1. Introduction

Coated-recycled paperboard is considered to be a fundamental material for the packaging industry due to its advantages such as high strength-to-weight ratio, high surface smoothness, printability, sustainability, recyclability, and so on. To convert paperboard into a packaging container, the raw paperboard is first printed at a printing line. Then, it is subjected to cutting and creasing processes. The aim of these two processes is to convert the printed paperboard into a blank form before forming a glued box. Finally, the blank is folded and glued to obtain a packaging product (Gellerstedt, and Henriksson, 2009). Since paperboard is a kind of composite material made of laminated thin papers and numerous fibers, its forming or shaping behaviors, especially cutting, are fairly complicated. In addition, reaching a successful cut-off performance tends to be more difficult with paperboard than when dealing with other uniform sheet materials. Thus, the paperboard cutting operation is known to be strict towards dust generation and sheared profile quality.

There are a few researchers who have investigated various deformation characteristics of paperboard during a cutting process. S. Nagasawa studied about white-coated paperboard subjected to a wedge indentation. Through the variation of a blade tip thickness ranging from 30 to 160 $\mu$m, the probability of a thread-dross occurrence and the width of the dross appeared to be significantly increased when increasing the tip thickness of the wedge blade (Nagasawa, et al., 2002). Apart from that study, cutting characteristics of coated paperboard subjected to a developed straight punch/die shearing process was investigated regarding the variation of mechanical conditions. It was revealed that the deformation characteristics of the worksheet at the sheared zone were strongly affected by the punch/die clearance. Also, the cut edge of the worksheet was found to be deteriorated under a too large clearance (Nagasawa, et al., 2010).
of paperboard was also reported to affect the generation of dust in cutting processes. An excessively low moisture content causes the paperboard to be fragile. As a result, thread-like and/or fine dust tends to be generated easily (Nagasawa, et al., 2002) and (Stora Enso Co., Ltd., 2013). A literature survey shows that there are many difficulties during the cutting process (Nagasawa, et al., 2002), (Stora Enso Co., Ltd., 2013), (Nagasawa, et al., 2007) and (Carey, 2013). The generation of dust and delamination at the cut edges of worksheets are serious problems. To avoid such difficulties, smart cutting technologies/methods are strongly required.

Cutting or shearing under a negative punch/die clearance is an empirical technique proposed for generating clean cut edges on sheet materials. By using this negative clearance, a high compressive pressure is theoretically generated in the material volume at the sheared zone. Consequently, any unexpected cracks at the sheared zone would be delayed in case of metal cutting (Neugebauer, et al., 2013). A couple of researchers experimentally and numerically studied about sheet material cutting under this clearance. They stated that the quality of the sheared edges in term of smoothness, flatness and roll-over size was improved (Kondo, 1973), (Fan and Li, 2009), (Mitsomwang and Nagasawa, 2013) and (Hirota, et al., 2009). Almost all the investigations concerning the negative clearance cutting were focused on metallic and resin sheet materials. These advantages of the negative clearance seem to also be attractive for cutting paperboard.

Although the negative punch/die gap is often applied to rotary cutting systems in the converting industry of soft sheets, the cutting characteristics of materials such as paperboard or other kinds of composites, which have complicated structures and properties have not been sufficiently investigated and revealed under this negative clearance condition (Bell, et al., 1986). Due to the lack of understanding mentioned above, this work aims to investigate and reveal the effect of negative clearance on the cutting characteristics of white-coated paperboard subjected to a straight punch/die shearing. Aside from the negative clearance, other cutting cases under the positive and zero clearances were also conducted, and their cutting characteristics were compared and discussed against the negative clearance case.

2. Mechanical Conditions of Apparatus and Specimens

White-coated paperboard which had a thickness \( t_S = 0.45 \) mm was chosen. Its basis weight was 350 g \( \cdot \) \( m^{-2} \). Physical and mechanical properties of the paperboard were characterized using a scanning electron microscope (SEM) and an uni-axial tensile test machine. Figure 1 shows the SEM micrographs of the paperboard. The fiber layer shown in Fig. 1 (c) consisted of approximately eight thin-fibrous layers, while the coating layer was a mixture of ground calcium carbonate (amount \( \approx 60 ~ 80\% \), kaolin (10 ~ 20\%) and binder (0.5 ~ 18\%) (Holik, 2006). The stress-strain curves for the machine direction (MD) and the cross machine direction (CD) of the worksheet are illustrated in Fig. 2. Specimens were prepared to have a length \( l_P \) and a width \( w_P \) of 70 and 20 mm, respectively.

![Fig.1 SEM. micrographs of paperboard (a) coated surface (b) uncoated surface and (c) Cross-sectional view](image)

![Fig. 2 Stress-strain curves of paperboard (Based on JIS-P8113)](image)

To cut off the paperboard with the cross angle \( \phi \), the straight punch/die shearing apparatus shown in Fig. 3 was used. The main punch and dies were made of cold-work tool steel (JIS-SKD11) which had a hardness of 58 ~ 60 HRC. During shearing, the main punch was moved downward into the die cavity by the pushing force of the press machine. Movement of the counter punch and strippers was controlled by their attached backing springs. For the striker, the stiffness of the
backing springs was 4.5 N·m⁻¹, while the stiffness was 5.0 N·m⁻¹ for the counter punch’s backing spring. In this cutting system, a load cell (Capacity = 20 kN) was installed to investigate the shearing load resistance \( F \). Also, a high speed camera was set up to record the side-view deformation of the paperboard during shearing.

In this experimental investigation, the negative punch/die clearance defined in Fig. 4 (a) was varied from \( c/\ell_S = -0.035 \) to \(-0.28\). Additionally, the conventional positive clearance shearing of the paperboard using \( c/\ell_S = 0.035 \) as shown in Fig. 4 (b) and zero clearance shown in Fig. 4 (c) were carried out. The number of specimens was 10 pieces for each case of the clearance. The feed velocity of the main punch \( V \) was fixed as 0.05 mm·s⁻¹ throughout the experiment. Before the shearing test, the paperboard specimens were kept in a temperature of 296 ± 1 K and a relative humidity of 50 ± 1 % in a controlled room for 24 hours. The shearing test was carried out in the same room.

![Fig.3 Schematic of straight punch/die set](image1)

![Fig.4 Definition of clearances and cutting direction](image2)

3. Effects of clearance \( c/\ell_S \) on cutting characteristics

3.1 Cutting load resistance and side-view deformation of worksheet

Figure 5 illustrates the relationship between the cutting line force \( f (\equiv F/(2\ell_P)) \) and the normalized indentation depth of punch \( d/\ell_S \). For this investigation, the cutting or shearing line was carried out in perpendicular to the M.D. of the paperboard (\( \phi = 90^\circ \), as defined in Fig. 4 (d)). Since there was a little dispersion of \( f \), the upper and lower bounds with \( f \) for clearance were plotted into this figure. The indentation depth \( d/\ell_S \) was defined to be zero when the lower surface of the main punch touched the upper surface (coated side) of the paperboard. As shown in this figure, the following features of \( f \) were revealed: (i) In the shallow indentation (0 < \( d/\ell_S \) ≤ 0.2), \( f \) was similar for all the clearance cases. (ii) In the intermediate indentation stage 0.2 < \( d/\ell_S \) ≤ \( d_{peak}/\ell_S \), \( f \) was remarkably increased when \( c/\ell_S = -0.28 \). And \( f \) tended to be decreased when the punch/die overlapped distance was decreased (by changing \( c/\ell_S \) from \(-0.21 \) to \(-0.035 \)). For the zero and the positive clearances, \( f \) tended to be smaller than that of the negative clearance cases. (iii) The peak value of cutting line force \( f_{peak} \) in the negative clearance case was apparently larger than that of the positive and zero clearance cases. When the overlapped distance between punch and die was increased, this peak value appeared to be dramatically increased. Seeing the peak position \( d_{peak}/\ell_S \) in the case of negative clearance, the peak position occurred at a slightly shallower indentation depth, compared to the other clearance cases. Namely, \( d_{peak}/\ell_S \) was ranging from 0.66 ~ 0.69 when the negative clearance was used, while it was approximately 0.7 for the cases of zero and positive clearance. (iv) The breaking position \( d_{break}/\ell_S \) tended to occur at the shallower depth of indentation (\( d/\ell_S \approx 0.68 ~ 0.72 \), when the negative clearance was varied between \( c/\ell_S = -0.035 \) and \(-0.28 \). On the other hand, this position was postponed to \( d/\ell_S \approx 0.72 ~ 0.73 \) when the positive and zero clearances were considered. (v) In the cases of positive and zero clearance, \( f \) dropped almost to zero when the worksheet was completely separated. However, \( f \) appeared to be increased again after passing through the break point in the cases of negative clearance. This after-breaking resistance increased with the indentation depth, and its magnitude was large when a large-overlapped clearance was used.

Figure 6 shows the side-view photographs of the paperboard sheared at several indentation depths for all of the clearance cases. At the position \( d/\ell_S \approx 0.4 \), a roll-over (wearing) deformation was observed on the upper surface of the outer portion and the lower surface of the inner portion in all the clearance cases. When the indentation depth of the main punch reached the breaking state of the worksheet, \( d/\ell_S \approx 0.68 ~ 0.72 \), the videos taken by the high speed camera revealed...
that the deformation/flow behavior of the worksheet was affected by the punch/die clearance. This is described in section 3.2. After the separation state, the detached gap between the outer portion of the worksheet and the side edge of the punch was observed in the negative clearance cases as shown in Fig. 6 (c) ~ (g) at \( dltS \approx 0.75 \), and the size of the detached gap increased when increasing the punch/die overlapped distance. In contrast, this gap was not observed in the zero and positive clearances as shown in Fig. 6 (a) and (b). The detached gap is appeared to be caused by the lateral elongation/expansion of the compressed center zone in the case of negative clearance cutting. In the case of positive clearance cutting, since both sides of inner and outer portions pull each other, the wearing surfaces appeared to be always in contact with the punch and die. Finally, at the final indentation state of the main punch, \( dltS \approx 0.8 \sim 1 \), the deformation characteristic of the worksheet in each clearance case was quite the same as that observed at \( dltS \approx 0.75 \).

3.2 Material/fiber flow & Cutting mechanism

In order to clearly explain the deformation behaviors of the paperboard, especially at the breaking state, the material/fiber flow at the sheared zone for the representative negative and positive clearances was analyzed using an image-based binary process. At each interesting indentation depth, a reference photograph and another one captured at the deeper indentation depth of +18 \( \mu m \) were prepared and processed by a binary-stated analysis code. Figure 7 shows...
the binary-stated deformation of the paperboard at $d/t_s \approx 0.25, 0.50$, breaking position and 0.75. As seen in this figure, the black-gray zone represents the area where the material/fiber is flowed under a high velocity state. On the other hand, a lower-velocity flow of the material or a dead state is represented by the plain-gray zone.

Seeing Fig. 7 (a) ~ (c) at the shallow indentation depth, $d/t_s = 0.25$, the dead state indicated by the plain-gray zone was observed at the center shearing zone in the case of large negative case $c/t_s = -0.105$. For the smaller negative and the positive cases, a slight flow state of the material occurred at the center shearing zone. When the indentation depth reached $d/t_s \approx 0.5$, the flow tended to be stopped in the negative clearances $c/t_s = -0.105, -0.035$, while the flow still occurred in the positive clearance case.

Through investigation of the recorded video and this binary-state analysis result, the final breaking behavior of the worksheet appeared to be characterized by the clearance. In the positive case, when the punch reached the breaking position, the outer portion was distinctly separated from the inner portion. However, at this state, there were many uncut fibers that were pulled out from the outer and/or inner portions following the downward movement of the punch. This motion is shown by the high-velocity flow (black zone) in Fig. 7 (c) at breaking position. Seeing the negative cases shown in Fig. 7 (a) and (b) at the breaking position, there was not any fiber/material flow at the center shearing zone. This indicated that the paperboard was cut off without any fiber pulling phenomenon as in the positive clearance case. After the final breaking position, as shown in Fig. 7 (a) ~ (c) at $d/t_s \approx 0.75$, a stable movement of the outer portion from the center shearing zone was observed in the negative clearance cases, while this portion seemed to be stationary when the positive clearance was applied. Next, in order to discuss about the mechanism of paperboard cutting under the positive and negative clearances, the conceptual schematics shown in Fig. 8 were introduced.

![Fig. 7 Binary-stated value of material flow of the worksheet for representative $c/t_s$](image)

As shown in Fig. 8 (a) for the positive clearance, the material volume $V_{Pos}$ is laid in the clearance between the main punch and the die. During shearing, when the main punch is pushed to a certain indentation depth such as $d/t_s \approx 0.5$, $V_{Pos}$ tends to flow into the right-lower direction. At this state, an in-plane tensile stress is caused by the bending moment of the sheared zone in the outer and inner portions. Since both the portions are not strongly clamped by the stripper and the counter punch, such in-plane tensile state contributes to pull out the paper fibers and cause de-bonding from the laminated layers. Then, although the main punch is pushed downward to a deep indentation state, the pulled fibers could not be cut off. Consequently, they become threads adhered to the sheared edges. The investigation results of the generated thread is shown and explained in the next section.

Considering the negative clearance case shown in Fig. 8 (b), since the bending moment at the sheared zone does not occur and the sheared zone is remarkably suppressed due to existence of the compressed volume $V_{Neg}$ (dead state) as illustrated in Fig. 8 (b) at $d/t_s = 0.5$, an in-plane tensile state of stress is not introduced in the outer and inner portions. Afterwards, the in-plane pulling phenomena of fibers tended to be suppressed. In other words, under the negative clearance, the paperboard is cut off by out-of-plane pure shearing stress.

**Fig. 8 Conceptual schematic of cutting mechanism for negative and positive clearances**

[DOI: 10.1299/jamdsm.2014jamdsm0026] © 2014 The Japan Society of Mechanical Engineers
3.3 Investigation of sheared edge-lines for clearance

After cutting, the sheared edges of the inner (right) and outer (left) portions were inspected using a scanning electron microscope (SEM.). Figure 9 illustrates some representative SEM photographs for the positive, zero and negative clearances. Seeing the positive clearance case shown in Fig. 9 (a), there were a lot of long-thin threads at the sheared edges. Here, such threads are named “whisker-like dust”. By using this clearance, the sheared surfaces of the inner and the outer portions were fairly flat and parallel to the moving direction of the main punch. As shown in Fig. 9 (b), the feature of sheared edges in the zero clearance was rather similar to the case of positive clearance. The whisker-like dust was often observed. In the case of negative clearances shown in Fig. 9 (c) and (d), the sheared edges of the worksheet were relatively clean, compared to the positive and zero clearances. In the case of large negative clearance \(c/t_S = -0.21\), almost none whisker-like dust was observed, while uneven sheared surfaces were observed. Namely, an inclined breaking surface was formed on the outer portion of the worksheet. Based on the geometry of this sheared profile, the sheared outer portion was named “Foot”. Regarding the inner portion, there was a small protrusion on the upper side (coated layer) of the worksheet. This protrusion was called “Toe”.

In the case of negative clearance, the toe resisted against the main punch motion after passing through the peak position, although the paperboard was completely separated. Consequently, the cutting load appeared to be increased for \(d/t_S > d_{\text{break}}/t_S\), as seen in Fig. 5.

As discussed in the section 3.2, de-bonding of laminated layers and fiber pulling-out phenomena under the positive clearance seem to cause occurrence of whisker-like dust. In order to confirm a whisker generation mechanism, some geometric features (i.e., their shape and width) of whisker-like dust and fibers buried in the paperboard were investigated and compared. Figure 10 (a) shows the representative SEM micrograph of the whisker-like dust observed in the case of \(c/t_S = 0.035\), while the micrograph of the fibers buried in the paperboard is illustrated in Fig. 10 (b). Seeing these figures, it was found that the geometry size of the whisker-like dust was fairly the same as that of fiber buried in the paperboard. The width average (from the minimum value up to the maximum value, for the number of specimens) of whisker-like dust \(w_{\text{Dust}}\) and that of buried fiber \(w_{\text{Fiber}}\) were 17.39 (9.2 ~ 30.7 \(\mu\)m) and 18.92 (12.3 ~ 30.0 \(\mu\)m) \(\mu\)m, respectively. Through this geometric matching, it was confirmed that the whisker-like dust was generated from the fibers buried in the paperboard.

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Fig. 9 illustrates some inspected surfaces for small areas of the sheared worksheet. Since Fig. 9 seemed to be insufficient for confirming the dust-suppression ability of the negative clearance, the occurrence of whisker-like dust was measured furthermore for the six zones chosen on the sheared edge-lines shown in Fig. 11.

Figure 12 shows the probability of the whisker-like dust occurrence with respect to the clearance for the outer and the inner portions. Here, all the counted whisker-like dust had a length longer than 100 µm. In the case of positive clearance, the whisker-like dust occurrence was observed as \( p_w = 90 \sim 100\% \) in the measured population (140 pieces for 6 positions). Similarly, the occurrence was \( p_w = 60 \sim 100\% \) on the sheared edge lines, when the zero clearance was used. Seeing the probability of whisker-like dust occurrence in the negative range \( c/l_S = -0.035 \sim -0.021 \), it was dramatically decreased in both the outer and the inner portions. And, when the punch/die clearance was \( c/l_S = -0.28 \), the whisker-like dust occurrence appeared to be completely suppressed. It was found that the negative clearance cutting is effective for reducing the generation of the whisker-like dust at the sheared edge lines.

![Fig. 11 Investigation areas along sheared edges](image)

![Fig. 12 Probability of dust occurrence for clearance](image)

![Fig. 13 Relationship between \( l_D \) and \( c/l_S \) (Number of specimens: 140 pieces)](image)

![Fig. 14 Relationship between \( w_p \), \( w_T \) and \( c/l_S \) (Measured position: center of sheared, line, Number of samples = 100 pieces)](image)

Next, the features of foot and toe generated in the negative clearance cases were investigated. Figure 14 shows the
relationship between the measured widths of foot \((w_F)\) and toe \((w_T)\) with respect to the punch/die clearance. Here, the width parameters \(w_F\) and \(w_T\) defined in Fig. 9 were measured by a three dimensional laser scanning microscope. Figure 15 illustrates an example of a three dimensional image of the foot (Fig. 15 (a)) and its profile observed through the section plane (Fig. 15 (b)).

From Fig. 14, it was found that both \(w_F\) and \(w_T\) were linearly varied respecting the punch/die clearance \(-c/t_S\) (here, \(c < 0\)), and such width parameters were approximated by Eq. (1) and (2) using the least-squares method. Seeing the slope of Eq. (1), the width of foot tended to be slightly larger than that of the used distance \(-c/t_S\). And as seen in Eq. (2), the slope was approximated as \(\approx 1\). This indicates that the aspect ratio of \(w_T/|c|\) was almost 1.

\[
\begin{align*}
w_F/t_S &= -1.14c/t_S + 0.03 \\
(1) \\
w_T/t_S &= -1.04c/t_S + 0.01 \\
(2)
\end{align*}
\]

Fig. 15 Results from laser scanning microscope: (a) 3-Dim. image and (b) measured profile of foot (Specimen: an outer portion)

4. Effects of direction angle \(\phi\) on cutting characteristics

From section 3, it was revealed that the negative punch/die clearance was superior for cutting off the paperboard. Here, the cutting line direction was across the machine direction (MD) of paperboard \((\phi = 90^\circ)\). To make arbitrary shaped patterns of packaging boxes, various cutting line directions are normally processed with respect to the paper making direction of the worksheet. In order to confirm the applicability of the negative clearance cutting, the cutting characteristics of the worksheet and the features of its sheared edge-lines were further examined with respect to the cutting line directions. Here, the cutting directions were chosen as follows: (i) the worksheet was sheared in the diagonal direction \((\phi = 45^\circ)\); (ii) the cutting direction was parallel to the M.D. \((\phi = 0^\circ)\) and (iii) the cutting directions were across to the M.D. \((\phi = 90^\circ)\) which was the same condition as the section 3. In the investigation of \(\phi\), the negative clearance and the feed velocity \(V\) of the main punch were chosen as \(c/t_S = -0.035\) and \(V = 0.05 \text{ mm} \cdot \text{s}^{-1}\), respectively.

4.1 Cutting load resistance and side-view deformation of worksheet

![Diagram of cutting load resistance and side-view deformation of worksheet]
Figure 16 shows the relationship between the cutting line force $f$ and the indentation depth $d/\Delta$ for the three cutting directions $\phi = 0, 45$ and $90^\circ$. In the shallow indentation depth $d/\Delta \leq 0.2$, $f$ was not affected by the cutting direction. However, in the range of $0.2 < d/\Delta \leq d_{peak}/\Delta$, the direction which was perpendicular to the M.D. ($\phi = 90^\circ$) resulted in the higher cutting line force, compared to the other two directions. Figure 17 shows $f_{peak}$ with respect to $\phi$. $f_{peak}$ was linearly approximated with $\phi$ by using Eq. (3).

$$f_{peak} = 0.06\phi + 27.04$$

(3)

In paperboards, a lot of buried in fibers tend to be orientated in the same direction as its machining direction (M.D.). To completely cut off the paperboard under the direction $\phi = 90^\circ$, a high level of cutting force appears to be required for breaking such large numbers of orientated fibers. A similar tendency of $\phi$ effect on peak value of cutting line force had been also observed and reported in a wedged indentation cutting of a paperboard (Nagasawa, et al., 2000).

Figure 18 represents the relationship between the peak and breaking positions ($d_{peak}/\Delta$, $d_{break}/\Delta$) and the cutting direction $\phi$. From this figure, those two positions were almost invariant with the considered directions. Figure 19 illustrates the side-view deformation of the paperboard at $d/\Delta \approx 0.4, 0.75$ and final indentation state ($d/\Delta \approx 0.88 ~ 0.9$) for the cases of $\phi = 0$ and $45^\circ$. From Fig.19, at the shallow indentation depth $d/\Delta \approx 0.4$, the roll-over state was observed on the upper and the lower surfaces of the worksheet in all of the cutting directions. After the separation state, as represented at $d/\Delta \approx 0.75$, the outer portion in the both cases tended to be detached from the side edge of the punch. Considering Fig. 19 (a), (b) and Fig. 6 (c), it was revealed that the deformation characteristics of the worksheet during the shearing seemed unaffected by the cutting direction

$$d_{peak}/\Delta = 0.035, V = 0.05 \text{ mm/s}^{-1}$$

4.2 Investigation of sheared edge-lines for $\phi$

Figure 20 shows SEM micrographs shot at the inner and the outer portions in the cases of $\phi = 0$ and $45^\circ$. Here, the clearance and the feed velocity were $c/\Delta = -0.035, V = 0.05 \text{ mm/s}^{-1}$, respectively. For all of these cutting directions, the whisker-like dust was not observed. Similarly, the foot and the toe were formed at the inner and outer portions, respectively.

Figure 21 illustrates the probability of whisker-like dust occurrence $p_w$ with respect to the cutting direction $\phi$. It was confirmed that the generation of the whisker-like dust at the sheared edge lines is uniformly suppressed in all of the cutting directions when the negative punch/die clearance is used. In Fig. 22, the relationship between the length of
whisker-like dust $l_D$ and $\phi$ is plotted. The length of whisker-like dust $l_D$ was almost invariant among the cutting directions $\phi = 0, 45$ and $90^\circ$. It was limited to $l_D \approx 400 \ \mu m$ in average for the inner portion, while it was about $200 \ \mu m$ for the outer portion. The difference of $l_D$ for the both portions seems to be caused by the in-plane stress state and the difference of stiffness between the stripper and counter punch. Also, this difference makes the asymmetric geometry between the foot and toe. The toe and foot widths $w_F$, $w_T$ are shown in Fig. 23. Since the dispersion was not so large in this case, it was detected that $w_F$ and $w_T$ slightly varied with respect to $\phi$.

Fig. 20 SEM micrographs of inner and outer portions for $\phi = 0$ and $45^\circ$

\begin{align*}
\text{(a) } & \phi = 0^\circ \\
\text{(b) } & \phi = 45^\circ
\end{align*}

400 $\mu m$

Fig. 20 SEM micrographs of inner and outer portions for $\phi = 0$ and $45^\circ$

\begin{align*}
(c/t_S = -0.035, V = 0.05 \text{ mm s}^{-1})
\end{align*}

Fig. 21 Probability of dust occurrence for $\phi$ (Number of samples: 60 pieces)

\begin{align*}
\text{(a) Outer portion} & \\
\text{(b) Inner portion}
\end{align*}

Fig. 22 Relationship between $l_D$ and $\phi$

(5. Conclusions)

In order to reveal cutting characteristics of white-coated paperboard subjected to a straight punch/die shearing, a shearing experiment was carried out by varying the punch/die clearance $c$ and the cutting-directional angle $\phi$. Through the experimental investigation, the following conclusions were obtained:

(1) The application of the negative clearance resulted in the higher peak value of the cutting line force, compared to the zero and positive configurations. This peak value was apparently increased with the punch/die overlapped distance. Moreover, under the negative clearance condition, the paperboard worksheet tended to be separated at the shallower indentation depth of the punch, compared to the positive case.

(2) The material flow behavior at the sheared zone in the negative and positive clearances was found to be different.
In the case of negative clearance, the material flow in the lateral direction at the sheared zone was suppressed, while the material flow apparently occurred in the case of positive clearance. The suppression of the material flow in the case of negative clearance contributes to prevent the generation of the whisker-like dust.

(3) The shearing under the negative clearance was confirmed to be superior for cutting off the paperboard worksheet. The negative clearance shearing reduced the probability of the whisker-like dust occurrence and prevented the generation of long dust at the sheared edge-lines of the worksheet.

(4) Under the positive clearance condition, an in-plane tensile state of stress on the worksheet induced by the bending deformation at the sheared zone contributes to de-bond buried fibers and pull them out from the worksheet. The phenomena seem to cause the generation of the whisker-like dust at the sheared edge lines.

(5) In the case of negative clearance, the inclined breaking surface (foot) and the protrusion (toe) were observed on the outer and the inner portions of the sheared worksheet. Their geometry was strongly affected by the punch/die clearance. The relationship between the widths of the foot and toe were found to be linearly related to the punch/die overlapped distance.

(6) Regarding variance of $\phi$ under the negative clearance, the cutting off position and the occurrence probability of the whisker-like dust seemed to be almost invariant with $\phi$. Although, the widths of foot and toe were slightly affected by $\phi$.

References

Bell, J. L., Douma, J.D., Keinath, D. P. and Moore, R. E., Rotary die cutting, United State Patent number US4608895 (1986).

Carey, K. B., Tech notes for die making and die cutting, (online), available from <www.aadieinc.com/newsletters/ABC%20Flake.pdf>, (accessed on 23 October, 2013).

Fan, W.F. and Li, J.H., An investigation on the damage of AISI-1045 and AISI-1025 steels in fine-blanking with negative clearance, Materials Science and Engineering A, Vol. 499 (2009), pp. 248-251.

Gellerstedt, G., Ek, M. and Henriksson. G., Pulp and paper chemistry and technology (Paper products physics and technology Vol. 4 (2009), De Gruyter, Stockholm.

Hirota, K., Yanaga, H. and Fukushima, K., Experimental and numerical study on blanking process with negative clearance. Journal of Solid Mechanics and Materials Engineering, Vol. 3, No.2 (2009), pp. 247-255.

Holik, H., Handbook of paper and board (2006), WILEY-VCH, Ravensburg.

Kondo, K., Precision shearing method, United State Patent number US 3724305 A (1973).

Mitsomwang, P. and Nagasawa, S., Cutting behavior of acrylic thick sheet subjected to squared punch shearing, Journal of Chemistry and Chemical Engineering, Vol. 7, No.7 (2013), pp. 653-665.

Nagasawa, S., Fukuzawa, Y., Katayama, I., Yoshizawa, A and Furumi, T., Effects of edge clearance and board thickness on shearing characteristics of paperboard die cutting, SOSEI-TO-KAKOU, Vol. 41, No. 469 (2000), pp. 126-131 (in Japanese).

Nagasawa, S., Fukuzawa, Y., Yamaguchi, T., Murayama, M., Yamaguchi, D. and Katayama, I., Effects of blade tip shape on thread dross occurrence in paperboard die cutting, SOSEI-TO-KAKOU, Vol. 43, No. 498 (2002), pp. 624-628 (in Japanese).

Nagasawa, S., Kikuchi, H., Taga, T., Murayama, M., Fukuzawa, Y. and Katayama, I., Cutting characteristics on surface layer of paperboard by center bevel blade, SOSEI-TO-KAKOU, Vol. 48, No. 558 (2007), pp. 650-654 (in Japanese).

Nagasawa, S., Yamashita, Y., Abdul Hamid, D., Y Fukuzawa and Hine, A., Out-of-plane shearing characteristics of coated paperboard, International Journal of Mechanical Sciences, Vol. 52 (2010), pp. 1101-1106.

Neugebauer, R., Krausel, V., Barthel, T., Jesche, F. and Schonherr. J., Influence of a defined pre-load on the stress state in the precision cutting process, CIRP Annals-Manufacturing Technology, Vol. 62 (2013), pp. 271-274.

Stora Enso Co., Ltd., Paperboard Guide, (online), available from <www.storaenso.com/products/packaging/Documents/paperboard_guide.pdf>, (accessed on 19 September, 2013).