Application of Finite Element Method to Analysis of Ductile Fracture Criteria for Punched Cutting Surfaces*1

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Many types of punching processes are utilized in the production of automobile parts and other components. In normal punching with a punch and a die, a sheared surface and a fractured one are usually formed on the cut surface. Here, to produce highly accurate parts, it is important to estimate the ratio of the sheared surface to the cut surface and to economically produce smooth cut surfaces, optimal tools and punching conditions must be selected within the limits of cost constraints. The finite element method (FEM) has been applied to the analysis of the ratio of the sheared surface to the fractured surface on the cut surfaces. For this, the ductile fracture criteria for the fracture initiation of the cut surface have been proposed by several researchers. It is difficult to determine the fracture criteria on the cut surface by tensile tests or bending tests because the punching process consists of many complicated steps. In this study, we apply the FEM to four punching arrangements to evaluate the ductile fracture criteria proposed by Oyane and by Cockcroft and Latham. We find that the morphology of the cut surface is affected by clearance between the punch and the die, by blank holding conditions and by ductile fracture criteria. [doi:10.2320/matertrans.P-M2013811]

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1. Introduction

Punching is carried out within a variety of sheet metal forming processes. The cut surfaces formed by the punching are characterized by a complex mixture of deformation and fracture behaviors over an extremely small region. Although these behaviors may be controllable to a degree through practical experience, they are too complex to confidently predict through theoretical analysis. Accordingly, a number of researchers have employed the finite element method (FEM) to simulate punching-related phenomena and thereby to better understand cutting behavior under punching. Coarse meshes and/or triangle elements which are used in the some analyses, are difficult to improve the precision of solutions. The some ductile fracture criteria have not been compared in several punching systems to determine the boundary between the sheared surface and the fractured surface.

Because punching is normally accompanied by ductile fracture, the FEM simulations of punching utilize the ductile fracture criteria based on the void theory. On a practical level, however, punching entails a number of complex phenomena that thwart attempts to reproduce actual stress conditions with standard tensile testing, and this in turn complicates efforts to determine a critical value (hereafter indicated as $C_{cr}$) by using test samples alone. Instead, researchers have often sought to determine the critical value by comparing the fracture initiation points on the cut surfaces obtained through the actual punching with the fracture initiation points (or ductile fracture criteria) obtained through the FEM simulation.

In this paper, we report on our use of the FEM simulations of punching under four sets of arrangements, including two pertaining to the fine blanking. Using the ductile fracture criteria proposed by Oyane and by Cockcroft and Latham to calculate the fracture initiation points on the cut surfaces, we compare the effects of varying punching conditions and die clearances on the ductile fracture criteria ($C$ value). Then, with regard to the fine blanking, we compare the cut surfaces of actual punched blanks with the results of the FEM simulations conducted under comparable ductile fracture conditions. We investigate the applicability of the FEM simulation to the prediction of fracture occurrence in the punching.

2. FEM Simulation

2.1 Punching conditions

Punching conditions are determined by a number of physical factors, including the design of the punch, die, blank holder and counterpunch, together with other factors such as the method by which the blank is held. In this paper, we discuss the FEM simulation of the punching under the four arrangements illustrated as Fig. 1(A) through 1(D).

In Fig. 1, (A) illustrates a typical punching arrangement, in which the mechanism consist of only a punch and a die. (B) is an arrangement which utilizes a blank holder in addition to a punch and a die. (C) is an arrangement consisting of a punch, a die, a blank holder and a counterpunch. (D) is an arrangement like that of (C) but also having V-rings on both the die and the blank holder. The arrangements (C) and (D) are both suitable for the fine blanking.

2.2 Analysis model

As an example of the analysis model used for the FEM simulations, Fig. 2 details the arrangement (D), which, as
mentioned above, features the V-rings along the die and the blank holder and is capable of the fine blanking. The blank is assumed to be a circular disk which has 100 mm in diameter and 3.6 mm in thickness. The punch diameter and the die bore diameter are both taken to be 40 mm. The punch corner radius and the die corner radius are taken 0.01 and 0.5 mm, respectively. The die bore diameter is fixed. The clearance is provided by adjusting the punch radius to have twice on the diameter. The blank consists of axisymmetric elements and is assumed to be an elastic-plastic material in the FEM analysis. The punch, the counterpunch, the blank holder and the die are rigid bodies.

The blank material is assumed to be isotropic and is associated with the flow rule. Material properties are set to those of normalized carbon steels S35C. Referring to the work of Yoshida, we utilized the Swift equation to express the stress–strain relation for S35C within its plastic region shown in eq. (1).

\[
\sigma = 1000(\varepsilon_0 + \varepsilon_p)^{0.23} \text{ [MPa]} \tag{1}
\]

\(\sigma\) is the flow stress, \(\varepsilon_0\) is the initial plastic strain (= 1.04 \times 10^{-2}), and \(\varepsilon_p\) is the equivalent plastic strain. The material properties for S35C which are used in this analysis were summarized in Table 1. The relationship between the flow stress and the plastic strain is shown in Fig. 3.

### 2.3 Ductile fracture criteria

Of the various sets of ductile fracture criteria that have been proposed, we selected two criteria for this analysis which are the Oyane criterion and the Cockcroft Latham criterion. The criterion proposed by Oyane is shown in eq. (2).

\[
\int_0^{\bar{\varepsilon}} \left( \alpha + \frac{\sigma_H}{\sigma_{eq}} \right) d\bar{\varepsilon} = C_1
\]

\[
\int_0^{\bar{\varepsilon}} \left( \alpha + \frac{\sigma_H}{\sigma_{eq}} \right) d\bar{\varepsilon} = C_{1cr} \tag{2}
\]

The criterion proposed by Cockcroft and Latham is shown in eq. (3).

\[
\int_0^{\bar{\varepsilon}} \frac{\sigma_{max}}{\sigma_{eq}} d\bar{\varepsilon} = C_2
\]

\[
\int_0^{\bar{\varepsilon}} \frac{\sigma_{max}}{\sigma_{eq}} d\bar{\varepsilon} = C_{2cr} \tag{3}
\]

\(\sigma_H\) is the hydrostatic stress, \(\sigma_{eq}\) is the von Mises stress, \(\sigma_{max}\) is the maximum principal stress, \(\bar{\varepsilon}\) is the equivalent plastic strain, and \(\bar{\varepsilon}_f\) is the equivalent plastic strain at the fracture. \(\alpha\) is the material constant. \(C_1\) and \(C_2\) are the calculated values at which fracture occurs at the critical values \(C_{1cr}\) and \(C_{2cr}\), respectively. These values are reported to be proper to the material.\(^{7,8}\)

The ductile fracture criterion proposed by Oyane (eq. (2)) takes a porous ductile body and presumes that, along with increasing the plastic deformation, the hydrostatic stress history of that body affects the formation, coalescence and growth of voids, with fracture beginning when the void density reaches the critical value \(C_{1cr}\). The ductile fracture criterion proposed by Cockcroft and Latham (eq. (3)) is based on the condition that fracture begins when the integral
of the deformational history for the maximum principal stress \( \sigma_{\text{max}} \) reaches the critical value \( C_{2\text{cr}} \).10)

2.4 Tool motion

In the present analysis, we take the punching process to be a quasi-static phenomenon in which the position of each of the punching tools is controlled. More specifically, we take the movements of the tools under each of the four arrangements of Fig. 1 to be as follows.

Under the arrangement (A), we consider the blank to be placed upon the die and then punched with the punch. Under the arrangement (B), we consider the blank to be punched while held in place between the blank holder and the die, the gap between which is maintained at the initial plate thickness. Under the arrangements (C) and (D), we consider the tooling to move as it would under the fine blanking. The tool movement under the fine blanking is illustrated in Fig. 4.

1. First, the blank is held (compressed) between the punch and the counterpunch, and between the blank holder and the die.

2. Second, the punch and the counterpunch together stroke over a distance equal to the thickness of the blank.

2.5 Analysis conditions

The initial compression under the fine blanking was set at 0.01 mm (corresponding to a compressive load of approximately 450 kN). It is not considered that a frictional force acts on contact surfaces (i.e., between the blank and the tools, or between each of the tools).

Punching is a phenomenon that begins with plastic deformation and extends to shearing and fracture. In the FEM analyses, the elements of the blank tend to behave large deformation in the vicinity of the cut surface. The elements can sometimes break in large deformation analyses. In cases of large deformation of elements and those of piercing into a rigid body such as a tool, at point where an element comes in contact with such a body, we applied the re-meshing of MSC.Marc function, which regenerates such elements by shifting the nodes that reconstruct them.11) In the present analysis, we investigated the distribution of \( C_1 \) (of Oyane) and \( C_2 \) (of Cockcroft and Latham) along the cut surface as simulated under differing clearances within each of the four punching arrangements. We did not attempt to express the condition of the cut surface, for example the element kill method etc. Here, based on the experimental values for S35C of the Ref. 12), we use 0.32 for the constant \( \alpha \) within the ductile fracture criterion proposed by Oyane (eq. (2)), in which case critical value \( C_{1\text{cr}} \) comes out to 0.21.

Table 2 lists the clearance and meshing conditions used within the analyses.

<table>
<thead>
<tr>
<th>Table 2 Analysis conditions.</th>
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<tbody>
<tr>
<td>Clearance, ( \mu ) % ( t )</td>
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<tr>
<td>Adaptive re-meshing control</td>
</tr>
<tr>
<td>Number of initial meshes, ( M_{\text{ini}} )/mesh</td>
</tr>
<tr>
<td>Initial mesh size, ( M_{\text{p}} )/mm</td>
</tr>
<tr>
<td>Percentage of adaptive re-meshing to initial mesh, ( M_{\text{p}} )/%</td>
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</tbody>
</table>

![Fig. 5 Schematic diagram of displacement control of the tools in each step of the fine-blanking process.](image)

3. Analysis Results

3.1 Ductile fracture criteria used in the simulation

Figure 5 shows the distribution of \( C_2 \) of Cockcroft and Latham as determined by FEM simulation for the arrangement (D) punching (the fineblanking with V-rings) with a clearance of 0.28% \( t \). The maximum integral values of \( C_2 \) at some steps along the path of the punch are plotted in Fig. 5. The distribution of \( C_2 \) along the cut surface upon the completion of the punching operation is also plotted. Here, the cut surface length \( l \) is taken as the linear length of the cut surface minus the rollover (shear droop) and the die corner radius \( R \).

Similar values were obtained for both of the calculations. Furthermore, similar results were also obtained with regard to \( C_1 \). Thus, for the values for the ductile fracture criteria of Oyane and of Cockcroft and Latham as determined by the FEM simulation, we can utilize the distributions of \( C_1 \) and \( C_2 \) along the cut surface at the last step of the punching operation. We compare those values to the critical values \( C_{1\text{cr}} \) and \( C_{2\text{cr}} \) to determine the initiation of the fractured surface. We do not assess conditions of the cut surfaces at the points beyond these critical values after the fracture occurs.

3.2 Cutting surfaces produced by actual fine blanking

Figure 6 shows that the cutting surfaces of two disks that, using the fine blanking with the V-rings on a commercial press which is the same as the arrangement (D), were punched with punch/die clearances of \(( a) 0.28% \) \( t \) and \(( b) 6.9% \) \( t \), respectively. The cut surface of the specimen punched with a clearance of 0.28% \( t \) is sheared across its entirety. The fractured surface is not appeared. The cut surface of the specimen punched with a clearance of 6.9% \( t \) has a rollover of \( l/t \approx 0.06 \) and a die corner radius of \( l/t \approx 0.14 \), with the remainder taken as the straight section length. At the point
along the straight section where the sheared surface is minimal, a fractured surface is apparent from the $l/t = 0.28$ position on the cut surface.

### 3.3 Results of FEM simulation

The distribution of $C_1$ along the cut surface as obtained with an FEM simulation utilizing the Oyane fracture criteria is shown in Figs. 7(a) and 7(b). Simulations were carried out for the arrangements (A) through (D) of Fig. 1 at a clearance of (a) 0.28\% $t$ or (b) 1.4\% $t$. Here, under an assumption that the critical value $C_{1cr}$ of the Oyane fracture criterion is 0.21 mentioned in the Ref. 12), we compare the values of $C_1$.

In case of a clearance of 0.28\% $t$ (Fig. 7(a)), we can see from $C_1$ distribution under the arrangement (D) for the fine blanking (with the V-rings) that $C_1$ values are entirely below 0.21 and thus that the cut surface would be entirely sheared. However, under all other arrangements (A through C), we see that $C_1$ distribution along the cut surface varies little from one arrangement to another and that fracture occurs on the cut surface from the $l/t = 0.27$ position or even somewhat below that position. In case of a clearance of 1.4\% $t$ (Fig. 7(b)), we see that the fracture surfaces are produced under all punching arrangements. Also, with increasing clearance, $C_1$ and $C_2$ become larger. Thus, when the critical value is 0.21, it is necessary to provide a clearance of 0.28\% $t$ or less so as to obtain an entirely the sheared surface under the fine blanking.

The Oyane criterion utilizes hydrostatic stress history as a criterion for fracture determination. Figure 8 shows the distribution of hydrostatic stress for each of the punching arrangements of Fig. 1 as obtained from FEM simulation under a clearance of 0.28\% $t$ at 40\% stroke, i.e., at the point where the punch has been pushed to 40\% of the plate thickness. However, these distributions change very little to the end of the stroke. Under the arrangement (D) for the fine blanking with the V-rings, distribution of the hydrostatic compressive stress is concentrated at the tip of the die and the punch. Under the other arrangements (A through C), in contrast, almost the entire length of the cut surface is under the hydrostatic tensile stress.

Here, the hydrostatic compressive stress acting on the cut surface is thought to suppress the initiation and formation of cracks upon it, thus facilitating efforts to obtain the sheared surface along the entire surface.

Next, in Figs. 9(a) and 9(b), we see the distribution of $C_2$ along the cut surface as obtained by FEM simulation utilizing the fracture criteria of Cockcroft and Latham. As with the Oyane, we employed clearances of 0.28\% $t$ and 1.4\% $t$ under the punching arrangements of Fig. 1(A) through 1(D).
Although earlier research on precision punching has shown in Fig. 7(a)), we see from Fig. 9(a) that the critical value of fracture index by Cockcroft and Latham along the cutting surface of each die component type; (a) Clearance 0.28% t (b) Clearance 1.4% t.

For a clearance of 0.28% t and the fracture initiation point given under the Oyane fracture criteria (i.e., $l/t = 0.27$, as shown in Fig. 7(a)), we see from Fig. 9(a) that the critical value $C_{2cr}$ under the Cockcroft and Latham fracture criteria comes out to 0.74. Here, evaluating at the critical value $C_{2cr} = 0.74$, we find the $C_2$ distribution across the cut surface obtained under the arrangement (D) fine blanking with V-rings to be almost entirely below 0.74. Thus, as with the simulation under the Oyane fracture criteria, it appears unlikely that a fractured surface would form in this case. Similarly, for a clearance of 1.4% t, we find that fracture would be likely to occur even under the fine blanking with the V-rings arrangement, as was also found to be the case under the Oyane fracture criteria.

Furthermore, from the results under all applications of the Oyane or Cockcroft and Latham fracture criterion, we would predict that the fine blanking at a clearance of 0.28 to 1.4% t would produce a cut surface with a fractured surface. Although earlier research on precision punching has shown a slight dependence on material properties of the blank and on punching conditions, a clearance of 1% t has nonetheless been reported to be a limit up to which fracture will not occur in the fine blanking. Our results qualitatively agree with this finding.

Figures 10 and 11 show the $C_1$ and $C_2$ distributions along the cut surface obtained under the fracture criterion of Oyane and of Cockcroft and Latham, respectively. We find that the fracture initiation when the critical fracture value under the Oyane fracture criterion is set at $C_{1cr} = 0.21$ and the fracture initiation when the critical value under the Cockcroft and Latham fracture criterion is set at $C_{2cr} = 0.74$ are both at the position $l/t = 0.25$ along the cut surface. This agrees closely with the fracture initiation position of $l/t = 0.28$ apparent in Fig. 6. From this, it is possible to predict the occurrence of the fractured surface by means of the FEM simulation using the fracture criteria.

4. Conclusions

With regard to the fine blanking and the other punching processes under various conditions, we found the following upon the application of FEM simulation to fine blanking and other punching processes under the ductile fracture criteria of Oyane and of Cockcroft and Latham.

(1) When using the Oyane fracture criterion under a clearance of 0.28% t, the cut surface obtained under the fine blanking with the V-rings arrangement was found to be entirely sheared surface. The cut surfaces obtained under the other punching arrangements would contain a mixture of the sheared and the fractured surfaces.

(2) For the fine blanking with the V-rings arrangement, the cut surface having a mixture of the sheared and the fractured surfaces can be predicted to form at a clearances of 0.28% t or larger.
(3) Under the fine blanking with the V-rings and with either the Oyane or the Cockcroft and Latham ductile fracture criteria, the values tended to be higher as the clearance is larger, it is considered that the fractured surface occurs on the cut surface at the point beyond the critical value of the fracture criteria.

(4) Under the arrangement (D) for the fine blanking with the V-rings, the fractured surface forms on the cut surface of the blanks punched with a clearance of 6.9% $t$. Upon investigation by FEM simulation under both the Oyane fracture criterion and the Cockcroft and Latham fracture criterion, the fractured surface initiation point was found to be at nearly the same position as the fractured initiation point on the actual blanks (those punched with a 6.9% $t$ clearance).

From the above, the FEM simulations making use of ductile fracture functions can be used to predict whether a cut surface will have a fracture component.

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