A ROLL-BONDING MACHINE FOR POLYMERIC FILMS

Nikhil Padhye¹, David M. Parks¹, Alexander H. Slocum¹, Bernhardt L. Trout²

¹Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA, 02139, USA
²Department of Chemical Engineering
Massachusetts Institute of Technology
Cambridge, MA, 02139, USA

MOTIVATION
An ongoing activity at the NVS-MIT Center for Continuous Manufacturing (NVS-MITCCM) envisions continuous manufacturing of pharmaceutical products from thin polymeric films. Such a manufacturing process is intended to operate in a minimum number of steps, and the final drug-product be made from start to finish in a continuous manner at one facility. This methodology promises to accelerate the introduction of new drugs in the market, minimize the generated waste, reduce the use of energy and raw materials, carry out quality checks inline, as opposed to post-production, and increase the overall reliability and flexibility of the production process [3]. A crucial step in this downstream process is bonding of multiple incoming layers of films (each layer ∼ 100 µm thick) in a continuous mode. Here, we present the design of a continuous roll-bonding machine to carry this task with precision.

Notation

- $h_1$: film-stack thickness at the inlet [m]
- $P$: line loading [N/m]
- $h_o$: total thickness at the outlet [m]
- $e^p$: plastic strain in film-stack [m/m]
- $L$: total load [N]
- $w$: width of the film [m]
- $M$: moment per unit width [N]
- $E_{film}$: modulus of film [MPa]
- $\sigma_{y,film}$: yield strength of film [MPa]
- $R$: radius of roller [m]
- $E_{roller}$: modulus of roller [MPa]
- $\sigma_{y,roller}$: yield strength of roller [MPa]
- $\tau$: duration of contact in rollers [s]
- $V_2$: exit speed of the films [m/s]
- $\bar{\sigma}_x$: average principal stress in x-direction
- $\bar{\sigma}_y$: average principal stress in y-direction

 FUNCTIONAL REQUIREMENTS OF MACHINE
Bonding multiple incoming layers of polymeric films during continuous manufacturing requires appropriate levels of active plastic deformation over a certain interval of time [2]. The polymer films of interest have a yield strength $\sigma_{y,film} \sim 6−8$ MPa and a modulus $E_{film} \sim 200−300$ MPa, and feed speeds around 30 mm/min. Typically 10%-20% plastic deformation is required over a short interval ($5−20$ s) to achieve bonding. The machine should have sufficient flexibility to operate in a wide range about these specifications.

DESIGN AND ANALYSIS OF ROLL-BONDING MACHINE
A possible solution is to design a machine comprising of two rigid-rollers capable of exerting sufficient loads over the desired interval of time. Rollers made of stainless steel ($\sigma_{y,roller} \sim 600$ MPa and a modulus $E_{roller} \sim 180−200$ GPa) can be treated rigid in comparison to relatively ductile polymer films. Flattening of rollers, which may be an issue in the context of rolling metals, is unlikely here since polymeric films have a small yield strength in comparison with that of the rollers. The steel rollers can also provide sufficient traction on the incoming films for necessary forward drive.

In general, the total strain ($e_{total}$) comprises both elastic ($e^e$, recoverable) and plastic ($e^p$, non-recoverable) strains, i.e. $e_{total} = e^e + e^p$. To a first approximation we can ignore the elastic strains assuming that the plastic strains will dominate in this deformation processing situation, i.e. $e_{total} = e^p$. Therefore the material can be treated as rigid-plastic, i.e. a material which is perfectly rigid prior to yielding and perfectly plastic afterwards. The analysis presented here is adopted from [1]. A rigid perfectly-plastic rolling scheme is shown in Figure 1, and from the rolling geometry we have

$$d = \frac{a^2}{R}$$ (1)
where,

\[ d = \frac{h_1 - h_o}{2} \]  

(2)

The von Mises yield criterion in conjunction with plane-strain condition (in the y-direction) leads to

\[ |\bar{\sigma}_x - \bar{\sigma}_z| = 2\sqrt{3}\sigma_{y,film} \]  

(3)

By considering the equilibrium of a differential element and following the von Karman’s procedure [5], the line loading (\( P \)) and the moment per unit width (\( M \)) applied to the rolls can be estimated as follows:

\[ \frac{P}{(\sigma_{y,film}/\sqrt{3})a} = 2 + \frac{a}{\bar{h}} \left( \frac{1}{2} - \frac{1}{3} \frac{a}{R} \right) \]  

(4)

\[ \frac{M}{(\sigma_{y,film}/\sqrt{3})a^2} = 1 + \frac{a}{4\bar{h}} \left( 1 - \frac{a}{R} \right) \]  

(5)

where, \( \bar{h} = \frac{h_1 + h_o}{2} \) is the mean film thickness.

From the geometry of deformation, if \( V_2 \) is the exit velocity of rolled-stock, the time of compression (\( \tau \)) in the rollers (if \( d \ll R \)) can be estimated as

\[ \tau = \frac{\sqrt{R(h_1 - h_o)}}{V_2} \]  

(6)

Typically if the coefficient of friction between the rollers and the strip is large, and/or the strip has lower yield strength the frictional traction at the interface exceeds the yield stress of the strip in shear so that there is no slip in the conventional sense at the surface i.e. plastic shear will take place in the rolled stock, while the surface will “stick” to the rolls with static friction. It is worth emphasizing that the above procedure incorporates no-slip assumption and, homogeneous deformation i.e. the vertical segments of the bar deform vertically as if they were separated from each other so that no shear stress can arise in them. After considering several trade-off designs we selected steel rollers of \( R = 100 \text{ mm} \), so as to achieve desired active plastic-straining during rolling. For example, \( \sigma_{y,film} = 6.0 \text{ MPa} \), \( h_1 = 1 \text{ mm} \), \( h_o = 0.8 \text{ mm} \), then \( 2d = 0.2 \text{ mm} \) (indicating 20% plastic compression), and \( a = 4.47 \text{ mm} \).

FIGURE 1. Rigid perfectly-plastic rolling scheme.

From equations 4 and 5, \( P = 6.82 \times 10^4 \text{ N/m} \) and \( M = 150.89 \text{ N} \), respectively. If we assume the width of the strip to be 20 mm, then the total load \( L = 1359.3 \text{ N} \) and total torque is 3.01 Nm. If \( V_2 \) is 30 mm/min then the residence time (\( \tau \)) would be 8.94 s. This illustration demonstrates that we can successfully achieve active plastic-deformation in the rollers in a few seconds.

It is worth mentioning that rigid-plastic analysis presented here does not take into account any strain hardening, heating effects, etc. and in actual process compression loads can differ. Other machine elements, discussed next, were sized and selected appropriately for successful functioning of the roll-bonding machine. For the sake of brevity we abstain from presenting those calculations here. In principle, sophisticated finite element procedures along-with accurate constitutive material models can be employed for accurate predictions of stresses, strains, etc.; however, the goal of this paper is to present analyses to identify the approximate operating loads and thereby select appropriate machine elements for a roll-bonding machine. During actual operation, like any other operating machine, the compression loads and angular-speed of rollers are tuned so as to meet the desired performance.

Figure 2 shows the CAD model of roll-bonding machine that we have developed. Table 1 lists the main components of the machine along with their functionality. The two cylindrical rollers with shafts are mounted on two separate ‘U’ shaped stages. The stages carrying the rollers are attached on the linear-sides such that distance between them can be adjusted. The distance between the rollers is measured by a micrometer. The position of the roller-carrying-stages attached to the linear slides is set using the two
FIGURE 2. CAD model of the Roll-Bonding Machine. The cylindrical rollers provide adequate line-loading to achieve plastic deformation on incoming films over a desired interval of time.

TABLE 1. Major components of the Roll-Bonding machine and their functionality. Functional requirements of each element have been carefully analyzed ([4]) before making design choices. Machining and assembly were carried out such that the parallel between the rollers was accurate up-to $\pm 0.003''$.

<table>
<thead>
<tr>
<th>Machine Element</th>
<th>Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rollers</td>
<td>Compression rollers capable of applying several kilo-Newton of line-load were machined out of stainless steel with a surface finish of $R_a \sim 6\mu m$. The diameter of each roller is 200 mm.</td>
</tr>
<tr>
<td>Linear Slides</td>
<td>Carry the stage of the compression rollers, and enable setting the relative gap between the rollers. The slides were purchased from Stelron Components Inc.</td>
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<tr>
<td>Micrometer</td>
<td>Measures the distance between compression rollers which are mounted on the linear slides.</td>
</tr>
<tr>
<td>Load Cell</td>
<td>Purchased from Omega (model LC 305-1K) to measure the compression load (N). It is mounted on the left roller-stage.</td>
</tr>
<tr>
<td>Springs</td>
<td>Extension springs are used to secure the left roller-stage and load cell against the position handle.</td>
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<tr>
<td>Position Handle</td>
<td>Drive the left roller-stage through a threaded-rod and set its position.</td>
</tr>
<tr>
<td>Threaded Rod (Right)</td>
<td>Set the position of the right roller. Locking nuts secure it in the desired position.</td>
</tr>
<tr>
<td>Pulley System</td>
<td>Attached to the shafts of the rollers, and interconnected by a double-sided timing belt (not show so as to avoid clutter).</td>
</tr>
<tr>
<td>Stepper Motor</td>
<td>Purchased from Applied Motion Products (Model STM-23QN). An appropriate gear train was selected to provide a minimum angular speed of 0.08 rpm and maximum torque of 50 Nm to drive the compression rollers.</td>
</tr>
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threaded-rods. A load cell is mounted on the left roller-carrying-stage to measure the compression loads. The two threaded rods are secured to the main frame by the action of locking-nuts. During operation the position of the right-roller-stage is kept fixed, and the position of the left roller-stage is adjusted through threaded rods and a position handle. The rotatory motion of the position handle that drives the left threaded rod causes the sliding motion of its roller-stage. Two extensional springs are mounted on the frame and the left roller-carrying-stage such that load cell is well secured against the left threaded rod.

During operation, the position of the left roller-carrying stage is adjusted till a desired level of load or displacement is noted on the load cell or micrometer, respectively. The shafts are driven by a system of pulleys and double-sided timing belts using a stepper-motor. The stepper motor is attached to the main frame of the machine, and during operation an appropriate level of tension is maintained in the timing belt which drives the pulleys on the shafts. To ensure that timing belt does not slip over the pulleys when driving the shafts, an idler pulley is mounted to take up the slack in the timing belt, which occurs as rollers are brought closer. The angular speed of the motor dictates the exit speed \( V_2 \) of the films from the rollers. Figure 3 shows a snapshot of roll-bonding of multiple layers through our devised mechanism.

\[
\text{FIGURE 3. Roll-bonding of polymeric films.}
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The overall success of the roll-bonding mechanism lies in precisely applying the line-load without introducing unwanted deflection or failure of any machine element during compression between the rollers. In order to evaluate the accuracy of our system we have tested the standby performance (i.e. compression without the presence of films) in the displacement-controlled mode by imposing different levels of displacements by using the micrometer and measuring the load from load-cell as rollers are brought into the contact. This procedure was repeated many times with a maximum load of 1.5 \( kN \), and a load vs deflection curve (with error-bars) is shown in the Figure 4. From these results it can be concluded that the load follows the displacement in a linear fashion with good repeatability. The stiffness of the roll-bonding mechanism based on the load vs displacement curve is estimated to be \( 5.3 \times 10^6 \text{N/m} \).

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\text{FIGURE 4. Load vs Displacement characteristics of the roll-bonding mechanism.}
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REFERENCES