INFLUENCE OF THE GAP THROTTLE EFFECT ON THE WINDING PROCESS AND ROLL QUALITY

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ABSTRACT

In the paper industry the winding technology has a significant influence on the quality of finished rolls. The rising productivity and quality efforts require a constant optimization of the winding process concerning the winding speed, the damage-free structure of the wound rolls and the appropriate transport stability. The air between the layers of the roll negatively affects the achievable quality. Up to now, grooved or nip rollers were used to avoid air entrainment. These principles were proved to be insufficient at high winding speeds in their operation limits.

The innovative application of a gap throttle foil reduces the air entrainment to such an extent, that a higher contact pressure between the incoming layer and the roll is reached. In this work the performance of the gap throttle effect during winding was theoretically investigated. A simulation tool, which calculates the inner state of stress in a wound roll under different process parameters by the use of a gap throttle foil, was developed. Especially the influence of web tension, web speed, roll radius, gap throttle foil thickness and immersion depth are considered as parameters. Furthermore additional elements like contact rollers to support the gap throttle effect are investigated.

The results prove, that the effect can be used to achieve higher radial tension in the roll. Subsequent investigations show, that the effect amount and its stability can be increased considerably by an additional small pressure on the web surface at the mounting area of the web. This novel principle for winding machines should be investigated furthermore, because without niprollers, a paper friendly winding process and a winding quality comparable to the quality of center-surface winder could be realized.

NOMENCLATURE

b	[m]	length in axial direction
F	[N]	force
h	[m]	gap width
L	[m]	length of gap throttle foil
p	[bar]	hydrodynamic pressure
p_a	[bar]	ambient pressure
q	[m²/s]	flow
R	[m]	roller radius
s	[µm]	gap throttle foil thickness
s_x	[µm]	mesh size
T	[N/cm]	web tension
t	[µm]	paper thickness
u	[m]	web deflection
U	[m/min]	speed
V	[m³/s]	volume flow
x	[m]	circumferential coordinate
α	[°]	circumferential angle
η	[mPas]	dynamic viscosity
ρ	[kg/m³]	density
Δ		difference
μ		friction coefficient
σ	[N/mm²]	tension

Indices

a	ambient
c	core
eq	equivalent
F	foil
G	sliding
GTF	gap throttle foil
k	curving
l	left
max	maximal
min	minimal
MD	machine direction
R	friction
r	radial
0	initial value

INTRODUCTION

Raising production rates require a continuous optimization of the winding process. Because of the increasing winding-velocities more air is entrained between the incoming web and the roll at the converging gap, which is one reason for decreasing roll qualities. Previous principles to decrease the air entrainment like nip and grooved rollers require complex machine designs. Furthermore the nip and/or grooves can negatively affect the winding result, especially on high-class papers and foils.

A study at the Institute of Engineering Design (LMK) from 2002 [1] showed, that it is possible to reduce the air entrainment at wrapped rollers with a gap throttle foil even at high velocities. The effect is based on a gap throttle foil, which is fixed in the converging gap between web and roller.

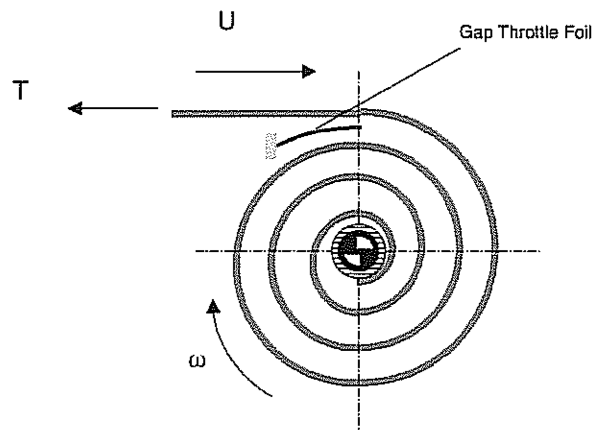


Figure 1 Sketch of a gap throttle foil in the winding process

For the analysis of a gap throttle foil positioned between web and roll at the mounting area of the web (fig. 1) a simulation program will be introduced, which calculates the tension in the roll taking into account the air entrainment and the gap throttle foil and which allows a wide range of parameter variations. Essential parameters are web tension, winding speed, winding radius and gap throttle foil parameters like foil geometry, immersion depth and support pressure.

Subsequently the physical principles for the hydrodynamic pressure build-up at wrapped rollers in analogy to the foil bearing theory, relevant existing winding models with and without air entrainment and the gap throttle effect will be explained, to derive a mathematical model of the gap throttle effect for the winding process. Using a finite-difference-algorithm, this mathematical model is transferred into a numerical set of equations, which is solved in the developed simulation program. Afterwards a case study will be presented. The computed results will be compared to the results of existing models and examined for their plausibility.

BACKGROUND

Current winding models for calculating radial and tangential tensions, which are one indicator of the winding quality, differ in their considered influences. Based on previous studies of Altmann [2], Yagoda [3] and Pfeiffer [4], Hakiel [5] develops a nonlinear winding model, which offers the possibility to compute the radial and tangential tensions of a centerwound roll with negligence of Coulomb's and Newton's friction, air entrainment, permeability and side leakage. The roll is considered as an accumulation of concentric rings lying on top of each other.

Humberg [6] idealizes the friction between two rollers as border case of a roller and a plane. For the computation of the shear stress between the roller and the plane resp. web, caused by friction, a numeric analysis was done with finite element methods. In the future it will be consequently and methodically important to extend the mechanic winding models by those parameters of friction.

These models have in common, that they neglect the air entrainment at the converging gap and the hydrodynamic pressure between the layers resulting from the entrained air. It is widely accepted [7, 8] that in a foil bearing the gap width and the fluid pressure are nearly constant in a great part of the wrap, and that the constant gap width h_0 can be calculated using the foil bearing equation which is based on the Reynold's equation. Based on the foil bearing theory (infinitely wide web, ideally smooth surface and a completely air dense web), an equivalent gap width h_{eq} for a wrapped roller can be calculated. The assumed equivalent gap width h_{eq} substitutes the rough surfaces of the web and roller with an equivalent distance. With the foil bearing equation and the experimental measurement of the boundary speed U_{max}, the determination of the equivalent gap width is possible with the equation:

$$\frac{h_{eq}}{R} = 0{,}643 \cdot \left(\frac{12 \cdot \eta \cdot U_{\max}}{T} \right)^{\frac{2}{3}} \qquad \{1\}$$

In this context the boundary speed U_{max} is defined as the web speed at which Coulomb's friction is lost and only Newton's friction between web and roller exists. With this basic assumption it is possible to calculate the hydrodynamic pressure resp. the transferable friction force F_{max} in the wrap of the roller by using the finite differences method for solving the equation of fluid pressure, web deflection and tension simultaneously. A detailed description can be found in the paper published by Schüler er al. [9]. The next figure shows a calculated theoretical (Sim.) friction force profile and experimental results (EXP.) from our LMK-test rig.

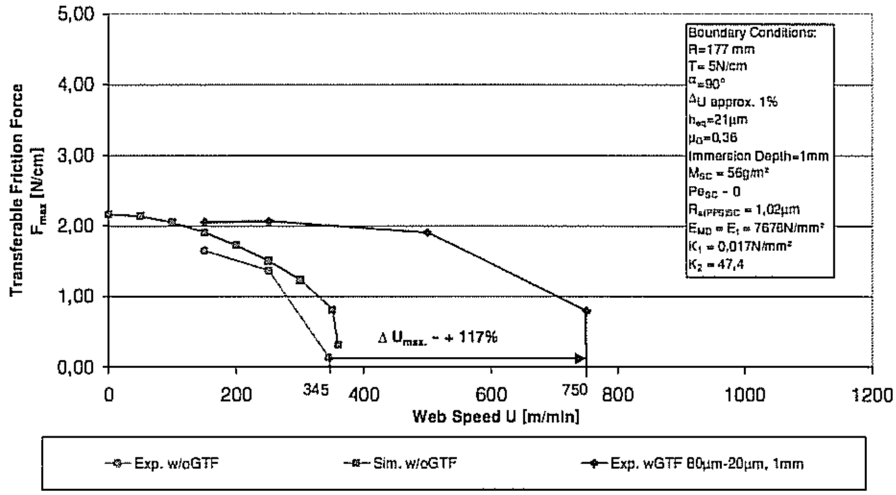


Figure 2 - Transferable friction force versus web speed without and with gap throttle foil(GTF)

The analysis of the gap throttle effect on wrapped rollers [9, 10] showed, that the numeric algorithm based on the Reynold's equation and foil bearing theory is able to compute the hydrodynamic state on a wrapped roller in a sufficient way (Exp. w/oGTF; Sim. w/oGTF). The experimental results confirmed the effect of the gap throttle foil and compared to the conventional system "wrapped roller" the boundary speed U_{max} could be raised by 117%.

Furthermore the investigations [10] showed, that a small support pressure at the outside of the web surface, located at the mounting area of the web resp. at the end of the gap throttle foil, enables an approx. duplication of the transferable friction forces at a web speed of 250 m/min in comparison with the conventional system "wrapped roller" and an approx. triplication of the achievable boundary speed by the same boundary conditions.

Compared to wrapped rollers there are different geometric conditions in the winding process. The conditions at the mounting area of the gap are nearly identical, but at the end of the first layer the web doesn't open to the ambient pressure, it forms a spiral which ends at the core. A layer is surrounded by an increasing number of layers during the winding process, resulting in an increasing pressure. Thus, the air between the layers is more and more compressed and the air gap becomes thinner. Assuming that the entrained air won't leak from the roll, the resulting air films will separate the web layers and the air can be idealized as an ideal gas under adiabatic conditions Good [11] combines the Young's modulus of air and paper to an equivalent radial Young's modulus $E_{r,eq}$.

$$E_{r,eq} = \frac{h_0 + t}{\dfrac{t}{E_{r,Paper}} + \dfrac{h_0 \cdot (p_0 + p_a)}{(\sigma_r + p_0 + p_a)^2}} \qquad \{2\}$$

This combination is equivalent to a serial connection of two springs. This equivalent radial modulus of elasticity can be used in Hakiel's winding model [5] to consider air entrainment in the winding process.

Good's [11] results showed, that the air films between the paper layers lead to a reduction of the radial Young's modulus, because they are much more compressible than the paper layers. The radial tension level decreases in comparison to a winding process without air entrainment. Furthermore the studies show, that air entrainment in the winding process can be computed in a sufficient way by using the foil bearing theory [12].

GAP THROTTLE EFFECT

The gap throttle effect can be demonstrated with a simple model of a viscosity pump [9]. In a viscosity pump the two walls of a gap with the height h are moving with a constant velocity U. Assuming the walls are inflexible across the length L and the ambient pressure p_a exists at both ends of the pump, the equation for computing the volume flow can be derived out of the simplified Navier-Stokes equations and the continuity equation for a flat, laminar, stationary and incompressible flow.

$$\dot{V} = (U_1 + U_2)\cdot\frac{h\cdot b}{2} - \frac{h^3\cdot b}{12\cdot\eta}\cdot\frac{dp}{dx} \qquad \{3\}$$

If a gap throttle foil with the length $L_F < L$ is inserted in the middle of the two walls, the pressure difference Δp , in comparison to the ambient pressure p_a, arises. If the volume flow in front of and behind the gap throttle foil is equal, the equation for the pressure difference is:

$$\Delta p = \frac{6\cdot\eta\cdot U\cdot(h_1 - h)}{\frac{h_1^3}{L_F} - \frac{h^3}{2\cdot(L_F - L)}} \qquad \{4\}$$

In a representative example for a winding process (η = 0,018mPas, U = 150m/min, L = 20mm, L_F/L = 1/3, h = 21μm, thickness of the gap throttle foil negligible small) the following figure shows the computed values at different conditions.

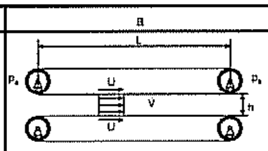
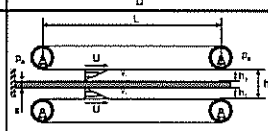
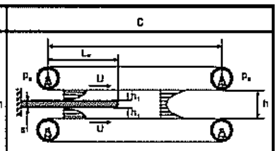
	a	b	c
			
Volume flow $\dot{V}$	$\dot{V} = U\cdot h\cdot b$	$\dot{V} = \frac{h\cdot s}{2}\cdot U\cdot b$	$\dot{V} = U\cdot h\cdot b - \frac{\Delta p\cdot h^3\cdot b}{12\cdot\eta\cdot(L_F - F)}$
Pressure differenz Δp			$\Delta p = \frac{6\cdot\eta\cdot U\cdot(h_1 - h)}{\frac{h_1^3}{L_F} - \frac{h^3}{2\cdot(L_F - F)}}$
$\dot{V}$ [ml/s²]	52,50	26,25	35,00
Δp [mbar]	0,00	0,00	-54,54

Figure 3 – Viscosity pump models without and with gap throttle foil

The example shows, that the gap throttle foil can reduce the fluid's volume flow, according to the foil's geometry, by a massive amount. If the foil's thickness is neglected, the volume flow in case b is exactly the half of the volume flow in a viscosity pump without a gap throttle foil (case a).The volume flow in case c is slightly bigger than in case b. But in reality the resulting negative pressure leads to a deflection of the elastic At first the analytic computable negative pressure of 54 mbar (case c) appears to be small. In comparison to a pressure of 28 mbar resulting from a web tension of 5 N/cm (roll radius 177 mm), the potential of the gap throttle effect becomes apparent.

SIMULATION PROGRAMM

A simulation program based on the finite differences method, which was developed at the LMK [13], allows the calculations of radial and tangential tensions in the roll. The use of this method enables the calculation in dependence of web tension, web speed, roll radius, gap throttle geometry, immersion depth of the gap throttle foil and support pressure. The support pressure is considered as a locally higher ambient pressure at the outside of the roll. In analogy to the converging gap at a wrapped roller [10] the hydrodynamic state between web and the top layer are computed. For the calculation of the interactions with the paper layers deeper in the wrap the important assumptions and the mathematic coherences are shown.

Assumptions

- The ambient fluid is air. The entrained fluid adheres on the web surfaces. The flow is laminar, isoviscous and isotherm.
- All values are constant across the web width.
- Side leakage is neglected
- The influence of Coulomb's friction between paper and air resp. paper and paper is neglected. The web is impermeable and completely flexible.
- Both sides of the paper are ideal smooth. A minimal contact gap h_{min} substitutes the roughness of web and roll.
- If the web lifts, the web deflection is constant from a certain point on.
- The velocities of the incoming web and the existing roll are equal.

Radial and Tangential Tension

For computing the radial and tangential tensions and the gap width, two differential equations ({5}, {7}) are needed, which are linked by their mutual values. The state of tension in the roll is computed with Hakiel's [5] model. The model is base on an ordinary second-order differential equation

$$r^2 \cdot \frac{d^2\sigma_r}{dr^2} + 3 \cdot r \cdot \frac{d\sigma_r}{dr} + \left(1 - \frac{E_t}{E_r}\right) \cdot \sigma_r = 0 \qquad \{5\},$$

which results from the paper's material behavior and the balance of forces at an infinitesimal small web element. To be able to solve this differential equation in the simulation program, it will be approximated with the finite difference method. By means of the combined, equivalent radial Young's modulus $E_{r,eq}$.({2}) the model is extended by air entrainment.

Hydrodynamic Pressure

For the computation of the air pressure p_0 and the air gap width h_0 between the incoming web and the last wound layer it is expected, that a minimal contact gap width h_{min}, which results from paper roughness [14], exists between the bottom side of the outer layer and the topside of the layer below.

$$h_{\min} = 3 \cdot Rq_{eq} \quad with \quad Rq_{eq} = \sqrt{Rq_1^2 + Rq_2^2} \qquad \{6\}$$

Rq_1 and Rq_2 are the RMS-roughnesses of both contact surfaces.

In an isothermal flow the density ρ is proportional to the pressure p. This leads to the compressible Reynolds equation:

$$\frac{d}{dx}\left[p \cdot U \cdot h - \left(\frac{p \cdot h^3}{12 \cdot \eta}\right) \cdot \frac{dp}{dx}\right] = 0 \qquad \{7\}$$

According to [9] the equation for computing the pressure in the gap is derived analog to the derivation of the compressible Reynold's equation, by using the finite difference method. The used mesh is shown in the following figure:

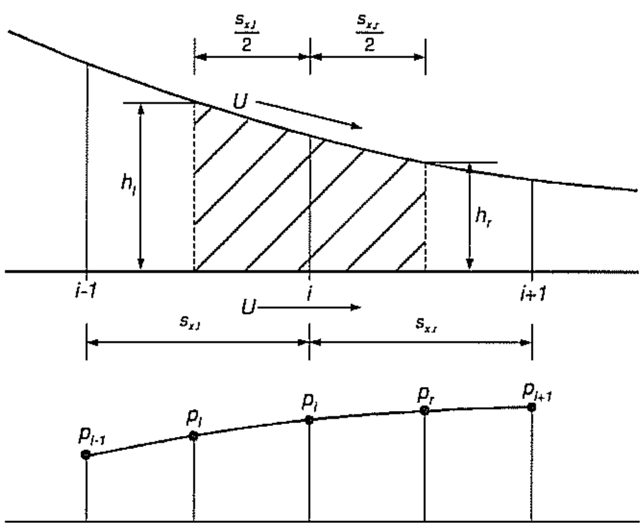


Figure 4 – Notations of finite difference method, gap width and pressure [13]

The continuity condition, which says, that the mass flow at the left and at the right side are equal, leads to the following equation for p_i:

$$p_i = \frac{a_l \cdot p_{i-1} + a_r \cdot p_{i+1} + 12 \cdot \eta \cdot U \cdot (p_l \cdot h_l - p_r \cdot h_r)}{a_l + a_r} \qquad \{8\}$$

with the coefficients

$$a_l = \frac{p_l \cdot h_l^3}{s_{x,l}} \quad and \quad a_r = \frac{p_r \cdot h_r^3}{s_{x,r}} \qquad \{9\}.$$

With the help of the coefficients p_l and p_r the equation can be solved isothermal compressible or incompressible. In case of a compressible computation the coefficients are as follows:

$$p_l = \frac{(p_{i-1} + p_i)}{2} \quad and \quad p_r = \frac{(p_i + p_{i+1})}{2} \qquad \{10\}$$

For an incompressible flow:

$$p_l = p_r = 1 \qquad \{11\}$$

For h the following approximations are used:

$$h_l = \frac{(h_{i-1} + h_i)}{2} \quad and \quad h_r = \frac{(h_i + h_{i+1})}{2} \qquad \{12\}$$

To get the initial pressure p_0 for the use in the equivalent radial modulus of elasticity $E_{r,eq}$, the computed pressure flow will be arithmetically averaged over a wide angle.

Web deflection

Comparable to wrapped rollers the roll's outer layer is assumed to be undeflected, if it is tensed straight in front of the theoretical mounting edge and passes into an circular arc, with the distance of h_{min} above the layer below.

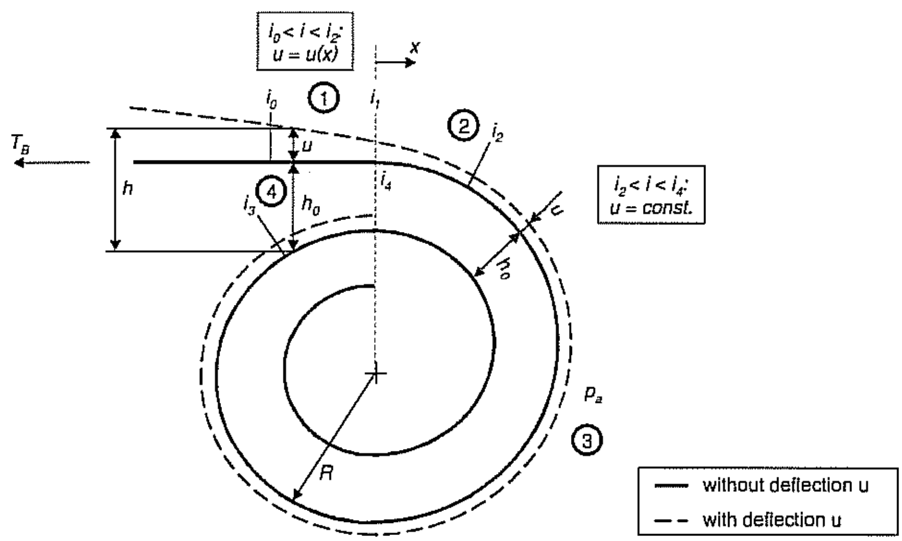


Figure 5 – Unstrained and strained web [13]

The radius R can be assumed to be constant across the whole region, because the thickness of the paper and the air film height are negligible small compared to the radius.

The balance of forces in the radial direction of an infinitesimal small web element provides, after simplification for small angles, the connection between radius of curvature r_k, pressure difference Δp and web tension T_B [10].

$$\frac{1}{r_k} = \frac{\Delta p}{T} \qquad \{13\}$$

At the mounting area the reciprocal radius of curvature approximately matches the second derivation of web deflection.

$$\frac{1}{r_k} = -\frac{d^2u}{dx^2} = \frac{\Delta p}{T} \qquad \{14\}$$

Everywhere else ($i > i_1$) the undeflected web is curved with the radius R. The reciprocal radius of curvature from the undeflected web and from web deflection can be approximately added.

$$\frac{1}{r_k} = \frac{1}{R} - \frac{d^2u}{dx^2} = \frac{\Delta p}{T} \qquad \{15\}$$

For the transition point of the mounting area into the region curved with the radius R at the grid point i_1 applies the following equation.

$$\frac{1}{r_k} = \frac{0{,}5}{R} - \frac{d^2u}{dx^2} = \frac{\Delta p}{T} \qquad \{16\}$$

With the finite-difference-method and the coefficient c_r we get:

$$u_i = \frac{u_{i-1} + u_{i+1}}{2} + \frac{s_x^2}{2} \cdot \left(\frac{\Delta p}{T} - \frac{c_R}{R} \right) \qquad \{17\}$$

with the coefficient $c_R = 0$ for $i < i_1$

$c_R = 0{,}5$ for $i = i_1$

$c_R = 1$ for $i > i_1$

With the computed web deflections u_i it is possible to compute the gap width for an angle of 360°. To get the initial gap width h_0 for the winding model, analog to the calculation of the initial pressure p_0, the gap widths are averaged over a wide angle. The computed data is passed to the modified model based on the models from Hakiel [5] and Good [11] to compute the state of tension in a roll with entrained air films.

CENTER WINDING WITHOUT AND WITH GAP THROTTLE EFFECT

At first additional simulations based on Hakiel's [5] and Good's [11] models were used for the validation of the numerical results. The mechanical properties of an almost impermeable SC-paper were used for the following simulations.

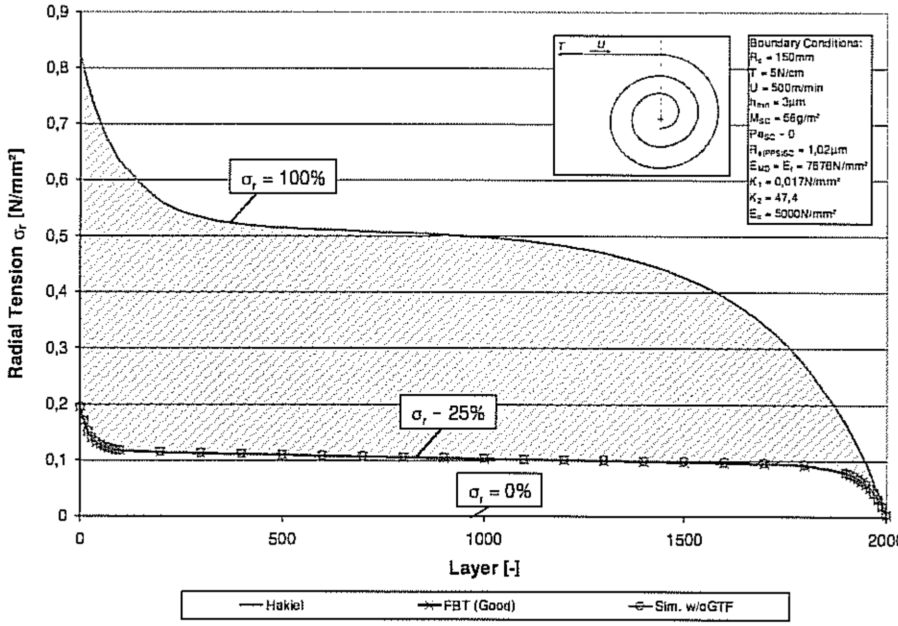


Figure 6 – Radial tension calculated with the model of Hakiel, Good and the new gap throttle model

The radial tension distribution based on Hakiel's model represents the tension level without air entrainment ($\sigma_r = 100\,\%$). In comparison to that, the tension level decreases with air entrainment on an average level of 25 %. The model based on Good and the new numeric gap throttle model have a deviation of ±1 %. Therefore the computation using the minimal contact gap width h_{min} correlates well with the foil bearing theory.

This basic model was extended with a gap throttle foil with a thickness of 80 µm. At the converging gap it immersions one millimeter over the theoretical mounting edge of the web.

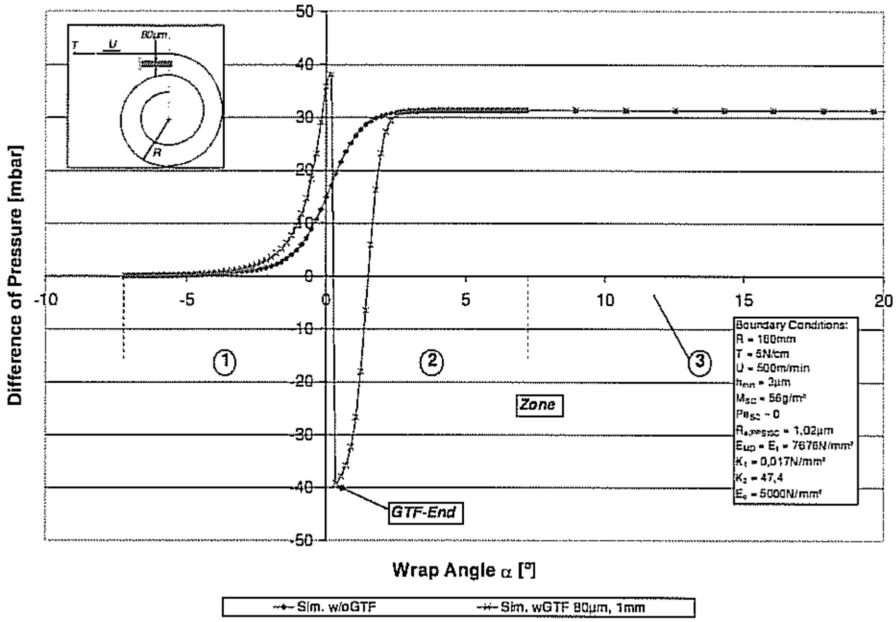


Figure 7 - Hydrodynamic pressure difference versus wrap angle without and with gap throttle foil

In the mounting area both simulations show an increase of pressure (zone 1). By using a gap throttle foil (Sim. wGTF 80µm, 1 mm) the pressure gradient is higher and the hydrodynamic pressure reaches a higher level. According to the viscosity pump (fig. 3), there is a significant decrease of pressure at the end of the gap throttle foil. In zone 2 and 3 the hydrodynamic pressure is approximately constant. The balance between web tension, ambient pressure and pressure in the gap (zone 1, 2, 3) leads to the resulting gap width which is shown in the next figure.

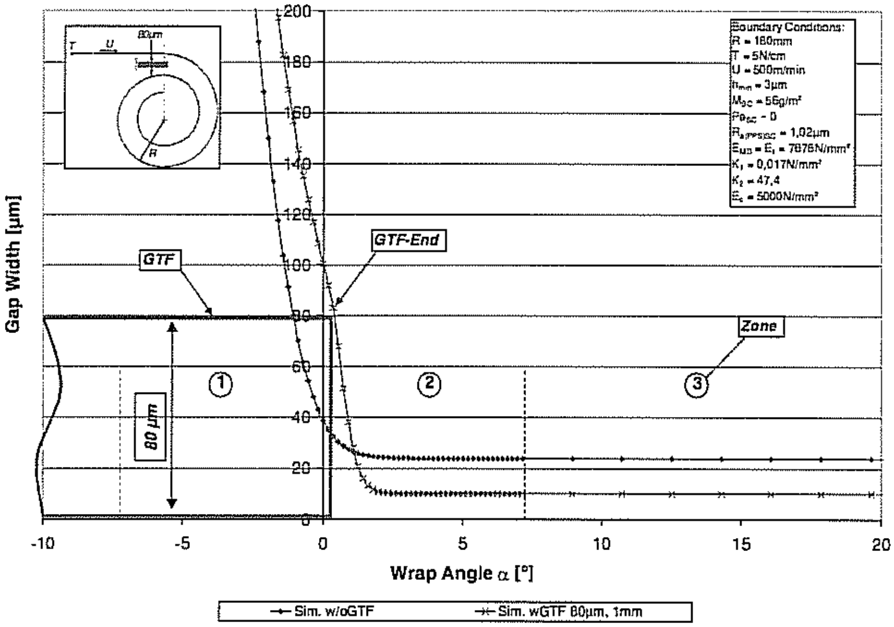


Figure 8 - Gap width without and with gap throttle foil

The gap width is reduced to the minimal contact gap h_{min} at the end of the gap throttle foil, which leads to the high raise of the pressure (fig. 7). The negative pressure at the end of the gap throttle foil and the reduced mass flow are the reasons for the reduced gap width behind the end of the gap throttle foil. The average gap width reaches a level of 9,98 µm with a gap throttle foil compared to 23,77 µm without a gap throttle foil.

The computed radial tension distribution is shown in fig. 9. For comparisons there are also shown the computed radial tensions based on the foil bearing theory and by using a linear reduced gap throttle foil. The influence of a support pressure of 25 mbar in the area of the gap throttle foil is also presented.

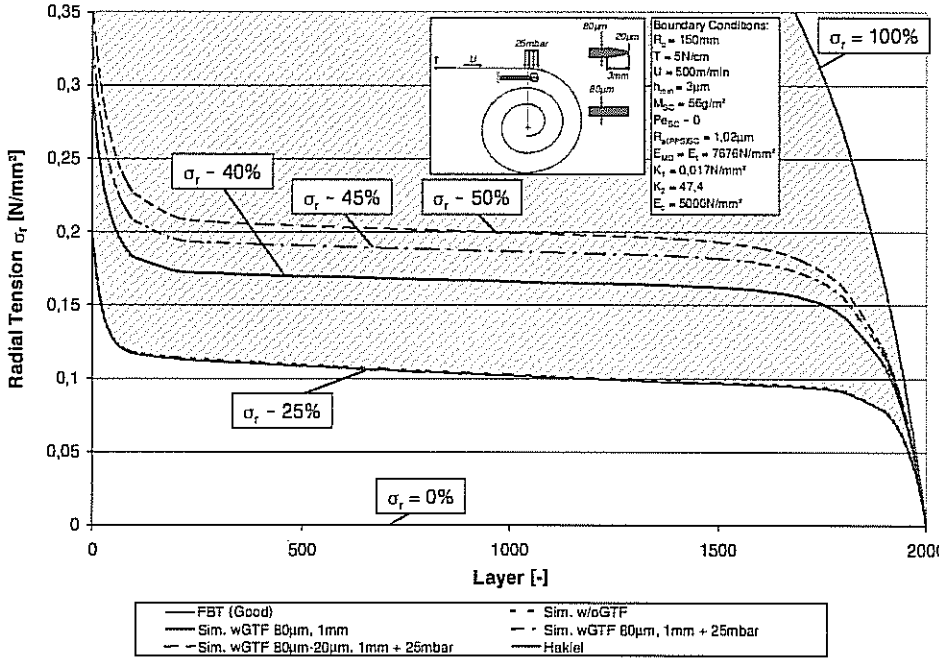


Figure 9- Radial tension without and with gap throttle foil resp. with support pressure

Comparing to the simulation with air entrainment but without a gap throttle foil (σ_r ~ 25 %), the use of a gap throttle foil with rectangular profile averagely raises the radial tension on a level of approx. 40 %. If there also exists a small support pressure on the web, the average radial tension can be raised up to approx. 45 %. A linear reduced foil and a support pressure of 25 mbar raise the average radial tension on a level of approx. 50 % related to the simulation without air entrainment ($\sigma_r = 100$ %). Those results show the high potential of the gap throttle foil in the winding technology.

The tangential tension distributions with air entrainment are shown in the following figure.

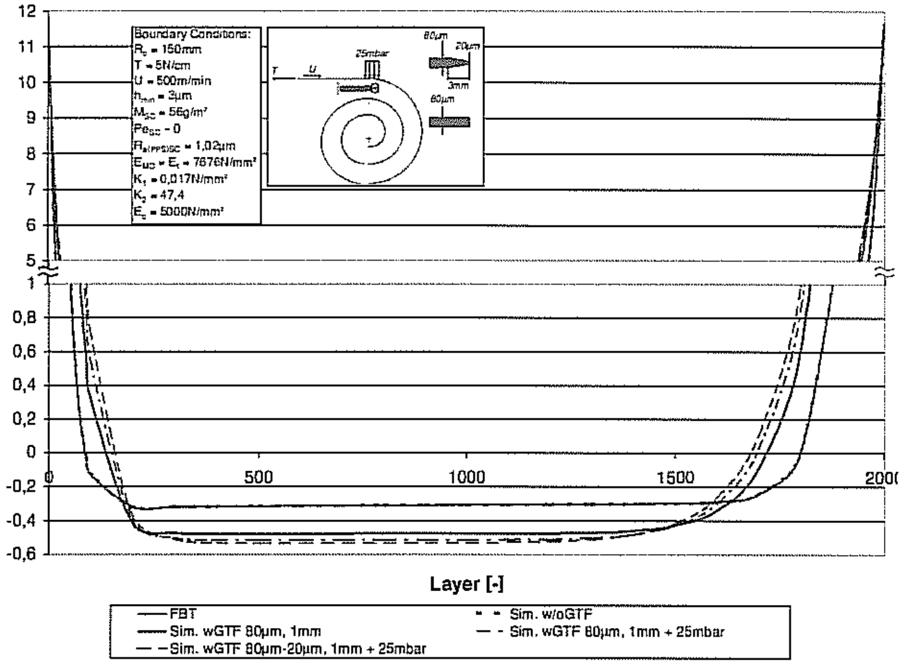


Figure 10 - Tangential tension without air entrainment, without and with gap throttle foil and with support pressure

The figure above shows on the one hand, that there are good correlations with the results from the foil bearing theory. On the other hand it becomes obvious, that the tangential tension level differs only slightly from profiles by using the gap throttle foil. There are small differences at the core and at the outer winding layers. The almost identical tangential tension distributions are resulting from the fact, that the tangential tensions in the roll and the thickness of the paper depends on the radial tensions.

CONCLUSIONS

Comparable to the results from the web transport on wrapped rollers [10], the simulation results for winding show the high potential of the gap throttle effect. The novel principle decreases efficiently the air entrainment and strongly influences the radial tensions in the roll.

Furthermore the simple construction principle abets an inexpensive realization at existing and new machines. Constructively complicated grooved or nip rollers possibly can be avoided.

If the theoretical results are validated by practical experiments, the gap throttle effect opens up new possibilities to the paper and foil mills to improve the winding quality with only some simple retrofits. The distributors of winders get a new inexpensive principle. The main purpose is to reach a winding quality comparable to the quality of center-surface winder. Especially by the use of a gap throttle foil with a support roller, winding can be more gently. So the gap throttle effect is useful to avoid the disadvantages of nip influences and a higher winding quality is achievable.

It is conceivable, that the manipulation of the internal stresses in centerwound rolls with the gap throttle foil is easier for small webs than for wide webs. Best results will be achieved for flexible materials with low air permeability and high surface roughness.

Another point of view is the increased process stability and productivity. By using the gap throttle effect one can achieve higher winding speed by stable process conditions and a higher machine load can be expected.

At this time further investigations to decrease and verify the assumptions in the gap throttle model are already taking place.

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"Predicting Traction in web handling"
ASME Journal of Tribology Vol. 121, S. 618-624, (1999)

Influence of the Gap Throttle Effect on the Winding Process and Roll Quality	**E.G. Welp, A. Kleinert, and V. Smukala**, Ruhr-University Bochum, Germany.
Name & Affiliation John Shelton Oklahoma State University	**Question** How practical have you found this, rolls are predominantly imperfect, out-of-round, eccentric and such things? Have you found a way to hold this foil so that you don't suddenly have it wound in the roll?
Name & Affiliation Andreas Kleinert Ruhr-University Bochum	**Answer** If you put the gap throttle foil deeper in the converging gap, it gains contact. The risk is that it will break or be pulled into in the roll. I have experimental data where the gap throttle is 1 mm before the mounting edge of the incoming web and it works there as well. The immersion depth has an influence on the amount of the effect.
Name & Affiliation Tim Walker TJWA	**Question** In your transport roller trials, how wide was the web?
Name & Affiliation Andreas Kleinert Ruhr-University Bochum	**Answer** It was 600 mm wide.
Name & Affiliation Jim Dobbs 3M	**Question** It is easy with the transfer roller to have a fixed geometry of your web and your converging nip. Obviously, with a winding roll, it would be very desirable to not construct all of the machinery that is currently used for the rider roll just to hold your gap throttle device in a variable geometry position. Could you comment?
Name & Affiliation Andreas Kleinert Ruhr-University Bochum	**Answer** Today, the nip roller moves with rising roll diameter, so you can use the same solution for the gap throttle effect.
Name & Affiliation David Pfeiffer JDP Innovations	**Question** An imperfect web with a rider roll has the advantage that the rider roll is trying to make the imperfect web into a cylindrical roll. The gap throttle foil will do what center winding would do in a vacuum more or less. It will not have the advantage to compress the high spots as the rider roll will do.
Name & Affiliation Andreas Kleinert Ruhr-University Bochum	**Answer** That is true, but with the gap throttle effect, a more gentle handling of the web occurs. The effect should be used especially for high-class paper grades.

DISCUSSION III

Leaders: **B. Becker[1] & J. K. Good[2]**,
[1]Alcoa, Inc. & [2]Oklahoma State University, USA

Name & Affiliation	Comment
Bernie Becker Alcoa, Inc.	As a discussion leader, I have to say something. This concerns getting rid of nip rollers, not a day goes by that I am not asked if there is some other way to get rid of air besides a nip roller. I would welcome any comments from the group on that.
Name & Affiliation	**Answer**
Herong Lei Eastman Kodak	One option is to wind a roll in a vacuum or in a space and that's not going to happen. Can we put some kind of a vacuum device there to suck more air out of the nip?
Name & Affiliation	**Comment**
Bernie Becker Alcoa, Inc.	I have also been asked if you can use air pressure or electromagnetic force or anything that doesn't touch that outer layer because we have so many defects. We are trying to wind at pretty high temperatures on aluminum foil and aluminum sheet and the maintenance cost of these rolls are pretty high.
Name & Affiliation	**Question**
Herong Lei Eastman Kodak	Dr. Good: In your keynote speech paper, you cited a paper by Steve Burns talking about a different kind of winding model. Older models, so far, are built on a base that we wind one web after another. In this paper by Steve Burns, he is talking about doing the whole thing in one shot. He doesn't add one layer on top of another. Do you have any comments on that way of handling the winding models?
Name & Affiliation	**Comment**
Keith Good Oklahoma State University	One of the difficulties with modeling the wound roll as a continuum as Burns has rather than a series of layers that are laid on top of one another in an accretive Hakiel type solution is the proper treatment of boundary conditions. The web approaching a winder does so in a pre-stressed or pre-strained condition. The deformations that produced those stresses and strains occurred upstream of the winder. In an accretive model a deformed layer with a given circumferential stress can be added to the outside of the winding roll. From equilibrium a certain pressure beneath that layer results if you do not consider the deformation of the layers beneath. You can consider this deformation which was what David Pfeiffer and I did in our "tension-loss" models. The difficulty in a continuum model is introducing the pre-strain or pre-stress conditions that originated in the web prior to the winder correctly into the outer boundary of the wound roll continuum. We have wound and instrumented many rolls of various web types in our research here at the WHRC. Accretive models of

the type developed by Hakiel have been proven accurate in many trials. Highly compressible webs (K_2<40) will require "tension loss" computations in addition to retain such accuracy, but using an accretive solution nonetheless.

Name & Affiliation	Comment
Marko Jorkama Metso Paper	We have also looked at that paper.. I do not think that it is correct. One thing is missing that the total displacement field is incompatible and they are applying compatibility equations and that is where it goes wrong. That is my opinion, at least.

Name & Affiliation — **Comment**

Bernie Becker, Alcoa, Inc.

I want to return to the discussion on controlling air films wound into rolls. Is there any kind of a noncontacting way to get rid of the air such as electromagnetic fields,\ or air pressure jets blowing on the outside?

Name & Affiliation — **Comment**

Keith Good, Oklahoma State University

I have never seen these studies, but I have always heard of attempts trying to wipe the air layer off before it enters the winding roll which did not work well. Now we see the results of Mr. Kleinert's work, which looks very promising. Then you start to ask yourself could the piece of foil be something porous where there could be a vacuum applied to the piece of foil so that we could wind in a normal environment. It brings up some interesting questions.

Name & Affiliation — **Question**

Jim Dobbs, 3M

The first thing I remember about vacuum is that for most of us there is only about 14 psi total amount of it available, assuming you are able to achieve anywhere near a vacuum. The question I have for you is why do you wind your rolls hot?

Name & Affiliation — **Answer**

Bernie Becker, Alcoa, Inc.

This a cold rolling mill. This is a result of the plastic deformation of the material.

Name & Affiliation — **Comment**

Jim Dobbs, 3M

Yes, but you could cool it before you wind it.

Name & Affiliation — **Comment**

Bernie Becker, Alcoa, Inc.

We are flooding it already with a coolant. We are doing our best to cool it and also achieving the mechanical properties at the same time.

Name & Affiliation — **Comment**

Jim Dobbs, 3M

It just seems dangerous to wind up a hot roll of material.

Name & Affiliation — **Comment**

Bernie Becker, Alcoa, Inc.

It is very dangerous and, as a matter of fact, it leads into another comment concerning the three-dimensional models that Paul Hoffecker presented. They are extremely important in our industry because when you wind at those kind of temperatures, creep is a big concern. We create a lot of baggy webs by winding at those temperatures with caliper variations. We use tensions levelers to deal with it downstream in the finishing processes.

Name & Affiliation	Comment
Ron Swanson 3M	Concerning getting rid of the air entrainment: If you do the Knox-Sweeney integration you must integrate from minus infinity to infinity. Where is infinity? It turns out that infinity is about 32 times your air film height which is still small. Where the two layers come together may be a distance about 10 mils wide, anything outside of that is infinity. So scrapers and whatnot have to penetrate way in there, which is what we heard from the gap-throttle discussion. There is a way to get a scraper in there. Infinity is very close to where the two nips come together.

Name & Affiliation	Comment
Keith Good Oklahoma State University	When Mr. Kleinert was discussing the gap throttle effect I remembered winding pull tabs into wound rolls at high speed. Bernie was talking about the dangers of being around these wound rolls of aluminum which are under high stress and they are moving 2,000 feet per minute. When one of his wound rolls fails, they call it a wreck. It is dangerous. I guess my point is that in winding in pull tabs, just into paper and film rolls, every once in a while, you lose it. There are considerable pull forces that are developed on the pull tab as it is inserted into the roll. You could easily develop frictional forces on the surface of the pull tab that would result in stresses in excess of the ultimate tensile strength of the steel. I can see the reliability issues being difficult to deal with.

Name & Affiliation	Comment
John Shelton Oklahoma State University	This regards the core explosions Marko Jorkama of Sonoco presented: I would like to point out that this is not the usual vibration problem. It is often mistaken for being a vibration textbook problem, but it is entirely different. The critical velocity we are dealing with here is when the inertia forces overcome the stiffness of the shaft and you see very little of this in vibration texts. You see little about rotating elements, but it is also not like a gas or steam turbine, where you have a large mass on a limber shaft. The core is stiff. If you have a large mass on a limber shaft after you go through the natural frequency, this starts rotating about the center of gravity instead of the former geometric center of rotation. If the core is initially crooked, it cannot rotate about either center. It is too stiff to shift over to rotating about the center of gravity. There are some subtle differences. It is confusing in that the critical velocity is numerically equal to the natural frequency, but a difference is that there is no damping whatever to this whirling core or wound roll mode. It is just in a certain position and it is rotating; but not vibrating. That is not

damped at all. Therefore, it must be avoided for those two reasons I mentioned – the stiffness of the core compared to a limber shaft and the fact that there is no damping. You must avoid the critical velocity. Another aspect is the half-critical frequency; that is another misconception. Rollers are made from tubes and often are not turned or machined concentrically inside and out. If you start with an elliptical tube and machine it on the outside, you have a moment of inertia that varies twice per revolution with a maximum and minimum each revolution. It is being disturbed at twice the rotational frequency, so it vibrates at half its natural frequency. It is the disturbance that is causing the vibration. These are just some subtle differences between what happens in rotating machinery compared to the usual textbook vibration problem.

Name & Affiliation	Comment
Bob Lucas GL&V USA, Inc.	I was involved in a joint project with Sonoco dealing with core problems of only 107" wide presses, not 170" wide presses. Some of the things that are happening in these wider presses are much more extreme, but the mechanics are the same. What you described, John, where there is no damping, you are right. This is a state of whirl. But once you get a certain whirl deformation forces are created that create yet more deformation. Deformation data that was collected took off and expanded into a spiral and finally self destructed. It was a beautiful classic example. Of course, in the process, it destroyed all our instrumentation but we got good data.

Name & Affiliation	Comment
Keith Good Oklahoma State University	This comment is for Marko Jorkama regarding his work on roll vibration. You discussed the time of recovery of the material after any one of the rolls that had indented the outside of the winding roll. That seemed to me to be a problem that would be a really interesting one to work with ABAQUS explicit. Wound rolls with nips and tires impinged against a road have some similarity. With tires which are rotating you get standing waves of deformation before and after the contact zone. After you reach a critical velocity waves of motion begin to travel about the tire. If this same behavior exists in wound rolls you would think that some winder vibration problems might be self generated since the wound roll may provide the disturbance.

Name & Affiliation	Comment
David Pfeiffer JDP Innovations	I have a comment on roll vibration which relates to Bob Lucas' previous comment on the instability and whirl of cores and rolls. Many potters experience this instability when their clay sculpture goes too fast on their potter's wheel. The clay ends up on the other sides of the room! I asked the question yesterday, does anyone want to know

what a LearMeter is and I didn't get a bite. It has to do with roll bouncing and vibration.

Name & Affiliation
Tim Walker
TJWalker & Associates

Answer

First off, the potter's story: My wife has tried doing that and she has asked a potter for advice on how you get that pot started. The advice she got was first you must find your own center. Dave, what is a LearMeter?

Name & Affiliation
David Pfeiffer
JDP Innovations

Comment

Dave Daly and I were studying the vibration frequencies of rolls. The elasticity of the deformable roll surface and the mass of the roll determines the natural frequency. This is responsible for the generation of a washboard road effect which can be generated at the outside radius of a winding roll. The friction between layers is largely responsible for locking in the deformations which resulted from the vibration. We developed an instrument to measure the locking together of web layers and tested several grades of paper. We called the instrument the "LearMeter", the name was derived from the measurement of laminar shear. In order to make the layers shear against each other, we put a metal hinge plate in and put a deck of paper sheets 13 millimeters thick, roughly 3x5 sheets, so they would bend at the joint between these two metal plates. To provide the radial normal force between the layers of paper as they would be wound in a roll we clamped the layers with negator constant force springs, developing about 69 kilo Pascals or 10 psi pressure between the sheets. Then at a radius of about 100 millimeters, we hung a weight and developed a moment to bend the pack. For grades that tend to bounce and vibrate, such as un-calendared craft, the bending would occur in jumps. As you raised the weight, it would suddenly go to another deflection angle and move in steps and would take a high moment force to generate a bend. A grade which is less prone to bouncing and vibration, such as newsprint, would require a lesser moment force to bend it and deflect the package a given number of degrees. Catalog, which is a finely finished, thinner version of newsprint, would take still less moment force to bend it 20-30 degrees. Coated and super calendared, lightweight magazine publishing grade would take a minimum amount of force to deflect it. This kind of instrument can be used to measure the tendency of a grade to vibrate.

Name & Affiliation
Tim Walker
TJWalker & Associates

Question

The second comment I have is that IWEB to me is a wonderful education opportunity. I think it fills a gap between fundamental training and advanced training for experts, but I also wonder if there is a need to grow the audience for this conference. One of the challenges for coming to this conference is getting up to speed on all these topics. Many of these topics are very advanced; many have seven conferences or 14 years' worth of background. One of my areas of interest is training. I think there could be a demand for training at advanced level from past proceedings' information and I didn't know if there could be a survey here of interest in that type of thing. It could be done on off years – on even numbered years, instead of odd years. I know that is a little different than what Bruce Feiertag does with the application seminar here. There is a need for something between introductory training and this level of conference. I don't know how many people think there is such a need that needs to be filled or not.

Name & Affiliation	Comment
Karl Reid Oklahoma State University	I would like pick up on both those comments and get a little more feedback on that.

Name & Affiliation	Question
Tim Walker TJWalker & Associates	The second comment I have is this IWEB to me is a wonderful education opportunity. I think it fills a gap between fundamental training and advanced training for experts, but I also wonder if there is a need to grow the audience for this conference. One of the challenges for coming to this conference is getting up to speed on all these topics – a lot of very advanced topics that have seven conferences or 14 years' worth of background on it. One of my areas of interest is training. I think there could be a demand for training at advanced level from past proceedings' information and didn't know if there could be a survey here of interest in that type of thing. It could be done on off years – on even numbered years, instead of odd years. I know that is a little different than what Bruce does with the application seminar here. There is a need for something between introductory training and this level of conference. I don't know how many people think there is such a need that needs to be filled or not. How many people think they have someone at their company who would come to an advanced level training somewhere between an introductory class and the IWEB? Do you think that would increase the number of people who would come to IWEB and enjoy it?

Name & Affiliation	Comment
Bernie Becker Alcoa, Inc.	That's a good point, Tim. I am always torn between the practical applications and the theory. If you remember, I gave a paper in 1997 and I think it is the only paper presented that didn't have an equation in it so far at IWEB. So I think this audience likes equations maybe, but I really enjoy the empirical modeling. It takes me a while after being gone two years even to get back up to speed on some of these equations. Good point.

Name & Affiliation	Question
Neal Michal Kimberly-Clark	Yesterday, Dave Roisum brought up the challenge why do equipment manufacturers not use some of the fine models that have been developed and design better equipment. I would say, as a research body, we sometimes fall short of the mark in giving practical applications of how these different models and very high-end mathematical equations truly apply to the real world situations. I wanted to ask a question of Keith Good: If there is anything as researchers, as these various people continue to research – what ways can they verify or validate what they have. What tools are available to be able to prove or disprove theories and these models and these equations, such that people that are in the manufacturing area can actually use them or say, hey, here's something that we can hold onto or here's that we can use, here's something that an equipment manufacturer can use to design better equipment. Is there anything in particular that you would suggest from a validation/verification standpoint?
Name & Affiliation	**Answer**
Keith Good Oklahoma State University	You are speaking generally with respect to winding here?
Name & Affiliation	**Question**
Neal Michal Kimberly-Clark	Yes, from a winding standpoint. We have had different papers – we had two almost identical talking about the same thing. It is difficult looking at both of them to understand how they compare to each other.
Name & Affiliation	**Answer**
Keith Good Oklahoma State University	The scientific world is one of steps, Neal. Sometimes one step is a theoretical step, the next step might be verification. Sometimes when you are lucky, it all comes together. You have seen several studies where winding models have been verified with pressure measurements. This is a good method in that if your model and test pressures agree you can also gain confidence that your tangential stresses are correct. The equation that relates the tangential stresses and the radial pressure is a simple equilibrium equation. So those in research have experimental methods by which they can gain confidence in the results produced by their models. One of the challenges in modeling is what to do when your inputs are not known. Sometimes the scientific community needs to be involved in basic research to help understand what we might think are the simpler concepts, stress and modulus in non-homogenous webs for example. So the tendency if you are modeling winding would be to verify your model with a homogenous material for which stress and modulus are well defined. As the models progress then in another "step" one begins to explore the applicability of their

model to some of the more difficult materials. The paper that Balaji Kandadai presented at this IWEB is an example of such work.

Here enters the machinery builder. In many cases their customer is unwilling to divulge what web will be wound and at what speeds the process and thus the winding will occur. Thus the machinery builder probably has no knowledge of the web properties that would be required to execute a winding model, so a winding model will not influence the design of the winder. My suggestion Neal is that the only rational way to solve this problem is to get people inside the companies proactive and fluent in the use of the models and have them set design constraints (roller diameters, surface finish, control methods, instrumentation, etc.) that are included with the request for bids that are sent to the machinery builders.

Name & Affiliation	**Comment**
Bob Lucas GL&V USA, Inc.	It is one thing to have academic pursuits to theorize on a particular mechanism or model. One thing that is so important with the IWEB activity is that we have a chance to get some reality checks. It is so important for the person who is conducting the research to have a sense of what is going on in the real world so he can make some practical judgments of what factors should and should not be included in the models. There is nothing wrong with theoretical research, but you have to keep your feet on the ground so you don't get too esoteric. There is some judgment tied in with experience. For instance, when should we incorporate viscoelasticity into our models? Our decision whether to incorporate viscoelasticity into a model might be influenced if we knew the stress duration was on the order of fractions of second versus creep time constants that may be on the order of several seconds, minutes, or hours. If we add viscoelasticity to this model of a process we have increased the complexity of the model without providing benefit. You have to know when to apply it and there are so many things that can be solved relatively simply without getting too carried away with the theory and you still gain insight into the process. When you develop these models, you are probably never going to get it perfect, but you develop an insight into the process and that is what, to me, is important. You blend that in with some good practical experience and then you have something to work with.

Name & Affiliation	**Comment**
Jim Dobbs 3M	I think we are shooting too high here with the machine builders. An engineer doesn't really have to understand how a bolt fails or a fastener fails to look up in a table and select the appropriate fastener and put the machine

together. First of all, machines are built without even the ability to get Dave Roisum's criteria of two data points to figure out here and here, so that you might guess the answer is somewhere in between. Machines are commonly built without even the most basic fundamentals to know that your pack force is in units of pli instead of psi. All kinds of basic stuff are omitted from the machine. If we are that level, we are not going to get beyond fighting and struggling when we get a new machine, going through the same old thing again – translating into engineering units and even an imperfect model is better than what we are doing now.

Name & Affiliation	Comment
Bernie Becker Alcoa, Inc.	I appreciate your comment, Jim, because I have gone to our equipment suppliers and urged them to go to the short course here to just get a basic idea of the terminology and the things we are talking about. So far, I don't think a single one has come. I don't know if it is because they think they know or they don't want to spend the money or the time. I can't really explain that, but I have been really disappointed by that.

Name & Affiliation	Comment
David Pfeiffer JDP Innovations	I have a comment for Neal Michal on his question of how do we get a model that works in all these situations based on John Shelton's universal theory for what solves all problems. One very useful principle is the minimum energy state. If you want to know when a trough forms in a web, it forms when it can go to that state because it is a minimum energy for the deflected web to form that trough. That principle will solve a lot of problems. It is one of the governing principles I used when I developed my simple roll structure program. It was simply based on the energy balance that in a given zone of the roll, you are putting in a certain strain energy that resulted from web tension to become strain energy in the roll. Eventually, that is converted to a combination between pressure compression energy and tensile residual energy. Energy and energy balance and minimum energy principles are good to use for a unified theory of something that will allow you to check your results.

Name & Affiliation	Comment
Keith Good Oklahoma State University	This comment is given in response to Bob Lucas's comment earlier: I agree with you we should keep our models as simple as possible to solve those problems that we know are important from field experience. But I think as part of any research strategy that you develop, you ought to set aside part of it for high risk adventures. For instance, a couple of years ago, I wouldn't have believed that Andreas Kleinert's foiling of the air film with his gap throttle effect was possible, but I am glad there was

	someone ready to take that risk and try something new.
Name & Affiliation	**Comment**
Mike Madaras Goodyear Tire & Rubber	I agree with what Tim Walker and Bernie Becker said about having some advanced training courses to bridge between basic and the advanced theory levels. Here are the equations, here are the models, and here are the fundamentals, then a person who comes to the conference will understand more. That might help bridge the gap for industry people to use the tools. I think that might be worth trying.
Name & Affiliation	**Comment**
Dilwyn Jones Emral Ltd.	I wanted to return to the question of why people aren't using the tools we have developed; why people aren't using these equations and so on. A colleague of mine in the UK has actually put a lot of these equations into a small piece of software called TopWeb. That is one solution to getting the results of research more widely used.
Name & Affiliation	**Comment**
Keith Good Oklahoma State University	Dilwyn, this was part of the motivation that I had for writing the keynote article on winding I presented this morning. I tried to show the reader the important facets of winding per Bob Lucas's comment and I tried to give them direction in terms of what is available in the literature. I know the people working in industry don't have much time to read – they are being forced to solve problems and time is crucial, they are faced with new problems and crises in production environments each day. It is a problem we need to help them with – whether it is with software, a fast means of getting information, etc.