論文

Tensile Characteristics of Connecting Portions of Paperboard Subjected to Indentation of Nicked Center Bevel Blade

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The design assignment of connecting portions on a paperboard is important in order to stabilize the transport of the paperboard during die cutting. A mechanical estimation of various deformations of connecting portions is desired to predict an allowable assignment of connecting portions. The main purpose of this study is to reveal the elongation properties of the connecting portion of a paperboard with respect to several primary parameters such as nick width and crushed blade tip thickness. The result shows that there is a lower bound width of the connecting portion; the tensile strength of the connecting portion strongly depends on the cutting direction and grain (machine) direction of the paperboard. It is also clarified that the presence of string like dust affects the tensile strength of the connecting portion and that increasing blade tip thickness reduces the tensile strength of the connecting portion.

Key words: shear, paperboard, tensile strength, cutting energy, damage mechanics, orthotropic, tip thickness

1. Introduction

A pushing cut method^(1,2) is widely used for converting a sheet material into various packaging box. Center bevel blades bended with a complicated pattern are embedded in a die board and the blades are indented to the sheet material on a flat counter plate. In this cutting process, a few of connecting portions are assigned on the sheet material cutting lines in order to stably transport it. The connecting portions are generated by making nicks (small concave parts) on the cutting blades.

Fig. 1 illustrates a schematic diagram of a cutting pattern with the connecting portions. After cutting off the sheet material on a die cutter, the sheet material moves into the stripper by pulling its end side and the waste parts are stripped out by tearing the connecting portions.

(a) Flatbed die cutter and stripper (b) Paperboard cutting pattern

Fig.1 Schematic of cutting process and connecting portions

If the strength of the connecting portions is too weak, then the transportation of the sheet material is difficult due to the unstable decomposition of all the parts, while the stripping of waste parts is not performed when the strength of connecting portions is too strong. In other words, an appropriate strength of connecting portions, which exists in a certain range, must be designed for a stable transporting and stripping of the sheet material.

This design was empirically done for deciding the width of each connecting portion and the distance between the neighboring region. Furthermore, the occurrence of torn-inferior portions ought to be reduced with respect to the width of connecting portion. It is supposed that the occurrence of inferior connecting portions depends on the mechanical properties of the work sheet, the width of connecting portion and the crushed tip thickness of blade.

Therefore, it is required to reveal the effects of nick width and tip thickness of blade on the mechanical strength of a connecting portion of a sheet material.

In this paper, in order to reveal the mechanical characteristics of connecting portions on a cutting line, a white-coated paperboard has been cut off in the directions of 0, 45, and 90 degree to the grain direction by using a nicked straight blade and its tensile testing was carried out.

As the mechanical characteristics of connecting portions, there are several modes such as the out-of-plane shearing, the in-plane shearing and the in-plane normal tensile. The in-plane normal tensile was discussed here. The tip thickness and the nick width of the blade were varied for investigating experimentally their effects on the tensile strength or the breaking energy of the sheet.

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2. Experimental procedure and condition

Table 1 shows the tensile properties for the supplied white-coated paperboard specimen, the thickness of which $t = 0.475$ (0.46~0.49) mm, the measured basic weight $\rho_S = 411\sim 413$ g/m². Where, the σ_B is the tensile strength of paperboard in the grain direction (the machine direction, MD) and the across direction (CD), while the e_B is the logarithmic strain in the same directions, derived from the standard method JIS-P8113 (the cross head speed $V_f = 1$ mm/min). The side length and the width of the specimen were 100 mm $\times$ 25 mm for the tensile test in MD. The measured distance D_m was 18 mm.

Fig. 2 shows a schematic of making a connecting portion and a profile of nick-specimen. The nick-specimen has a round concave shape in the radius of 3 mm and the root width b_0 of 4 mm. It is loaded with the 6 mm diameter holes by using fixture pins. At the center position of nick-specimen, a connecting portion was created by indenting a center-bevel cutting blade onto its coated surface. Here, the blade had a nick width b_n . All the nicks were processed by grinding or the electric discharge wire cut method.

Fig. 3 shows schematic of a tensile testing equipment and a making method of connecting portions. In the tensile testing, the normal logarithmic strain e was calculated as $\log_e(1+e_N)$. Here, ΔD_m is a variance of measured length D_m with nick-specimen, and $e_N = \Delta D_m / D_m$ is the nominal strain. The normal stress σ was evaluated as $F/A/(1+e_N)$, where F is an applied load; $A = b_n t$ is the nominal section area of connecting portion. The cutting blade had a bevel angle $\alpha = 42^\circ$, with a tip hardness of 690HV, and an initial tip thickness $w = 5 \mu\text{m}$. The feed velocity of cross head was $V_f = 1$ mm/min for both the processing.

At the root notch of cutting line, the stress concentration is seems to occur, similar to the stress distribution around the crack-tip of the Strip-Yield model ^{3),4)}. Since the σ is evaluated as an average value in a connecting portion, the σ seems to be decreased with decreasing of the b_n , provided that the in-plane stretched distance of a cutting line is sufficiently large to plastically yield the connecting portion. Therefore in the following, effects of the b_n and the w on the tensile properties were investigated.

When the effect of tip thickness on the tensile strength of connecting portion was investigated, the w was chosen as 5, 10,

23, 40, 54, 78 and 103 μm for $b_n/t = 0.99$ in case of $\phi = 90^\circ$. The tips used were filed using emery papers to form the tip thickness $w = 10\sim 103 \mu\text{m}$.

(a) Tensile equipment (b) Making a connecting portion

Fig.3 Schematics of experimental procedure

Table 1 Tensile properties of paperboard

Items	Unit	MD	CD
		Average (min.~max.)	
Young's modulus	E	MPa	1488
		2747	(1345~1622)
		(2522~2921)	
Proof stress	$\sigma_{0.2}$	MPa	7.2
		17.8	(6.8~7.7)
		(15.6~20.3)	
Ultimate tensile strength	σ_B	MPa	14.2
		36.2	(13.9~14.9)
		(33.0~38.7)	
Breaking strain	e_B	%	7.2
		3.8	(7.0~7.4)
		(3.6~4.0)	

(Specimen size: 100x25x0.475 mm, $D_m = 18$ mm)

In order to investigate the dependency of grain direction to the cutting line, the grain direction angle ϕ was chosen as 0, 45 and 90° for $b_n/t = 0.99$ and $w = 5 \mu\text{m}$. For the effect of the width of connecting portion, the b_n/t was chosen as 0.29, 0.48, 0.76, 0.99, 1.26, 1.62, 1.85 and 2.1 keeping $w = 5 \mu\text{m}$ and $\phi = 90^\circ$.

All the specimens of paperboard were pre-processed: being kept for more than 24 h at the room temperature 291 K, the humidity 44%. The making of connecting portion and the tensile test were carried out at the average room temperature 292 K, the average humidity 44%. The numbers of nick-specimens were 10 pieces for each condition.

Fig.4 Estimated parameters on tensile testing with nick-specimen

After tensile testing of the nick-specimen, the maximum stress σ_P and the breaking strain e_F were measured for the nick-specimens as shown in **Fig.4**. The breaking energy per unit volume ϵ_F was estimated with the tensile elongation of a connecting portion using the expression (1).

Fig.2 Outline of nick-specimen and blade profiles

$$\varepsilon_F = \int_0^{e_F} \sigma de \quad (1)$$

In the special case of $b_n/b_0=1$, as there were no cutting line cracks on the nick-specimen, the σ_P and the e_F were denoted as σ_{PI} and e_{FI} , respectively. The corresponded breaking energy ε_F was also denoted as ε_{FI} for $b_n/b_0=1$.

3. Results and discussion

3.1 Effect of grain direction angle on tensile properties

Table 2 shows the tensile properties of nick-specimens without cracks ($b_n/b_0=1$) and the loading holes of 6mm diameter. Since the nick-specimen had a concave of 3mm radius and the width b_0 was relatively small, the tensile strength was apt to be larger than that of the specimen in Table 1. In the followings, the strength of the connecting portion was discussed with the nick-specimen in Table 2.

Table 2 Tensile properties of nick-specimen ($b_n/b_0=1$)

Items	Unit	MD($\phi=90^\circ$)	$\phi=45^\circ$	CD($\phi=0^\circ$)
		Average (min.~max.)		
Breaking energy	ε_{FI} MPa	1.30 (1.23~1.36)	0.89 (0.82~1.01)	0.78 (0.74~0.83)
Maximum tensile stress	σ_{PI} MPa	45.8 (43.9~48.3)	28.3 (27.3~30.3)	22.4 (21.7~23.3)
Breaking strain	e_{FI} %	4.7 (4.6~4.9)	6.0 (5.4~7.0)	6.9 (6.1~8.0)

(Specimen size: 40x10x0.475mm, $D_m=18$ mm)

Fig. 5 shows the tensile properties of connecting portion which had $b_n/t=0.99$ in terms of grain direction angles $\phi=0, 45$ and 90° . Since the σ_P and e_P were remarkably reduced in case of $\phi=0^\circ$, it seemed that the matrix material of paperboard is frangible in cross grain direction. From Fig.5(d), the e_F was not almost decreased in case of $\phi=90^\circ$, while that was reduced to around 35% for $\phi=0^\circ$, comparing with the case of $b_n/b_0=1$.

Fig.5 Tensile properties with respect to grain direction angle

It means that the elongation performance of paper fibers is fundamentally independent to the crack generation by the cutting blade.

Whereas, as the σ_P and the e_P are apt to be reduced for arbitrary angle ϕ of $0\sim90^\circ$ due to the generation of the cutting line crack, the breaking energy ε_F per unit volume was relatively reduced. The ε_F and the σ_P MPa were linearly approximated with ϕ° as the expressions (2), (3).

$$\varepsilon_F = 0.0039 \phi + 0.052 \quad (\text{for } b_n/t=0.99, \phi=0\sim90^\circ) \quad (2)$$

$$\sigma_P = 0.35 \phi + 4.37 \quad (\text{for } b_n/t=0.99, \phi=0\sim90^\circ) \quad (3)$$

So far, it is found that the breaking resistance of connecting portions is varied with the grain direction angle. Namely, the maximum stress σ_P and the breaking energy ε_F can be estimated linearly with the grain direction angle ϕ .

3.2 Effect of nick width on tensile properties

Fig. 6 shows top views of paperboard surface subjected to indentation of blade which had the nick width b_n/t of 0.29~1.24. There were cracks or broken area on the surface of paperboard. In case of $b_n/t < 0.76$, the cracks seemed to severely damage the connecting portions. The breaking profile of connecting portion was illustrated in Fig.7 for $b_n/t=0.99$ and 1.24.

Fig. 8 illustrates the relationship between the stress σ and the strain e during tensile loading on the nick-specimen. Here, $\phi=90^\circ$ and $w=5\mu\text{m}$ were used for $b_n/t = 0.48\sim1.24$. In case of $b_n/t = 0.29$, since the connecting portion was severely damaged because of broken during the blade indentation, it could not be inspected with the tensile testing. When b_n/t was larger than 0.76, the tensile loading was successfully carried out for 10 pieces, while that was sometimes failed in case of b_n/t being less than 0.48.

Fig.6 Top views of connecting portions subjected to indentation of blade with a nick ($w/t=0.01$, $\phi=90^\circ$, CCD microscope)

Fig.7 Top views of connecting portions after tensile testing ($w/t=0.01$, $\phi=90^\circ$, CCD microscope)

Fig.8 Comparison of nick width effect on tensile response

(a) Maximum stress and breaking energy in connecting portion

(b) Peak and breaking strain in connecting portion

Fig.9 Effect of nick width on tensile properties ($w/t=0.01$)

Hence, it is found that there is actually a lower critical tensile strength of connecting portion for a certain range: $b_n/t=0.48\sim 0.76$. Fig. 9 shows the relationship between the nick width b_n/t and the tensile properties (the maximum stress σ_p , the breaking energy ε_F , the peak strain e_p and the breaking strain e_F). In Fig. 9 (a), the σ_p/σ_{pI} was linearly approximated with the next normal equation (4) for $b_n/t=0.48\sim 1.24$, while the σ_p/σ_{pI} was almost saturated with 1.0 for $b_n/t > 1.5$.

$$\sigma_p/\sigma_{pI} = 1.04(b_n/t) - 0.51 \quad (\phi=90^\circ) \quad (4)$$

From this equation, it is found that $b_n/t \approx 0.5$ was the lower bound condition of tensile strength, while 90% of the full tensile strength ($b_n/b_0=1$) was kept for $b_n/t > 1.5$. Through the behavior of e_p and ε_F , it is confirmed that their values have reach close to the value of specimen without cutting line for $b_n/t > 2$.

3.3 Effect of tip thickness on tensile properties

Fig. 10 shows top views of paperboard surface subjected to indentation of blade which had the w/t of 0.022~0.216. The

crack on the surface of paperboard was increased with the w/t . Fig. 11 shows a top and a front view of connecting portion after tensile testing in case of $w/t=0.216$.

Fig. 12 illustrates the relationship between the stress σ of connecting portion and the corresponded strain ε by varying the blade tip thickness w/t . Here, $b_n/t=0.99$ and $\phi=90^\circ$ were considered. Fig. 13 shows the maximum stress σ_p and the breaking energy ε_F with respect to the variance of w/t .

It is clarified that the σ_p and the ε_F are decreased with increasing of the blade tip thickness. Observing the sheared sections of paperboard, there were string-like dusts located beneath of the blade tip as shown in Fig.10 and Fig.11 for $w/t>0.083$. The occurrence of string-like dust of white-coated paperboard was known for $w>50\mu\text{m}$ in case of $\alpha=42^\circ$ as reported by Nagasawa *et al*⁵⁾.

From Fig.13, it is concluded that the tendencies of the σ_p and the ε_F with the w/t are changed in terms of the occurrence of string-like dusts.

Fig.10 Top views of connecting portions subjected to indentation of blade with a nick ($b_n/t=0.99$, $\phi=90^\circ$, CCD microscope)

Fig.11 CCD microscope photographs of connecting portion after tensile testing ($b_n/t=0.99$, $\phi=90^\circ$, $w/t=0.216$)

Fig.12 Comparison of tip thickness effect on tensile response

Fig.13 Variance of maximum stress and breaking energy of connecting portion with respect to blade tip thickness

The relationship between the e_P and the w/t and the relationship between the e_F and the w/t were shown in Fig. 14. It is confirmed that the e_F is gradually decreased with increasing of the w/t . Hence, it is estimated that the increasing of crushed tip thickness affects to the tensile strength and the breaking strain of connecting portion using these results.

By comparing Fig.14 with Fig.9 (b), the e_F of the former was relatively larger than that of the latter for $b_n/t=0.99$ and $w/t=0.01$. Since the gradient of σ - e response becomes almost zero at the position of e_F , it must be noted that the detection accuracy of e_F is low and depends on the environmental factors such as the humidity variance.

Fig.14 Variance of peak and breaking strain of connecting portion with respect to blade tip thickness ($b_n/t=0.99$)

Applying the linear approximation to the σ_P , the ε_F , the e_P and the e_F with respect to the w/t , the following expressions (5)~(8) were derived. The coefficients $\bar{\Sigma}_1$, $\bar{\Sigma}_0$, $\bar{E}_1$, $\bar{E}_0$, $\bar{F}_{P1}$, $\bar{F}_{P0}$, $\bar{F}_{F1}$ and $\bar{F}_{F0}$ were shown in Table 3.

$$\sigma_P/\sigma_{P1} = \bar{\Sigma}_1 (w/t) + \bar{\Sigma}_0 \quad (5)$$

$$\varepsilon_F/\varepsilon_{F1} = \bar{E}_1 (w/t) + \bar{E}_0 \quad (6)$$

$$e_P/e_{F1} = \bar{F}_{P1} (w/t) + \bar{F}_{P0} \quad (7)$$

$$e_F/e_{F1} = \bar{F}_{F1} (w/t) + \bar{F}_{F0} \quad (8)$$

Table 3 Coefficients of normal equations (5)~(8)

w/t	$\bar{\Sigma}_1$	$\bar{\Sigma}_0$	$\bar{E}_1$	$\bar{E}_0$	$\bar{F}_{P1}$	$\bar{F}_{P0}$	$\bar{F}_{F1}$	$\bar{F}_{F0}$
<0.08	-6.56	0.79	-2.37	0.32	-2.35	0.51	-1.21	1.02
0.22>, >0.08	-1.46	0.37	-0.71	0.18	-1.04	0.40	-3.02	1.14

4. Conclusions

Varying the nick width b_n from 0.14 to 1.0 mm, and varying the tip thickness w from 5 to 103 μm for a center bevel blade having the apex angle of 42° , a connecting portion on a cutting line was processed with a white-coated paperboard specimen, the thickness t of which was 0.475 (0.46~0.49) mm.

By using this structure of paperboard specimen, a tensile testing was carried out. Through this work, the followings were derived.

- (1) By putting the cutting direction angle ϕ with the grain direction to $0, 45$ and 90° , the peak (maximum) stress σ_P , the breaking energy ε_F were investigated. Both the quantities approximately have a linear relation to the variance of ϕ . The connecting portion is relatively frangible for $\phi=0^\circ$, compared with that of $\phi=90^\circ$.
- (2) The σ_P and the ε_F are remarkably decreased with increasing of the w but with decreasing of the b_n .
- (3) In case of $w/t=0.01$ and $\phi=90^\circ$, the lower critical condition of connecting portion is that the $b_n/t > 0.5$ for keeping a certain positive value of the σ_P .
- (4) The occurrence of string-like dust affects to the correlation of the σ_P and the ε_F with respect to the w/t .

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