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Ductile damage and simulation of fine-blanking process by FEM①

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Abstract: Based on the Curson-Tvergaard void damage plastic potential equation and by using orthogonal rules of plastic material, the influence of void volume fraction on stress and strain fields was introduced into Levy-Mises flow rules. The variation principle of rigid plastic material with void degradation was demonstrated. Furthermore, FEM equations coupled with damage factor were presented to study the void growth and the criterion to judge the damage was also given. Using the developed system, the fine blanking process was simulated and the sheared surface of the part edge was predicted. Meanwhile, the influence of process parameters, such as punch-die clearance, V-ring force, counter force, radius of punch and die edges, on the height and quality of the sheared surface was analyzed. The calculation results were compared with the experiments, which can be used to guide the design of fine-blanking process.

Key words: fine-blanking; ductile fracture; FEM simulation **Document code:** A

1 INTRODUCTION

Fine blanking process is widely used in clock industry, automobile industry and aviation industry, etc. It is a plastic shearing operation, the material is stressed beyond its ultimate strength between the two cutting edge, then the shearing band is formed due to the plastic slip. Meanwhile, the fine blanking is also the separation operation, crack occurs due to strain concentration, metal flow line is cut off and shearing crack is enlarged to the smooth shearing band. However, at the last stage of fine blanking process, the material at the corner of the die may bear the tensile stress, so the tearing phenomenon exists and rupture zone is formed. Therefore, how to control the fracture and separation is the key technique in fine blanking process. The quality of fracture section and the way of crack expansion vary with technology parameters. So studying fine blanking process is an important and meaningful work to prevent and control the damage and tearing process.

Ductile damage is initialized due to void initiation, growth and hole coalescence in fine blanking process around the foreign matters under the condition of compressive strain and stress triaxiality. In the past, fine blanking process is analyzed in the same way as analyzing the common plastic forming process, which only describes the macro-phenomenon without considering the ductile damage and crack expansion. In fact, there exist two different damage mechanisms[1] in fine blanking: void fracture and slip fracture. However, current classical fracture mechanics can not describe the initiation and development process of the crack for the material without cracks. And the constitutive relationship and flow rule of classical elastic-plastic mechanics can not describe the initiation and development process of cracks for the materials with some cracks. Therefore, the two mechanics can not be united with each other.

At present, though it is a powerful and useful tool to analyze the plastic deformation, FEM only performs mathematical calculations according to the stress-strain relationship[2~4]. However, in the factual plastic deformation, stress, strain and damage should be coupled simultaneously. Only considering the influence of the damage in the calculation of stress and strain, the whole deformation can be described comprehensively. Therefore, based on the plastic potential function for void material, provided by Curson-Tvergaard[5,6], and the study of fine-blanking process, the revised Levy-Mises flow rules and the FEM equations coupled with damage for the void blanking of materials are presented. Using the developed system, the process of fine blanking is simulated and the shearing band of the parts is predicted. Meanwhile, the influence of process parameters on the height and quality of the shearing band is also analyzed.

2 FLOW RULES AND FEM FORMULATION[7]

This research regards the rigid plastic material as the object. In the constitutive relationship, it is assumed that the materials are isotropic, the elastic deformation and the volume force are not considered; and the matrix material is incompressible.

According to the orthogonal flow rules of plastic materials, the plastic strain increment is

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$$\dot{\varepsilon}_{ij} = d\lambda'' \frac{\partial \phi}{\partial \sigma_{ij}} \quad (1)$$

where ϕ is the Gurson-Tvergaard plastic potential function[5,6], $d\lambda''$ is the proportion coefficient. Then the strain component can be directly obtained in accordance with the following expression:

$$\dot{\varepsilon}_x = d\lambda'' \frac{\partial \phi}{\partial \sigma_x} = \frac{\partial \lambda''}{\sigma_M^2}\left[(2\sigma_x - \sigma_y - \sigma_z) + q_1 q_2 \varphi \sigma_M \mathrm{sh}(q_2 \sigma_{kk}/(2\sigma_M))\right]$$
$$= \frac{3d\lambda''}{\sigma_M^2}\left[\sigma'_x + \frac{1}{2} q_1 q_2 \varphi \sigma_M \mathrm{sh}\left(q_2 \frac{\sigma_{kk}}{2\sigma_M}\right)\right] \quad (2)$$

where σ_M is effective stress of the matrix metal; q_1 and q_2 are the modification coefficients; Under the condition of even drawing and compression, $|\sigma_{kk}/\sigma_M| \approx |\sigma_{kk}/\sigma_e| = 1$, and $\sigma_e = 3\sigma'_{ij}\sigma'_{ij}/2$ is macro effective stress. So equation (2) can be revised according to Taylor Progression. The coefficient β reflects the dependence of q_1 and q_2 on σ_{kk}/σ_M and the error due to sh[$q_2\sigma_{kk}/(2\sigma_M)$] being approximately as $q_2\sigma_{kk}/(2\sigma_M)$. Therefore, β is the function of σ_{kk}/σ_M. Then,

$$\dot{\varepsilon}_x = 3d\lambda''(\sigma'_x + \beta\varphi\sigma_m)/\sigma_M^2$$
$$= d\lambda'(\sigma'_x + \beta\varphi\sigma_m) \quad (3)$$

Therefore, for void material, the flow rule is represented by the following expression:

$$\dot{\varepsilon}_{ij} = d\lambda'(\sigma'_{ij} + \sigma_{ij}\beta\varphi\sigma_m)$$
$$= d\lambda'[\sigma_{ij} - \delta_{ij}(1 - \beta\varphi)\sigma_m] \quad (4)$$

where φ describes the void volume fraction of the damage in material, and δ reflects the influence of the damage on the strain increment. The deformation energy of unit volume is

$$d\dot{\omega} = \sigma_{ij}\dot{\varepsilon}_{ij} = \frac{3}{2} d\lambda' \left[\frac{3}{2}\sigma'_{ij}\sigma'_{ij} + \frac{1}{2}\beta\varphi\sigma_{kk}\sigma_{kk}\right] \quad (5)$$

Here the nominal effective strain of the void material is defined as follow:

$$\tilde{\sigma} = (1/2)(3\sigma'_{ij}\sigma'_{ij} + \beta\varphi\sigma_{kk}\sigma_{kk})^{1/2} \quad (6)$$

where $\dot{\tilde{\varepsilon}}$ is the effective strain rate to $\tilde{\sigma}$. $\tilde{\sigma}$ and $\dot{\tilde{\varepsilon}}$ are conjugate energy to $d\dot{\omega}$, namely, $d\dot{\omega} = \tilde{\sigma}\dot{\tilde{\varepsilon}}$. Then,

$$d\lambda' = 3\dot{\tilde{\varepsilon}}/(2\tilde{\sigma}) \quad (7)$$

Substituted equation (7) into equation (4), we have

$$\dot{\varepsilon}_{ij} = (3\dot{\tilde{\varepsilon}}/\tilde{\sigma})[\sigma_{ij} - \delta_{ij}(1 - \beta\varphi)\sigma_m]/2 \quad (8)$$

from equation (8), we find that the yield stress is relevant to the hydrostatic stress σ_m.

Based on the variation theory of rigid plastic material and considering the void in material, the plastic deformation does not comply with the volume incompression. Using the similar method for ideal rigid plastic material, the discretization theory can be got for the void material. So the variational form of equilibrium equation for the void material is

$$\phi = \int_V \tilde{\sigma}_S \dot{\tilde{\varepsilon}}\, dV - \int_{S_p} p_i v_i\, dS \quad (9)$$

which can be converted to nonlinear algebraic equation by utilizing the FEM discretization procedure. The nonlinear simultaneous equations can be solved by using Newton-Raphson method.

3 VOLUME EXPANSION DAMAGE ANALYSIS AND CRITERION

Dislocation glide motion is the micro foundation of metal plastic deformation and it generally conducts along shear plane. Large plastic strain may lead to shearing band along slip direction, where severe deformation results in void initiation and decreases the bearing capacity. After void initiation, if stress triaxiality is larger, the void will grow, which promotes the forming of slip band and void initiation in slip band. Therefore, under the condition of higher stress triaxiality, there are slip in shearing band and void growth simultaneously, then it is possible to lead to the void fracture, and the fracture section is a rough rupture zone. Also, shearing slip fracture is possible, and the relative fracture section is flat and smooth. However, when the stress triaxiality is negative, there is no void growth, but large plastic deformation will lead to direct void initiation around foreign matters, which results in softening of the material in shearing band and decreasing the bearing capacity. At last, the fracture will occur in slip plane and the fracture section is also flat and smooth. All in all, the ductile damage is determined by the state of stress and strain. For low stress triaxiality, plastic slip from large deformation results in the damage. While for high stress triaxiality, there exists slip along shearing band and void growth simultaneously. Therefore, two separation ways are possible.

In the past, many fracture criteria adopts the critical void volume fraction to judge whether the crack appears, and generally the critical void volume fraction is considered a constant. But the experimental and simulation results show that the critical void volume fraction varies with stress triaxiality in the fracture section[8]. The critical void volume fraction reflects the degree of volume expansion and porosity of the material when crack occurs. Void volume fraction decreases when stress triaxiality increases, so it is obvious that the state of stress and strain affects not only the critical strain but also the volume expansion and porosity fraction. In high stress triaxiality, the foreign matters often peel off from the matrix metal. Therefore, we assume that the critical expansion rate and critical effective strain are restricted with the same function. Then a new criterion for void fracture is derived[9] as

$$\int A(\sigma_{ij})\, d\varepsilon = D_f \quad (10)$$

when $f \geqslant f_c$, void fracture; $f < f_c$, slip fracture. f is the volume expansion damage factor and f_c is its critical value.

4 SIMULATION OF FINE BLANKING

We simulate the whole process of fine blanking from the beginning of deformation to its fracture by using rigid plastic FEM for void material. In the developed simulation system, the following functions have been solved: description of arbitrary shaped dies, automatic generation of initial mesh, boundary nodes contact with die or separation from die, automatic adjusting of the decreasing coefficient, remeshing technique, optimum of node coding. Especially, it also solves the transfer of element damage information after remeshing.

Fine blanking process is conducted in special die structure using special press with considering the reasonable blanking and lubrication conditions. Fig.1 shows the basic die structure of fine blanking. Before punch contacts the workpiece, side force through the internal-side of V-ring is generated, which prevents the workpiece to be torn in shearing zone and the cross flow of the metal. As punch contacts the workpiece, the ejector presses the workpiece. And the material in deformation zone is in three dimensional compressive stress state, which can improve the plasticity of the material. Furthermore, the material will be separated due to plastic shearing along the cutting edge of the die. This research simulates the blanking and punching process respectively, mainly analyzes the influence of V-ring force, counter force and blanking clearance on the quality of fracture section. For blanking, the initial conditions are as follows: material is 20 steel, plate thick is 3.3 mm, diameter of the die is 16 mm, distance between the V-ring mark and cutting edge is 3.2 mm and its depth is 1.1 mm, and radius of the die is 0.06 mm, and radius of punch is zero. For punching, the initial conditions are as follows: material is 50 steel, plate thick is 2.9 mm, outer diameter of the workpiece is 16 mm, distance between the V-ring mark and cutting edge is 4.1 mm and its depth is 1.1 mm, radius of the die is zero and radius of punch is 0.05 mm.

V-ring force can improve the deformation condition through changing the state of stress. When the V-ring force is small, the plate will be warped due to the bending moment and the workpiece will be torn. However, if the V-ring force is too large, the plate will be thinned and the die will be damaged. Fig.2 shows the influence of the V-ring force on the fracture section. Here, F_G is the counter force and S_P is the blanking clearance.

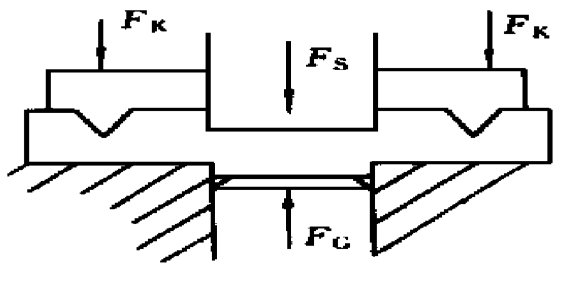

Fig.1 Diagram of fine blanking

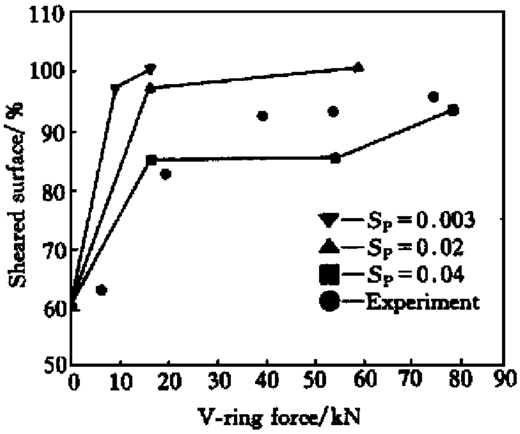

Fig.2 Influence of holding force on sheared surface (for blanking, $F_G = 0$, $S_P = 0.04$)

In fine blanking process, V-ring force and counter force react with each other and the three dimensional compressive stress is formed to improve the quality of the fracture section. If the counter force is too small, the three dimensional compressive stress can not be formed. In the appreciate range of the counter force, the sheared surface increases with the increasing counter force. Fig.3 shows the influence of the counter force on the sheared surface in blanking. Here, F_K is the V-ring force and S is the plate thick.

The punch-die clearance is the key factor which affects the quality of the fracture section. Generally, fine blanking process adopts small clearance and combines the first and the second shear zone to ensure the blanking plane to the sheared surface as possible. Fig.4 and Fig.5 show the influence of different clearance on the sheared surface percentage in blanking and punching, respectively. The figures show that less punch-die clearance, larger sheared surface percentage of the fracture section. Meanwhile, clearance variation affects the way of crack expansion. If the clearance is little, crack expands along a line, so high perpendicularity section can be obtained. In addition, many other factors also affect the quality of fracture section, such as the radius of punch and die, dimension of V-ring, the material. The small radius of die is fit for blanking, while the small radius of punch is for punching. The purpose of small radius is to prevent material to be damaged when it goes through the die (for blanking) and the punch (for punching) in high hydrostatic stress.

If the distance between the V-ring and cutting edge is too small, the bending moment will exist. At the side of punching, the compressive stress accumulates, which surpresses the fracture forming. At the side of the die, tensile stress accumulates, which

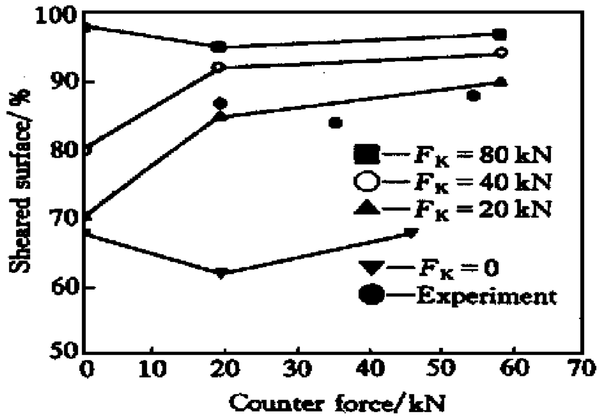

Fig.3 Influence of back force on sheared surface
(for punching, $F_G = 0$, $S_P = 0.04$)

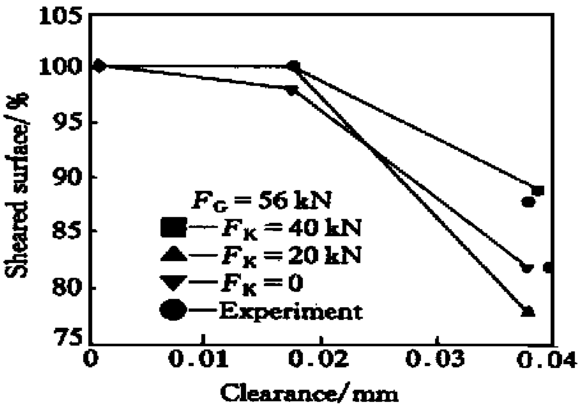

Fig.4 Influence of clearance on sheared surface (blanking)

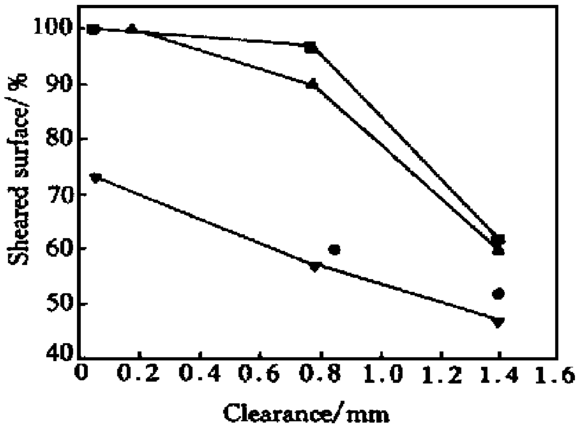

Fig.5 Influence of clearance on sheared surface
■ — $F_G = 56$ kN, $F_K = 80$ kN; ● —Experiment;
▲ — $F_G = 56$ kN, $F_K = 40$ kN; ▼ —— $F_G = 0$, $F_K = 8$ kN

decreases the compressive stress at the tip of the cutting edge. So the crack will form early and tearing is possible. The quality of the fracture section is relevant to the chemical components and mechanical property of the material, plate thick and surface conditions. Higher carbon content, higher strength, more difficult to metal forming. About the structure, the more pearlite in the material, the sheared surface is less. Of course, there are some other factors to affect the quality of the fracture plane, such as the scrap bridge, shape of the part, speed of the die, the wear degree of the die.

5 CONCLUSIONS

This research studies the whole deformation process of fine-blanking by using the compressive rigid plastic FEM. In order to consider the influence of ductile damage and to couple it with the stress and strain, the traditional Levy-Mises flow rules is revised. Relative FEM equations for the materials with void are deduced and a new criterion to judge the damage is given. At last, this paper mainly discusses the influence of process parameters, such as V-ring force, counter force, clearance, on the height and quality of the shearing band.

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