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Numerical simulation and optimization of clearance in sheet shearing process[①]

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Abstract: An analysis model to simplify the shearing and blanking process was developed. Based on the simplified model, the shearing process was simulated by FEM and analyzed for various clearances. An optimum clearance in the process was determined by new approach based on orientation of the maximum shearing stress on the characteristic line linking two blades, according to the law of crack propagation and experiments. The optimum clearance determined by this method can be used to dictate the range of reasonable clearance. By the new approach, the optimum clearance can be obtained conveniently and accurately even if there is some difference between the selected points, where the initial crack is assumed originated, and the actual one, where the initial crack occurs really.

Key words: sheet shearing and blanking; cyclical symmetry model; clearance, optimization; FEM

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1 INTRODUCTION

The sheet metal shearing process is very complicated due to its deformation and fracture. During the process, the fierce deformation and limit strain are much greater before fracture than any other process. So, up till now, the intricate appearances during the shearing process cannot be explained properly.

With regard to deformation, shearing process is more complicated than other forming processes such as deep drawing, bending, bulging, and burring. In analysis of forming processes, the prediction and evaluation of stress, strain, velocity, and deformation can be made by theoretical method based on some assumptions, but similar analysis of shearing process cannot be made theoretically. The deformation is focused on the small region in sheet metal during shearing process and the distortion extent of the grid by FEM is much severe, as a result that remeshing must be made timely. Further, because the problem associated with fracture is much intricate, not only is the fracture criterion selected properly, but also it must be applied to the simulation of shearing process by FEM.

Despite various difficulties, researchers have made study on certain problems of shearing process[1-4]. Especially in theses years, scientific workers have simulated the whole shearing process and achieved some theoretical and practical results by using FEM[5-10]. Further study on shearing problem will be helpful to reveal the mechanisms of deformation and fracture in the process. Also, it is significant in theory and application to optimize the variables of the process and to develop new technologies of fine blanking.

In this paper, the simplification of model, disposal of fracture, and remeshing of grid are made before simulation of shearing process by FEM. The clearance, an important parameter in the process, is optimized, and the selected optimizing approach and objective are more feasible and practical.

2 MODEL OF FEM

2.1 Model of geometry

The shearing line in blanking process may be close or unclose. The latter is also called shearing, in which the shearing line is straight generally, and it is used widely. While conventional processes of blanking and shearing are all called blanking. For shearing problem, the geometrical sizes and applied forces of punch and die are alike in general. On the side of punch, if the sizes of the blank holder and ejection and applied forces are alike to those on the side of die, the strains and stresses near the punch are the same as those near the die. In this situation, the part of punch is of cyclical symmetry to that of the die, and the symmetrical center point is at the middle of line linking the blades of punch and die. Apparently, the shearing problem with straight shearing line is special cyclical one.

If the shearing line is close, such as round in general, its model is near to the cyclical one due to

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the deformation are focused on a small region while the width of deformation is much less than the radius of punch or die. The geometrical model of shearing is shown in Fig. 1. If the sizes of blank holder and the forces applied to the blank are alike, the model accord with the situation of cyclical symmetry, so it can be simplified as cyclical one[11].

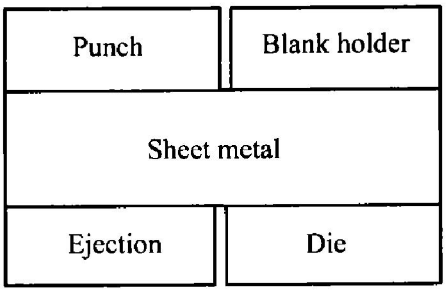

Fig. 1 Schematic diagram of sheet shearing process

Fig. 2 (a) and (b) are two simplified shearing models, which are both half of whole shearing one. In the figure, *A* and *B* are boundaries and one of them is symmetrical to the other. That means that one of symmetrical boundary coincides with the other after turned 180° circling the symmetrical center point *O*. The shape of boundaries can be chosen arbitrarily on the basis of requirement according with cyclical symmetrical conditions.

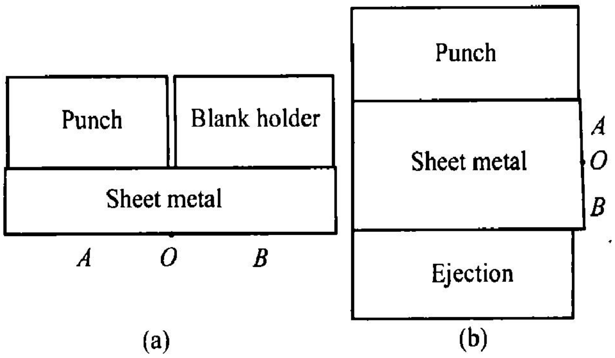

Fig. 2 Simplification of shearing model

The equations of displacement on the symmetrical boundaries shown in Fig. 2 are given below:

$$\begin{bmatrix} u_B \\ v_B \\ \theta_B \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_A \\ v_A \\ \theta_A \end{bmatrix} \qquad (1)$$

where $\theta = \pi$, so

$$\begin{cases} u_B = -u_A \\ v_B = -v_A \\ \theta_B = \theta_A \end{cases} \qquad (2)$$

The equations shown in Eqn. (2) are relative relations of displacement because the punch or the die is motionless in practice, so the actual displacement of the punch or the die must be led to modify the equations.

Apparently, the forces applied to the symmetrical boundaries are also in accordance with symmetrical conditions. The theoretical analysis and evaluation by FEM indicate that the results from using simplified model are same as those from using whole one.

The shearing problem can be simplified as a two-dimensional one as the length of shearing line is much longer than the width of deformation region, and further can be simplified as cyclical symmetrical problem.

The boundary shape of cyclical symmetry can be selected on the basis of the requirement and in accordance with cyclical conditions. The corresponding boundary equations can be gotten. The actual model and the meshing grids are shown in Fig. 3. Two types of two-dimensional solid element are chosen in FEA. One is 6-point triangle, and the other is 8-point quadrangle. The practice indicates that convergence of FEA using triangle element is better than using quadrangle for solving shearing problems.

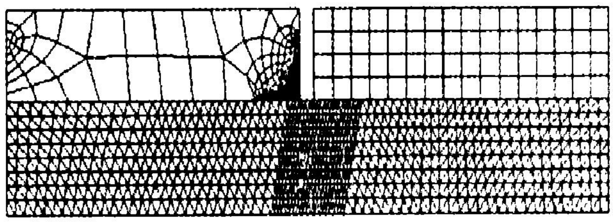

Fig. 3 Geometrical model of cyclical problem by FEM

In accordance with practical situation, the corner of the blades of the punch and die are assumed as quarter rounds in the numerical simulation.

2.2 Model of material

Due to the assumption that shearing process is independent to the velocity, the relationship between equivalent stress and strain of used material in simulation can be further assumed to be in accordance with that of hardened exponent. The sheet metal is also modeled with the von Mises yield criterion, isotropic hardening and the Prandtl-Reuss flow rule. The model is implemented using the commercial FE code, ANSYS.

The geometrical dimensions and mechanical properties of used material are summarized in Table 1.

Table 1 Dimensions of die and properties of used material

Names of variables	Value
Relative clearance(c/δ)	10%
Relative corner radius of blade (r_p/δ, r_d/δ)	0.01
Elasticity model(E)/Pa	2.1×10^{11}
Strength coefficient(B)/MPa	650
Hardened exponent(n)	0.18
Length of shearing line/mm	50

3 DUCTILE FRACTURE CRITERION

Fracture is not avoidable occurring in shearing process. There are various theories developed corresponding to fracture criterion, such as stability, crack, damage accumulation, and probability of fracture. Besides the theory of stability being used to solve necking fracture problem in even deformation, other theories associated with fracture criterion are not perfect, but some of criterions, after being simplified, have been used in solving fracture in actual plastic processes in many literatures.

It has been found that the criterion suggested by Cockroft and Lathem predicts the most reasonable fracture strain in metal forming operations. This criterion states that fracture takes place when the following relation is satisfied:

$$\int_0^{\bar{\varepsilon}^f} \sigma_{max}\, d\bar{\varepsilon} = C_1$$

where $\bar{\varepsilon}^f$ is effective strain and $d\bar{\varepsilon}$ is increment of equivalent strain, and C_1 is the material constant.

In the shearing operation, deformation is concentrated along the shearing band where the stress ratio is not expected to change. Therefore, Cockroft and Lathem's criterion may be approximately by Eqn. (3) shown as follows at the shearing band. Consequently, it may be assumed that fracture takes place at the given effective strain:

$$\bar{\varepsilon}^f = C^* \tag{3}$$

where C^* is the material constant and can be obtained experimentally by measuring the punch penetration that causes the crack to begin, and numerically computing the maximum effective deformation. This simplified method are adopted in some literatures[12, 13].

In this paper, an eliminating element technique is adopted to apply the fracture criterion to the simulation of the shearing process. This means that if the equivalent strain of some element satisfies the Eqn. (3), the crack is initiated, so the element must be eliminated from the analysis model and the stiffness of the eliminated element can be considered zero in the following simulation.

The constant value C^* of used material is considered to be proportional to the even stretching ratio. According to Ref. [12], the value of C^* used in this paper can be determined conveniently, where C^* = 3.88, corresponding to $n = 0.22$. The stretching ratio can be determined by the given condition or by experiment.

4 OPTIMIZATION OF CLEARANCE

The clearance is one of the most significant variables in shearing process. In general, a reasonable clearance must be determined before designing a manufacturing die in order to ensure the quality of parts to be obtained, to lower punch force, and to enhance the life-span of the die set.

Apparently, if we know the optimum clearance and consider the errors of die manufacturing and wearing coefficient, the reasonable clearance can be determined easily.

Generally, in order to determine the parameters of shearing process, three kinds of aspects, cross section quality and precision of part to be obtained, and punch force must mainly be considered. The optimum clearance is dictated by aspect to be considered. Analyses indicate that punch force is little susceptible to the change of clearance in some range[14, 15]. So, the main purpose in shearing process is to obtain a good cross section quality of part. If the cracks initiated up and down meet at the same direction during their propagations, it is assured to obtain a final shearing part, which is good in quality, such as smaller burr, approximately clean and straight plane of the cross section[15]. Thus, the punch force and wearing coefficient in the shearing process with corresponding clearance are all small. The approach of optimization of clearance based on the law of crack propagation and crack coincidence in shearing process is described below by FEM.

4.1 Maximum shearing stress and its orientation on line linking two blades of punch and die

As the orientation of crack propagation at the final fracture position is roughly the same as the direction of line linking two blades, it is necessary to analyze the maximum shearing stress and its orientation.

In analysis of plane shearing process, the stresses, σ_x, σ_y, and τ_{xy} can be obtained directly by using the commercial software, ANSYS 5.5. If the maximum shearing stress and its orientation angle are presented by τ_{max}, α respectively, they can be given based on the stress state theory on the point, so

$$\tan\alpha = -\tau_{max}/\tau_{xy} + \sqrt{(\tau_{max}/\tau_{xy})^2 - 1} \tag{4}$$

The angle between the line linking two blade and the vertical direction is represented by β, called as incident angle of the line linking the two blades, so

$$\tan\beta = c/(\delta - S) \tag{5}$$

where S is the displacement of the punch.

It is manifested that even if the maximum stresses are changed in different positions of the punch at the same point along the line linking two blades, they decrease from the point of one blade to the symmetrical center, and differences are little except for points near the blades based on results by FEM.

The values of $\sin 2\alpha$ and $\sin 2\beta$ at the relative positions of 20% and 30% punch travel are shown in Fig. 4 respectively. The distance from punch blade to some point on the line linking two blades is represented by L_e. The result indicates that the value of β increases but changes little as the displacement of the punch increases. The value of α changes dramatically as the displacement of punch varies.

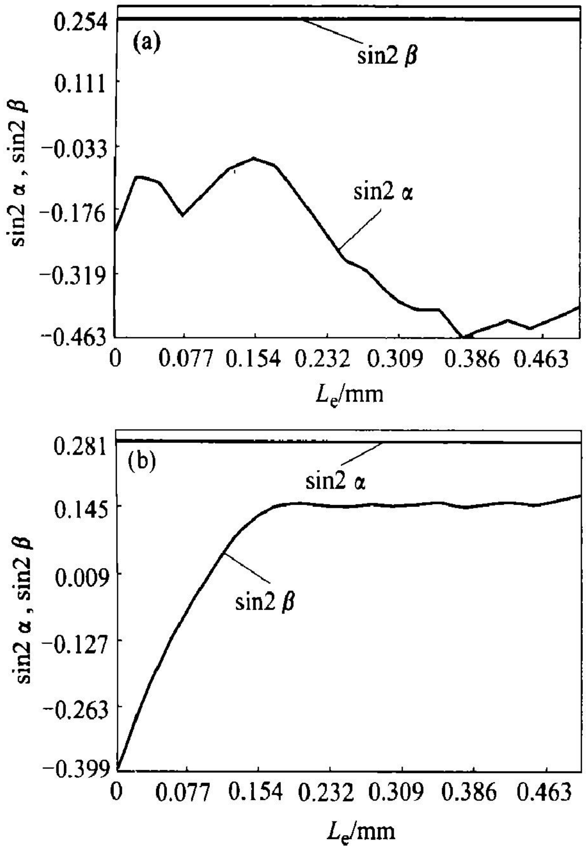

Fig. 4 Orientation angle α of maximum shearing stress and incident angle β of line linking two blades
(a) —20% of relative displacement;
(b) —30% of relative displacement

The figure also shows that the orientation of the maximum shearing stress varies on the special line linking two blades. The orientation of maximum shearing stress on the special line is close to the direction of the line as the displacement of punch increases.

In fact, there are two adverse situations as a result of unreasonable clearance chosen in shearing process. If the clearance is too small, the angle of crack propagation is larger than the angle between the line linking two blades and the vertical direction line at the fracture position. Contrarily, if the clearance is too large, the angle of crack propagation is smaller than the angle of the line linking two blades and the vertical direction line at the fracture position. Consequently, between the two clearances there must be an optimum clearance, with which in shearing process the angle of crack propagation approximately coincides with that between the line linking two blades and the vertical direction line at the fracture position.

4.2 Determination of optimum clearance

The original crack is not initiated at the tip blade rightly, but at the point on the side edge close to the blade, and the differences of shearing stress and its orientation on different points near the blade are very large. The simulation analysis validates that the differences of orientations of shearing stresses on the line linking the two blades except for small fragment near the tip blade are little for some range of clearances, especially for the optimum clearance. The evaluation of simulation indicates that when the number of considered points increases, the optimizing clearance changes little. Consequently, the points near the blade are not considered in optimizing the clearance of the shearing process by FEM.

To determine the optimum clearance, the object is aimed at the minimum differences between α and β on the line linking two blades at the fracture position based on simulating and experimental results for different clearances.

The shearing experiments of used materials for different clearances are made, and the displacements of the punch are measured at the fracture positions. For different samples with same clearance, the displacements of punch are obtained respectively, the average of which is used as final result. This experimental technique is simple and convenient to operate. The relative clearance c/δ and the displacement of the punch S_Δ/δ corresponding to the fracture position are shown in Table 2.

Table 2 Punch displacement at fracture position

c/δ	8%	10%	12%	14%
S_Δ/δ	30.21%	31.83%	33.25%	35.67%

The shearing process is simulated by FEM, and the orientation of maximum shearing stress is obtained. The clearance of the process is optimized by comparing the orientation angle α with the blade inclined angle β for different clearances at range of 8%–14%. When the clearance equals to the value in Table 2, the displacement of punch is chosen as one corresponding to the fracture position. Otherwise, when the clearance of simulation is between two experimental values affirmatively, in this condition the clearance can be determined by difference method according to two experimental values corresponding to the fracture positions measured in experiment. The final optimizing clearance by FEM is equal to 11.6%.

The values of sin 2α and sin 2β are shown in Fig. 5 at the relative clearance of 11.6%. The figure indicates that the orientation of maximum shearing stress is very close to that of the line linking two blade.

The clearance of shearing process has been optimized by FEM in Ref. [12]. The author assumed that when the orientation of initial crack is in accordance with that of the line linking two blades, the corresponding clearance is considered as the optimum one. That is to say, the initial crack position must be determined accurately before clearance is optimized. The assumption of initial crack position must be made firstly by this technique in the literature. While the difference of stress near the blade is large as described above, the optimizing clearance given by FEM may be different from the actual one greatly.

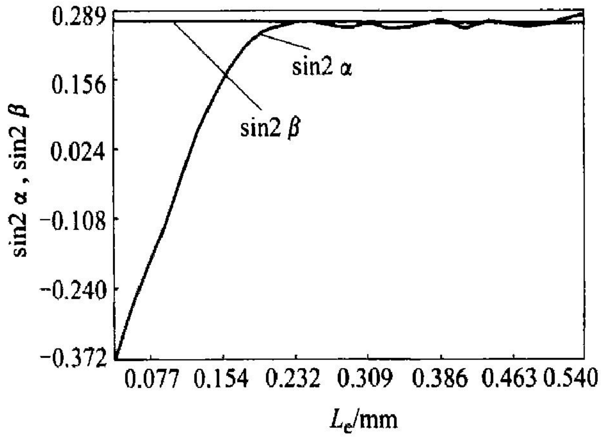

Fig. 5 Distributions of sin 2α and sin 2β with optimum clearance on line linking two blades

5 CONCLUSIONS

1) A simplified model on shearing process is made. It is proposed that many shearing and blanking processes are in accordance with the cyclical condition, so they can be simplified as cyclical ones, and the simulating time can be decreased greatly. Also, the symmetrical boundary shape can be selected for requirement.

2) Based on the orientation of maximum shearing stress on the special line linking two blades and experimental results, the optimizing clearance is obtained for sheet metal shearing problem.

3) A new technique is developed, by which a reasonable optimizing clearance can be obtained accurately without determining initial crack position.

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