

Computer-aided sequence planning of shearing operations in progressive dies

Alan C. Lin and Dean K. Sheu

Abstract—This paper aims to study the methodology of building the knowledge of planning adequate punches in order to complete the task of strip layout for shearing processes, using progressive dies. The proposed methodology uses die design rules and characteristics of different types of punches to classify them into five groups: prior use (the punches must be used first), posterior use (must be used last), compatible use (may be used together), sequential use (certain punches must precede some others) and simultaneous use (must be used together). With these five groups of punches, the searching space of feasible designs will be greatly reduced, and superimposition becomes a more effective method of punch layout. The superimposition scheme will generate many feasible solutions, an evaluation function based on number of stages, moment balancing and strip stability is developed for helping designers to find better solutions.

Keywords—Manufacturing Systems, Advances in Metal Forming, Computer-aided Design, Progressive Die

I. INTRODUCTION

There are three types of operation involved in progressive dies use: shearing, bending and forming. Shearing is used for products like lead frames in the IC industry, and it is also the preparation process required for the other two; because the external profiles and internal holes of the strip must be trimmed before these two operations can be performed.

Progressive die design is a highly experience-intensive task. Designers have to do a lot of time-consuming trial and error, involving tradeoffs and compromises [1]. Although the design rules and empirical equations are all listed in the die design handbooks and publications [2-4], they are too scattered and incomplete. They can do little to help designers, who need a more efficient and effective way to manage the design process.

The first work in a progressive dies design is to read the drawing of the sheet metal part to understand all its specifications and requirements. The designer will then decide the appropriate punches according to internal holes and external profiles; this process is called dedicated punch design. The designer will plan how to superimpose the designed punches on the strip in question. Using the sheet metal part in figure 1(a) as an example, the 8 punches used to produce the part are shown in figure 1(b). Punch layout using superimposition is quite straight-forward. The designer simply tries to place each punch on an appropriate stage of the strip [5].

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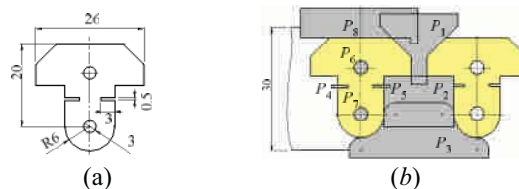


Fig. 1(a) Sheet metal part, (b) Dedicated punch design

When planning punch layout using superimposition, the main problems which designers need to address are: how many stages are needed, how many punches are needed and which punches should be placed at which stage. The number of stages can be from 1 to n , and one stage can have one to n punches. These combinations make the number of possible designs so huge that the task becomes very difficult. In this study, we aim to solve this problem of incredible numbers of possible solutions when planning punch layout using superimposition. We first evaluate the features of the part to be produced, and then with the help of die design rules, most inappropriate solutions will be excluded. Finally, an evaluation function is used to find the better solutions for the designer to choose among.

Schaffer [6] and Nakahara et al [7] were probably the pioneers in studying strip layout for progressive dies. They used CAD/CAM techniques for the automation of die design. Some followers have tried to integrate other techniques into the CAD/CAM environment. Bergstrom et al [8] added some functions like unfolding a bent part and calculation of shearing and bending forces, and Choi et al [9] used knowledge based rules in their study.

To reduce the huge search space and calculation time, AI techniques and heuristic searching schemes are becoming more popular for solving strip layout. Thanapandi et al [10] used genetic algorithms for the same purpose. Tor et al [11] integrated objective oriented techniques and blackboard architecture, and Zhang et al [12] took one step forward by adding case-based reasoning. Ong et al [13], on the other hand, used fuzzy set theory. Based on these studies, one observation which can be made is all the studies are more oriented toward testing the feasibility of using these techniques. None have involved the topics of punch design and layout using superimposition.

II. PUNCH LAYOUT PROCESS

In this study, there are three steps needed to solve the punch layout design.

Step 1: Punch design

The punch design is to envision and then design all the punches needed to form every feature on the product.

Step 2: Feasible punch layout

When all the punches needed are well designed from the last step, we will then find the entire feasible punch layout; this means to find the entire layout that does not violate the punch and die design rules.

Step 3: Layout evaluation

There are many feasible punch layouts. We use an evaluation function to find out better layouts for the designer. In this study, the punch design is assumed to be a known condition, which lists and reserves all the punches needed for the product. So, we will stress feasible punch layout and layout evaluation.

III. FEASIBLE PUNCH LAYOUT

The task of punch layout is to place n punches into progressive stages. Mathematically speaking, there are many combinations of punch and stage; the feasible layouts are those which do not violate die design rules. We need three steps to deal with feasible layout: punch grouping, expansion of number of punches and punch layout

A. Punch grouping

Based on relationships between punches and the characteristics of the punches, punch grouping involves dividing punches into five groups: prior use, posterior use, compatible use, sequential use and simultaneous use.

- (1) Prior rules: In figure 2, the running stop and side cut punch P_8 must be placed in the first stage, and the pilot punches of P_6 and P_7 will be next to them.
- (2) Posterior rules: The parting punch for bridge or carrier should be placed at the last stage. So at least one of punches P_1 , P_2 , or P_3 is used as a parting punch for disconnecting a part from the strip at the last stage.
- (3) Simultaneous rules: If the dimensional accuracy among some of the features is of great concern, the features should be created in the same stage; this means the punches for the features should be in one group. The pilot punches $[P_6, P_7]$ and the notch punches $[P_4, P_5]$ are all required to be in one stage due to accuracy concerns.
- (4) Sequential rules: If a small internal feature is very near to a large processing area, then the small feature must be processed after the previous processing is finished to avoid unwanted deformation. The accuracy of the distance between the two narrow notch features is crucial; the punches $[P_4, P_5]$ should never be applied earlier than the P_2 punch.
- (5) Exclusive rules: If footprints of punches overlap in their superimposed layout, or the punches are so close that the dies may become too weak to sustain the punching force, these punches should not be placed at the same stage. The exclusive sets for different punches are listed below:

$$\hat{E}P_1 = \{P_2\}; \quad \hat{E}P_2 = \{P_1, P_3, [P_4, P_5]\};$$

$$\hat{E}P_3 = \{P_2\}; \quad \hat{E}[P_4, P_5] = \{P_2\}$$

The compatible set of different punch P_i , noted as CP_i , which contains all the punch elements which can be placed

at the same stage with P_i . The compatible set of punches can be found as follows:

$$CP_1 = \{P_3, [P_4, P_5]\}; \quad CP_2 = \{\Phi\};$$

$$CP_3 = \{P_1, [P_4, P_5]\}; \quad C[P_4, P_5] = \{P_1, P_3\}$$

The CP_2 is an empty set, which means that punch P_2 will not be able to be placed at the same stage as any others, and it must be alone. As long as the compatible set for punch P_i is found, it is easy to find all the compatible groups for the punches in one stage.

- 1-punch compatibility = $(P_1), (P_2), (P_3)$
- 2-punch compatibility = $(P_1, P_3), ([P_4, P_5])$
- 3-punch compatibility = $(P_1, [P_4, P_5]), (P_3, [P_4, P_5])$
- 4-punch compatibility = $(P_1, P_3, [P_4, P_5])$

In this case, the maximum number of punches which can show compatibility is four, noted as $Tmax = 4$, and there is no possibility to place 5 or more punches at one stage.

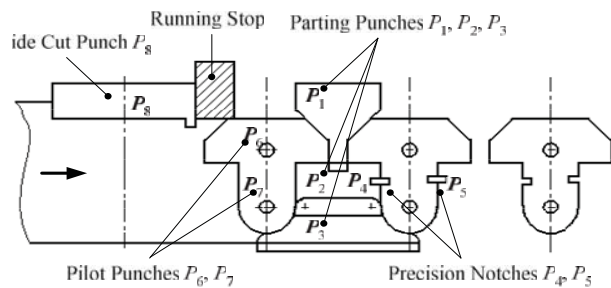


Fig. 2 Punch grouping

B. Expansion of number of punches

Progressive dies, according to definition, have at least two sets of die combined; hence with n punches, the minimum number of stages is two, and the maximum is n. The next problem is how many punches at one stage; this can be solved by expansion of number of punches. Using 8 punches as an example, 2-stage design can be expanded totally in 7 ways; there are 1+7, 2+6, 3+5, 4+4, 5+3, 6+2 and 7+1. The 3-stage design can be found by expanding the 2-stage. Taking 2+6 as an example, there are 2 punches at the first stage and 6 punches at the second, and it can be expanded into 2+1+5, 2+2+4, 2+3+3, 2+4+2 and 2+5+1. There are two rules for the expansion.

Rule 1: Expansion of number of punches

When expanding the number of punches, if the number of punches at the last stage is m, and if $m > 1$, it can be expanded to the next stage number.

Rule 2: To halt the expansion of number of punches

In any expansion series of number of punches, if the second number from the last is greater than the maximum number of punch which can show compatibility ($Tmax$), the expansion halts.

C. Punch layout

The punch layout is a process to arrange the five groups of punches into stages, there are two steps in this process:

- (1) Eliminate infeasible expansions of number of punches
- (2) Arrange appropriate punches into stages

Elimination of infeasible expansion of number of punches is a procedure to remove all those which do not follow the grouping rules. This helps to reduce calculation space. Through these two steps, there are a total of 47 sets of arrangement with the 8 punches; however, only 14 of them are not violating the rules. We will then try to arrange the punches into stages, the rules and steps used are stated as follows:

- (1) Place those punches for which the stages are already known.
- (2) Place exact numbers of punches, based on the expansion of number of punches, and place them from largest number first, then the second and third largest in sequence.
- (3) Check if the arrangement is consistent with the five rules.
- (4) Every punch should be placed once and only once.

IV. LAYOUT EVALUATION

Through the process of punch layout, many inappropriate layouts have been deleted, and the rest are feasible solutions. This study uses three evaluation criteria to find better solutions from among them. The evaluation criteria are: number of stages (F_n), moment balancing (F_b) and strip stability (F_s). The evaluation score E_v is calculated using the following equation:

$$E_v = w_1 \times F_n + w_2 \times F_b + w_3 \times F_s \quad (1)$$

Where $0 \leq w_1, w_2, w_3 \leq 1$, and $w_1 + w_2 + w_3 = 1$. The weighting factors w_1, w_2, w_3 in (1) are chosen by the designers. All these three evaluation factors are formulated to range from 10 to 100. The sum makes up the evaluation score.

A. Number of stage factor F_n

From the manufacturing point of view, more stages mean a bigger die, a higher cost and less choice for production planning, because a big die can hardly fit into a small press bed. The number of stage factor, F_n , is 100 for two stages design and 10 for n -stage. For any N -stage design, the factor can be obtained by means of the following linear interpolation:

$$F_n = 100 - 90 \times (N-2) / (n-2) \quad (2)$$

Where N is the number of stages, n is total number of punches.

B. Moment balancing factor F_b

It is strongly suggested to have die design with appropriate punch layout that will have the center of resultant reaction force matched with the ram of the press machine. The moment balancing factor is a measurement of how close the center of the resultant reaction force is to the position of the ram of the press.

The torque equilibrium equations are used for calculating the center of the resultant reaction force [14]. The punching force F is the multiplication of the shearing area A and ultimate strength τ_s . The shearing area A is actually the product of strip thickness T and total shearing length L .

The center of resultant reaction force (\bar{x}, \bar{y}) can be found by the following equations.

$$\bar{x} = \frac{\sum_{i=1}^n (F_i \times X_i) / F}{\sum_{i=1}^n (\tau_s \times L_i \times T \times X_i) / (\tau_s \times L \times T)} \quad (3)$$

$$\bar{y} = \frac{\sum_{i=1}^n (F_i \times Y_i) / F}{\sum_{i=1}^n (\tau_s \times L_i \times T \times Y_i) / (\tau_s \times L \times T)} \quad (4)$$

Even in the worse conditions, the center of the resultant reaction force seldom deviates from the die block center by more than half of its width (X) or depth (Y), so we define maximum deviation D_{max} and real deviation d as:

$$D_{max} = \sqrt{0.5X^2 + 0.5Y^2} \quad (5)$$

$$d = \sqrt{(\bar{x} - X)^2 + \bar{y}^2} \quad (6)$$

The moment balancing factor can be calculated by (7).

$$F_b = 100 \times (1 - 0.9 \times d / D_{max}) \quad (7)$$

C. Strip stability factor F_s

When the strip moves from one stage to another, scrap material will be punched out of the strip according to plan, and the connecting length between the part and the strip will also be reduced. The part attached to the strip will easily get disturbed and is vulnerable to shock if it has a short connecting length. There are four types of length-reducing pattern: L_n , L_{above} , L_{below} and L_{wave} . As shown in figure 3, the L_n type is when the connecting length decreases linearly with number of stages. The linear reduction of L_n is considered to be a good trend, and if one length-decreasing pattern fits the linear type, we should give this a score of 70 out of 100. The equations for strip stability are shown in the following.

$$F_s = 70 \times \left\{ \sum_{k=1}^{N-1} k \times (L_k / L_{Lk}) \right\} / \sum_{k=1}^{N-1} k \quad (8)$$

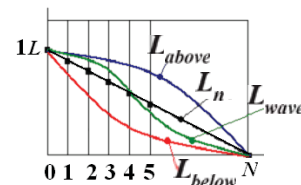


Fig. 3 decreasing trend

Where N is the number of stages, L_k is the exact connecting length at the k^{th} stage, L_{Lk} is the connecting length at the k^{th} stage in L_n pattern and k is the weighting for the k^{th} stage. In (8), the real connecting length L_k of the attached part at stage k is divided by the length of linear pattern L_{Lk} . If the ratio of L_k / L_{Lk} is greater than 1, this implies the layout is longer than the linear pattern, on the other hand, a smaller ratio implies shorter length. In the equation, the ratio at the k stage has been multiplied by a weighting value of k ; this would make the ratio of later stages have more influence on the total score. The advantage of this weighting factor can be seen from figure 3 where the connecting length of pattern L_{wave} is decreasing rapidly at later stages; however the good performance at earlier stage levels influences the result and produces a final score close to the L_n pattern.

V. CASE STUDY

The example here, shown in figure 4, uses a 5-stage layout of $(P_8) + ([P_6, P_7]) + (P_3) + (P_2) + (P_1, [P_4, P_5])$ to demonstrate the whole process. The 14 layouts and their scores based on the three evaluation criteria are also shown in table 1. It is easy to find that different layouts will have various punching areas,

connecting lengths, and centers of resultant reaction force, so, the evaluation scores will be changed accordingly.

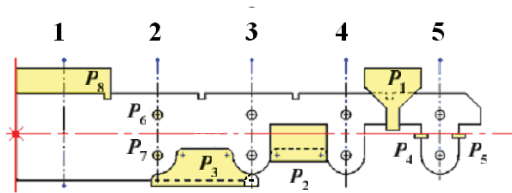


Fig. 4. A 5-stage layout

Number of stage factor $F_n = 55$
 Moment balancing factor $F_b = 88.36$
 Strip stability factor $F_s = 94.485$
 Evaluation score $E_v = 73.51$

Table 1 Evaluation score for the 14 sets of feasible solution

Stage	Punch Layouts	Number of Stage F_n	Moment Balancing F_b	Strip Stability F_s	Evaluation Score E_v
4-Stage	$(P8) + (P6, P7) + (P2) + (P1, P3, P4, P5)$	70	95.24	96.40	82.97
5-Stage	$(P8) + (P6, P7) + (P1) + (P2) + (P3, P4, P5)$	55	93.52	84.47	71.55
	$(P8) + (P6, P7) + (P2) + (P1) + (P3, P4, P5)$	55	82.23	80.54	68.11
	$(P8) + (P6, P7) + (P2) + (P3) + (P1, P4, P5)$	55	81.83	87.59	70.14
	$(P8) + (P6, P7) + (P2) + (P2) + (P1, P4, P5)$	55	88.35	94.48	73.51
	$(P8) + (P6, P7) + (P2) + (P4, P5) + (P1, P3)$	55	86.60	88.12	71.26
	$(P8) + (P6, P7) + (P2) + (P3, P4, P5) + (P1)$	55	76.71	70.26	63.92
6-Stage	$(P8) + (P6, P7) + (P2) + (P1, P4, P5) + (P3)$	55	77.10	69.01	63.32
6-Stage	$(P8) + (P6, P7) + (P3) + (P2) + (P4, P5) + (P1)$	40	97.75	73.76	61.68
	$(P8) + (P6, P7) + (P2) + (P3) + (P4, P5) + (P1)$	40	92.63	70.62	59.71
	$(P8) + (P6, P7) + (P2) + (P1) + (P4, P5) + (P3)$	40	93.26	60.92	56.93
	$(P8) + (P6, P7) + (P1) + (P2) + (P4, P5) + (P3)$	40	95.39	62.89	57.95
	$(P8) + (P6, P7) + (P2) + (P4, P5) + (P3) + (P1)$	40	96.23	73.54	61.31
	$(P8) + (P6, P7) + (P2) + (P4, P5) + (P1) + (P3)$	40	96.48	66.49	59.24

VI. CONCLUSIONS

The punch layout for progressive dies is a design work trying to place punches into a die block, and it needs experienced designers to handle it. The real challenge is that n punches will have many possible solutions. Even after screening with design rules, the number of feasible solutions is still many for designers to choose from, and it becomes difficult to quickly produce a good layout. In our study, we propose a new approach to solve superimposed punch layout problems. The method can effectively reduce the searching space first, and then the use of three evaluating factors with user-defined weightings helps to find appropriate layouts. The procedure of punch layout takes designer's expertise and die design rules into consideration, so the result can yield better performance.

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