Modeling and Simulation of the Creping Process

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ABSTRACT

The manufacture of low density paper such as tissue and towel utilizes the creping process that consists of adhesively bonding the paper in wet state onto the surface of a smooth drying cylinder and scraping it off with a blade once the sheet is dry. In this paper, a fracture mechanics description of the creping process is presented. A mechanism of creping process is proposed as a periodic debonding with a mixed-mode fracture criterion with buckling of an elastic thin film. Finite element models validating creping mechanism will also be presented. Numerical calculations show results consistent with experimental data and known industrial observations. The model provides guidance in understanding and optimizing the creping process to produce high quality products.

INTRODUCTION

Creping process is the dominant micro-contraction process practiced in towel and tissue manufacturing. In this process, a continuous paper web is adhesively bonded to the surface of a large rotating drum (the Yankee Dryer), dried completely, and scraped off using a blade, typically at 5000 feet per minute. Prior to reaching the creping blade, the sheet is flat, smooth in most cases, and compact resembling the structure of writing paper. Immediately following the creping process, the sheet is "bulky" or has much lower density, soft or pliable, with low bending stiffness, and has regular surface undulations that cause the perception of softness, which is the primary end-use property of tissue grades. It is said, "tissue is made at the creping blade". Creping is a very poorly understood process, and the process operating parameters on a tissue machine have been primarily obtained through trial and error, and difficult to control. Yankee dryers are large steam-heated drums with polished cast iron surface. Yankee dryers can be as large as 24 feet in diameter and 18 feet in width. The surface speeds can be as high as 6500 feet per minute. The creping doctor blade is pressed against the drum to remove the adhesively bonded sheet. In the process, there is constant wear of the blade due to metal-to-metal contact and erosion of the Yankee dryer surface. The blade changes can be as frequent as every four hours resulting in lost production. Periodically, the Yankee dryer surface has to be reground to regain surface smoothness and uniformity. The steam heating systems has to be serviced periodically. In essence, the creping dryer is an enormously complex piece of equipment that is expensive to purchase and install and demanding to maintain. A systematic method to understand the creping process in a fundamental sense is needed in order to identify a generic set of fundamental process parameters such as energy input during debonding, the intensity or energy density required, and the best condition for the substrate when the energy is input to cause selective debonding, etc. Furthermore, the input parameters to the creping process that are significant should be identified based on published literature and industry knowledge and their effects on the sheet structure should be described in a computational model.

BACKGROUND

Hollmark [1] studied the creping process primarily through filming the process at high speed and developed a qualitative description of the creping process. He varied two parameters, namely, the creping angle, and the adhesion between the sheet and the dryer surface. The adhesion was changed by varying the percent resin content in the adhesive spray. Although it was concluded that the adhesion is probably the most important factor, specific adhesive properties were not identified. No attempt was made to develop analytical models for the process. Oliver [2] published his literature search on the creping process and made some general conclusions regarding the parameters that are important to the creping process, namely, creping blade angle, "adhesion", and the concentration of dissolved hemicellulose that affect the adhesion. Very few scientific publications exist in the area of tissue making. Almost all of them deal with the mechanism of adhesion of the paper web to the dryer surface, strictly through experimental observations. Any progress made in the creping area has been traditionally through "unexpected results" described in numerous patents, without any description of the fundamentals of the process. There is no report of a systematic and coordinated analytical and experimental study of the creping process in the open literature.

The pictures of the creping process, taken by Hollmark [1], have been used as the starting point to form a hypothesis for developing an analytical model [3]. The creping process can be schematically represented as shown in Figure 1 [3].

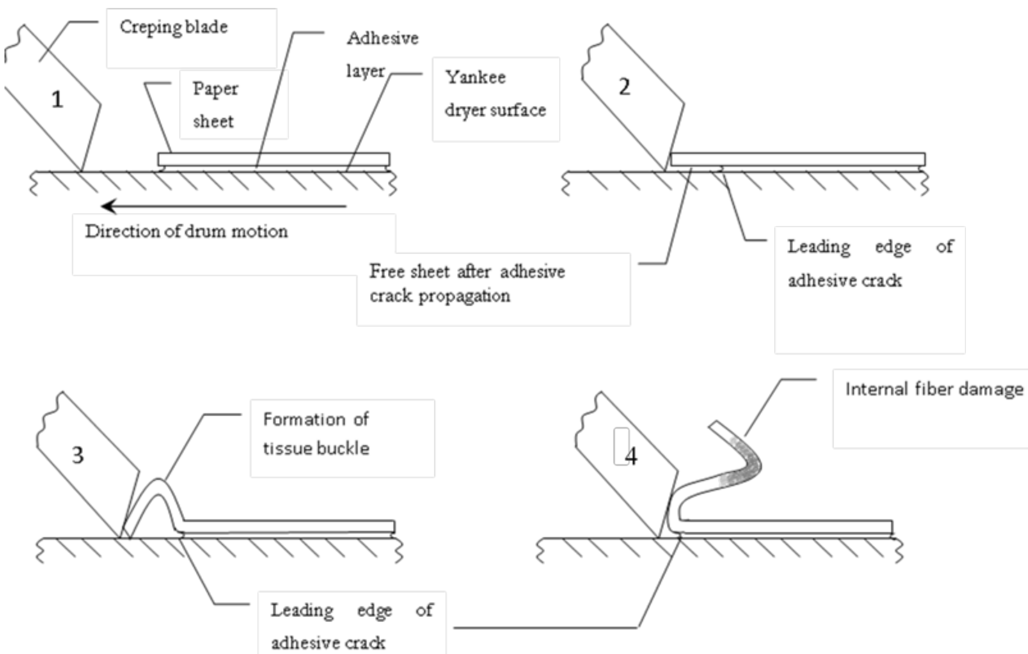

Figure 1. Mechanistic Description of Creping Process

An idealized mechanics description of the creping process in its steady state is given below (see Figure 1):

1. Ahead of the creping blade, there exists a delamination length over which the sheet is not attached to the dryer. As the sheet is further pushed against the blade by the rotation of the dryer drum, crack propagation continues.
2. The crack continues to grow until it is energetically favorable for the free segment of the sheet to buckle. At this point the sheet buckles.
3. As the sheet is pushed further, some delamination growth takes place during buckling.
4. When the buckling is complete, the sheet completely collapses and forms the crepe fold. At this instance, the energy in the system drops well below the energy required for crack propagation, and the crack is arrested.
5. When the next segment of the sheet that is bonded to the dryer contacts the blade, delamination and buckling takes place. The entire cycle is repeated.

From a mechanics point of view, the process is a continual competition between interfacial crack propagation and buckling. This concept has been analytically modeled by Sun [4].

CREPING EXPERIMENTS

A laboratory creping simulator that can realistically simulate creping process up to 2500 feet per minute has been built at NC State University. The creping simulator has been used to study the process under a variety of conditions and results have been verified to correspond to expected large-scale trials [3].In this device, discrete paper samples can be attached to an electrically heated drum and scraped off with a creping blade mounted on a three axis load cell. The creping force which is the tangential direction to the drum is measured. In an experiment to understand the creping process, a thin strip of paper, 2.5 in. wide and 6 in. long, with the longer dimension in the machine direction was bonded to the drum using Polyvinyl Alcohol (PVA) at 1.0% concentration. The paper was machine made and dried without creping. The basis weight of the paper used was 32 g/m^2. The Yankee dryer was run at 144 m/min (180rpm) and the creping angle was set to 80 degrees. The contact force of the creping blade and Yankee dryer in the normal direction was preset to 85N before creping. The tangential force trace was measured during creping process to study the effects of various process parameters. In order to understand the creping mechanism, the machine was slowed down to 15.8 m/min in order to capture the creping force during the process of creping, and a typical force trace is shown in Figure 2.

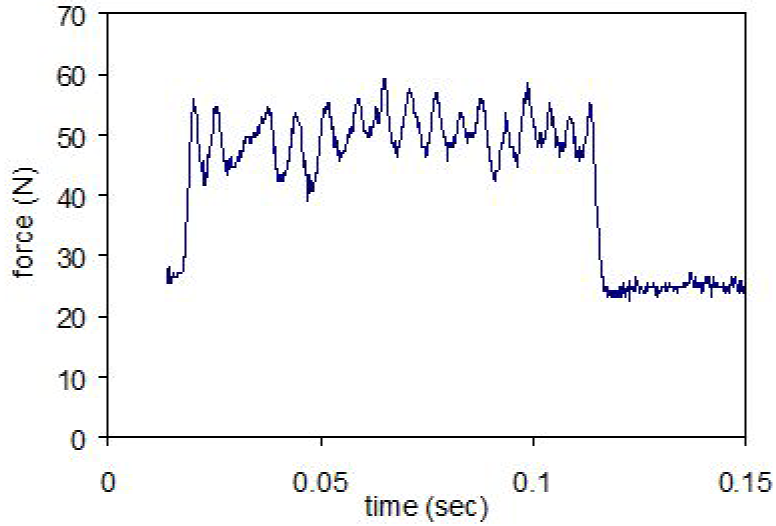

Figure 2. Creping Force trace during creping process

Each crepe fold formation is represented by each period in the trace from a low force to a peak and back to the low value. For example, the second crepe fold starts near 42 N, reaches a peak near 55 N, and when the crepe fold collapses, it reaches the low value again, and the cycle repeats with every crepe fold. The variation in the data is due to the variation in the paper structure since we are dealing with dimensions at the fiber length scale. It can be observed that the change in creping force in a single period is around 15 N, which is quite significant.

CREPE MODELING AND NUMERICAL SIMULATION

In this section, a finite element model for the creping process is presented in 2-D. The FEA model is generated by setting the creping problem using a crack propagation analysis available in ABAQUS/Standard.

The Debonding Criterion

ABAQUS allows three fracture criteria [5]: critical stress criterion, critical crack opening displacement (COD) criterion, and crack length versus time criterion. The critical stress criterion is more suitable to be applied in the creping problem to be studied here. The criterion is defined as

$$f = \sqrt{\left(\frac{\hat{\sigma}_n}{\sigma^f}\right)^2 + \left(\frac{\tau_1}{\tau_1^f}\right)^2} > 1 \qquad \hat{\sigma}_n = \max(\sigma_n, 0) \tag{1}$$

where σ_n is the normal component of the stress carried across the interface at the distance specified.; τ_1 is the shear stress component at the interface; σ^f and τ_1^f are the normal and shear failure stresses, which should be specified.

Elements and Meshes

The thin film of paper studied here is a semi-infinite structure with the edge subjected to external loads. In order to model it by FEA, a relatively long structure has to be used. Since the debonding length is about 1 mm, a 2 mm long strip is modeled in the analysis to be computationally economical. Numerical results show that this length is long enough and the film edge has little influence on the process.We will consider the adhesive as an elastic layer and define the layer accordingly. First-order,4-node bilinear solid elements (CPE4), was used to model the paper. The meshes of the structure are shown in Figure 3. It can be observed that an initial crack has been assumed, which is 0.01mm and is lifted through a small distance to initiate the crack propagation. The mesh is refined near the debonding interface so that accurate stress distribution can be obtained in this critical area. In order to find a suitable mesh, i.e., with sufficient precision while minimum number of elements, a study with progressively refined meshes were carried out and it was determined that a mesh with 1239 CPE4 elements model the problem accurately and predict the final crack length. The creping blade is modeled as a rigid surface tilted to achieve desired creping angle and the blade moves inward along the film-adhesive interface.

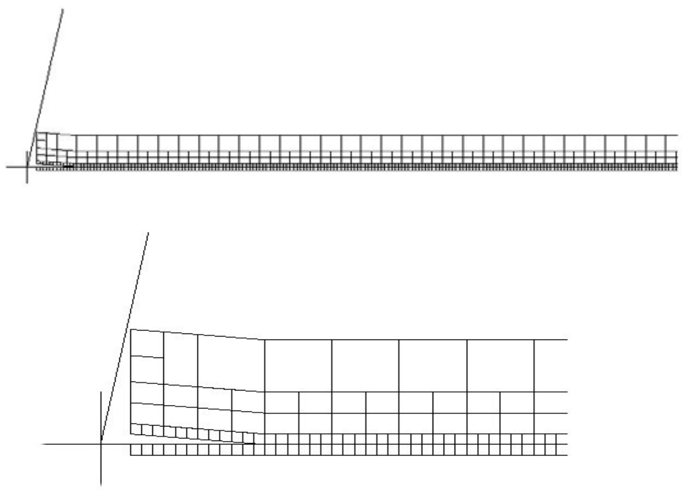

Figure 3. Finite Element Meshing for Creping Simulation

Debonding Procedure

In order to simulate the debonding process, contact surfaces have to be defined. In the FEA model, two contact surface pairs are defined through the master and slave pair definition. The first pair is the contact interface between the film and adhesive. The other pair is the blade surface and film edge surface. Finite sliding is chosen due to the fact that the structure undergoes a large deformation. In the simulation, a parameter called HCRIT, which is a specified distance that is allowed for the master surface to penetrate into the slave surface, has to be carefully chosen.

The bonded film-adhesive pair is defined through the initial conditions function in ABAQUS. A node set that defines the bonding interface from the slave surface has to be defined. This initially bonded interface will be checked by the crack propagation criterion to determine the crack front in each calculation step. The debond function is used for the crack propagation simulation with defined normal and shear failure stresses at the interface. A key parameter that controls the crack propagation in the simulation is the characteristic distance r used in Equation (1). The criterion checks the stresses at the interface at a distance *r* ahead of the crack tip. Therefore, it can be predicted that with smaller *r*, one can achieve longer crack length. A characteristic distance is chosen to be *r*=0.01mm for the entire simulation. A quasi-static simulation is performed and the inward motion of the rigid blade is modeled through the definition of boundary conditions. Since the structural deformation is geometrically nonlinear, NLGEOM parameter has to be included in step definition. Meanwhile, since the debonded film is expected to become unstable and buckle, the calculation may lose the convergence. Therefore, a control parameter STABILIZE is used. The function of this parameter is to add damping dashpot elements to the structure automatically by ABAQUS when it is necessary.

Postbuckling Simulation

Although the convergence problem is resolved by using the automatically added dashpot elements, it is found that divergence is exhibited briefly after the debonded film buckles. In order to further the postbuckling analysis, another step by using RIKS method is carried out. An initial loading imperfection is defined to ‘trigger’ the postbuckling deformation.

RESULTS AND DISCUSSION

The debonding and buckling of the structure simulated using the finite element method is shown in Figure 4. From the simulation, it is observed that the crack propagates with no buckling of the film at the beginning. Once the crack propagates to a certain distance, the inner portion of the debonded film that is separated by the contact point buckles. With a small vertical loading disturbance applied to the structure, the debonded film snaps through upward. It is noticed that during the buckling of the debonded film, there is no further crack growth. This observation validates the hypothesis based on experimental observations that once the debonded film buckles, the external axial force at the blade drops greatly and therefore no further crack propagation exhibits.

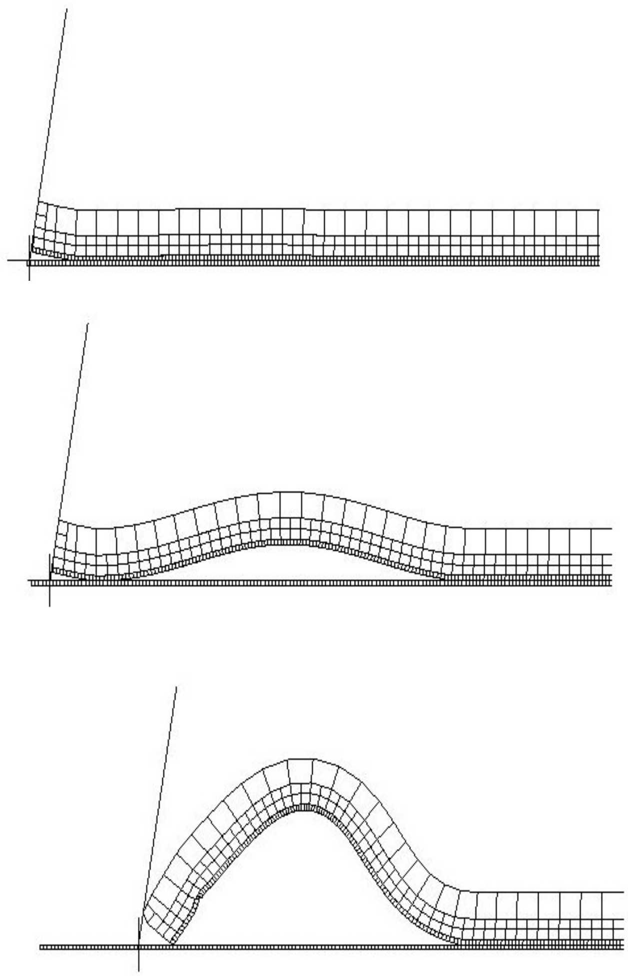

Figure 4. Creping process simulation results from crack growth to buckling

This observation is further validated by Figure 5, where the curve of axial force versus end shortening is plotted from the simulation. The axial force increases rapidly in the initial part of axial compression, and once debonding starts the compliance increases as indicated by a smaller slope of the curve and finally reaches a peak when the film starts to buckle and drops significantly during buckling. This phenomenon was observed in the experimental results shown in Figure 2.

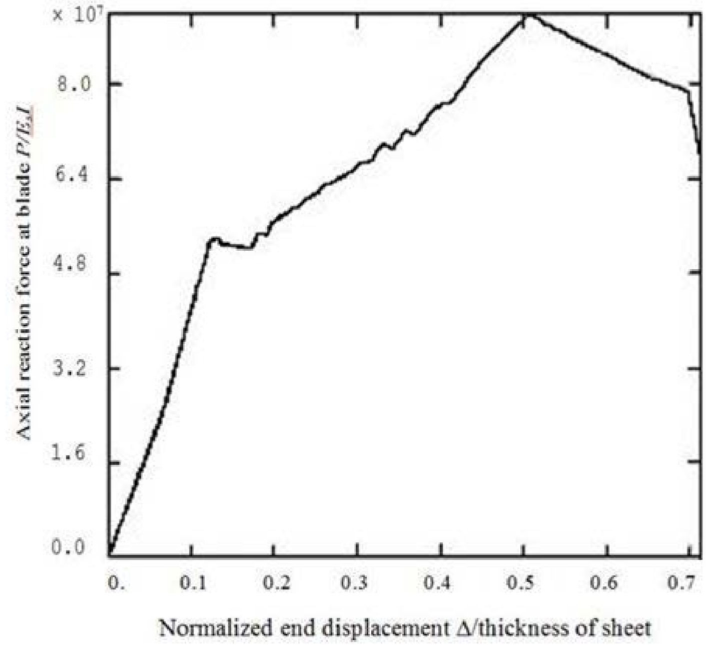

Figure 5. Axial reaction force versus normalized end displacement

Figure 6 shows the reaction force and total crack length versus end displacement. It is seen that the reaction force increases as soon as the blade hits the sheet while the total crack length continues to stay at 0.1 mm, the initial crack length. Between end displacements of 0.05 mm and 0.06 mm, crack propagation occurs from 0.1 mm to 0.5 mm and the reaction force reaches a peak. Further end displacement causes the crack to propagate but the force starts to drop sharply due to buckling. However, during the initial stages of buckling, there is further crack growth as indicated by crack growth accompanied by a decrease in axial force, and eventually, the crack growth ceases and the buckling is complete.

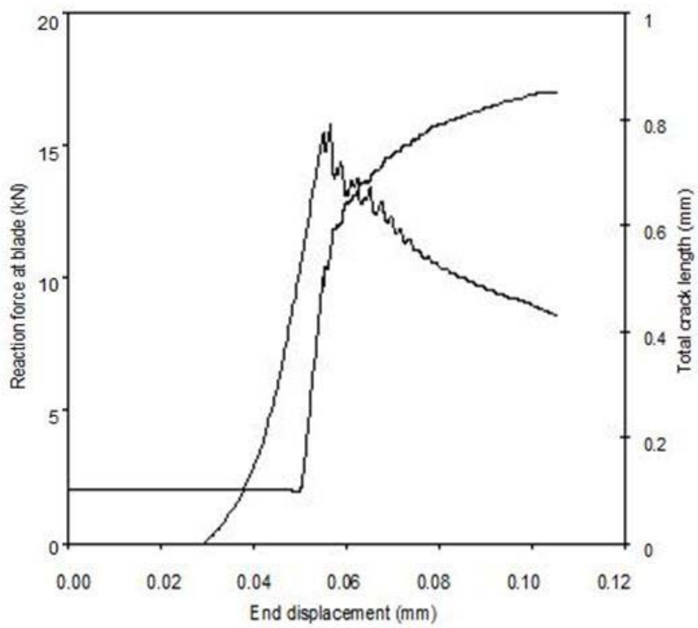

Figure 6. Blade reaction force and total crack length versus end displacement.

CONCLUSIONS

In this paper, the debonding and buckling of a thin paper sheet that is bonded to a rigid surface is studied by finite element approach. The critical stress criterion is used for the film debonding. The Riks method is used to simulate the instability of debonded paper and the post buckling behavior of debonded paper during creping. The simulation results successfully reproduced the debonding and buckling mechanism that has been observed from the experimental study on a laboratory simulator. The mechanism that was observed in experiments is validated, i.e., the debonded film exhibits a contact and snap-through buckling with a unilateral constraint, and once it buckles, the external axial force drops greatly so that the crack propagation stops.

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