くさび刃による板紙の切断変形特性

Wedged Deformation Characteristics of Paperboard with Center Bevel Blade Pushing
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Abstract: This paper reports on deformation behavior of paperboard and the breaking phenomena on the surface layer during indentation with a center bevel cutter. The cutting deformation of paperboard with respect to varying apex angle of blade was observed using CCD camera in order to reveal effect of the blade tip angle on the surface failures of the paperboard. The surface breaking strength of paperboard was analyzed by using Finite Element Method. Through the experiment and FEM simulation, the following were revealed: 1) There is a certain critical value of tip angle \( \alpha_c \) at which the inflection load response disappears and also the surface failures are restricted. 2) When the tip angle is less than the \( \alpha_c \), there is the inflection point as the surface-layer breaking and its surface breaking point was strongly related to the maximum principle stress on the surface. 3) The deformation flow and its resistance are strongly affected by the de-lamination and the raised-upper layer.

1. Introduction

Coated paperboards are widely used for packaging containers. The paperboard is processed with indentation of a center bevel blade cutter on a rigid flat plate. Several works have studied the cutting mechanics and the effects of tip shape on occurrence of surface cracks or thread dross \(^{[1]}\). \(^{[2]}\). Kikuchi et al. have reported on the shear test of the kraft paperboard by varying the apex angle of blade \(^{[3]}\). The surface failures of the kraft paper were restricted when the tip angle was large and the deformation flow was affected by de-lamination in the In-Plane layers. In this study, the pushing shear test of a white-coated paperboard was investigated by varying the tip angle \( \alpha \) and the effect of tip angle on the surface breaking was discussed experimentally and numerically in order to reveal the critical condition of tip angle on the surface failures of the white-coated paperboard.

2. Experimental and simulation condition

2.1. Experimental method

The authors used the experimental method for the pushing shear test of the paperboard \(^{[2]}\), \(^{[3]}\). Fig.1 illustrates the experiment setup for a blade pushing into a paperboard. The lower crosshead moved upward with a feed velocity \( V=1.0 \text{ mm/min} \). The line force \( f=6.0 \text{ kN/m} \) is defined as a cutting force per unit length of a blade. The cutting blade had a length \( 44 \text{ mm} \), thickness \( b=0.72 \text{ mm} \) and the tip thickness \( w=5.0 \text{ mm} \) in average. The tip angle \( \alpha \) of center bevel blade was chosen as \( \alpha=30, 42, 53, 75, \text{ and } 85^\circ \). The cutting tip had a hardness 690HV, and the core of the blade had a hardness 330HV (SK5). A white-coated paperboard with the nominal basic weight of \( 230 \text{ g/m}^2 \) was used as a test material. The direction angle \( \phi \) of cutting line with the grain direction (MD) was chosen as \( 90^\circ \). All specimens had the thickness of \( t=0.475 \text{ mm} \) in average, the length of \( 60 \text{ mm} \) and the width of \( 40 \text{ mm} \). The tensile properties in MD of paperboard that derived from the standard method JIS-P8113 were shown in Table 1 \(^{[3]}\). To evaluate the deformation flow of the paperboard during wedge indentation, a CCD camera was used for recording the image on the side view of paperboard. The image based binary difference of the material flow field for each indentation depth with the referenced image data at the previous indentation depth of \( +17 \mu \text{m} \) was processed (time difference: 2sec).

2.2 FEA simulation

An elastic finite element analysis (MSC.MARC2005R3) with non-linear contact problem was carried to estimate the stress distribution on the surface of the paperboard subjected to the center bevel indentation. The paperboard was considered as a deformable body, while the cutter and the counter plate were modeled as rigid contact bodies, as shown in Fig.2. The tip angle of blade was chosen as \( \alpha=15, 30, 42, 53, 75, 85^\circ \). The tip thickness \( w \) was \( 5.0 \text{ mm} \). The paperboard was considered to be a half symmetric of a rectangle body with the side length of \( 10 \text{ mm} \) and the sheet thickness of \( r=0.44 \text{ mm} \). The quadrilateral first order plane strain element type was considered with the side length of 10 mm and the sheet thickness of \( t=0.44 \text{ mm} \). The coulomb friction coefficient was considered here for the tools and the paperboard. It was chosen as \( \mu_c=0.45 \) for the cutter and the upper surface of paperboard, while it was chosen as \( \mu_p=0.35 \) for the backside of paperboard and the plate surface \(^{[3]}\). The material properties were considered to be orthotropic and perfectly elastic in the three directions (MD, CD, TD) by governing the HOOKLW subroutine. The material properties for both MD and CD direction were shown in Table 1 \(^{[3]}\). The Poisson’s ratios and the moduli transverse of elasticity are derived by Murayama et al. \(^{[1]}\). The \( E_t \) is the TD true strain. 

\[ E_t=16.8 \exp(5.8 \alpha) \]

Fig.2 shows the surface breaking strength of white-coated paperboard and the definition of measurement path on the surface layer. The arc length \( a \) was measured from the center of cutting tip and its depth \( d \), was roughly \( 1.2 \mu \text{m} \).

Table 1. Tensile properties of white-coated paperboard

<table>
<thead>
<tr>
<th>Tensile properties</th>
<th>Average (max-min)</th>
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<tbody>
<tr>
<td></td>
<td>MD</td>
</tr>
<tr>
<td></td>
<td>279(2920.2–2521.5)</td>
</tr>
<tr>
<td>( E/\text{MPa} )</td>
<td>17.8(20.3–15.6)</td>
</tr>
<tr>
<td>( \sigma_{\text{f2}}/\text{MPa} )</td>
<td>36.2(38.7–33.0)</td>
</tr>
<tr>
<td>( \varepsilon_{\text{a}} (%) )</td>
<td>3.7(3.96–3.57)</td>
</tr>
</tbody>
</table>

3. Results and discussion

The blade indentation was numerically and experimentally conducted on the surface layer of paperboard. Fig.3 shows the experimental and FEM results on the cutting resistance (the cutting line force \( f=6 \text{ kN/m} \)) for the paperboard for a half-before indentation \( d/s=0.6 \) by varying the \( \alpha \). In the early stage for \( d/s=0.4 \), the FEM f/d/s curves were almost same not changed with the variance of the \( \alpha \) and they were also similar to the experimental results. For the \( \alpha=30^\circ, 42^\circ \) and \( 53^\circ \), the experimental first inflection point \( f_{\text{IC1}}, d_{\text{IC1}}/L_{\text{IC1}} \) was found...
at $d/t=0.35-0.4$ with $f=8-14\mathrm{kN/m}$, while the first inflect -ion point did not occurred for $d/t=0.5$ in cases of $\alpha=75^\circ$ and $85^\circ$.

Fig.4(a),(b) shows the experimental deformed profile and its binary processed image in the side view of the paperboard on $d/t=0.2,0.5$ for $\alpha=30^\circ, 85^\circ$. For all the cases of $\alpha$, a half-circle was observed beneath the blade tip, for $d/t=0.2$. It was understood that the early compressive stage was equivalent to a concentrated load state that does not depend on $\alpha$ for $d/t=0.3$. For $\alpha=53^\circ$, after passing through the first inflection point, the upper layer with the blade tip level was transformed in the lateral, while the compressive flow occurred in the lower layers without any surface breaking for $85^\circ$. Seeing all the tip angles, the surfaces layer is separated in the lateral direction for a certain keen angle blade, while the surface deformation was radically expanded flow in the normal direction to the wedge surface line without any surface separation for $\alpha=75^\circ$. Hence, the critical angle $\alpha$ exists which contributes to begin the surface breaking at the first inflection point in the early stage ($d/t=0.5$). These results were relatively similar to that of the kraft paperboard cutting $^{[3]}$.

Next, we discuss numerically the effect of tip angle variation on the surface breaking strength by calculating the maximum principal stress $\sigma_1$ and the maximum shear stress $\tau_{max}$ on surface layer.

![Fig.3 Effect of tip angle on cutting load resistance](image)

<table>
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<tr>
<th>$d/t$</th>
<th>Video</th>
<th>Diff. with $+17\mathrm{mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
</tr>
<tr>
<td>0.5</td>
<td><img src="image" alt="Image" /></td>
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</table>

(a) $\alpha=30^\circ$

![Fig.4 Side view and binary-stated displacement of paperboard](image)

<table>
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(a) $\alpha=85^\circ$

![Fig.5 Calculated vector of principal stress for $\alpha=30^\circ$ and $85^\circ$](image)

Fig.5 shows the relationship between the arc length $a/t$ and the first principal stress $\sigma_1/\sigma_0$ and the maximum shear stress $\tau_{max}/\sigma_0$ in the surface layer at $d/t=0.35$. Form the peak value $\sigma_{IP}$ (on the measured path) of $\sigma_1$ was roughly larger than three times of $\sigma_0$ for $\alpha=42^\circ$. From Nagasawa's analysis $^{[3]}$, it is known that the surface breaking strength of white-coated paperboard is roughly $\sigma_1/\sigma_0=3$ when the tip thickness $w$ was varied under keeping $\alpha=42^\circ$. From Fig.6(a), it can be also understood that the surface breaking strength is characterized by the ratio $\sigma_1/\sigma_0$ when the $\alpha$ is varied. For $\alpha=75^\circ$, the $\sigma_1$ was smaller than $2\sigma_0$ at $d/t=0.35$ and it was confirmed that $\alpha=42^\circ$ the surface layer would be cracked when $d/t=0.35$, while it was could not broken when $\alpha=75^\circ$. From Fig.6(b), the peak value of $\tau_{max}/\sigma_0$ was also decreasing with increased with the $d/t$. When $\alpha$ is increased, the $\sigma_1/\sigma_0$ and the $\tau_{max}/\sigma_0$ are decreased under keeping the $d/t$. Here, the peak position of $\sigma_1/\sigma_0$ roughly located at $5\mu m$ apart from the tip edge of cutting blade, while the peak of $\tau_{max}/\sigma_0$ value was located near at the tip edge. Namely, a locally high shear stress occurred near the edge tip for all the case. Adding this, the peak value of $\tau_{max}/\sigma_0$ was always larger than $7$.

![Fig.6 Distribution of stresses on surface layer](image)

(a) First principal stress $\sigma_1/\sigma_0$ and maximum shear stress $\tau_{max}/\sigma_0$ in term of indentation depth by varying tip angle

Fig.7(a) shows the FEM results of the relationship between the $d/t$ and the $\alpha$ by varying the $\sigma_1/\sigma_0$. Here, the round-solid symbols show the experimental inflection point $d_{c1}/t$ for $30^\circ<\alpha<53^\circ$. Eq.2 was derived as the linear approximation for this $d_{c1}/t$. The gradient of Eq.2 was similar to the contour line of the FEM results ($\sigma_1/\sigma_0=3$-5). Namely, it was found that the surface breaking strength strongly depends on the maximum principal stress and also on the tip angle. It seems that the TD compression of the tip contributes to restrict the lateral (In-plane) elongation of the surface layer due to the grain inside friction. In the case of $\alpha=75^\circ$, $85^\circ$ the $d_{c1}/t$ was observed, and the $\sigma_1/\sigma_0$ was less than 3 for $d/t<0.45$. It was confirmed that the surface breaking strength $\sigma_1/\sigma_0$ at the $d_{c1}/t$ was apt to be increased with the $\alpha$ for a certain extent ($\alpha=60^\circ$). From Fig.7(b) it is not supposed that there is a correlation between Eq.2 and the contour line of $\tau_{max}/\sigma_0$. Namely, the failure criterion at the first inflection point $d_{c1}/t$ remarkably depends on the tensile principal stress and there is a critical tip angle for restricting the surface breaking as the first inflection point.

4. Conclusion

From both experiment and the numerical analysis of wedge indentation to a white-coated paperboard, we conclude that the surface breaking of the paperboard occurs at the inflection position $d_{c1}/t$ for $\alpha=60^\circ$ degree with a certain critical value of the principle tensile stress, while the compressive deformation without the surface breaking is observed due to decreasing of the principle tensile stress and maximum shear stress when $\alpha=70^\circ$.

References