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Modeling slice-push cutting forces of a sheet stack based on fracture mechanics

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ABSTRACT

It is a well known phenomenon that cutting materials with a slicing motion is much easier than cutting by simply pushing the knife down into the material. Energy-based analyses proof that slice-push cutting reduces the overall cutting forces with an increasing slicing motion. In this investigation, a model describing the cutting of a thin and planar material with an asymmetrical knife is developed, using equilibrium of forces and basic concepts of fracture mechanics. Finite-element-simulations are performed to determine the relationship between cutting forces and the parameters describing crack propagation. Consequently, normal pressure on the crack surface caused by the flanks of the cutting edge of the blade is the main cause leading to a crack tip opening and thus propagation of the crack. Overall cutting forces are augmented by the friction forces caused by the relative motion between cutting knife and material. Thus, the slicing motion allows the advance force to be reduced. The presented model is experimentally verified by sideways cutting stacked paper sheets.

1. Introduction

In the paper industry, cutting of sheets and sheet stacks is an essential finishing process, which requires high quality. There are four types of cutting strategies [1]: Parallel Vertical Cut, Parallel Slide Cut, Swinging Vertical Cut, Swinging Slide Cut. The parallel slide cut strategy superimposes a sideways motion that is perpendicular to the cutting direction. It has been found that cutting forces may be reduced due to the additional sideways motion of the asymmetrical cutting knife, also called slicing [2]. The pure push cutting motion becomes slice-push cutting, and is defined by the slice-push ratio ξ. Atkins et al. [3,4] introduce an energy based analysis of this slice-push cutting and define the resulting cutting forces as

$$\{F\}^T d\{f_{rel}\} = dU + e_{fr} dA, \tag{1}$$

where $\{F\}$ is the vector of the cutting force, $\{f_{rel}\}$ is the vector of the relative displacement between cutting tool and workpiece, U is the deformation energy, e_{fr} is the specific surface energy, and A is the newly created surface. Since the surface energy depends on the material and is regarded as constant, it is argued and shown that a force reduction may be obtained by increasing the slicing motion. Similar observations are made for cutting food materials [5]. Mechanics of wire cheese cutting and estimation of fracture toughness depending on wire thickness and cutting force were discussed in [6]. Cutting

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Nomenclature

Abbreviation	Description
a	crack length
A	surface
b	distance between crack tip and applied load half remaining width of DENT-sample
B	plate thickness
c	parameter for fitting
e	unit vector
e_{fr}	specific surface energy
E	Young's modulus
f_{rel}	relative displacement
F_i	force in direction I
F_{res}	resulting force
G	shear modulus
$\mathcal{G}$	energy release rate
$\mathcal{G}_c$	critical energy release rate
K_i	stress intensity factor of mode I
K_{Ic}	fracture toughness
L	contact length
n	normal vector
O	transformation matrix
p	contact pressure
P	line loading (mode I)
Q	line loading (mode II)
R	line loading (mode III)
s	stress vector
U	deformation energy
v_r	relative velocity
v_i	velocity in direction I
W	width of the DENT-sample
X	general x-direction
Y	general y-direction
Z	general z-direction
β	asymmetrical cutting angle
ξ	slice-push ratio
μ	friction coefficient
ν	Poisson ratio
ϖ	friction-cutting angle ratio
σ	normal stress
τ	tangential stress
$\{\}$	vector
$[]$	matrix
$'$	superscript for considerations in local coordinate system
DENT	double-edge-notched-tension
FEM	finite element method
SIF	stress intensity factor

of soft solids and viscous liquids with a flexible wire was performed in [7]. The resulting catenary-like shapes depend on the observed friction and tension between wire and workpiece. Neder [8] discusses in his dissertation the cutting of prepreg material and concludes that the slicing motion adds additional shear stress to the fibers of the material. Thus, the fibers are cut more easily due to the additional displacement and its resulting normal and shear stress, complementing the tensile stress from the pushing motion of the cutting knife.

Zhou et al. [9,10] and Reyssat et al. [11] discuss the slice-push cutting process on bio materials. They both conclude that the slice-push motion creates a three dimensional state of stress within the workpiece, and thus the resulting equivalent stress is higher than when solely cutting with a pushing motion. Consequently, the material fails earlier and the desired crack is created. However, this approach only explains the initial cutting phase and not the process occurring at the crack tip after the onset of cutting. Similar observations were done by Feiler in his dissertation [12] regarding brittle materials and using the maximum shear stress hypothesis.