Effect of mechanical conditions on cutting characteristics of polycarbonate sheet subjected to straight punch/die shearing

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Abstract

This paper aims to reveal cutting characteristics of a 0.5 mm thickness polycarbonate sheet subjected to a straight punch/die shearing. The punch/die clearance was varied to be 2 ~ 20% of the worksheet thickness. Also, the feed velocity of the punch was adjusted ranging from 0.05 ~ 1.0 mm s⁻¹. From experimental results, a crack initiated in the vicinity of a cutting tool corner was observed to be largely propagated into the bulk of the worksheet. This deviated propagation seemed to be affected by an in-plane/lateral unbalanced stress state in the worksheet. The variation of the feed velocity had almost no effect on the pattern of crack initiation and its propagation. In addition, the shearing problem was numerically studied by using a two dimensional FEM simulation to discuss about the crack propagation and the dependency of the cutting characteristics on the punch/die clearance.

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1. Introduction

A polycarbonate sheet shows several unique properties such as high transparency to the visible light, excellent toughness, etc. According to their properties, the polycarbonate sheet is often a choice for many applications e.g. transparent panels, electrical devices and so on. To convert a raw polycarbonate sheet into net or near net shape...
products, the punch/die shearing process is one of the most attractive mechanical cutting methods. Hatanaka et al. (2003) and Takamura et al. (2011) investigated the punch/die shearing of metallic materials and presented about the edge features of sheared sheets, which consisted of roll-over, burnished, fracture and burr zones. A number of research works confirmed that the sheared edge features were affected by shearing conditions. Klocke et al. (2001) showed that a too large punch/die clearance caused a poor quality of sheared edges of steel sheet. The effect of an applied lateral pre-load on the edge features of steel sheets subjected to a shearing process was investigated by Neugebauer et al. (2013). In that work, a critical level of the applied compressive stress which increased the burnished zone was revealed.

However, since the deformation and fracture mechanisms of ductile polymers are largely different from those of ductile metals, the understanding of metal cutting characteristics seems to be inadequate to completely predict the shearing characteristics and the sheared edges of polymer sheets. Until now, the cutting characteristics of ductile polymer sheets subjected to punch/die shearing processes seem to be insufficiently revealed and discussed.

Therefore, in this work, a ductile polycarbonate sheet was subjected to a punch/die tool shearing. Here, some mechanical conditions (i.e. punch/die clearance and shearing velocity), were varied and investigated. Moreover, an finite element method analysis of the worksheet shearing problem was conducted in a two dimensional. Also, a constitutive equation (stress-strain relationship) of the polycarbonate sheet was developed and used.

2. Experimental investigation

A polycarbonate sheet which had a thickness \( t_S = 0.5 \) mm was chosen. Its properties were evaluated by an uniaxial tensile test. Fig. 1 shows the stress-strain curves of the worksheet. Shearing specimens were prepared to have a width \( w_S \) and a length \( l_S \) of 20 and 70 mm, respectively. Then, they were sufficiently washed by water and dried.

To cut off the worksheet, the straight punch/die shearing tool shown in Fig. 2 (a) was used. During shearing, the punch was pushed downward by the servo actuator of a press machine until the worksheet was separated. The displacement of the stripper and the counter punch were controlled by their attached springs. A load cell and a high speed camera were installed to record the cutting load resistance \( F \) and the side-view deformation of the worksheet. The clearance defined in Fig. 2 (b) was varied to be \( c/t_S = 0.02, 0.1 \) and 0.2. The shearing velocity was varied as \( V = 0.05 \sim 1.0 \) mm s\(^{-1}\). When investigating effects of \( c/t_S \) and \( V \) on the cutting characteristics, the right die and the right stripper were removed. This shearing is called “one line cutting”. However, these two parts are necessary for the two line cutting test which is discussed later. The test was done using 5 specimens for each condition.

\[ 2.1. \text{Effect of punch/die clearance} \]

Fig. 3 shows the relationship between the cutting line force \( f (=F/w_S) \) and the normalized indentation depth of punch \( d/t_S \). Since there was a little fluctuation of \( f \), the upper-bound and lower-bound line force were plotted. Here, \( d/t_S \) is defined to be zero when the lower surface of the punch touches the upper surface of the specimen. From this figure, it was revealed that: (i) the gradient of \( f (\partial f/\partial (d/t_S)) \) in the shallow indentation depth \( d/t_S \leq 0.1 \) tended to slightly increase when \( c/t_S \) decreased. (ii) The 1st inflection point \( (f_1) \) was increased with the decrease of \( c/t_S \). This point seems to correspond to the yielding point of the worksheet during the process. As the clearance \( c/t_S \) increased, the 1st inflection position \( (d_1/t_S) \) was delayed. (iii) The peak point of \( f (f_{\text{peak}}) \) appeared to increase when decreasing
c/t S. And its position (d_peak/t S) was postponed when increasing c/t S. (iv) The second inflection position (d_n/t S) tended to be postponed, especially in the largest c/t S case. However, the tendency of second inflection force f n with respect to c/t S was not clearly detected. (v) The breaking position (d_break/t S) tended to be slightly delayed when c/t S was increased, especially under the large clearance case, c/t S = 0.2.

![Graph showing cutting line force vs normalized depth of indentation](image)

**Fig. 3. Cutting line force of worksheet for c/t S.**

Fig. 4 shows the representative side-view deformation of the worksheet at some indentation depths for c/t S = 0.02 and 0.2. Looking at the side-view photographs, the deformation of the worksheet seems fairly similar for all of the c/t S cases. At the shallow depth (d/t S = 0.4), roll-over deformation was observed on the surfaces of the worksheet. As the indentation reached a certain depth, cracks initiated near the cutting corners started to be largely propagated. This starting position appeared to correspond to d_peak/t S. The inner crack was propagated into the inner portion bulk, while a large propagation of the outer crack was not observed, as shown in Fig. 4 (a) and (b) at d/t S = 0.9. As for the final cutting state, the propagation of the cracks appeared to stop and then the remaining volume was cut off at the center line as shown in Fig. 4 for d/t S ≥ 1.0. The stopping of crack propagation seem to cause the occurrence of the 2nd inflection point. Fig. 5 shows the side-view photographs of the sheared edges for the both portions taken by an optical microscope. It reveal that the deviated propagation of the crack strongly deteriorate the quality of the sheared edge of the worksheet. In the next section, this deviated propagation is further investigated and discussed.

![Photographs of sheared edges](image)

**Fig. 5. Photographs of sheared edges of worksheet (Conditions: c/t S = 0.02, V = 0.05 mm·s⁻¹).**

### 2.2. Investigation of deviated propagation of crack

By looking at the side-view deformation videos recorded during shearing, the deviated propagation of the crack seemed to be related to the lateral sliding of the worksheet. To confirm this relationship, a two line cutting (symmetry) test was additionally carried out. The left and the right dies were used. Also, the both strippers were applied. Here, the clearance c/t S and the feed velocity V were fixed as 0.02 and 0.05 mm·s⁻¹, respectively.

Fig. 6 shows f-d/t S curves in the cases of one and two line shearing. From this figure, the gradient d/d(t S) in the case of one line cutting was slightly higher than that of the two line case. The positions d_1/t S, d_peak/t S, and d_n/t S appeared to be slightly delayed in the two line shearing case. Only f_1 and f_peak were not different for the two cases. Seeing the side-view photographs, Fig. 7, a reverse tendency of the deviated propagation was observed when the two line case was considered. Namely, a large propagation of crack was observed on the outer portion. But, for the inner portion, this large propagation did not occur.
Hereafter, the lateral sliding of the worksheet during shearing process was analyzed. To do this, the side-view deformation videos were extracted into photographs at several indentation depths. The difference of the indentation depth between the two nearest photographs was approximately 15 μm. Then, all of them were processed using an optical flow analysis code implemented on the support system of software development LabView version 2011.

Fig. 8 shows the material flow analysis result. The vectors represent the flow direction of the worksheet. During the crack propagation state (d/\(s\) ≥ 0.8), in the one line shearing case, the inner portion was apparently slid towards the right side of the center shearing zone, while the sliding of this portion in the case of two line shearing was remarkably suppressed. The outer portion did not present a large movement in the one line cutting case. However, in the case of two line cutting, it appeared to slide outward the center of the shearing line.

Through the above flow analysis result, it was clearly revealed that the deviated propagation of the crack was affected by an in-plane unbalanced stress state on the worksheet. To describe such state of stresses, the conceptual schematics shown in Fig. 9 were introduced. In the case of one line cutting shown in Fig. 9 (a), in-plane tensile stress is generated in the inner portion due to its lateral sliding. This stress contributes to the large propagation of the outer portions (relatively to the inner portion), cracks initiated in the outer portions are propagated.

2.3. Effect of shearing velocity

To investigate the influence of \(V\) on the cutting characteristics, the clearance was fixed as \(c/t_S = 0.02\) and the one line cutting case was considered. Fig. 10 shows \(f-d/t_S\) curve for \(V\). The following features were revealed: (i) the velocity had almost no effect on the gradient \(\partial f/\partial(d/t_S)\). (ii) The latter half position \(d_B/t_S\) and \(d_{\text{Break}}/t_S\) slightly increased as \(V\) increased. On the other hand, the former half position \(d_1/t_S\) and \(d_{\text{Peak}}/t_S\) were almost unaffected by \(V\). (iii) When increasing \(V\), both \(f_1\) and \(f_{\text{Peak}}\) increased, while \(f_o\) tended to decrease.

By seeing side-view deformation of the worksheet, it was found that the variation of \(V = 0.05 \sim 1.0 \text{ mm·s}^{-1}\) had almost no effect on the shearing deformation of the worksheet. In all of the velocity cases, the apparent roll-over
zone was observed at $d/t_s \approx 0.4$. Then, the initiated outer and inner cracks were propagated. After the propagation was stopped, the residual volume of the worksheet was cut off. The large burr was observed on the inner portion for all of $V$ cases. Fig. 4 (a) and 11 shows the side-view photographs in the cases of $V = 0.05, 0.25$ and $1.0 \text{ mm s}^{-1}$.

3. Finite element analysis (FEM) work

The MSC.MARC/MENTAT ver. 2012.1.0 software was used to develop and simulate a two dimensional FEM model (one line shearing) shown in Fig. 12. The polycarbonate body was generated using the 4-node plane strain quadrilateral element. The fine elements (side length = 12.5 μm) were used for the sheared zone, while the farther zone was modelled using coarse elements. The punch, die, stripper and counter punch were assumed to be rigid bodies. Automatic remeshing process was employed. The Coulomb tan$^{-1}$ friction model was assumed. The friction coefficients $\mu_P$, $\mu_D$, $\mu_S$ and $\mu_C$ were assumed to be 0.3. For this FEM analysis, no damage model was considered.

The material model was based on the $\sigma$-$\epsilon$ curve tested in the machine direction of the polycarbonate. The Young’s modulus $E$ was assumed to be 1590 MPa. The value of Poisson’s ratio $\nu = 0.38$ reported by Dowling (1999) was assumed. The mechanical properties of resin sheets, such as the initial yield stress and work-hardening effect tend to be affected by elongating condition. Therefore, in the FEM work, the stress-strain property, which was evaluated from the tensile test, was modified for the shearing simulation. Fig. 13 shows the original constitutive equation (stress-strain curve) versus the modified one that resulted in a good fit between the simulated and the experimental $f$, as shown in Fig. 14. Through this figure, it was confirmed that the proposed constitutive equation is adequate for the simulation.

3.1. Effect of punch/die clearance on primary crack propagation

After getting the material model, the effects of $c/t_s$ were simulated. Fig. 15 shows the simulated $f$ for $c/t_s$. Comparing the $f$ shown in Fig. 15 with the experiment (Fig. 3), $f$ for each case of $c/t_s$ was simulated for $0 < d/t_s \leq d_{\text{peak}}/t_s$. However, for the latter-half stage of peak ($d/t_s > d_{\text{peak}}/t_s$), the simulated $f$ deviated from the experiment results. This indicates that an appropriate damage model is necessary for simulating the later-half cutting state.
Next, in order to discuss about the propagation of the initiated cracks, the state of stress at the position where the cracks start to propagate in each c/t_s case was investigated. This position was known from the experiment and corresponded to d_peak/t_s. Fig. 16 illustrates the vector diagrams of the 1st (max.) $\sigma_{P1}$ and 2nd (min.) $\sigma_{P2}$ principal stresses plotted at $d_{peak}/t_s$ for each c/t_s case. A quite high tensile stress was detected near the cutting tool corners in all of the c/t_s cases. The tensile stress near the tool corners seems to be a major factor affecting the propagation of the cracks. To furthermore discuss about the critical condition for the crack propagation, the values of $\sigma_{P1}$ and $\sigma_{P2}$ at $d_{peak}/t_s$ were plotted with respect to the clearance c/t_s, as show in Fig. 17. Here, the principal stresses appeared to be linearly related with c/t_s. Their dependencies on c/t_s were expressed by Eq. (1) ~ (4)

\[
\begin{align*}
\sigma_{P1} &= -448.1c/t_s + 430.4 \\
\sigma_{P1} &= -427.4c/t_s + 244.3 \\
\sigma_{P2} &= 35.9c/t_s - 77.5 \\
\sigma_{P2} &= 51.2c/t_s - 82.1
\end{align*}
\]

(near the punch corner),
(near the die corner),
(near the punch corner),
(near the die corner).

Fig. 17 reveals that the magnitude of the tensile stress at the tool corners was quite high in the case of small clearance. At the same time, under this small clearance condition, the maximum shear stress of ($\sigma_{P1}-\sigma_{P2}$)/2 was calculated to also be quite high. It was revealed that the position at which the primary cracks propagated appeared to be mainly determined by the maximum tensile stress and/or the shear maximum stress at the tool corners.

4. Conclusions

Through the above results, it was revealed that: (i) As c/t_s increased, the yielding point of the worksheet, $f_{peak}$ and $d_{peak}$ were postponed. During shearing, two cracks were initiated near the tool corners and propagated. Then, one of them largely propagated into a bulk of the worksheet. (ii) From the comparison of one and two line shearing, the deviated propagation was strongly determined by an unbalance of in-plane stress in the worksheet. (iii) An adequate constitutive equation for the simulation, until $f_{peak}$, was developed based on the stress-strain curve gotten from the tensile test. Added to this, the appropriate modification of the initial yield point of the worksheet and its work-hardening was proposed. (iv) The maximum principal and/or maximum shear stress near the tool corners appeared to be a major factor determining the starting position of the crack propagation. The level of such tensile/shear stress was higher in the case of smaller c/t.

References


