Abstract: Asymmetric plunge cutting by using grooved knife edge plate was proposed for advanced die cutting process of polycarbonate sheet (PC). The cutting load response and the deformation profile of PC sheet were experimentally and numerically investigated by varying the tip thickness and the tip angle of knife edge in the counter plate. The standard steel cutting rule is a 42degree center bevel blade. The deformation profile of wedged sheet was observed by a CCD camera. An elasto-plastic finite element analysis (FEA) was conducted in order to reveal the cutting characteristic. Through this works, the following ware found: 1) the plunge cutting of polycarbonate sheet is remarkably affected by the bending effect of lower grooved counter plate. 2) The deformation profile of worksheet and the cutting load response were characterized by the lower tip thickness, when the tip thickness less than 50μm. 3) The combination of the lower and the upper wedged angle is primary factor to explain the bent up of PC sheet

Key Words: Shearing / Plunge cutting/ Die cutting /Finite Element Method

1. INTRODUCTION

Die-cutting of various sheet materials is in general processed using a formed-strip blade and a counter flat plate in a specified pattern[1]. The worksheet transformed in a plane direction that mounted on a hard counter flat plate in a platbed die cutter [2]. When a thick resin sheet is cut off, a set of upper and lower wedges is possibly considered in order to reduce any failures with unexpected cracking and keep a stable quality of sheared profile, because only a half-thickness indentation of each wedge is required for cutting off the worksheet. In order to keep a quality of sheared profile and reduce a propagation of cracks, a plunge cutting by the upper and the lower knife seems to be superior. A new combination of a grooved lower counter plate and an upper cutting blade is proposed for transforming the worksheet and the maintainability of the flatbed die cutter. The structure of plunge cutting blades is basically symmetric with the grooved counter plate that regulates the worksheet in the same plane level. The cutting resistance in the upper blade is different from the cutting resistance of the grooved lower counter plate. However, to set up the upper/lower wedges without any misalignment is generally difficult and then the production cost of plunge cutting die-set tends to increase. Therefore, we proposed to use a trapezoidal-grooved counter plate for promoting separation of sheared worksheet by the upper-wedge indentation for cutting of the polycarbonate sheet [3].

In the present study, the combination die set of a 42° center bevel steel blade and a trapezoidal-like protruding portion which is grooved on a steel counter plate was prepared in order to cut off a polycarbonate sheet of 0.5mm thickness. The effect of the lower groove profile on the sheared profile of worksheet and the cutting load response will be numerically and experimentally investigated. The finite element method (FEM) with considering the breaking model technique of the worksheet was conducted in order to reveal the shear profile.

2. EXPERIMENTAL&SIMULATION METHOD

2.1. Experimental condition

The plunge cutting die set by using grooved knife edge plate was proposed and use to pushing cut off a polycarbonate (PC) sheet[3]. The in-plane tensile properties of PC sheet were as follows: the Young's modulus $E=2.65$GPa, the proof stress $\sigma_\text{Y}=52.9$MPa, the ultimate strength $\sigma_\text{B}=66.0$MPa, and the true strain of breaking point $\varepsilon_\text{B}=0.57$ under the strain rate of 0.1s⁻¹[4]. All the rectangle formed PC sheets had the thickness of $t=0.5$ mm, the width of $B=20$mm and the length of $L=40$ mm. The experiment setup for a 42°steel blade pushing into a PC sheet stacked on a grooved counter plate. The upper crosshead moved downward with a feed velocity $V=3.0$mm/min. The upper blade has the tip thickness of $w=5\mu$m, apex angle of $\alpha=42^\circ$. In order to identifying the lower grooved edge knife, the tip angle $\alpha_\text{L}$ and the tip
thickness $w_U$ were used and symbolized as $w_U - \alpha_U$ (e.g., $0.01-42$: $w_U = 10 \mu m$, $\alpha_U = 42^\circ$). The edge profile of groove was chosen as $\alpha_U = 30^\circ, 42^\circ, 60^\circ$, $w_U = 10$, 30, 50$\mu m$, the depth of groove $g_U = 0.5$mm, and the width of groove $l_U = 1.3$mm.

During the cutting process, the indentation depth of the upper/lower edges $d/d_U$ and the displacement $c$ of the upper blade were investigated by varying the tip thickness $w_U$ of lower grooved edge. After cutting off, the sheared profile of PC sheet, described with $\beta_U$, was also investigated. The sheared profile parameters were discussed with that of simulation.

![Fig.1 Schematic diagram of experiment apparatus](image)

![Fig.2. Sheared profile of PC sheet](image)

**2.2. FEM Simulation condition**

An elasto-plastic MSC.MARC finite element analysis with non-linear contact problem was carried to simulate the center bevel blade indentation on the PC sheet stacked on the grooved counter plate. The PC sheet was considered as a deformable body, while the cutter and counter plate were modeled as rigid contact bodies as shown in Fig.2. The PC sheet was assumed to be a half symmetric model of a rectangle with the side length of 10mm and the sheet thickness $t = 0.5$mm. The quadrilateral first order plane strain element type was considered and it was initially divided into 100 elements for the half model. In the process of automatic remeshing calculation, the maximum side length was chosen as 20$\mu m$. The material properties were assumed to be isotropically elasto-pastic. The material properties of simulation model were as the experiment.

The Cockcroft and Latham expression\[5\] was used as the ductile fracture criterion and is linked with the simulation. The normalized Cockcroft and Latham criterion equation was shown in Eq.1. Stress and strain distribution at the deformation region of the sheet material are calculated and compared with the fracture threshold $C$. Namely, the element is fractured when the value of the right-hand side of Eq.1 reaches 1.0 ($I_C = 1.0$).

$$I_C = \frac{1}{C} \frac{\int \sigma_{max} d\bar{\varepsilon}}{\sigma}$$

Where $\bar{\varepsilon}$ is the equivalent fracture strain, $\sigma_{max}$ the maximum principal tensile stress, $\sigma$ the equivalent stress, $\varepsilon$ the equivalent strain and $C$ the critical fracture threshold. The critical fracture value $C$ was assumed 2.1. The crack propagation was simulated by the element deleting method, when the critical values are satisfied.

The arctangent-coulomb friction model was assumed for each contact surface. The friction coefficient between cutting blade and worksheet was assumed to be $\mu_C = 0.2$ and the friction coefficient of lower grooved edge was $\mu_p = 0.7$. Here, the relative velocity threshold of arctangent model was chosen as 0.01.

![Fig.3. Simulation half model ($w_U = 10 \mu m$, $c/t = 0.5$)](image)

**Table 1. FEM simulation parameters**

<table>
<thead>
<tr>
<th>Object type</th>
<th>Workpiece:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutter:</td>
<td>elastic-plastic</td>
</tr>
<tr>
<td>Lower grooved:</td>
<td>rigid</td>
</tr>
<tr>
<td>Sheet thickness $t$</td>
<td>0.4mm</td>
</tr>
<tr>
<td>Tip thickness $w$</td>
<td>5$\mu m$</td>
</tr>
<tr>
<td>Grooved tip thickness $w_U$</td>
<td>10,30,50$\mu m$</td>
</tr>
<tr>
<td>Bevel angle $\alpha$</td>
<td>42$^\circ$</td>
</tr>
<tr>
<td>Grooved angle $\alpha_U$</td>
<td>42$^\circ$</td>
</tr>
<tr>
<td>Friction coefficient $\mu_C$</td>
<td>0.2</td>
</tr>
<tr>
<td>Friction coefficient $\mu_p$</td>
<td>0.2</td>
</tr>
</tbody>
</table>
3. RESULTS AND DISCUSSION

Fig. 4 shows experimental photographs of sheared PC sheet and FEM results of haft-cut PC sheet in case of $w_U=10\mu m$, $\alpha_U=42^\circ$. The upper and lower indentation depth $d$, $d_U$ were measured by varying the tip thickness of $w_U$. In case of $w_U=10\mu m$, the simulated deformation of PC sheet was fairly close to the experimental, while the simulated lower-wear profile was different from that of experiment in cases of $w_U=30$, 50\mu m. By observing the profile parameters, the relationship between the upper/lower indentation depth $d/t$, $d_U/t$ and the total blade displacement $c/t=(d/t+d_U/t)$ were shown in Fig. 5. Here, the experimental results were average values of 10 samples. The experimental results are good agreement with the simulation results.

![Fig. 4](image)

(a) $w_U=10\mu m$, $\alpha_U=42^\circ$

(b) $w_U=30\mu m$, $\alpha_U=42^\circ$

(c) $w_U=50\mu m$, $\alpha_U=42^\circ$

Fig. 5 Comparison of simulated indentation-depth with experimental result by varying lower tip thickness $w_U$.

![Fig. 5](image)

Fig. 6 shows the experimental-sheared profile of PC sheet after cutting off and the simulated profile by varying the lower tip thickness $w_U$. The inclined angle $\beta$, $\beta_U$ were measured from those pictures. Table 2 shows those measured inclined angles. The experimental values of $\beta$, $\beta_U$ were the average of 10 samples. The simulated lower side wear profiles were fairly different from the experimental results, especially for $w_U=50\mu m$.

This mismatching seems to be caused by the frictional sliding condition with blunt wedge and/or the yielding flow rules. In this study, since the friction coefficients were assumed to be 0.2 in constant. Regarding the frictional restriction between the lower counter plate and the PC sheet, the worksheet was bent up in the simulation for $c/t>0.5$, while they were kissed in the experiment. The lateral friction force was supposed to contribute to compress the core part beneath the wedge tip in the experiment. This difference seems to
cause the mismatching of \( \beta \) between the simulation and the experiment.

Through this simulation, it is found that the lower grooves bent the worksheet up and the bending effect of grooved counter plate increased the lower indentation depth \( d_U \) compared to the upper indentation depth. To make the ratio of \( d_U/d \) in even depth is supposed to be a desired-production purpose, for an example. In such a situation, to increase the lower tip thickness \( w_U \) is effect for controlling \( d_U/d \).

Table 2. Inclined angles of sheared section of PC sheet

<table>
<thead>
<tr>
<th>( w_U/\mu m )</th>
<th>( \beta/\degree )</th>
<th>( \beta_U/\degree )</th>
<th>( \beta_U/\degree )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>27.9</td>
<td>5.5</td>
<td>33.6</td>
</tr>
<tr>
<td>30</td>
<td>20.8</td>
<td>7.3</td>
<td>26.6</td>
</tr>
<tr>
<td>50</td>
<td>15.4</td>
<td>67.6</td>
<td>23.9</td>
</tr>
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</table>

4. CONCLUSION

From this study, it is found that the proposed asymmetric plunge cutting of polycarbonate sheet is remarkably affected by the bending effect of lower grooved counter plate. The FEM results of sheared profile was show good agreement with the experimental results for the lower wedge tip thickness \( w_U =10 \mu m \). However, when \( w_U >30 \), the numerically sheared profile was show fairly compared to experimental. It seem to be the non-linear sliding friction behavior at the lower wedged is generated. The lower tip thickness of 10-30\( \mu m \) and the lower tip angle less than 53\degree are suitable for getting a symmetric sheared profile. The friction coefficient \( \mu \) was affected to the cutting load response and deformation profile. Namely, the lower friction of knife edge is important factor to understand the cracking generation of worksheet.

5. REFERENCES


