Mechanical Characteristics of Center Bevelled Double Structure Blade

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This paper reports on deformation characteristics and mechanical features of a tapered bottom tip of a cutting blade subjected to pushing loads. Whereas a 16° high carbon steel bevel blade of 0.16 mm tip thickness was experimentally investigated, various tapered bottom tips were numerically analyzed for effect of tip thickness and apex angle using elasto-plastic Finite Element Method. From this research, the transition point at which a large increase of crushed height also known as the shimming effect starts has been revealed. Major findings of this research have been (i) tip thickness moves the transition point without changing cutting direction stiffness, and (ii) up to a certain range the apex angle controls the lateral deflection mode of the blade. [doi:10.2320/matertrans.MEP2008029]

1. Introduction

Problems that occur on a blade cutting tip during paperboard cutting inevitably affect the quality of wedged sheets. These problems include early damage of the cutting tip profile and the subsequent differences of blade height. To overcome this, empirically a thin plastic sheet underlay is placed, using expert’s technique, at the bottom side of the blade for pressure balancing. An alternative method, similar but different to the one described above is to use a double structure blade (DSB) where, pressure adjustment can be automatically performed by the deformation of the soft bottom tip which also acts as a relief element or ‘self shimming’ in order to avoid excessive cutting tip crushing. For detail deformation of a quenched cutting tip side, Nagasawa et al. has already studied the mechanics of a 42° quenched center bevelled blade subjected to a pushing load. However, there were no studies conducted on a DSB that has a combination of a quenched cutting tip and a sharp soft tapered bottom tip. This paper has focused on the deformation performance parameterized by the bottom tip angle α, the bottom tip thickness w2 regarding the applied line force in order to reveal the fundamental mechanism of bottom tip crushing and its load relief characteristic.

2. Experimental Method

A high carbon steel DSB (C0.8~0.9 mass%), whose two geometrical parameters were α2 = 16° and w2 = 0.16 mm, was initially cut to L = 10 mm length and 1 mm height of the cutting tip was removed in order to observe the bottom tip deformation. The DSB’s profile is shown in Fig. 1 and the mechanical properties of the core body with thickness b = 0.71 mm are as follows: yield stress σy = 746 MPa, work hardening coefficient H’ = 3.54 MPa, tensile strength σb = 1006 MPa, and fracture strain εf = 0.077. The flat side of the modified DSB was inserted in a compression machine holder, and provided the sharp bottom tip facing down to a hard SUS630 (550HV) counter plate. A static push loading test was conducted on the bottom tip as shown in Fig. 2 under the following conditions; feed velocity of the blade was V = 0.1 mm/min and the line forces f = FV/L ranged from 50 kN/m to 350 kN/m with 50 kN/m for every increment applied on different blade specimens without any paperboard in the experiment. Here, the upper line force of 350 kN/m was chosen as close to the structural buckling strength of a straight blade.

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3. Simulation Condition

An elasto-plastic FEA (finite element analysis) code with an updated Lagrange procedure and large strain was carried out to simulate the bottom tip deformation in conditions similar to experimental conditions. Furthermore, parameters $\alpha_2$ and $w_2$ were varied within the following ranges: $\alpha_2 = 10-90^\circ$, $w_2 = 0.112, 0.16, 0.208 \text{ mm}$. Their effect on the crushed height $h_{C2}$ is discussed here.

The element type of the finite element (FE) meshes used for the blades was the plain-strain quadrilateral element with four-point Gaussian integration. The mechanical properties of the blades were considered based on the values that were used in the experiment, while the friction coefficient was assumed to be $\mu = 0.18$ for the blade and the counter plate. The FE meshes of the blade consisted of 768 elements with minimum side length of 16.3 µm and the re-meshing function was not used. When the asymmetric-lateral deformation with the blade centerline occurred, the crushed height $h_{C2}$ was mainly investigated after unloading (Fig. 3).

4. Results and Discussion

4.1 Comparison of experiment and simulation

Figure 4(a) shows enlarged pictures of bottom tip deformation for the experiment, while Fig. 4(b) shows the deformed bottom tip with the equivalent strain values $\varepsilon_{eq}$ on the FEA of $\alpha_2 = 16^\circ$ and $w_2 = 0.16 \text{ mm}$. Both figures show the deformation for $f > 200 \text{ kN/m}$. From the FEA, a symmetric upsetting mode is seen to occur at $f = 200 \text{ kN/m}$. This situation explains that the bottom tip deformed in symmetric mode initially before switching to asymmetric mode ($f > 250 \text{ kN/m}$). The asymmetric deformation includes elastic bending of the blade and plastic flow of the bottom tip. It is referred here as the lateral buckling of the bottom tip. It is confirmed that the plastic-asymmetric deformation of the bottom tip on FEA can explain the experimental feature of asymmetric crushing.

The bottom tip crushed height $h_{C2}$ was analyzed with the normalized linear force $f_2 = f/f_0$. Here, the bottom tip’s critical yielding force $f_0 = 1.15\sigma_0 w_2$ is estimated as the compressive plain-strain constraint. Results for the experiment and FEA were then compared. All models have a small $h_{C2}$ of less than 8 µm and deformed almost symmetrically with the blade centerline when $f_2 < 1.5 (f < 206 \text{ kN/m})$. Large deformation of $h_{C2}$ was seen to gradually start when $f_2 > 1.8 (f > 247 \text{ kN/m})$. The $h_{C2}$ is linearly approximated with the linear force $f_2 (1.8 < f_2 < 2.6)$ as:

$$h_{C2} = 385.7 f_2 - 711.3 \quad \text{(Experiment)}$$

$$h_{C2} = 323.8 f_2 - 560.6 \quad \text{(FEA asymmetric)}$$

The considered simulation model explains the experimental features on varying of $h_{C2}$ with the line force $f_2$ as shown by similarity of eqs. (1) and eq. (2).

The total crushed height $h_C$ for the original DSB can be estimated by combining the normal blade’s crushed height $h_{C1}$ with the bottom tip crushed height $h_{C2}$. The contribution of cutting tip side on the total crushed height was roughly estimated to 15% with the gradient of $\partial h_C/\partial f_2$. The possible stress relaxation mechanism for the surplus crushing of the cutting tip, design of the transition point is important. Hence, in the following, $h_{C2}$ increase’s starting point of increasing of $h_{C2}$ and the gradient of $\partial h_{C2}/\partial f_2$ are discussed in terms of $\alpha_2$ and $w_2$.

4.2 Effect of varying bottom tip design parameters

4.2.1 Varying of bottom tip angle $\alpha_2$

The FEA of the bottom tip deformation was carried out by varying of tip angle $\alpha_2 = 10^\circ, 12^\circ, 14^\circ, 18^\circ, 20^\circ, 23^\circ, 26^\circ, 30^\circ, 33^\circ, 36^\circ, 42^\circ, 53^\circ$ and 90° respectively while keeping $w_2 = 0.16 \text{ mm}$. To perform appropriate relief mechanism for reducing surplus crushing of the cutting tip, design of the transition point is important. Hence, in the following, $h_{C2}$ increase’s starting point of increasing of $h_{C2}$ and the gradient of $\partial h_{C2}/\partial f_2$ are discussed in terms of $\alpha_2$ and $w_2$.
The $X_1$ and $X_0$ were approximated by using the power rule expression as shown in eq. (4), (5) and Fig. 6.

$$X_1 = 45.12 \alpha_2^{1.70}$$  \hspace{1cm} (4)

$$X_0 = -70.99 \alpha_2^{-1.66}$$  \hspace{1cm} (5)

The increase of $\alpha_2$ has obviously resulted in the increase of the bottom tip deformation resistance. In case of a very keen angle ($< 12^\circ$), the bottom tip is apt to be crushed in uncertain elastic buckling and the allowed maximum line force of the buckling strength is remarkably decreased.

Figure 7 shows the intercept of $f_2$ with respect to eq. (3). This intercept was calculated as $-X_0/X_1$ from $X_1$, $X_0$ on FEA simulation. A local maximum value was found at $\alpha_2 \approx 18^\circ$ from Fig. 7. The intercept of $f_2$ drops correspond to the transition of the blade centerline deflection mode between the asymmetric and the symmetric crushing of the bottom tip. In case of $\alpha_2 = 30^\circ$, where the bottom tip crushing is almost symmetric and the bottom tip pressure is kept in a certain large value when $f_2 = 1.8–2.5$. In case of $\alpha_2 = 26^\circ$, the bottom tip crushing is asymmetric. Synthetically, a range of $\alpha_2 = 16–20^\circ$ is superior for two features: 1) The critical line force $f_2$ corresponding to the large increase of the $h_{C2}$ has the local maximum condition. This means that the bottom tip pressure $p_2 = f/(1.15 \alpha_2 \alpha_{C2})$ and the cutting direction stiffness $d^2f_2/dh_{C2} = (1/X_1)$ of DSB are maintained in a certain large value for $f_2 < 1.8$, while the bottom tip pressure and the stiffness are reduced for $f_2 > 1.8$ due to increase of $X_1$. 2) The asymmetric crushing or lateral buckling of the bottom tip is superior to the symmetric upsetting of the bottom tip, because the former pressure decreasing has a large margin to avoid the cutting tip crushing when $f_2 > 1.8$.

### 4.2.2 Varying of bottom tip thickness $w_2$

Modifications were made to FEA model by varying $w_2$ to 0.208 mm and 0.112 mm respectively and keeping $\alpha_2 = 16^\circ$. A graph of the relationship between $h_{C2} = h_{C2}/b$ and $f_2$ was plotted in Fig. 8 and linear approximations were made with eq. (3) for $f_2 > 1.8$.

<table>
<thead>
<tr>
<th>$w_2/b$</th>
<th>$X_1$</th>
<th>$X_0$</th>
<th>$-X_0/X_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.29</td>
<td>0.29</td>
<td>-0.62</td>
<td>2.12</td>
</tr>
<tr>
<td>0.23</td>
<td>0.50</td>
<td>-0.89</td>
<td>1.78</td>
</tr>
<tr>
<td>0.16</td>
<td>0.40</td>
<td>-0.48</td>
<td>1.19</td>
</tr>
</tbody>
</table>

The factors $X_1$, $X_0$ derived from the approximations are shown in Table 1. Increase of $w_2$ has resulted in increase of the interception on $f_2 = f/f_{B0} > 1.5–1.8$ and resulted in high crushed height variance in case of tip angle $\alpha_2 = 16^\circ$ and tip thickness of $w_2 = 0.16$ mm. Namely, there is a transition point of the bottom tip crushing height $h_{C2}$ for $f_2 = 1.5–1.8$. Here, $f$ is applied line force and $f_{B0}$ is the yielding line force of the bottom tip.

(2) The bottom tip angle $\alpha_2$ is able to effectively control the transition point of the bottom tip crushing from symmetric upsetting to asymmetric-lateral bending. There is a local maximum condition with the transition point of line force at $\alpha_2 \approx 18^\circ$, while the deformation mode changes at $\alpha_2 = 26–30^\circ$. A very keen angle less than 12° resulted in an early deformation and limited to a lower cutting direction stiffness.

### 5. Conclusions

From the research of the bottom tip deformation with DSB, the following results were obtained:

(1) Plastic crushing of the bottom tip with asymmetric bending remarkably occurred at high line forces ($f_2 = f/f_{B0} > 1.5–1.8$) and resulted in high crushed height variance in case of tip angle $\alpha_2 = 16^\circ$ and tip thickness of $w_2 = 0.16$ mm. Namely, there is a transition point of the bottom tip crushing height $h_{C2}$ for $f_2 = 1.5–1.8$. Here, $f$ is applied line force and $f_{B0}$ is the yielding line force of the bottom tip.

(2) The bottom tip angle $\alpha_2$ is able to effectively control the transition point of the bottom tip crushing from symmetric upsetting to asymmetric-lateral bending. There is a local maximum condition with the transition point of line force at $\alpha_2 \approx 18^\circ$, while the deformation mode changes at $\alpha_2 = 26–30^\circ$. A very keen angle less than 12° resulted in an early deformation and limited to a lower cutting direction stiffness.

(3) The bottom tip thickness $w_2$ is able to effectively move the transition point of line force without changing the cutting direction stiffness of DSB.

### REFERENCES