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ORIGINAL ARTICLE

Development of a new method to determine bending sequence in progressive dies

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Abstract In progressive dies, two or more stations are used to produce sheet metal components. In each station, one or more processes are applied. The progressive dies reduce the time and cost of producing complex sheet metal components. However, the design and manufacture of these dies are difficult. CAD/CAM systems have been proved to be very useful tools for this task. The main problem of CAD/CAM systems used in progressive die design is determining the bending operations sequence. In this paper, a new method for determining the sequence of the bending operations is described. In this method, sequencing is done in two stages. First, the bending operations, which can be carried out simultaneously, are defined by a classification method. In this method, all the bends are initially divided according to their bending directions (feed direction or perpendicular to it). Then for each direction, the bends are divided into operation groups according to classification rules. Three rules are used to determine the bending operation groups in this paper. These rules are based on relations between the bends in the component. The sequence of the bending operation groups is then determined using fuzzy set theory. Four components taken from industry and previous papers are used to show the capabilities of the proposed method.

Keywords Bending sequence · Progressive dies · Fuzzy set theory

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1 Introduction

One of the most common processes used for sheet metal forming is bending. The bending process has many applications including electrical, automotive and in aircraft industries.

Bending dies are designed according to the sheet metal component shape, its dimensions, and tolerances [1]. Thus, several types of dies are used in sheet metal bending. When the number of parts is large and the shape is complex, the designers often use progressive dies to reduce lead time and production costs.

Individual operations in a progressive die are often relatively simple. But when the die contains several stations where in each station a few of these individual operations are to be combined, it is often difficult to plan the most practical and economical strip design for optimum operation of the die.

The sequence of operations is the most important problem in progressive die design. In other words, the sequencing is the key to progressive die design.

Most research in sheet metal working involves using analytical and experimental methods which address problems of sheet metal behavior in forming process. Although much work has been carried out on sheet metal behavior, little work has been done on the automation of die design and the sequence of operations in progressive dies.

In this paper, a new approach for sequencing bending operations in progressive dies is described. In this method, sequencing is done in two stages. First, the bending operations which can be carried out simultaneously are defined by a classification method. The sequence of the bending classes is then determined by using fuzzy set theory.

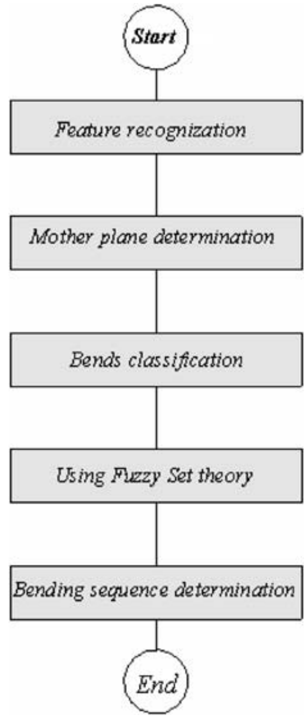


Fig. 1 The stages of bending sequence

2 Related work

Shaffer, Fogg, and S. Nakahara [2, 3] were the first people to work on computer-aided progressive die design systems. The early systems attempted to use basic computer graphics facilities and programs written in FORTAN to improve the productivity of die design [2]. These systems were mostly used for piercing and blanking operations.

In recent years, some researchers have focused on the bending process in progressive dies. De Vin et al. [4] have described the use of a tolerance tree in sequencing procedures for bending operations. This was used in an integrated computer-aided process planning (CAPP) system. Ong et al. [5] used a fuzzy set system to determine the sequence of bending operations in press brake machines. Gupta et al. [6] have developed a process planning system for sheet metal components. They applied a greedy algorithm to determine the bending sequence. Prof. Duflou et al. [7] suggested a penalty function method and the traveling salesman problem method to determine bending sequences in press brake machines. Most researchers have worked on the bending operations performed by press brake machines or robot-assisted bending [8–10].

A few researchers have used computer-aided systems for the bending progressive dies. Li et al. [11] and Prof. Choi et al. [12] were probably among the first to develop such systems for bending progressive dies. J H Kim et al. [13, 14] developed a fuzzy set theory method for determining the sequence of the bending operations. They modified fuzzy rules and weight factors for the rules.

These systems are mostly used as an assistant for the progressive die designer. Simultaneous bends determination is a major problem in these systems. Thus, the number of the bending stations suggested by these systems is often more than the actual industrial parts. So the die layout suggested by these systems is usually modified manually by the designer.

3 Process planning

In a CAPP system for sheet metal components, the determination of the bending sequence is one of the main problems. If N is the number of bends in a given part, then the domain of possible sequences in principle is N! [7]. However, this number is usually limited due to geometrical and technical constraints. In other words, the number of possible sequences depends on the shape of the component. A flow chart of the operations which are used for computer-aided bending sequence determination is shown in Fig. 1.

3.1 Mother plane

Mother plane has a very important role in bending progressive die design. The mother plane is a fixed plane which stays without any rotations throughout the bending operations. All the rotating planes are called children planes. The rules for the determination of mother planes are as follows:

– A plane surrounded by other planes
– A plane located in the center of the part
– The largest plane in the component

Figure 2 shows the mother plane for part 1; the mother plane is colored in this figure. When the determination of a mother plane is not clear from the conditions as stated above, it is determined by the minimum number of bends between a plane and the plane in the central plane [14].

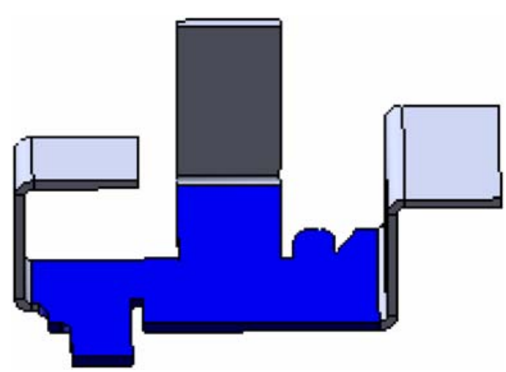


Fig. 2 Illustrated mother plane

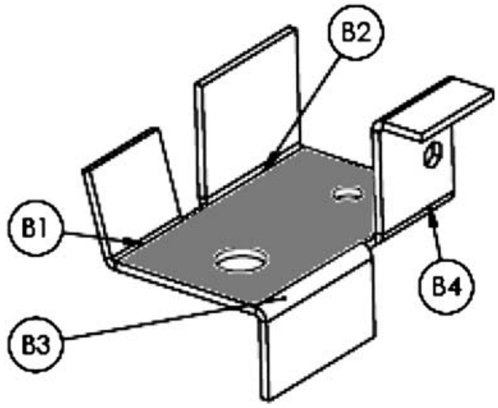


Fig. 3 Example for the classification rule 1

3.2 Bending classification method

The classification technique is applied to the determination of simultaneous bends which can be performed in one station. The die designers use different rules to define simultaneous bends, because several parameters affect this procedure. According to experimental studies, many factors affect the determination of the simultaneous bends. However, the following rules can be summarized [15].

Rule 1 The bends that have bend lines along one line and whose bending directions are the same (up or down bending) can be performed in one station. Thus, they are said to be in one group. In Fig. 3, according to rule 1, bends B1and B2 are in one class. But bends B3 and B4 are not in one group, since their bending directions are not similar (B3 is down and B4 is up).

Rule 2 The bends that have parallel bending lines and their bending directions are the same (up or down bending) and are placed on opposite sides of the mother plane can be performed in one station and are said to be in one group if the number of the planes between them and the mother plane are equal. In Fig. 4, the directions of bends B1 and B2 are the same and they satisfy the rest of the conditions of rule 2, hence, they are said to be in one group.

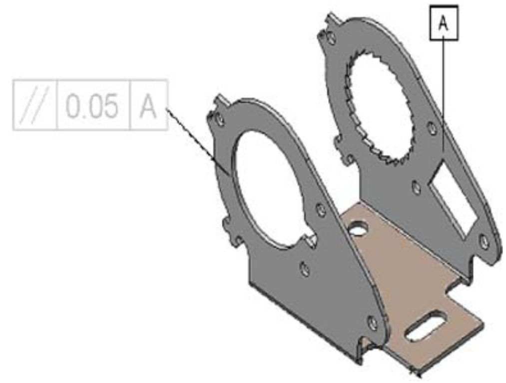


Fig. 5 Rule 3 for classification

Rule 3 Related bends. In some sheet metal components, two planes can be related through geometric or dimensional tolerances. To obtain the tolerance and to comply with the positioning errors, these bends should be (or better be) performed together. For example, in the part that is presented in Fig. 5, planes A and B have parallel tolerances. Thus, they should be performed together.

In the classification procedure, first, all the bends are divided according to their bending directions (feed direction or perpendicular to it). Then in each direction, the bends are classified. In other words, the bends which are parallel and perpendicular to the feed direction cannot be formed in similar groups.

3.3 Fuzzy set theory

The handling rules and criteria needed for determining the bending sequence is discussed in this section. These rules deal with the selection of the next best bend for the bending operation. Each of these rules establishes relationships between pairs of bending operation groups. A high membership grade indicated for a particular rule means that the bend group is a good selection for the next operation according to this rule. These relationships between the bending and criteria are represented as fuzzy relations, and the membership grades of these fuzzy

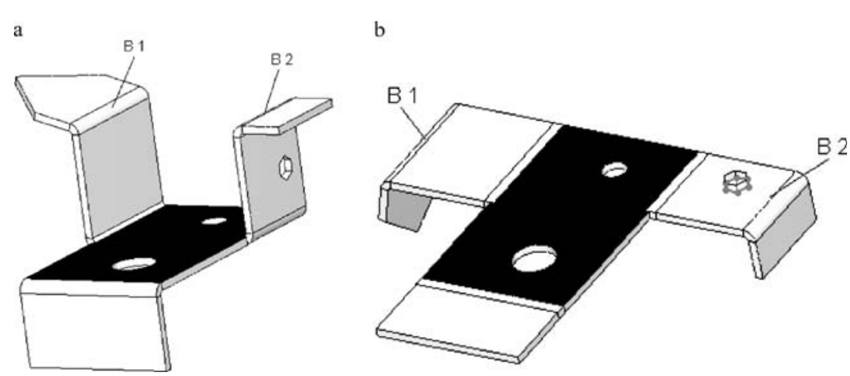


Fig. 4 Rule 2 for classification. **a** Sheet metal component. **b** Bends B1 and B2 can be bent together

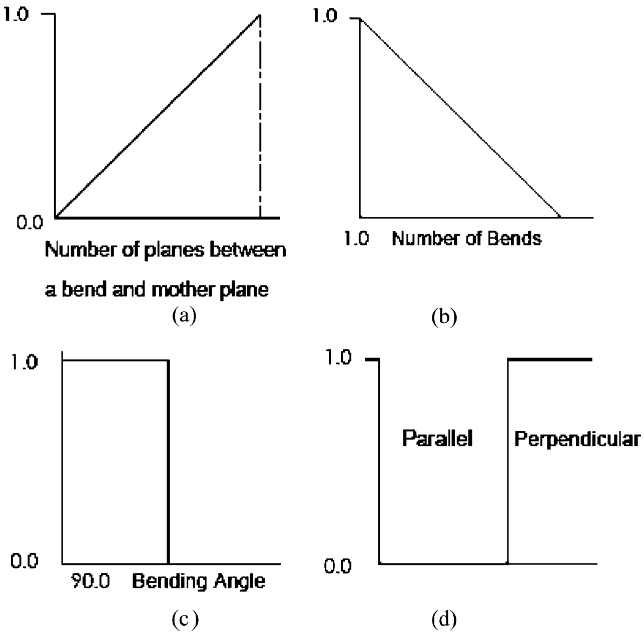


Fig. 6 Fuzzy membership function. **a** Distance rule. **b** Number of bends in a group. **c** Bending angle. **d** Feeding direction

relations are determined through fuzzy membership function, as shown in Fig. 6.

3.3.1 Sequencing rules

Fuzzy relations or sequencing rules describe the priority of each group. Thus, definition of these rules for a computer-aided system is important. According to previous studies and experience of the authors [15], the following rules are suggested:

Rule 1: Distance rule This rule describes the influence of the shape of a bend on the sequencing strategy. The further a bend is away from the mother plane, the higher its grade will be and thus should be bent earlier. The fuzzy functions presented in Fig. 6a are used to determine the grade of membership by this rule.

Rule 2: Number of bends in a group The higher the number of bends in a group, the more impact it will have on the overall shape of the part and vice versa. The more impact a group will have, the later it should be addressed in the operation. So the fuzzy relationship value of this rule can be represented as in Fig. 6b.

Table 1 A fuzzy matrix, [M]

$Rule1(r_1)$	$Rule2(r_2)$	$Rule3(r_3)$	$Rule4(r_4)$
$V_{1,1}$	$V_{1,2}$	$V_{1,4}$	$V_{1,4}$
$V_{2,1}$	$V_{2,2}$	$V_{2,3}$	$V_{2,4}$
$V_{n,1}$	$V_{n,2}$	$V_{n,3}$	$V_{n,4}$

Table 2 FVM set

$$\begin{bmatrix} V_{11} & V_{12} & V_{13} & V_{1,4} \\ V_{21} & V_{22} & V_{23} & V_{2,4} \\ \ldots\ldots. & & & \\ \ldots\ldots.. & & & \\ V_{n1} & V_{n2} & V_{n3} & V_{n,4} \end{bmatrix} * \begin{bmatrix} W(c_1) \\ W(c_2) \\ \ldots \\ \ldots \\ W(c_n) \end{bmatrix} = \begin{bmatrix} FVM(c_1) \\ FVM(c_2) \\ \ldots.. \\ \ldots. \\ FVM(c_{n1}) \end{bmatrix}$$

Rule 3: Bending angle This rule is to determine the fuzzy relationship value according to the angle of each plane. This is the angle between the mother plane and each rotated plane. If this 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 less than 90° and zero in other cases. These relationships according to bend angles are represented as fuzzy functions as shown in Fig. 6c.

Rule 4: Feeding direction [14] 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, 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

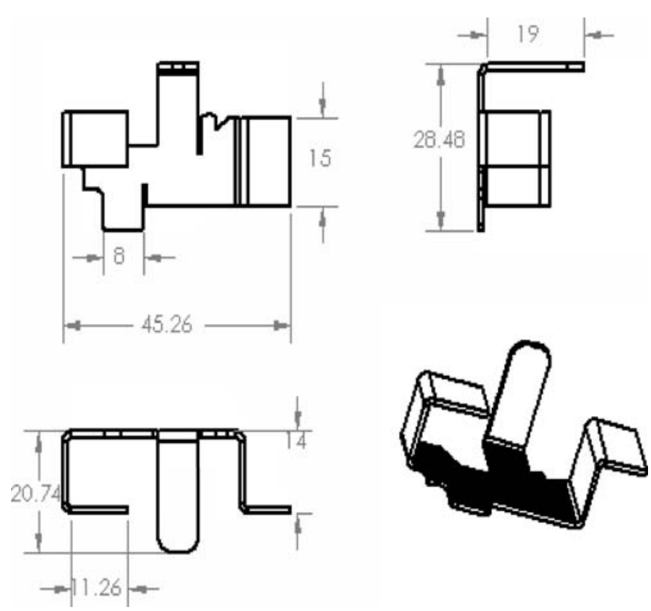


Fig. 7 First sample

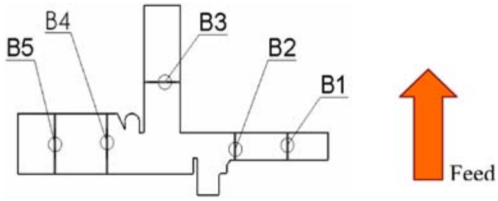


Fig. 8 Unfolded shape of the part and the feed direction

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. 6d.

Note: To determine the grade of the membership for each group, the maximum grade of its bends is chosen and later used in the fuzzy matrix.

3.3.2 Fuzzy matrix

Let C={c_i|i=1, 2,…….., n} represent the set consisting of all the remaining bend classes that are being considered for bending, where c_i is one of the bend classes.

Let R={r_j|j=1, 2, 3, 4} represent the set of four criteria in the handling rules, where r_j represents one of the criteria.

A fuzzy relation is a mapping from C×R into [0, 1], such that $(V_{ij})_c$, is expressed as follows:

$$\left(V_{ij}\right)_c = f\left(c_i, r_j\right) \tag{1}$$

Since related sets C and R are finite, a fuzzy relation f on C×R can be represented as a fuzzy matrix [M], the entries of which are $(V_{ij})_c$.

The determination of the grade, which may vary anywhere between zero and unity, is based on the sequencing rules. The fuzzy matrix [M] is shown in Table 1.

3.3.3 Determination of final value matrix (FVM) set

FVM is a matrix consisting of fuzzy values for each bend groups that are being considered. The fuzzy values are determined by implementing rules described in Section 3-3-1. These rules have been found to give suitable results in bending operations. The higher value a bend group has, the sooner it should be formed. The relative importance of the rules is represented as a fuzzy set W[R], as shown in Eq. (2).

Table 3 The fuzzy matrix of first sample

	R1	R2	R3	R4
Class one	1	0	0	1
Class two	0	0	0	1
Class three	0	1	0	0

Table 4 FVM matrix

	[M]×W[R]				
	R1	R2	R3	R4	Total
class1	1.2	0	0	0.2	1.4
class2	0	0	0	0.2	0.2
class3	0	0.8	0	0	0.8

$$W[R] = \{r_1 * 1.2, r_2 * 0.8, r_3 * 0.6, r_4 * 0.2\} \tag{2}$$

Thus, the FVM set can be presented by Table 2 and expressed as follows:

$$FVM(C) = [V].W[R] \tag{3}$$

4 Examples

To evaluate the described method, four components are selected (Figs. 7, 11, 14, and 16) and will be presented as follows:

Example 1 Figure 7 presents a part which is used in electrical components. To produce this part, five bending and several cutting operations are carried out. However, in the present paper, only bending operations will be investigated.

According to the rules regarding the mother plane, described in Section 3-1, the central plane of the part is determined as the mother plane.

The unfolded shape of the part is shown in Fig. 8. Amongst the bending operations, four are in perpendicular and one in feed direction. According to the classification rules, the classes of this part are determined as follows:

1. Bends b1and b5 are in one class (class one), according to rule 2.

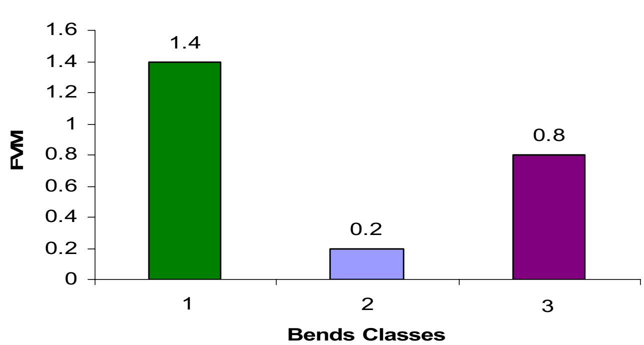


Fig. 9 FVM of the first sample

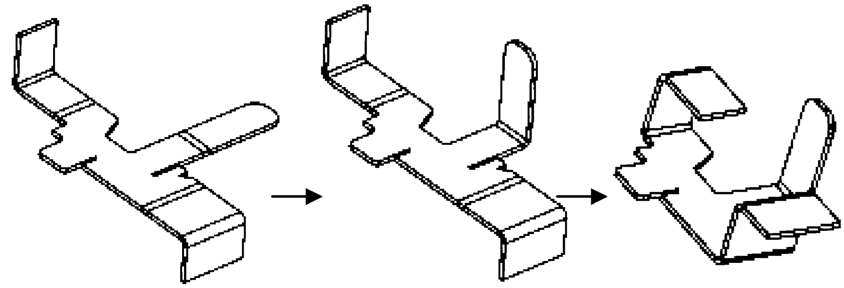


Fig. 10 The component shapes in three stations

2. Bends b2 and b4 are in one class (class two), according to rule 2.
3. Bend b3 is in one class (class three) since this bend is the only one perpendicular to the feed direction.

After the classification of the bending operations is determined, the sequence of the operations can now be determined according to the fuzzy matrix [M] as shown in Table 3.

The membership grades for class one are described as follows:

– From rule 1 (R1)—The bends in this class are each at maximum distance from the mother plane, so each has a grade 1 and hence the resulting grade of the class one is 1.
– From rule 2 (R2)—The number of bends in this class is two, thus its grade is zero.
– From rule 3 (R3)—The bends angles are 90°, thus its grade is zero.
– From rule 4 (R4)—The bends of this class are perpendicular to the feed direction, thus its grade is 1.

Hence, the final value matrix (FVM) is determined as Table 4.

According to Table 4, the final grade for class one is 1.4, class two is 0.2, and class three is 0.8 (Fig. 9). Thus, the sequence of the bending processes is as follows:

Bends b1 and b5 are performed in the first station. Bend b3 is performed in the second station. Bends b2 and b4 are performed in the third station.

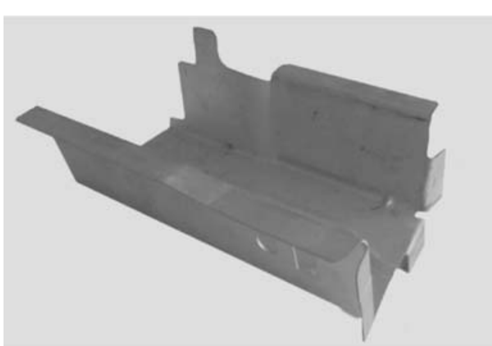


Fig. 11 Second part

In Fig. 10, the bending operations in the three stations are shown. These results are the same as the results in Refs. [13–14].

Example 2 A part of the Samand automobile (Iran Khodro Company) (Fig. 11) is the second example which is studied in this paper. This part has seven bends. Figure 12 shows the unfolded shape of the part.

According to the classification rules, the classes of this part are determined as follows:

– Class 1: bends B1 and B7
– Class 2: bends B3 and B5
– Class 3: bend B2
– Class 4: bend B4
– Class 5: bend B6

Final value matrix for the classes of this part is presented in Fig. 13.

Since the grades of class 3 and class 5 are similar, they are performed in one station. So the total number of the

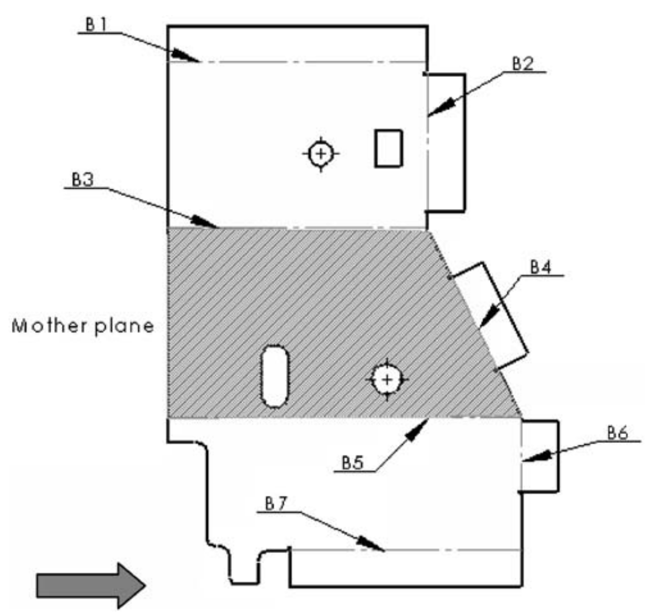


Fig. 12 Unfolded shape and feed direction

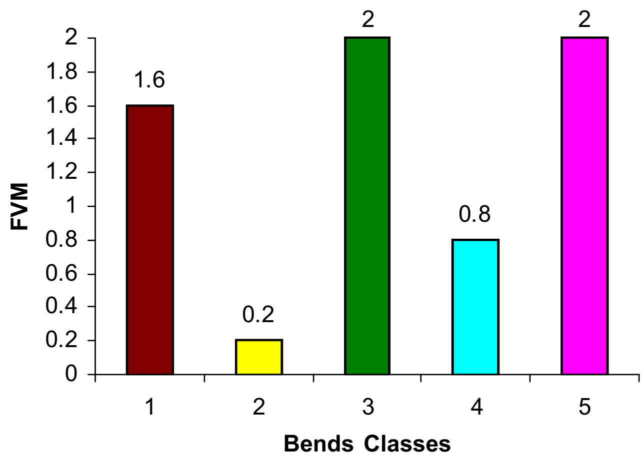


Fig. 13 FVM for second part

bending stations is four. The sequencing that is suggested for this part as follows:

- Station 1: bends B2 and B6
- Station 2: bends B1 and B7
- Station 3: bend B4
- Station 4: bends B3 and B5

Example 3 The component which is studied as the third example (Fig. 14a) is a part of GPI Company. This part has 12 bends. The unfolded shape of the part is shown in Fig. 14b.

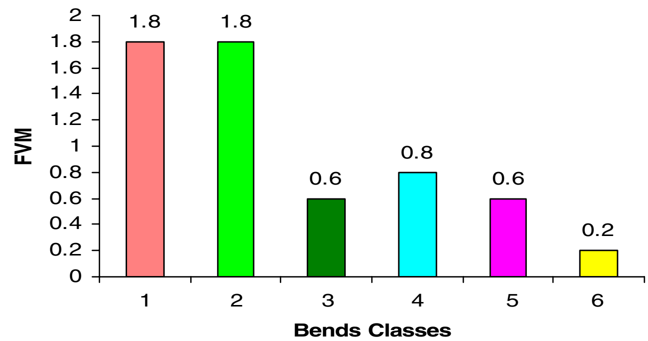


Fig. 15 FVM for second part

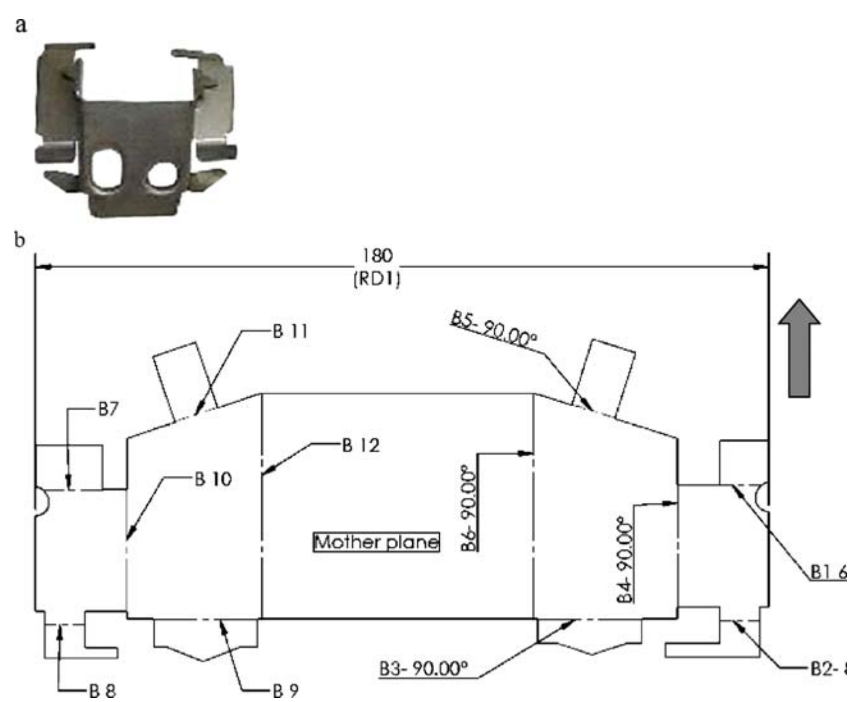
According to the classification rules, the classes of this part are determined as follows:

- Class 1: bends B1 and B7
- Class 2: bends B2 and B8
- Class 3: bends B3 and B9
- Class 4: bends B4 and B10
- Class 5: bends B5 and B11
- Class 6: bends B6 and B12

According to fuzzy membership functions, the final value matrix of these classes is presented in Fig. 15.

Thus, this part can be finished in four stations: The first station includes bends B1, B2, B7, and B8. In the second station, bends B4 and B10 are performed. In the third station, bends B3, B5, B9, and B11 are performed and in the fourth station bends B6 and B12 are performed.

Fig. 14 The part for the third example. **a** The finished part. **b** Unfolded shape and feed direction



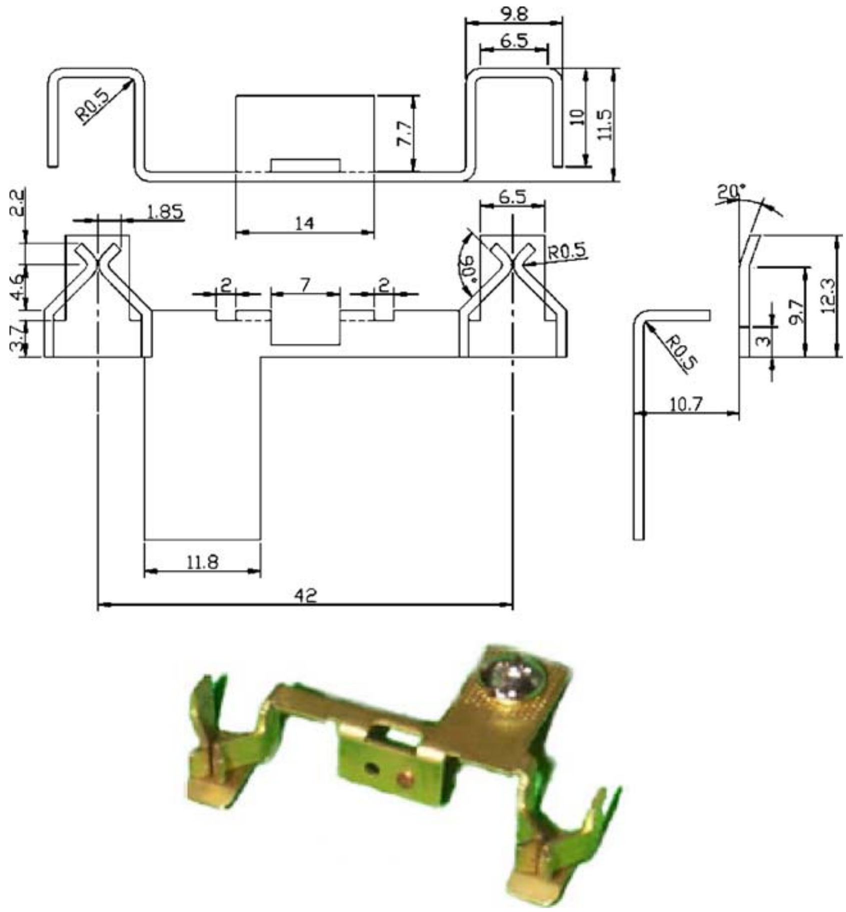


Fig. 16 Fourth part

Example 4 The fourth sample which is used in this paper is an electrical product. This part is shown in Fig. 16. It has 17 bends (unfolded shape is shown in Fig. 17). This part is used by Kim et al. [14] and here a comparison test is carried out as follows:

According to the classification rules used in the present work, the classes of this part are determined as follows:

- Class 1: bends B8, B3, B12, and B15 (according to rule 1)
- Class 2: bends B17, B5, B2, B7, B11, and B14 (according to rule 1)
- Class 3: bend B16 (this bend is the only one where none of the rules address it)
- Class 4: bends B13 and B6 (according to rule 2)
- Class 5: bends B4 and B10 (according to rule 2)
- Class 6: bends B1 and B9 (according to rule 2)

The final value matrix for this part is presented in Fig. 18.

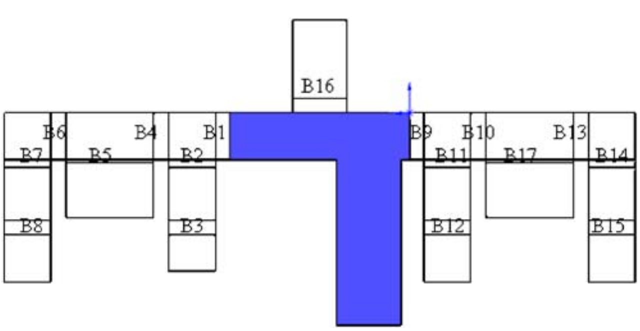


Fig. 17 Unfolded shape of fourth part

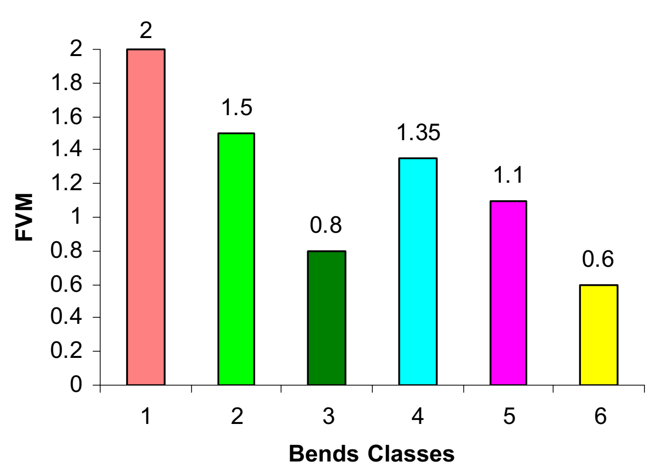


Fig. 18 FVM for the fourth part

According to FVM, the total number of the bending stations is six. The sequencing that is suggested for this part is as follows:

- Station 1: bends B8, B3, B12, and B15
- Station 2: bends B17, B5, B2, B7, B11, and B14
- Station 3: bends B13 and B6
- Station 4: bends B4 and B10
- Station 5: bend B16
- Station 6: bends B1 and B9

The number of stations suggested by the fuzzy set matrix in Kim et al. [14] is nine. The number of stations suggested with the present method is six which shows a clear reduction in the number of stations.

5 Conclusion

In this paper, a new method for the determination of bending sequences for progressive dies is presented. In this method, a classification system and fuzzy set theory are used for the sequencing. In the first step, the bends which can be performed in one station are determined by the classification system. The sequencing of the bends is then determined by using fuzzy rules and fuzzy sets. To the best of the authors' knowledge, the classification algorithm used in the present work is the first of its type. Four examples have been used to demonstrate the capability of the method. The results show that, compared with the existing automated systems, this method successfully determines the bending sequences for the parts and further reduces the number of the stations.

The drawbacks of this classification system are that it cannot completely determine the existence of simultaneous bends. This is due to the fact that the classification rules are not yet enough to cater for all possible situations in sheet metal components. This problem, along with the considerations for the existence of idle stations and their positions in the progressive dies, will be studied in future works by the authors.

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