THE EFFECT OF HIGH VELOCITIES, STARTUP AND SHUTDOWN ON WINDING

by

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ABSTRACT

The effect of high velocities on wound rolls is analyzed by applying a winding model accounting for the centrifugal effect. Also realistic velocity functions with startup and shutdown are considered. The effect of high velocities, startup and shutdown on winding is found to be significant.

NOMENCLATURE

- E_t elastic modulus of wound rolls in tangential direction (MD modulus)
- E_r elastic modulus of wound rolls in radial direction (stack modulus)
- E_c radial stiffness of the core at its peripheri (core stiffness)
- ν Poisson's ratio of wound rolls
- r radius to a point in the roll, made dimensionless by division by core radius
- s outside radius of the winding roll, made dimensionless by division by core radius
- h web thickness, made dimensionless by division by core radius
- σ_t in-roll tensile tangential stress
- σ_r in-roll tensile radial stress
- P in-roll radial pressure (compressive radial stress)
- δP incremental radial pressure caused by the winding on of a single lap
- T_w winding tension
- ρ roll density
- v winding velocity
- ω angular winding velocity

INTRODUCTION

Increasing winding velocities necessitate winding models which account for the centrifugal effect. Such models make it possible to analyze the effect of higher winding velocities on wound rolls. In 1980 Yagoda[1, 2] derived a linear anistropic model which accounts for the centrifugal effect. His analysis of newsprint showed that the centrifugal force would not significantly affect the stresses in wound rolls. However, he emphasized that this conclusion ought not be assumed to apply for winding problems in general. Since then, winding velocities has been considerably increased, and Olsen[3] has shown, contrary to Yagoda's conclusion, that the effect of the centrifugal force is significant.

The analyses of Olsen are based upon a nonlinear anistropic model. The model is derived by including the centrifugal force in the well-known nonlinear model of Hakiel[4]. This is done by applying the following equilibrium equation:

$$r\frac{\partial \sigma_r}{\partial r} + \sigma_r - \sigma_t = -\rho \left(\frac{v}{s}\right)^2 r^2 \tag{1}$$

where the right hand side is the contribution from the centrifugal force. In Hakiel's model this term is absent. By accounting for this term and following the derivation of Hakiel's model, it can be shown[3] that the incremental increase in radial pressure δP due to the winding on of a single lap, satisfy the following second order differential equation:

$$r^2\frac{\partial^2 (\delta P)}{\partial r^2} + 3r\frac{\partial (\delta P)}{\partial r} + (1 - E_t/E_r)(\delta P) = (3+\nu)\rho\, \delta\left(\frac{v^2}{s^2}\right) r^2 \tag{2}$$

Here $\delta(v^2/s^2)$ is the change in the square of the angular winding velocity $\omega = v/s$ compared with the square of the angular winding velocity of the previous lap. At the interface between the core and the web material being wound continuity of displacements yields

$$\left.\frac{\partial(\delta P)}{\partial r}\right|_{r=1} = [(E_t/E_c) - 1 + \nu]\,\delta P(1) + \rho\, \delta\left(\frac{v^2}{s^2}\right) \tag{3}$$

as an inner boundary condition. At the outside of the winding roll equilibrium gives the following outer boundary condition:

$$\delta P(s) = \frac{h}{s}\left(T_w - \rho\, v^2\right) \tag{4}$$

Since the elastic modulus in the radial direction E_r is assumed to be a function of the radial pressure P, the differential equation is nonlinear and no analytical solution to the problem can be found. Thus numerical analysis is neccesary. A central difference approximation results in a numerical method[3] for calculating the stresses in the rolls.

It should be emphasized that the model easily can be modified to apply to an outer boundary condition accounting for an undriven roller or accounting for the radial compression of the outer wrap. The model can also be generalized by dropping the strain energy constraint, which is implied in Eq.2. Since it is the effect of the centrifugal force which is under consideration, no such modifications or generalization are made.

HIGH VELOCITIES

Results of calculation carried out on newsprint and supercalendered paper are shown in Fig.1 and Fig.2. The figures display the stresses in rolls being wound with a constant winding tension of 3000 kPa and constant winding velocities as indicated in the figures. Note that the rolls are still rotating and thus no shutdown has occured.

The results show that the centrifugal force significantly influences the stresses in the rolls prior to shutdown. Later we will see that this also is true for finished rolls. As expected the effect is quadrupled when the velocity is doubled. We can also see that the effect is greater for supercalendered paper than for newspaper. This is due to the higher density of supercalendered paper. Analyses show that the effect of the centrifugal force on the radial pressure is approximately equal to reducing the winding tension from T_w to $T_w - \rho v^2$ when compared with a quasi-static model. This indicates that the outer boundary condition, Eq.(4), is where the dominating part of the centrifugal force is introduced. Since an increase in winding tension would make the centrifugal term in Eq.(4) less significant, we could ask if the centrifugal effect becomes insignificant for higher winding tensions.

To be able to answer such a question computations have been carried out with different winding tensions and different winding velocities on newsprint. In Fig.3 curves indicate the loss in radial pressure in the middle of the roll (r=2) due to the centrifugal effect as a function of winding velocity. We see that the effect is significant for quite high winding tensions. Note that for web materials denser than newsprint, the effect is even more significant. On an approximative basis we can say, as a thumbs rule, that the centrifugal effect is significant if the outer boundary condition, Eq.(4), is significantly influenced by the centrifugal term. According to this thumbs rule and Fig.3 we see that stresses in rolls being wound with high velocities are influenced by the centrifugal force.

This far only stresses in unfinished rolls have been considered. Rolls being brougth to a stop have not been discussed. The stresses in rolls are affected by the shutdown. The tangential stress will satisfy an equilibrium equation without the centrifugal term since the velocity is zero. For an instant shutdown[1] it can be shown[3] that the radial pressure is practically unaffected by the shutdown, whereas for the tangential stress the centrifugal effect is partially cancelled by the shutdown. Still, the total effect of the centrifugal force is significant, both to the radial pressure and the tangential stress.

STARTUP AND SHUTDOWN

Due to the infinite deceleration no real winders can carry out an instant shutdown. Therefore we need to concider the influence of more realistic velocity functions than functions with an instant shutdown. It is obvious that the shutdown must initiate at a radius considerably less than the final radius of the roll. Though some winders accelerate the core prior to winding, most winders start winding at zero velocity. Thus a realistic velocity function includes both startup and shutdown. In Fig.4 the winding velocity is displayed as a function of the radius of the peripheri of the winding roll. This velocity function and a winding tension of 3000 kPa yield

[1] With an instant shutdown we mean a velocity function which is constant for all but the last lap of winding. For this last lap of winding the velocity is equal to zero.

results as displayed in Fig.5. We see that the shutdown causes a significant rise in the radial pressure in the outer region of the rolls. Due to equilibrium this rise in radial pressure gives a drop in tangential stress in the same region. Though it is harder to see, the effect of startup is also significant, but since the effect is not critical we will only discuss the effect of shutdown.

The increase in radial pressure and decrease in tangential stress in the outer region of the roll, caused by the shutdown, are not desireable. Two reasons exist for not wanting such distributions of stresses. First, the stresses are inconsistent with the desire for smoothly distributed stresses. Stresses that vary too much throughout the rolls, complicate the adjustment of the customer's unwinders. Second, the rise in radial pressure and drop in tangential stress may cause roll defects such as buckles. At a paper mill for newsprint at Skogn in Norway, roll defects have occasionally been observed in the same regions as shutdown is initiated. So far, this is not documented well enough to prove the connection between the defects and the shutdown. After all, there could be other reasons such as nip induced defects or perhaps a combination of shutdown and nip effects. Anyway, we do not want the increase in radial pressure and decrease in tangential stress in the outer region of the rolls. Thus it is neccessary to search for ways of eliminating or minimizing the effect of shutdown.

Many parameters and variables exist in winding which could be adjusted to minimize the effect of shutdown. Since the properties of the core and the web are not controlled by the winding operators, we consider them as parameters which we can not adjust. That leaves us with the ability of adjusting the winding tension and winding velocity. Because shutdown is nothing but a decrease in winding velocity, we will only consider making changes in the velocity function. A decrease in the maximum level of the velocity function will reduce productivity. Thus we do not wish to decrease the maximum level of the velocity function. We are left with adjusting the peripheral radius at which shutdown is initiated. If we decrease this radius, we get a smoother shutdown. If we increase the radius, we get a more sudden shutdown. Velocity functions with a smooth shutdown and a sudden shutdown are displayed in Fig.6. We will analyse the effect of these velocity functions.

Analyses on newsprint and supercalendered paper wound with a winding tension of 3000 kPa and a velocity function with a smooth shutdown yield results as shown in Fig.7. Newsprint has a smaller drop in tangential stress compared to the previous example in Fig.5, but the area with lowered tangential stress has increased. It is hard to say whether the distribution of stresses has been improved or not. For supercalendered paper the drop in tangential stress has increased, and the area with lowered tangential stress has increased. Thus a smooth shutdown worsen the distribution of stresses in rolls of supercalendered paper.

Analyses with a sudden shutdown yield results as shown in Fig.8. For newspaper the area of lowered tangential stress has decreased, but the drop in tangential stress has increased. For supercalendered paper we see that the area of lowered tangential stress has practically vanished. This is due to the outer boundary condition which makes the tangential stress rise to positive values at the rolls peripheri. Thus a velocity function with a sudden shutdown gives no decrease in tangential stress. It looks as if the cure for minimizing the undesireable effect of shutdown in rolls of supercalendered paper is to delay shutdown as much as possible.

This cure for supercalendered paper does not have any good effect on newspaper. That is due to the fact that newspaper is much more compressible than supercalendered paper (in radial direction). For soft materials (i.e. easily compressed materials) the outer boundary condition does not influence the stresses deep enough into the rolls. If the effect of shutdown were to be removed the shutdown would have to be delayed so much that a real winder would not be able to handle the deceleration. Thus the effect of shutdown can not be removed by delaying shutdown. For harder materials, such as supercalendered paper, the outer boundary condition influences the stresses deeper into the rolls. The outer boundary condition is thus able to counteract the effect of shutdown.

It is the elastic modulus of the material in radial direction, also referred to as the stack modulus, which decides how compressible a material is. Often this modulus is modelled as

$$E_r = C_0 + C_1 \cdot P + C_2 \cdot P^2 + C_3 \cdot P^3 + \ldots \qquad (5)$$

where C_1,compareable to Pfeiffer's K_2 factor[5], is the most significant coefficient. The compressibillity of materials increases with decreasing values of C_1. It is hard to tell the value of C_1 which seperates those materials which can have their shutdown effects removed by a delay in shutdown and those materials which can not have their shutdown effects removed. However, it seems as if materials with $C_1 > 100$ may remove the effect of shutdown by delaying shutdown, and materials with $C_1 < 50$ are unable of doing so.

CONCLUSION

We have seen that for high winding velocities the centrifugal effect is significant to the stresses in wound rolls both prior to shutdown and after shutdown. Shutdown itself causes a drop in tangential stress and a rise in radial pressure in the outer region of the the rolls. For materials with relatively high K_2 factors this effect of shutdown may be removed by delaying the start of shutdown.

REFERENCES

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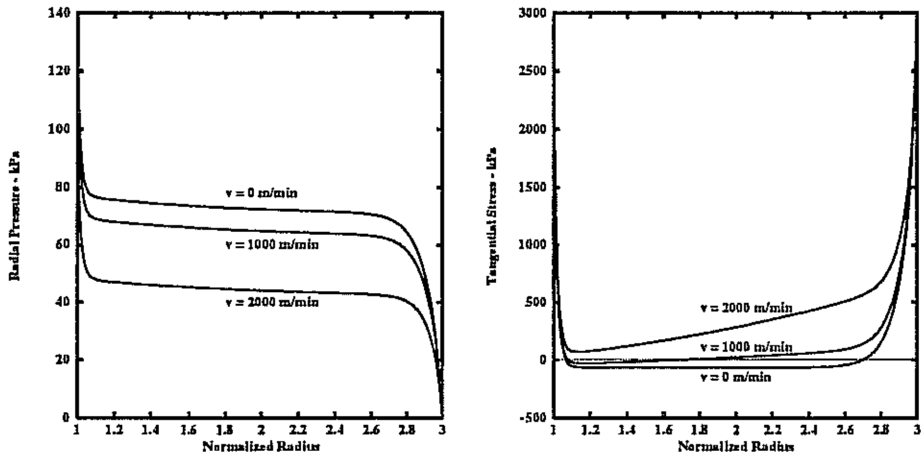

Figure 1: Stresses in rolls of newsprint for different winding velocities prior to shutdown.

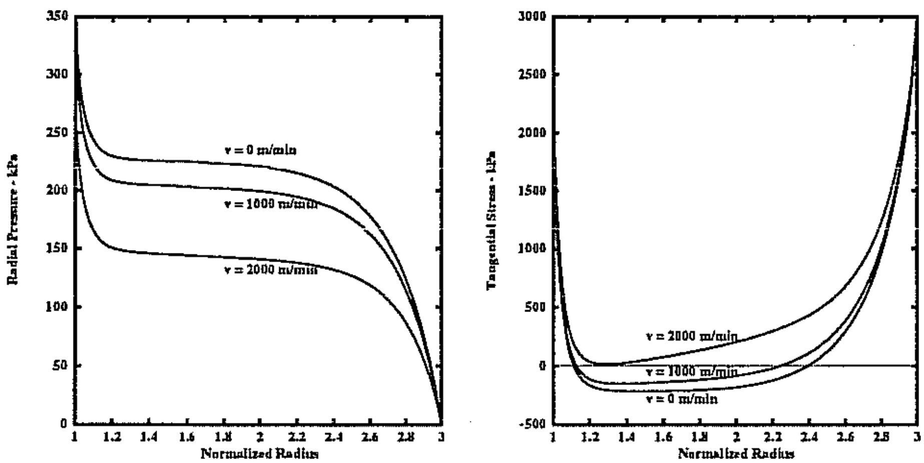

Figure 2: Stresses in rolls of supercalendered paper for different winding velocities prior to shutdown.

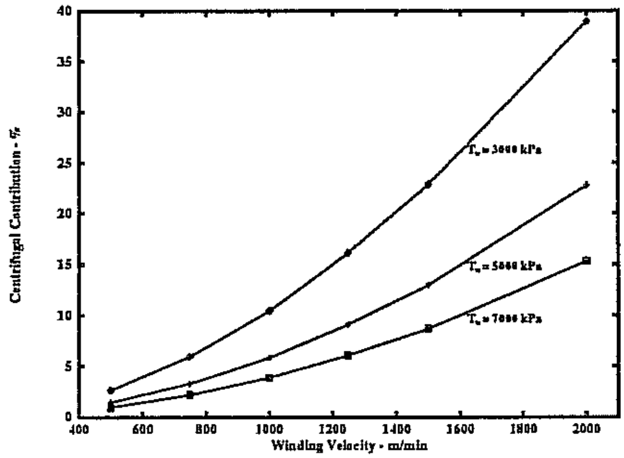

Figure 3: The loss in radial pressure as a function of winding velocity due to centrifugal forces in rolls of newsprint. Different curves represent different winding tensions.

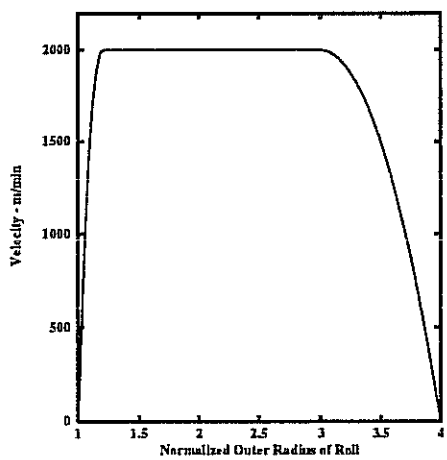

Figure 4: Winding velocity as a function of peripheral radius with startup and shutdown.

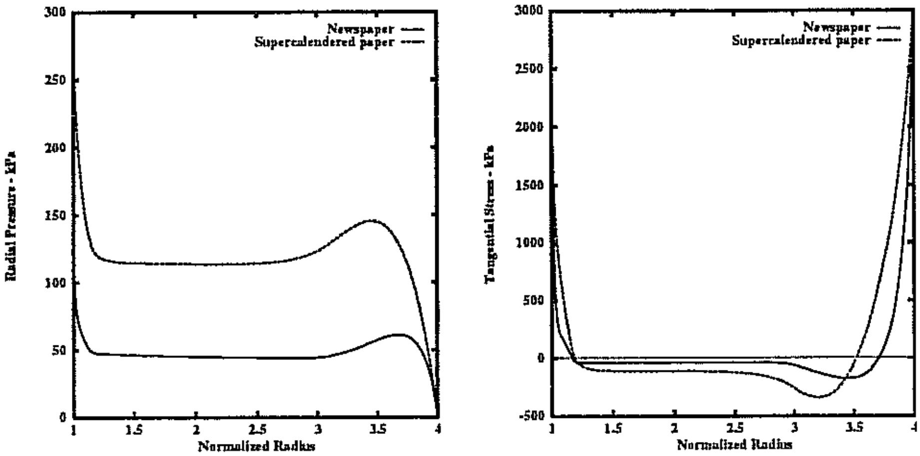

Figure 5: Stresses in finished rolls of paper wound with winding velocity as indicated in Fig.4.

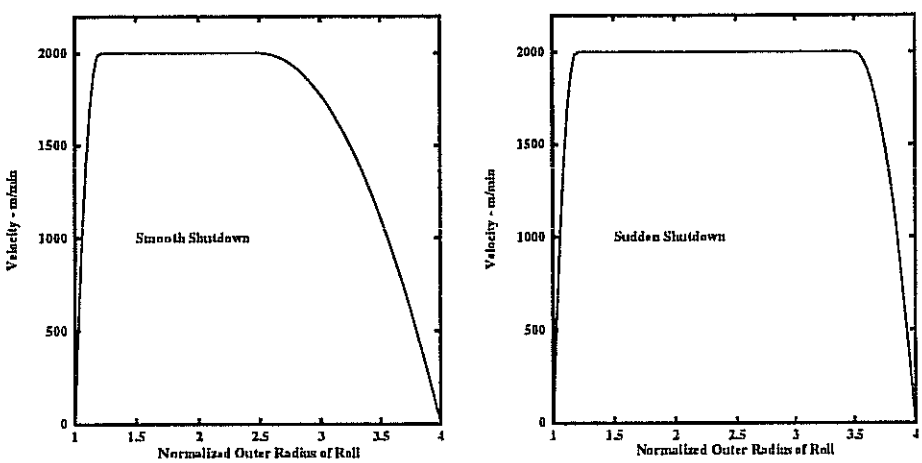

Figure 6: Winding velocity as a function of peripheral radius with smooth and sudden shutdowns.

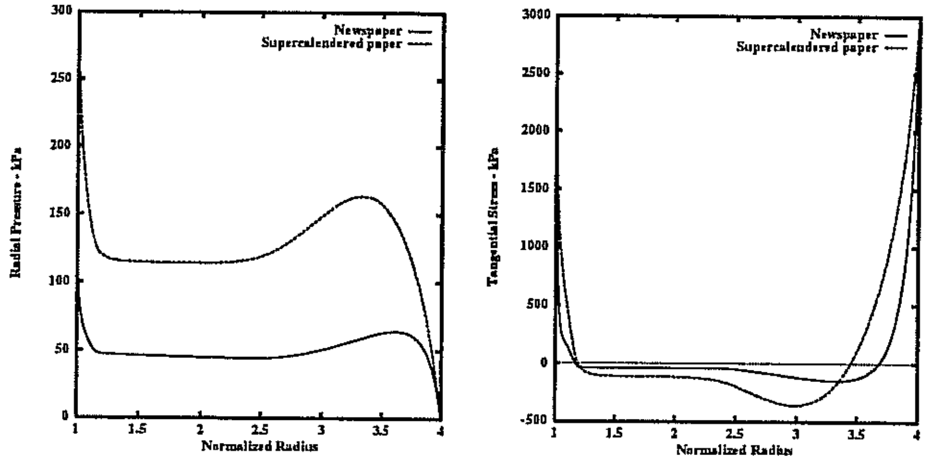

Figure 7: Stresses in finished rolls of paper with smooth shutdown.

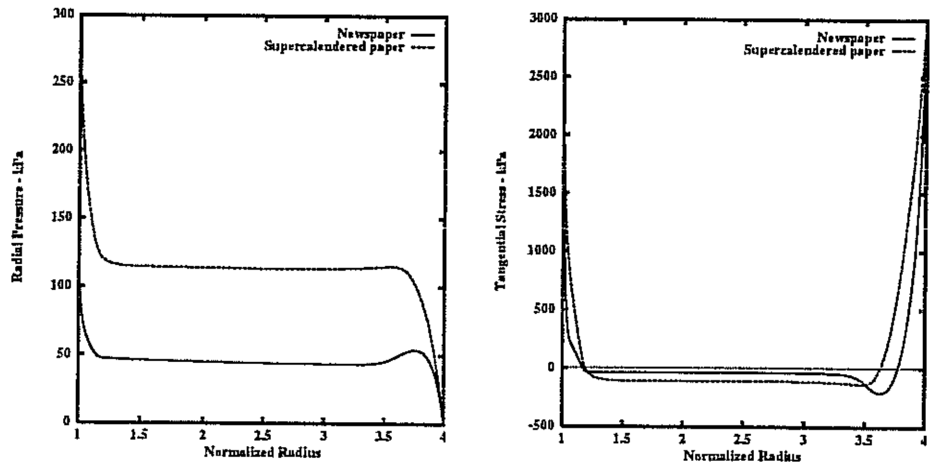

Figure 8: Stresses in finished rolls of paper with sudden shutdown.

	Newsprint	Supercalendered paper
thickness (μm)	71	70
Poisson's ratio	0.01	0.01
E_t (GPa)	3.37	3.89
A (kPa)	0.0	1660.7
B	50.6	141.1
C (kPa^{-1})	- 0.0964	0.0
D (kPa^{-2})	0.0001	0.0
core o.radius (m)	0.055	0.055
E_c (GPa)	1.5	1.5
roll density (kg/m^3)	650	980

Table 1: Winding Properties

Olsen, J.E.
The Effect of High Velocities, Startup and Shutdown on Winding
6/19/95 Session 1 11:10 - 11:35 a.m.

Question - I have a question concerning your curves showing accel and decel. I would expect under normal circumstances and reasonable acceleration rates you would consume a certain amount of the diameter of the roll on accel much more than decel. We have some results that look a bit distorted. I was wondering in your models what sort of acceleration and deceleration rates did you contend with? Are we talking 30 meters a minute, per second, or 50 or what?

Answer - To answer the question, I'm not really sure.

Question - Normally speaking, for normal production type of winding, the amount of roll diameter increased on deceleration is a relatively small portion, especially compared with the amount of diameter buildup consumed under acceleration.

Answer - But you see we have a normalized radius that has a big diameter.

Question - That makes my statement even more dramatic. If you have a certain length of paper required to accelerate the roll of paper to speed, that will represent a fairly large portion of your roll diameter buildup compared to your deceleration.

Answer - Since the startup defect is not that important, I sort of cheated a bit on the startup.

Question - At the end of acceleration is when you have the maximum angular velocity. That area is fairly significant The overall message you're conveying is correct.

Answer - I've done lots of calculations which I've not shown here and I've never seen any major defects which are not shown to you. I might look into it further, though.

Question - Is it possible that the decelerates are considerably less than the acceleration because of the moment of inertia of the roll. Also, since the centrifugal forces are only in effect while you're winding the roll, are they really, in effect, in the stored role, if you will? This is an excellent calculation of what the stress is while the roll is being wound, but once you stop, the centrifugal forces go to zero. And have you thought about if the roll then reverts to the static model?

Answer - That would depend a bit. If you have tightened the last wrap then you would not allow the centrifugal forces to vanish and they would still be there, locked in the roll. But if you let the roll lay there on the cylinders without tightening the last wrap, I'm not sure how much would vanish.

Comment - Good point. I would interpret that to mean the wound-in tension is reduced by those centrifugal stresses.

Question - When you set up your model and the deceleration stopped, did you assume the winding tension remained constant?

Answer - Yes, I did.

Question - In effect, it doesn't. The roll is trying to climb ahead of the drums which are stopping it. So there is an addition of tension because of the overhauling effect of the roll trying to go faster. So the tension does climb a bit during acceleration.

Answer - OK.

Comment - I think this is an excellent paper and we'll be seeing some papers tomorrow that talk about longitudinal dynamics in the vicinity of the winder. I think that's certainly a place for this kind of work to go because certainly during accel and decel we know very little about what the wound-on tension really is and the wound-on tension is probably the most sensitive input parameter in the wound-roll model. So, I think there's a bright future for the work you're doing.

Thank you.