4 0.0)) ((0.0 0.0
0.0 0.0 1.0 1.0) (0.0 0.0 0.0 0.0 0.4 0.2)) ((0.25 0.0 1.0 0.6 1.0 0.0) (0.3
0.0 0.8 0.36 0.4 0.0)) ((0.5 1.0 0.0 0.6 1.0 0.0) (0.6 1.0 0.0 0.36 0.4 0.0))
((0.25 0.0 0.0 0.0 1.0 1.0) (0.3 0.0 0.0 0.0 0.4 0.2)) ((0.5 1.0 1.0 0.7 1.0
0.0) (0.6 1.0 0.8 0.42 0.4 0.0)) ((0.5 0.0 0.0 0.0 1.0 1.0) (0.6 0.0 0.0 0.0
0.4 0.2)) ((0.75 0.0 1.0 0.6 1.0 0.0) (0.9 0.0 0.8 0.36 0.4 0.0)) ((1.0 1.0 0.0
0.6 1.0 0.0) (1.2 1.0 0.0 0.36 0.4 0.0)) ((0.0 1.0 0.0 0.0 1.0 0.0) (0.0 1.0
0.0 0.0 0.4 0.0)))
result : ((F1 0.6) (F2 1.86) (F3 2.36) (F4 0.9) (F5 3.22) (F6 1.2) (F7 2.46)
(F8 2.96) (F9 0.6) (F10 1.86) (F11 2.36) (F12 0.9) (F13 3.22) (F14 1.2) (F15
2.46) (F16 2.96) (F17 1.4))
nil

Command:
```

Fig. 17. The final fuzzy value of the product in Fig. 9(*c*).

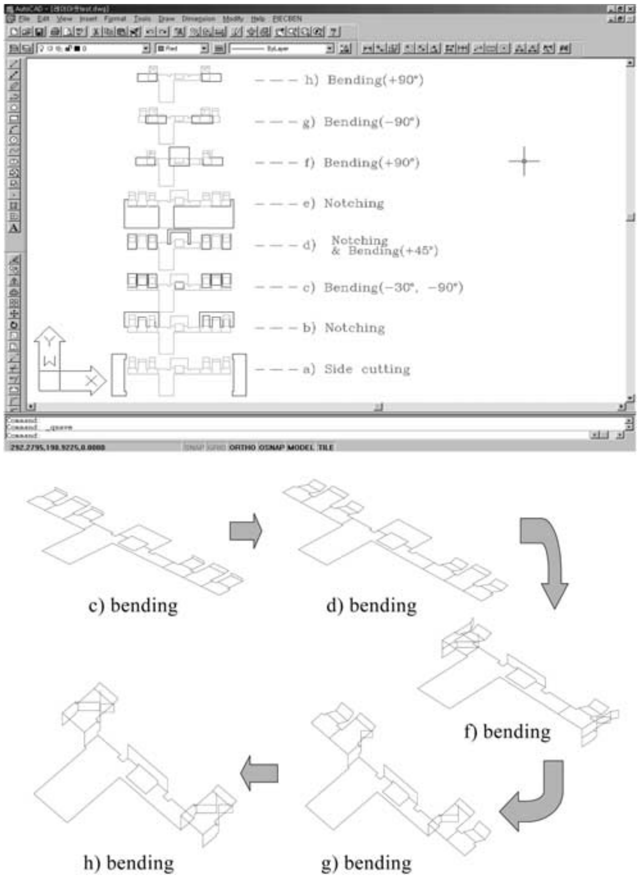


Fig. 18. A drawing of the strip layout generated in the strip layout module.

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 connected to its adjacent planes is bent first or unfolded last, as illustrated in Fig. 7(*b*).

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 a fuzzy function as shown in Fig. 7(*c*).

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 from the first bend to the other bend in the product structure that does not contain the central plane. The membership function in Fig. 7(*d*) 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 for bending next, 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.

$$VP = BLU_i \cdot BLU_j \geqslant 0.707 \tag{1}$$

where,

$VP =$ inner product of direction vector of unit vector
$BLUi =$ unit direction vector of the *i*th bend
$BLUj =$ unit direction vector of the *j*th bend

The bend angle relative to the virtual mother plane is calculated as follows and is shown in Fig. 8.

$$\theta_{n,sum} = ABS\left(\sum_{i=k}^{n} \theta_i\right) \tag{2}$$

The fuzzy membership function for this rule is shown in Fig. 7(*d*).

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. 7(*e*).

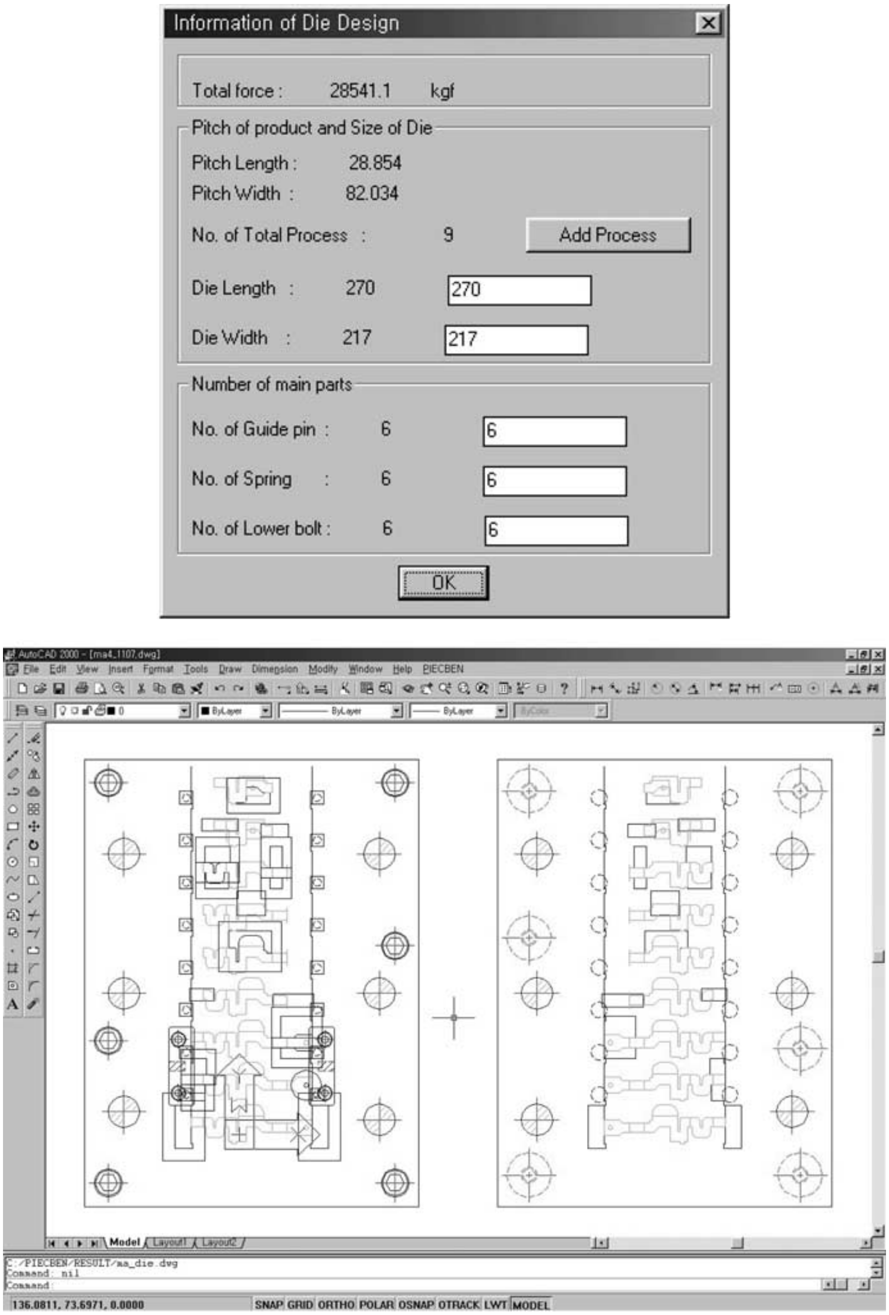
6. Feeding Rule. This rule is to determine the fuzzy relationship value of a fuzzy function according to whether or not the bend is in the feeding direction. After bending, an escape space is necessary in either the stripper plate of the upper die or the die plate of the lower die. The escape space should be the minimum considering the die strength, the part to be fixed, the loss of die material, and the manufacturing time. Bending process requiring a large escape space should be performed later to minimise 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. 7(*f*).

2.3.2 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. Let $B = \{b_i \mid i = 1, 2, \ldots, n\}$ 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 six criteria in the handling rules, where r_j represents one of the criteria.



Information of Die Design

Total force : 28541.1 kgf

Pitch of product and Size of Die

Pitch Length : 28.854

Pitch Width : 82.034

No. of Total Process : 9

Die Length : 270 [270]

Die Width : 217 [217]

Number of main parts

No. of Guide pin : 6 [6]

No. of Spring : 6 [6]

No. of Lower bolt : 6 [6]

```
C:/PIECBEN/RESULT/ma_die.dwg
Command: nil
Command:
```

136.0811, 73.6971, 0.0000

Fig. 19. A die set drawing generated in the die layout module for the sample in Fig. 9(*a*).

The grade, v_{ij}, is expressed as follows.

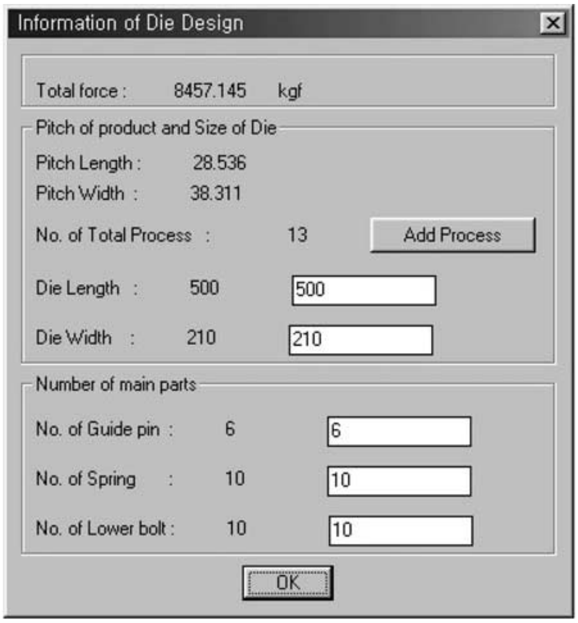
$$v_{ij} = f(b_i, r_j) \tag{3}$$

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. Determination of FVM (Final Value Matrix) Set. FVM is a fuzzy set consisting of bends that are being considered for the next bending. The grades of the bends in this set indicate how well the criteria of handling are satisfied when these bends are selected. 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 are different.

The following rules have been found to give fair results:

1. Distance rule.
2. Single plane rule.
3. Angle rule.
4. Parallel rule.



Information of Die Design

Total force : 8457.145 kgf

Pitch of product and Size of Die

Pitch Length : 28.536

Pitch Width : 38.311

No. of Total Process : 13

Die Length : 500 [500]

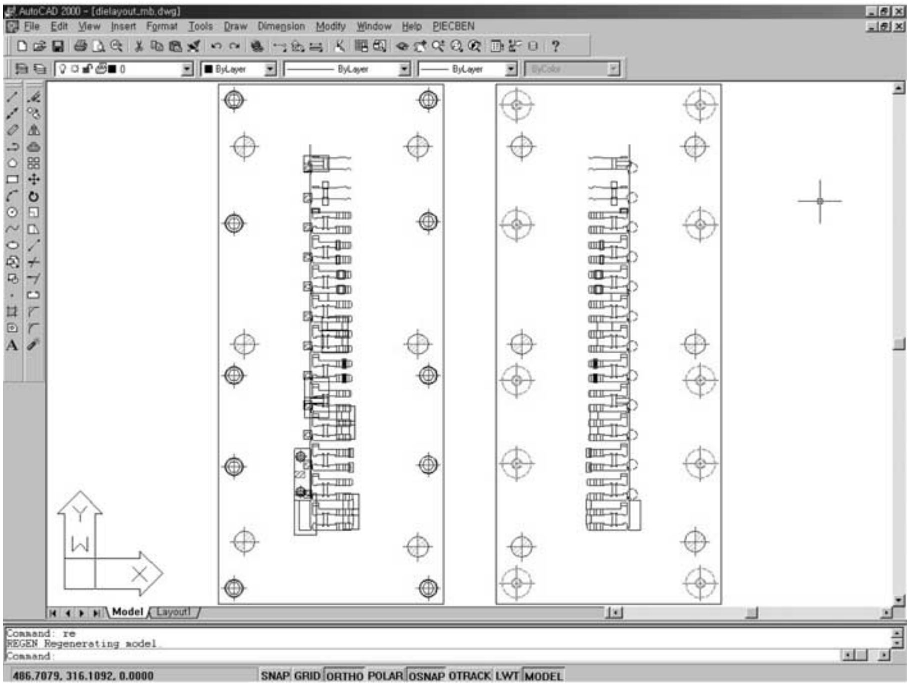
Die Width : 210 [210]

Number of main parts

No. of Guide pin : 6 [6]

No. of Spring : 10 [10]

No. of Lower bolt : 10 [10]



```
Command: re
REGEN Regenerating model.
Command:
```

486.7079, 316.1092, 0.0000

Fig. 20. A die set drawing generated in the die layout module for the sample in Fig. 9(*b*).

5. Simultaneous forming rule.
6. Feeding rule.

The relative importance of the rules is represented as a fuzzy set $W[R]$, as shown in Eq. (4).

$$W[R] = \{r_1 \times 1.2,\ r_2 \times 1.0,\ r_3 \times 0.8,\ r_4 \times 0.6,\ r_5 \times 0.4,\ r_6 \times 0.2\} \tag{4}$$

The relative importance of these rules can now be taken into account in selecting the next bend. 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 in the FVM set. From Eq. (5), the best bend to bend next can be found.

$$FVM(B) = [V] \times W(R) \tag{5}$$

$$\begin{bmatrix} FVM\ (b_1) \\ FVM\ (b_2) \\ \vdots \\ FVM\ (b_n) \end{bmatrix} = \begin{bmatrix} v(1,1)\ v(1,2)\ v(1,3)\ v(1,4)\ v(1,5)\ v(1,6) \\ v(2,1)\ v(2,2)\ v(2,3)\ v(2,4)\ v(2,5)\ v(2,6) \\ \vdots \\ v(n,1)\ v(n,2)\ v(n,3)\ v(n,4)\ v(n,5)\ v(n,6) \end{bmatrix} \begin{bmatrix} W\ (b_1) \\ W\ (b_2) \\ \vdots \\ W\ (b_n) \end{bmatrix}$$

Table 6. Fuzzy set matrix [*V*] (Fig. 9(*c*)).

	R1	R2	R3	R4	R5	R6
B1	0	0	0	0	1	1
B2	0.25	0	1	0.6	1	0
B3	0.5	1	0	0.6	1	0
B4	0.25	0	0	0	1	1
B5	0.5	1	1	0.7	1	0
B6	0.5	0	0	0	1	1
B7	0.75	0	1	0.6	1	0
B8	1	1	0	0.6	1	0
B9	0	0	0	0	1	1
B10	0.25	0	1	0.6	1	0
B11	0.5	1	0	0.6	1	0
B12	0.25	0	0	0	1	1
B13	0.5	1	1	0.7	1	0
B14	0.5	0	0	0	1	1
B15	0.75	0	1	0.6	1	0
B16	1	1	0	0.6	1	0
B17	0	1	0	0	1	0

Table 7. Fuzzy set matrix [*V*] × *W*(*R*) (Fig. 9(*c*)).

	R1	R2	R3	R4	R5	R6	Total
B1	0	0	0	0	0.4	0.2	0.6
B2	0.3	0	0.8	0.36	0.4	0	1.86
B3	0.6	1	0	0.36	0.4	0	2.36
B4	0.3	0	0	0	0.4	0.2	0.9
B5	0.6	1	0.8	0.42	0.4	0	3.22
B6	0.6	0	0	0	0.4	0.2	1.2
B7	0.9	0	0.8	0.36	0.4	0	2.46
B8	1.2	1	0	0.36	0.4	0	2.96
B9	0	0	0	0	0.4	0.2	0.6
B10	0.3	0	0.8	0.36	0.4	0	1.86
B11	0.6	1	0	0.36	0.4	0	2.36
B12	0.3	0	0	0	0.4	0.2	0.9
B13	0.6	1	0.8	0.42	0.4	0	3.22
B14	0.6	0	0	0	0.4	0.2	1.2
B15	0.9	0	0.8	0.36	0.4	0	2.46
B16	1.2	1	0	0.36	0.4	0	2.96
B17	0	1	0	0	0.4	0	1.4

2.4 Die Layout Module

The die layout module carries out the die design for each process obtained from the results of the strip layout. It then generates part drawings and an assembly drawing of the die set. In this module, the type of die set and stripper plate is decided by considering the complexity of the blank shape, and the number to be produced in a year, the number of processes, the material of the blank, and the blank size. To be decided on are the size of the die block, assuming a normal pressure of the die, and the geometric shape by the clearance between the die and the punch, the number and arrangement of springs and fasteners by the stripping force, and the number and arrangement of the dowel pins. In order to compensate for the geometric shapes of the die and punch, based on the blank shape of the strip layout for each process, the values for these are decided automatically.

The amount of springback is calculated as follows.

$$K = \frac{\alpha - \Delta\alpha}{\alpha} = \frac{r_p + t/2}{r_t + t/2} \tag{8}$$

where,

K = coefficient of springback
$\alpha - \Delta\alpha$ = bending angle after operation (rad)
$\Delta\alpha$ = angle of springback (rad)
r_p = punch radius (mm)
r_t = inner bending radius after operation (mm)

Blanking or piercing force is calculated as follows.

$$P = \tau t l \tag{6}$$

where,

P = force of blanking or piercing (kgf)
τ = shear stress (kgf mm^2)
t = thickness of workpiece (mm)
l = shear length (mm)

$$F = k\frac{bt^2(1.5 + \epsilon_r)\sigma_r}{6l} \tag{7}$$

where,

F = force of bending (kgf)
k = coefficient of correction for bending
b = length of bending line (mm)
ϵ_r = strain by bending
σ_r = shear strength (kgf mm^2)
l = length of the bending arm

Stripping force is calculated as follows.

$$F_{strip} = P \times (1.1 \sim 1.2) C_{strip} \tag{9}$$

where,

1.1 is used in the case of simple shape
1.2 is used in the case of complicated shape

$C_{strip} = 0.025 \sim 0.2$

The number of fasteners is calculated as follows.

$$F_{strip} = 300 \times d_f^2 \times n_f \tag{10}$$

where,

d_f = diameter of fastener (cm)
n_f = number of fastener

The number of springs is calculated as follows.

$$l_{workcom} = t + l_{punch} + l_{stripper} \tag{11}$$

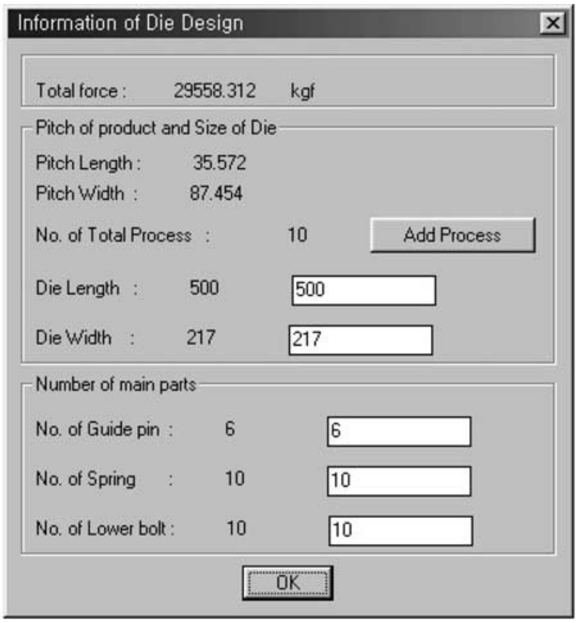
where,

$l_{workcom}$ = compression length of spring (mm)
l_{punch} = penetration length of punch (mm)

$$l_{totcom} = l_{prcom} + l_{workcom} \tag{12}$$

where,

l_{totcom} = total compression length of spring (mm)



Total force : 29558.312 kgf

Pitch of product and Size of Die

Pitch Length : 35.572

Pitch Width : 87.454

No. of Total Process : 10

Die Length : 500 [500]

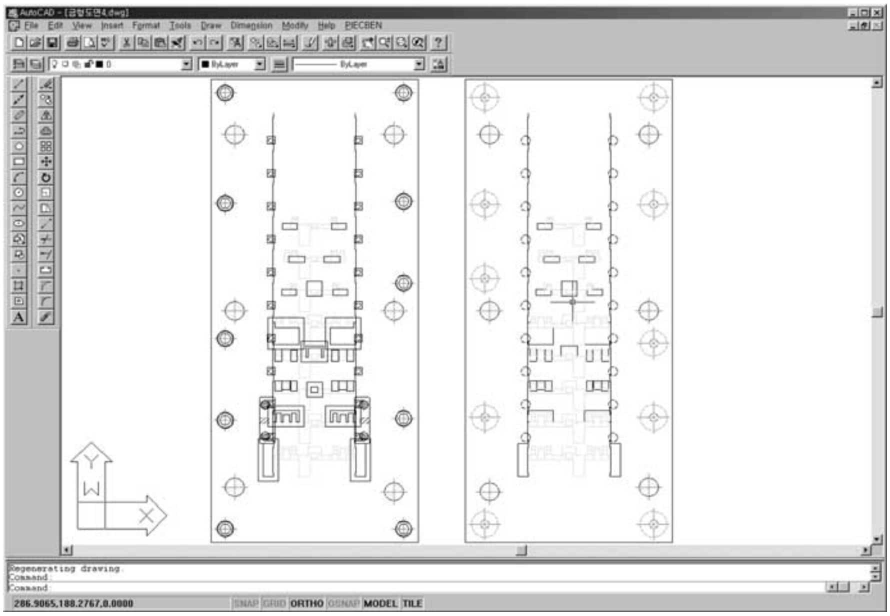
Die Width : 217 [217]

Number of main parts

No. of Guide pin : 6 [6]

No. of Spring : 10 [10]

No. of Lower bolt : 10 [10]



```
Regenerating drawing.
Command:
Command:
```

286.9065,188.2767,0.0000

Fig. 21. A die set drawing generated in the die layout module for the sample in Fig. 9(*c*).

l_{prcom} = preliminary compression length of spring (mm)

$$l_{spring} = \frac{l_{totcom}}{C_{br}} \tag{13}$$

where,

l_{spring} = free length of spring (mm)
C_{br} = deflection ratio of spring (mm)

$$F_{spring} = K_{spring} \times l_{totcom} \tag{14}$$

where,

K_{spring} = stiffness of spring (kg mm$-^2$)

F_{spring} = spring force (kg)

$$F_{strip} = F_{spring} \times n_s \tag{15}$$

where,

n_s = number of spring

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 products used as a sample are shown in Fig. 9.

3.1 Application to the Strip Layout Module

The product shown in Fig. 9(*a*) is composed of one feeding-direction bend and four bends perpendicular to the feeding direction. The development figure generated in the flat pattern layout module is shown in Fig. 10. When the rules are applied of each of the five bends, the bends, B1 and B5, have a unit fuzzy relationship value by the distance rule because of having one plane between the bends and the mother plane, and the bends, B2 and B3 and B4, have a zero value because of having a zero plane. The bends, B1 and B3 and B5, have a unit fuzzy relationship value, and the bends, B2 and B4, have a zero value by the single plane rule. The bends, B1 and B2 and B3 and B4 and B5, have a zero value by the angle rule, because of the 90° bend angle. The bends, B1 and B5, have a zero value by the parallel rule because the total sum of the angle relative to the mother plane is 0°, but the bends, B2 and B3 and B4, have a unit value because the total sum of the relative angle, is 90°. The bends, B1 and B2 and B4 and B5 have a unit fuzzy relationship value by the simultaneous forming rule because they have the same unit direction vector, but the bend, B3, has a zero value because it dies not have the same unit direction vector. The bends, B1 and B2 and B4 and B5, have a unit value by the feeding rule because they are located in the direction perpendicular to the feeding direction, but the bend, B3, has a zero value because it lies in the feeding direction.

Table 2 shows the fuzzy matrix [*V*] calculated automatically and Table 3 shows the fuzzy relationship value obtained by multiplying the respective column vector of this *W* set with the fuzzy matrix [*V*]. The value of FVM for indicating the final fuzzy relationship value for each bend is shown in Fig. 11. As shown in Fig. 11, the product in Fig. 9(*a*) is affected mainly by the distance rule so that the bends, B1 and B5, are performed in the first bending and the bends, B3, are preceded by the bends B2 and B4 by the results of the single plane rule.

The strip layout drawing generated in the strip layout module is shown in Fig. 12. It carries out preferentially notching and piercing in the outer region, before the bending operations. The outer shape, using the dialogue, designs the shapes of the notching punches, which is user-friendly, having the appropriate prompting statements for the various data required.

Each plane and the bends of the product, Fig. 9(*b*), are generated as a flat pattern layout drawing (Fig. 13). Figure 14 shows the value of FVM applied to each rule. The bends, B1 and B7, are bent simultaneously in the first bending process by the parallel rule as the angle relative to the mother plane is small. The strip layout drawing automatically generated in the strip layout module for the product, Fig. 9(*b*), is shown in Fig. 15. Tables 4 and 5 show the fuzzy set matrix for Fig. 9(*b*).

Figure 16 shows the development figure generated in the flat pattern layout module for the product, Fig. 9(*c*). The value of FVM applied to each rule is shown in Fig. 17. Figure 18 shows the strip the layout drawing generated in strip layout module for the product, Fig. 9(*c*). Tables 6 and 7 show the fuzzy matrix for Fig. 9(*c*).

3.2 Application to the Die Layout Module

This module interacts with the standard parts database and extracts standard parts such as fastener, spring, and dowel pin according to the design requirement. Based on the value of the "strip layout area", the thickness of the die and stripper plate, the diameter of the guide post, the working length, and the width of the die set are obtained from the database. There are 6 guide pins arranged in the upper and lower dies. Using the working force calculated in the strip layout and the die layout rule, the number of fasteners is 6. The fasteners are checked for interference with the guide pins and are arrayed on the same pitch. They are arranged on the position free of interference. According to the spring force calculated, the number of springs in the upper die is 6 by the die layout rule. They are also arranged on positions as shown in Fig. 21, after checking for interference with the fasteners and guide pins. Lift pins are arranged on the same pitch in a position free of interference. The dimension of the part to be pierced is the same as that of the punch, and the dimension of the part to be blanked is the same as that of the die. This module generates parts of the progressive die, i.e. punch and die, die plate, punch plate, stripper plate, guide pin, spring, fastener, dowel pin, and lift.

The die set drawings generated in the die layout module for the products as shown in Fig. 9 are shown in Figs 19 to 21. After all the die blanks are arranged, moments are calculated from the position and centre of gravity of each shape, to determine the balance force point. Matching this point to the centre of the die set produces a balanced pressing pressure and reduces the wear on the die and punch.

4. Conclusion

The study has developed an automated design system for process planning and die design by fuzzy set theory for electric products having intricate piercing and bending operations. This system quantifies the techniques and experience required in designing die sets and standardises design rules for formulating procedures for the design. It recognises 3D shapes and performs process planning according to sequences decided in the strip layout module, with information of shape data obtained by the shape recognition method. 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. It has the advantage that a novice who may have only some knowledge of tool design can use it. The design and working time for each part is reduced by making use of the results generated in this system. 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. The standardisation of the design, the high precision of the die, the preparation of material, the purchase of standard products, and the reduction of design time, not only expand consumer markets because of the rapid supply of products, but also play an important role in building an FMS system as an integrated CAD/CAM system.

Acknowledgements

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References

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