Mechanics of Creping in Tissue Making

Kui Pan  A. Srikantha Phani &  Sheldon Green

Department of Mechanical Engineering
University of British Columbia, Vancouver, BC
Outline

- Background
- Research Objectives
- Methodology and Results
- Conclusion
Creping Influences Tissue Properties

SEM cross-sectional image of tissue
H.F. Jang, FPI, 2013

Creping: a de-densification process

Wavelength: $\lambda \sim 0.3\text{mm}$
Amplitude: $A \sim 0.1\text{mm}$

MD: machine direction; CD: cross direction.
Dry-Creping Process

Yankee Dryer
Diameter ~3m
Velocity ~1500 m/min

Crepe Ratio = \frac{V_{in} - V_{out}}{V_{in}}

SC: solid content

- Felt: SC ~40%
- Pressure Roll
- Wet Web: 20°C, SC ~20%
- Adhesive Spray Nozzle
- Doctor Blade
- Cleaning Blade
- Reel
- Creped Tissue: 100°C, SC ~94%
Creping Regimes

Governing Parameters

Typical Control Parameters:

- Yankee surface speed $V_{in}(1000\sim2000\text{m/min})$
- Creping angle $\delta$ (80°~100°)
- Crepe ratio $\frac{V_{in}-V_{out}}{V_{in}}$ (10%~30%)
- Adhesion $G_c$ (50~400 N/m)
- Blade Friction (0.25~0.35)

$\delta$: Creping angle

Fundamental study is necessary. Guide the choice of adhesive chemicals, process parameters, blade type and so forth.

Current situation: trial and error.

quality, runnability and productivity
Creeping Mechanism

Micro-fold to Macro-fold Transition
High Speed Imaging Study
H. Hollmark, STFI 1972
Creeping ratio: 32%

Limited surface speed: 140 m/min
No further validation about the mechanism.
Outline

- Background
- Research Objectives
- Methodology and Results
- Conclusion
Research Objectives

Experiments:

- Observe the creping process under high speed to reveal relevant phenomenon and understand the mechanism.

Modeling:

- Develop mechanistic creping model to study the effects of process parameters (adhesion, creping angle…) and dynamic effects (creping ratio, surface velocity…) on tissue structure.
Outline

➢ Background

➢ Research Objectives

➢ Methodology and Results

➢ Conclusion
Methodology: High speed imaging

Creeping testing rig based on Lathe

Goal: reveal creping mechanism at high speed
Edge-on view of set-up

Laser information
Power: 500mW; Fan angle: 5°;
Length: 20mm; Thickness: 0.1mm.

Disk information
Radius: 89mm; $\omega_{max}$: 1500 rpm;
Maximum surface speed: 838 m/min.

Doctor blade
Creping angle $\delta$: adjustable;
Blade thickness: 1.2 mm.
Surface speed: $V_{in} = 217$ m/min
Creeping angle $\delta = 45^\circ$
No creping ratio: $V_{out} \approx 0$

Micro-fold to macro-fold transition is observed.
Surface speed: $V_{in} = 195$ m/min

Crepeing angle $\delta = 90^\circ$

No creping ratio: $V_{out} \approx 0$

Transition mechanism still exists, when we increase creping angle.
Creping Ratio by Hand Pulling

Surface speed: $V_{in} = 217$ m/min

Creping angle $\delta = 90^\circ$

Creping ratio: $\frac{V_{in} - V_{out}}{V_{in}} \approx 25\%$

Micro-fold to macro-fold transition disappeared
Indicating creping ratio is important.
Summary of Current Experiment

Lathe creping experiment

Relative high speed 800 m/min; System is stable; Creping process is clearly recorded; Verified micro-fold to macro-fold transition mechanism.

Limitations: Creping ratio not well-controlled; Non-uniform adhesion.
Methodology: Discrete Particle Model

Particle’s mass: \( M = \rho a_0 hw. \)

axial elastic force: \( f_a = k_a(|r_{i-1} - r_i| - a_0)e_{i,i-1} + k_a(|r_{i+1} - r_i| - a_0)e_{i,i+1} \)

damping force: \( f_d = -\eta_a([\dot{r}_i - \dot{r}_{i-1}] \cdot e_{i,i-1})e_{i,i-1} - \eta_a([\dot{r}_i - \dot{r}_{i+1}] \cdot e_{i,i+1})e_{i,i+1} \)

bending force and viscous bending force: \( f_b, f_v \)

\( h \) is thickness, \( w \) is width of paper, \( a_0 \) is initial spacing, \( \eta_a \) is damping coefficient, \( k_a \) is axial stiffness.

Spring damper coefficients are related to paper layer properties.
Cohesive force applied on particle:  
\[ f_c = -\sigma a_0 w e_\perp - \tau a_0 w e_\parallel \]

\( e_\perp \) and \( e_\parallel \): normal and tangential unit vectors

\( \sigma_c \): normal strength; \( \tau_c \): shear strength;
\( G_{IC} \): mode I fracture toughness; \( G_{IIC} \): mode II fracture toughness. (adhesion)

CZM parameters are related to adhesive layer properties.

Newton’s equations:  
\[ f_{tot} = f_a + f_d + f_b + f_v + f_c = Ma \]
Self-Contact Model

$d_t$: threshold distance. $d_t = h/100$.

When $d_s \geq d_t$, no contact force $F_{c1} = 0$.

When $d_s < d_t$,

*New function:* $F_{c1} = \alpha [e^{\left(\frac{\beta}{d_s}\right)} - 1]$. $\alpha, \beta$ are constants
Self-Contact Model

No self-contact

Include self-contact

\[ \Delta L = L - L' = 0.87L \]
Validation of Model

Buckle-delamination

maximum deflection:

\[ \zeta = h \sqrt{\frac{4}{3} \left( \frac{\varepsilon_0}{\varepsilon_*} - 1 \right) } \]

\[ \varepsilon_* = \frac{\pi^2 h^2}{12 a^2} \]

Creeping Simulation

Schematic of creping model

\( V \) is Yankee surface speed, \( \delta \) is creping angle.

Radius of Yankee (\( \sim 1.5\, m \)) \( \gg \) Paper thickness (\( \sim 0.1\, mm \))
Surface can be considered as flat
$V = 1200 \text{m/min}, \delta = 80^\circ$. 
Three stages:
- delamination propagation (Mode I)
- buckle initiation;
- buckling-driven delamination. (Mixed-mode)
Mixed-mode fracture toughness

\( G_{IC} \) is varied to change the mixed-mode.

Creping wavelength is dependent on both \( G_{IC} \) and \( G_{IIc} \);
Creping force is determined by \( G_{IIc} \).
Periodic Folding Simulation

FFT analysis:
\[ \lambda = 0.35 \text{mm} \]
\[ A = 0.052 \text{mm} \]

Schematic of tissue structure

Wavelength: \( \lambda \sim 0.3 \text{mm} \)
Amplitude: \( A \sim 0.1 \text{mm} \)

Creping angle: 85°;

\[ V_{\text{in}} = 20 \text{m/s} \]
\[ V_{\text{out}} = 0.7 \times V_{\text{in}} \]
Creping angle: 85°; V_in=20 m/s; V_out=0

A few micro-folds evolve into a macro-fold.
Larger modulus results in larger creping wavelength; Larger adhesion results in smaller creping wavelength.
Limitation of Current Model

- Currently one-dimensional model.
- Plastic deformation of fiber is not included.
Outline

➢ Background

➢ Research Objectives

➢ Methodology and Results

➢ Conclusion
Lathe creping experiment
Relative high speed 800 m/min; System is stable;
Clear view of creping process;
Micro-fold to macro-fold transition mechanism is verified
and it is found to be affected by creping ratio.
Discrete particle model has been developed. One-dimensional dynamic, creping-ratio included. Process parameters included.

Simulation of creping process.
Single fold formation shows three typical stages. The periodic creping process is successfully simulated and simulation results are close to experimental values.

Parametric studies.
Effects of modulus, adhesion, and creping angle. Need to be compared with experimental data.
Future Work

- Extend current model to microscopic level to account for fiber properties and explosive bulk.
Future Work

- Compare simulations with experimental data from commercial machine.

Pilot Tissue Machine, FPInnovations, Montreal.

Maximum Yankee surface speed: 1500 m/min;
Able to process parameters and furnish.
Thank you!