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Model of slice-push cutting forces of stacked thin material

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ABSTRACT

Adding slicing to push cutting processes can significantly reduce cutting forces. Creating an appropriate model for the calculation of forces is necessary to completely understand manufacturing processes. In this investigation, a model detailing the cutting forces of stacked thin material using an asymmetrical knife is developed. Equilibrium of forces and frictional effects at the cutting edge are analyzed to determine the components in vertical and horizontal direction of the total cutting force, and their dependency on the slice-push ratio. The friction effects of the new model are based on Coulomb friction. For comparison purposes, an existing shear friction model is extended to discuss the new presented Coulomb friction model. To support the findings, the newly developed model is experimentally verified.

1. Introduction

In the label paper industry, an in-depth understanding of all processes is necessary to improve quality, increase output, and lower production costs. One key finishing process in the production of paper labels is the cutting of label paper stacks with high speed and high precision. Sheets of label paper are usually printed with offset printing (or gravure printing), and then bundled to stacks of approximately 1000 sheets of paper, which are then cut into stacks. The cutting performance directly influences the output performance of the entire label cutting process. As shown in Fig. 1, the knife moves from top to bottom with the dead center sliding along a straight line for the parallel cut. This push cutting process can be enhanced by adding a slicing movement to the cutting knife. It can be defined as two separate motions in y- and z-direction. According to Klingelhöffer (1962), this slicing motion of the asymmetrical cutting knife may reduce cutting forces. The simple push cutting movement becomes slice-push cutting.

Atkins et al. (2004) study the cutting of cheddar cheese and salami, and present a energy-based model for the slicing and pressing cutting process. Atkins (2009) book further discusses energy-based approaches for slice-push cutting and presents them in detail. Reduced forces due to the slicing motion have mostly been investigated in the food industry. Kamyab et al. (1998) investigate the cutting of cheese by using a wire. Zahn (2009) introduces the slicing of food materials with ultrasonic vibration assisted cutting. Goh et al. (2005) discuss the cutting forces of cheese wire cutting through a mechanical approach. Zhou et al. (2006) discuss the effects of blade sharpness and slicing angle on the cutting forces. Reyssat et al. (2012) study the slicing of soft materials with a wire, concluding that the slicing reduces cutting forces. Downey (1975) did some investigations regarding the cutting of paper in his dissertation. A reduction in cutting forces was observed as well. Li'e et al. (2011) performed similar experiments for cutting of a paper stack with a guillotine knife under forced vibrations, where the vibrating blade subdivided the entire stack into smaller parts, thus improving cutting performance. However, no model regarding cutting forces for slice-push cutting of paper stacks has been created, yet.

In this paper, the cutting forces for guillotining paper stacks with a slice-push movement are investigated. A well known energy-based frictionless model, introduced by Atkins et al. (2004), is enhanced with the appropriate consideration of friction forces to calculate the total forces acting against the cutting blade. With a known shear friction model, the newly developed cutting force model based on Coulomb friction is discussed. Finally, the model is experimentally verified by cutting paper stacks with various slice-push ratios.

2. Equilibrium of forces between knife and sheet

When cutting stacked thin material, the friction forces occurring between cutting knife and sheets within the stack need to be defined. Rösner and Schulz (1978) discussed this equilibrium of forces for an unbent and bent stack of sheets. For the unbent sheets, the normal force between the sheets translates into a friction force,

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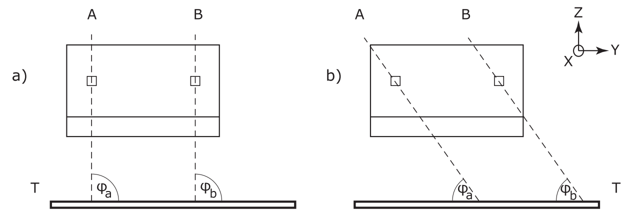

Fig. 1. Two different guillotining methods, with (a) parallel vertical cut ($\varphi_a = \varphi_b = 90°$), and (b) parallel slide cut ($\varphi_a = \varphi_b < 90°$), as defined by the Paper and Board Federation (2013). φ_a and φ_b are the angles of the guides (A and B) relative to the table (*T*).

which directly acts upon the blade. Its components in vertical and horizontal direction are only dependent on the cutting angle. If the stack shows large deformation, which is arising when cutting a paper stack, the bending of the sheets at the cutting knife due to the compression has to be considered. Therefore, a tilt angle α is introduced as shown in Fig. 2. α is mainly dependent on material properties and cutting edge sharpness. The cutting knife moves only in the x–z-plane and pushes the cut sheets away. Thus, the equilibrium of forces acting on a single paper sheet become

$$F_{EF} = \frac{F_K(\sin\alpha + \mu_{pp}\cos\alpha)}{(\cos\beta - \mu_b\sin\beta)(\cos\alpha - \mu_{pp}\sin\alpha) - (\sin\beta + \mu_b\cos\beta)(\sin\alpha + \mu_{pp}\cos\alpha)} \quad (1)$$

$$F_{Np} = \frac{F_K(\cos\beta - \mu_b\sin\beta)}{(\cos\beta - \mu_b\sin\beta)(\cos\alpha - \mu_{pp}\sin\alpha) - (\sin\beta + \mu_b\cos\beta)(\sin\alpha + \mu_{pp}\cos\alpha)} \quad (2)$$

$$F_{Fp} = F_{Np}\mu_{pp} \quad (3)$$

where F_{EF} is the normal force acting against the cutting knife, F_K is the vertical compression force between the inclined sheets, μ_{pp} is the friction coefficient between sheets, μ_b is the Coulomb friction coefficient between sheets and cutting knife, and β is the cutting angle. F_{Fp} is the friction force between sheets within the stack. Rösner and Schulz (1978) model F_K as being simple the force of gravity acting vertically upon the finished cut inclined sheets. However, in the presented new model, F_K represents the force caused by the vertical compression of the stack, because the cutting process is considered, and sheets are uncut and under loading from the knife.

3. Frictionless slice-push forces

To completely model the forces of slice-push cutting of stacks, an energy-based approach is used. Atkins (2009) models the cutting of thin slices of material by regarding the total energy balance of the process. This model is revisited here, because it is later expanded to include the previous discussed friction effects. Under the assumption that when cutting thin slices very little elastic strain is stored, the total energy necessary for cutting with a parallel vertical cut is the sum of the specific fracture energy and work of friction. It is defined by

$$F_C \cdot ds_C = e_{fr} \cdot w \cdot ds_C + W_F \quad (4)$$

with F_C being the total force necessary for cutting, ds_C being the tool displacement in cutting direction e_{fr} being the specific cutting force in cutting direction, w is the width of the workpiece, and W_F the work needed to overcome friction. This equation is only valid if the motion of the tool and the reached cutting depth are controlled by the cutting device, and no leading crack occurs. It should be pointed out that the tool edge radius, cutting angle, and clearance angle are not considered here. If the cut material would require overcoming bending stiffness, this would need to be added to the above equation. Next, the components of the cutting force without friction effects are derived.

As already discussed earlier, the parallel vertical cut can be superimposed with a sliding motion. Under the assumption that the specific cutting energy remains constant

$$e_{fr} \cdot w \cdot ds_C = \text{constant} \quad (5)$$

and the basic energy balance in Eq. (4) holds true and no friction occurs, the model for the vertical sliding cut defines the total energy necessary for cutting, which is provided by the vertical and sliding cutting motion. Regarding floppy materials with no friction, the total energy necessary is

$$e_{fr} \cdot w \cdot ds_C = F_V \cdot ds_V + F_H \cdot ds_H \quad (6)$$

with F_H being the horizontal force, ds_H being the tool displacement in horizontal direction, F_V being the vertical force, and ds_H being the tool displacement in vertical direction. The resulting force is given by

$$F_R = \sqrt{F_V^2 + F_H^2} \quad (7)$$

and the resulting displacement as

$$ds_R = \sqrt{ds_V^2 + ds_H^2} \quad (8)$$

so Eq. (6) can be rewritten as

$$e_{fr} \cdot w \cdot ds_C = \left(\sqrt{F_V^2 + F_H^2}\right)\left(\sqrt{ds_V^2 + ds_H^2}\right) \quad (9)$$

Since the vertical sliding cut combines push cutting and slicing, a dimensionless slice-push ratio is defined as

$$\xi = \frac{ds_H}{ds_V} \quad (10)$$

hence with Eq. (6) and $ds_V = ds_C$ we obtain the two forces based on the resulting force

$$\frac{F_H}{e_{fr}w} = \frac{\xi}{(1+\xi^2)} \quad (11)$$

$$\frac{F_V}{e_{fr}w} = \frac{1}{(1+\xi^2)} \quad (12)$$

The dimensionless resulting force can be calculated with

$$\frac{F_R}{e_{fr}w} = \sqrt{\frac{1}{(1+\xi^2)}} \quad (13)$$

With a known specific cutting force e_{fr}, and slice-push ratio ξ, these forces can be directly calculated.

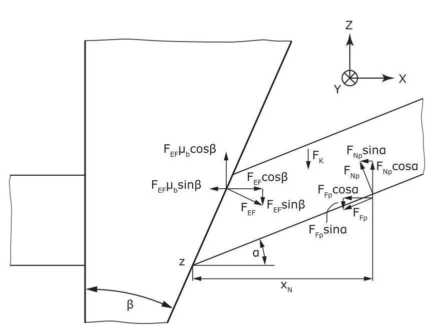

Fig. 2. Model for forces of friction between knife edge and paper, and friction between paper sheets, while considering the bent down paper, presented by Rösner and Schulz (1978). The bending of the cut sheets is represented by the angle α. F_K acts vertically upon the titled sheets within the stack.