# IRREVERSIBLE REDUCTION OF FOIL TENSION DUE TO AERODYNAMICAL EFFECTS

by

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**ABSTRACT**

Computation of the residual stress generated during the winding of a plastic film has been coped with by many authors. These studies are based on the assumption that the residual stresses mainly depend on two winding factors: (i) nominal foil tension and (ii) foil mechanical properties. Recently, several authors have introduced the effects of a third winding factor: nip force. But, in all the existing studies, the influence of the entrapped air layer and more generally, the aerodynamical effects are neglected.

Such an assumption is reasonable in the case of thick plastic film (thickness about 100 µm) or thin plastic films (thickness about 10 µm) wound under low velocities (about $1 m.s^{-1}$). However, in the case of industrial winding conditions in which film thickness is typically about 10 µm and velocity about $5 m.s^{-1}$, the effects of aerodynamical phenomena are experimentally known to be as important as the effects of foil tension itself.

From a more general point of view, the industrial winding conditions suffer from a lack of theoretical analysis since they are mainly based on empirism, which is not quite satisfactory.

We recently proposed a model in order to predict the residual stresses generated under realistic industrial conditions, including the effect of nip roll. This model is based on a new global approach in which the winding process is seen as a mechanism of air entrainment and air exhaust. To set this model in order, we were faced with several problems: (i) computation of the thickness of the entrained air layer, (ii) analysis of the air exhaust phenomena, (iii) analysis of effects due to film roughness... All the main parameters which govern the winding process (velocity, foil tension, nip force, foil bulk and surface properties...) are taken into account.

In the present paper, we propose to recall the basis of this new global approach and to focus our attention on one of its most important consequences: the irreversible reduction of foil tension during and after winding. Experimental check is presented for a large set of winding conditions. Comparison is based on the average air layer thickness and on the foil residual tension value.

**NOMENCLATURE**

N = index for last layer
I = index for current layer
H, U and W = non dimensional parameter in EHD theory introduced by Hamrock and Dowson
$t_e$ = thickness of entrapped air layer (m)

$R_{eq}$ = equivalent radius for nip roll and wound foil used in coefficients H, U and W (m)
$E_{eq}$ = equivalent Young's modulus for nip roll and wound foil used in coefficients U and W (m)
$\mu air$ = viscosity of air (Pa.s)
V = velocity of foil (m/s)
F = nip force per unit width (N/m)
$R_{nr}$ = nip roll radius (m)
$R_{wf}$ = wound foil radius (m)

$\sigma_r$, P = radial stress (Pa)

$\sigma_\theta$ = circumferencial stress (Pa)

$s_z$ = axial stress (Pa)

$\upsilon_{\theta r}$ = Poison's ratio of the foil, that is the ratio of the radial strain to the circumferencial strain for an element under pure circumferencial stress

$\upsilon_{zr}$ = Poisson's ratio of the foil, that is the ratio of the radial strain to the axial strain for an element under pure axial stress

$\upsilon_{\theta z}$ = Poisson's ratio of the foil, that is the ratio of the axial strain to the circumferencial strain for an element under pure circumferencial stress
$E_r$ = Young's modulus in the radial direction of the wound foil in compression (Pa)

$E_\theta$ = Young's modulus in the circumferencial direction of the wound foil in compression (Pa)

$E_z$ = Young's modulus in the axial direction of the wound foil in compression (Pa)
$K_1$ = coefficient introduced by Pfeiffer and Hakiel (Pa)
$K_2$ = coefficient introduced by Pfeiffer and Hakiel
$t_a$ = thickness of the air interlayer (m)
$t_{eq}$ = equivalent thickness of the air interlayer for air exhaust phenomenon (m)
r,s = current radius of a layer (m)
$R_{ext}$ = external radius (m)
$R_f$ = final radius (m)
$u$ = radial displacement (m)
$T_r$ = internal tension of the foil (Pa)

$\sigma_e$ = difference between $\sigma_\theta$ and $T_r$, due to elastic deformation (Pa)

$D_f$ = unwound foil density
$D_r$ = roll density

## INTRODUCTION

The occurence of aspect defects, i.e. wrinkles, during the winding of a thin plastic film is experimentally known to be strongly connected with process parameters such as winding velocity or nip force. The main role of these parameters is to master the air entrainment, or more generally aerodynamical effects.

The first studies were mainly based on the theory of accreted bodies. The first approach is due to Hirai (1959) but Brown and Goodmann (1963) established the theoretical bases for the phenomena of accretion. The first application of this theory to the problem of foil winding is due to Altmann (1967) and Tramposh (1967). Several improvements were proposed later: Yagoda (1980) Connolly and Winarski (1984), Hanish (1987) with an energetical formulation. Several authors introduce the non-linear behavior of the wound foil: Pfeiffer (1966-1987) and Hakiel (1987).

These models are in good agreement with experimental data for thick plastic film, paper or thin plastic film wound under very low velocity, because in all these cases, aerodynamical effects can be neglected.

For productivity reasons, the winding of thin flexible media is carried out under high velocity conditions which induces aerodynamical effects. Moreover, one of the most important industrial applications for thin flexible plastic films is magnetic coating. Because of the high level of quality required by this application, the roll must be free of defects.

A new contribution in the field of winding of thin flexible media is proposed through an approach in which aerodynamical effects are the central point of the model: Bourgin and Bouquerel (1992) and Bouquerel (1993). The roll is considered as a composite materiel made of: (i) a layer of film and (ii) a layer of air. The interlayer air is continuously entrapped and exhausted during and after winding.

The wound foil mechanical properties in the radial direction and in turn the residual stresses depend on the thickness value of the air layer. The foil tension is modified by irreversible phenomena of air exhaust. Globally, the winding process is seen as a coupled problem between solid mechanics and fluid dynamics, in which film surface roughness plays an important role. Lastly, the model allows foil tension reduction within the roll to be predicted.

Experimental results mainly based on the average value of the air layer thickness have been included to validate this new approach. Various conditions of foil roughness properties and winding conditions are tested.

## GENERAL STRUCTURE OF THE MODEL

The classical configuration of center winder with an impinging nip roller is shown in Figure 1. The foil is wrapped around a nip roll before being wound around a core. The velocity and the tension are prescribed. The nip roll is strongly pressed on the roll in formation.

The winding process presents two aspects closely linked to each other:

- **(i) the superimposition of each layer depends on the roll mechanical state:** the thickness of the entrapped air layer is a function of the roll radial mechanical properties which in turn depend on the residual air layers,

- **(ii) the roll in formation depends on the underlying layers:** each new superimposition compresses the roll and modifies its state of residual stresses (compressive elastic phenomena) and exhausts an amount of air through the roll edges (non elastic phenomena) and consequently reduces the foil internal tension (non elastic phenomena).

Therefore, the winding process must be seen as a cumulative process, having three main steps, successively repeted at each revolution: see synopsis in Figure 2.

This global approach of winding gives rise to following problems:

(i) - how to evaluate the thickness of the entrapped air layer ?
(ii) - how to characterize the radial mechanical behavior of a wound foil ?
(iii) - how to evaluate the amount of air exhaust ?

## MECHANISM OF AIR ENTRAPMENT

The mechanism or air entrapment can mainly be characterized by the value of the entrapped air layer thickness.The winding configuration is similar to a classical one: elasto hydrodynamic lubrication of two cylinders pressed against each other (Figure 3):

- the flow modifies the geometry (elastic bodies),
- the geometry is modified by the flow (pressure effects).

Hamrock and Dowson (1981) proposed the following expression for the lubricant film thickness:

$$H = 7{,}43 * U^{+0{,}65} * W^{-0{,}21} \qquad \{1\}$$

where H, U and W are non-dimensional parameters defined as follows:

$$H = \frac{t_e}{R_{eq}},\ U = \frac{\mu_{air} * V}{R_{eq} * E_{eq}} \text{ and } W = \frac{F}{R_{eq} * E_{eq}}$$

Where $t_e$ is the layer thickness, V denotes the foil velocity, $\mu_{air}$ is the dynamic viscosity of air, F is the nip force, $R_{eq}$ is the equivalent cylinder radius.

$$\text{with } \frac{1}{R_{eq}} = \frac{1}{R_{nr}} + \frac{1}{R_{wf}} \text{ and } \frac{2}{E_{eq}} = \frac{1-\nu_{nr}^2}{E_{nr}} + \frac{1-\nu_{wf}^2}{E_{wf}} \qquad \{2\}$$

E and ν are respectivaly Young's modulus and Poisson ratio.

(subscripts **nr** and **wf** hold for nip roll and wound foil respectively).

In the problem here, the lubricant is air and the two cylinders are the wound foil and the nip roll. This is very different from Hamrock and Dowson's configuration (oil and steel), but their formulation can be used here because of the same order of magnitude of the non-dimensional parameters in both cases.

Equation {2} requires Young's modulus ($E_{wf}$) and Poisson ratio ($\nu_{wf}$) of the wound foil to be introduced. Because of the hertzian contact between the nip roll and the wound foil, $E_{wf}$ depends on the radial Young's modulus of the last layers of the wound foil, say $E_r$. As it will be detailed later, Young's modulus of the wound foil is a non-linear funtion of the strain.

Thus $E_{wf}$ results from a coupled computation including:

(i) formula {1} and {2},

(ii) relation between radial deformation and nip force as given by Hertz theory,

(iii) relation between radial Young's modulus and air layer thickness (see later).

Two main parameters seem to be neglected in this formulation:

**(i) foil tension**: the velocity and the nip force are likely more important for the value of the entrapped air layer thickness than the foil tension is,

**(ii) roughness**: as noted by Jones (1992), under some specific conditions (winding low velocity), the entrapped air layer thickness remains constant at a value depending on roughness. In other words, roughness average value corresponds to a minimum value of the entrapped air layer thickness.

## BEHAVIOR OF THE WOUND FOIL

Computation of the residual stresses requires the wound foil mechanical behavior to be known. In the radial direction, the mechanical behavior is complex because of the influence of several effects: foil, geometry and dynamics, air movements and foil roughness (two adjacent foil layers are in contact). Such a response is certainly non-linear but Hooke's law is used, for the sake of simplicity (according to Pfeiffer's and Hakiel's models).

Radial Young's modulus is a function of roughness and residual air layer thickness under conditions of compression. It is obtained by means of a test developped in Rhône-Poulenc Films laboratory, in which the average air layer thickness is measured as a function of compressive stress: $t_a(P)$. Note that Young's modulus is clearly a function of the average air layer thickness (under the assumption that the air layer deformation is higher than the film layer deformation):

$$E_r = t_f * [\frac{d}{dP} t_a]^{-1} \qquad \{3\}$$

For some given value of the compressive stress, the residual air layer thickness reaches an equilibrium value called $t_{eq}(P)$ corresponding to a compromise between compression and foil deformation. In such a static case, Young's modulus only depends on compressive stress. It as been reported in Figure 4 a typical profile of the air layer thickness versus compressive stress for a 12μm thin PET film. The corresponding radial Young's modulus is shown in Figure 5.

Note that in the range of compressive stress values used in the roll, $E_r$ can be approximated by a linear function of the compressive stress:

$$E_r = K.\,P \text{ with } K \approx 50 \text{ up to } 200 \qquad \{4\}$$

This expression is similar to that deduced by Pfeiffer (1966) and Hakiel (1987) on the basis of experiments carried out on a pile of layers under compression. Note that coefficient K has the same order of magnitude (50 to 200).

In the general case, it is observed that the static conditions which correspond to the equilibrium state $t_a = t_{eq}(P)$ is not always reached: the air layer thickness can be greater than its equilibrium value. It involves a more realistic formulation for Young's modulus including the air layer thickness value:

$$E_r = f[t_a, P] \qquad \{5\}$$

This more complex relationship can be deduced from the previous experimental curves and elementary theoretical considerations.

Experimental results show that radial Young's modulus is lower by a factor of 100 than Young's moduli in the other two directions (circumferencial and axial): a wound foil is a strongly orthotropic body.

The other parameters of Hooke's law ($E_\theta$, $E_z$ $\upsilon_{\theta r}$, $\upsilon_{zr}$ and $\upsilon_{z\theta}$) wich do not depend on surface roughness are simply equal to the corresponding values of the unwound foil. Lastly, $\upsilon_{r\theta}$, $\upsilon_{rz}$ and $\upsilon_{z\theta}$ are deduced from symetrical considerations.

## COMPUTATION OF THE RESIDUAL STRESSES

The present publication is mainly devoted to air entrapment and exhaust. For this reason, the computation of the residual stresses through the accretion process are not detailed here. This problem was studied by many authors: Tramposh (1967), Altmann (1968), Pfeiffer (1966-1987), Yagoda (1980), Hakiel (1987). Globally, they express that the stress values at a given layer (radius r) results from the integration of all the effects due to the upper layers:

$$\sigma_{r,\theta \text{ or } z}(r) = \int_{s=r}^{s=R_{ext}} f \; [\, (E, R)_{core}, (E_r, E_\theta, E_z, \upsilon_{\theta r}, \upsilon_{zr}, \upsilon_{\theta z})_{foil}, S \,] \; T_r(s) \frac{ds}{s} \qquad \{6\}$$

Our formulation is similar to that of these authors, with the following differences:

(i) $E_r$ depends on radial compressive stress and on air layer thickness,

(ii) the equation is solved under two hypothesis: plane stress and plane strain conditions, while the previous authors only used the plane stress condition (narrow tape). The plane strain condition leads to the stress fields ($\sigma_r$, $\sigma_\theta$, and $\sigma_z$) in the center part of the roll where typical axial defects such as wrinkles can be observed.

(iii) the foil tension is not constant but is a decreasing function of the current outer radius $R_{rf}$. This point, which is a consequence of air exhaust phenomena will be detailed later.

## MECHANISM OF AIR EXHAUST

At each revolution, under the effects of nip roll and compressive stress, the air layer originally entrapped is partially exhausted through the roll edge: see Figure 6.

The thickness of air layer number I will be denoted as $(t_a)_{I,N}$ where N is the current total number of layers. After the superimposition of foil layer number N, the air layer thickness of all the underlying foil layers $(t_a)_{I,N-1}$ (where I<N) will decrease:

$$(t_a)_{I,N} = (t_a)_{I,N-1} - (\delta t_a)_{I,N-1} \qquad \{7\}$$

The initial value $(t_a)_{N,N}$ is given by Hamrock and Dowson's theory.

The problem is to specify the amount of exhausted air $(\delta l_a)_{I,N-1}$. As quoted before, the thickness of the air interlayer comprise between two layers of film decreases when subject to a compressive stress. In order to study this effect, which depends on film surface topography, an experimental device has been developed in Rhône-Poulenc Films laboratory. A layer of film is applied onto a substrate. The air layer initially entrapped is then forced to exhaust (under a prescribed pressure P) and the time required to reach the new equilibrium value of the air layer thickness : $t_{eq}(P)$ is measured. This time, say $t$, depends on the following parameters:

$$t = f\,(t_a, P, \text{foil roughness, device geometry}) \qquad \{8\}$$

A theoretical model of this test has been elaborated in order to extrapolate the time values from the test conditions to the roll conditions.

Because of the complexity of the real air flow in the interlayer space, the film surface is homogenized: complex flow in the real space (with roughness and thickness $t_a$) is equivalent in terms of air rate to a flow in a perfect space (smooth boundary condition and thickness $\langle t_a \rangle$). The "equivalent" thickness $\langle t_a \rangle$ is obtained by solving the Navier-Stokes equations in the homogenized configuration under the assumption that the total air rate is equal to the experimental one (which is known).

## CONSEQUENCE: FOIL TENSION REDUCTION

Lateral air flow induces an irreversible evolution of the roll properties which must be taken into account in the stress computation. As previously detailed, at each superimposition of an upper layer, the air interlayer thickness $(t_a)_{J,N}$ decreases of a value denoted $(\delta t_a)_{J,N}$. During each superimposition a given foil layer of radius $(r)_{I,N}$, undergoes an irreversible radial displacement resulting from air exhaust out of the underlying layers:

$$(\Delta v)_{I,N} = \sum_{J=I-1}^{J=1} (\delta t_a)_{J,N} \qquad \{9\}$$

This radial displacement induces a reduction of the internal tension as given by:

$$(\Delta T_r)_{I,N} = (T_r)_{I,N} - (T_r)_{I,N-1} = E_\theta \frac{(\Delta v)_{I,N}}{(r)_{I,N}} \qquad \{10\}$$

Note that this formulation is based on the assumption of a concentric layer submitted to radial displacement only. It is known that under some specific conditions, experimentally well known and recently measured by Good (1992), an important circumferencial slippage can occur. This phenomenon can be associated with air exhaust without foil tension reduction.It is mainly connected with the thickness value of the air layer: above a critical value which corresponds to an "aeroplanning" mechanism, the contact between two adjacent foil layers is not sufficient to avoid circumferencial slippage. This phenomenon is taken into account in the model presented here. Note that the evolution of the air layer thickness is a key point to understand circumferencial slippage.

The total radial displacement of a given layer is the sum of two components:

(i) a reversible component due to elastic radial compression, which can be evaluated by the well known stress computation used by all the authors,

(ii) an irreversible component due to air exhaust mechanism, as proposed here.

Foil tension reduction only depends on the second component. When aerodynamical effects can be neglected (low velocity), there is no air exhaust phenomenon and thus no tension reduction. The common assumption (constant foil tension), used by all the authors is valid in this case.

It is interesting to note that Good et al (1992) have recently concluded that under conditions in which aerodynamical effects cannot be neglected (winding without nip roll for example), a better agreement between theoretical formulation and experimental results is obtained with a value of the foil tension lower than its nominal value. Good suggested an explanation in terms of elastic compression of radius, which is not quite satisfactory. In a recent publication, Good (1992) proposed to add to the foil tension a component proportional to the nip force. Under our assumption, we do not need to introduce such a component but both approaches are in good agreement in terms of increase of stress values due to the nip force effect.

## EXPERIMENTAL DATA

The predictions of our model are validated in a few typical configurations, focusing our attention on aerodynamical effects and foil tension reduction.

The average residual air layer thickness $t_a$ is easy to evaluate through the measurement of the roll apparent density $D_r$ knowing the foil density $D_f$ and thickness $t_f$:

$$t_a = t_f \left[ \frac{D_r}{D_f} - 1 \right] \qquad \{11\}$$

This simple formulation is based on the asumption that the foil material is less compressible than the other "medium" made of air and roughness, which is quite satisfactory for plastic films (but not for paper). This parameter is very sensitive to all the governing parameters: foil properties and winding conditions.

It has been displayed in the Figures 7,8 and 9 the variations of the residual air layer thickness values for various velocity, tension and nip force values and for several thin PET films. Fairly good agreement exists between predicted values and experimental results in a large range of parameters.

It can be seen that the foil velocity has a large influence on the residual air layer thickness (same order of magnitude as nominal tension effect) and in turn on the residual tension. The foil tension of a given layer can be evaluated by using the following procedure: after winding, all the upper layers are cut off in their axial direction. According to Hooke's law, the circumferencial relaxation of the foil is proportional to its current circumferencial stress (residual tension): Figure 10.

Because of the inaccuracy of the measurement of the circumferencial relaxation, this technique only provides an order of magnitude.

It has been reported in table 1 two series of experimental data and theoretical predictions. Several remarks can be made:

(i) The large difference existing between the initial winding tension and the measured tension is the proof of air exhaust phenomena in our winding condition: $V = 6\ m.s^{-1}$,

(ii) Fairly good agreement exists between the predicted values and the experimental results.

## DETAILED ANALYSIS OF THE THEORETICAL PREDICTIONS

We propose to discuss here more in details the distribution within the roll of the main winding parameters. The foil considered is a thin smooth PET film (thickness about 12 µm) produced by Rhône-Poulenc Films Company and used for magnetic coating. The nominal winding conditions are: velocity = 6 $m.s^{-1}$, tension = 10 MPa, nip force = 1000 N/m. They remain constant during the winding process.

*Thickness distribution of the entrapped air layer: Figure 11*

Under the winding conditions (constant values of velocity and nip force), the thickness of the entrapped air layer slightly increases from the core to the outer layer: 0,25 µm up to 0,25 µm. This trend is associated with the increase of the current radius of the roll in formation.

*Distribution of the equilibrium value of the air layer thickness: Figure 11*

This curve represents the equilibrium value as a function of the pressure distribution which results from the ultimate superimposition. If the current air layer thickness is higher than this equilibrium value, the air layer is not in an equilibrium state: it is a transient state and air is continuously exhausting.

*Thickness distribution of the residual air layer: Figure 11*

The thickness of the residual air layer, which is the difference between the entrapped and the exhaust values, offers a typical shape:

—> from 0 m to 600 m, the thickness strongly increases: 0,20 µm up to 0,28 µm. This part can be called the "core zone effect".

—> from 600 m to 8000 m, the thickness remains constant or slightly decreases: 0,28 µm down to 0,24 µm. This average value is mainly governed by roughness and the main winding parameters. This central zone is in an equilibrium state.

—> from 8000 m to the end, the thickness strongly increases 0,24 µm up to 0,45 µm. This outer zone is out of the equilibrium: the air layer did not have enough time to reach its equilibrium value and air will continuously exhaust after winding. For this reason, this zone is very critical and subject to the occurence of aspect defects (even after winding), as observed.

*Radial irreversible displacement distribution ($u_r$): Figure 12*

The irreversible radial displacement of a given foil layer is the sum of the air exhaust thickness of all the underlyings foil layers after the superimposition of this given foil layer. The displacement is equal to zero for the first layer (no underlying layers) and for the last layer (not yet air exhaust mechanism). Note that the order of magnitude of this irreversible displacement is one mm.

*Radial stress distribution ($\sigma_r$): Figure 13*

This stress is always negative: the foil is in a compressive stress state. Near the core, the compressive stress rapidly decreases: - 0,40 Mpa down to - 0,15 MPa. The initial value is strongly connected to the core mechanical properties. In the central zone, the radial stress slightly increases: - 0,15 MPa up to - 0,22 MPa. In the final zone, compression decreases down to zero.

*Circumferencial stress distribution ($\sigma_\theta$) : Figure 14*

Depending on the location within the roll, it can be either negative (central zone) or positive (near the core and in the outer zone). In the central zone, the circumferencial stress value remains constant: - 0,24 MPa.

*Residual tension ($T_r$): Figure 15*

The residual tension results from film anelastic recovery due to air exhaust. It remains positive, with an average value comprise between 3 an 6 MPa (30 and 60% of the tension nominal value). Near the core and the outer zone, the residual tension is very close to its nominal value (10 MPa).

Note that circumferencial stress and residual tension are two sligthly different parameters: (i) the circumferencial **stress** in the current stress in the roll and (ii) the residual **tension** can be seen as the circumferencial stress of this layer if all the upper layers were removed.

For a given layer, the difference between circumferencial stress and residual tension values is due to the elastic compression of the upper layers.

*Axial stress ($\sigma_z$) Figure 16*

This value must be considered only in plane strain conditions, where it turns out to be a linear combination of radial and circumferencial stresses. It is always negative (axial compression) and looks very similar to the radial stress profile.

## CONCLUSION

Evaluating the stress field generated in a roll of a thin flexible medium wound under industrial conditions is a difficult challenge because it involves complex aerodynamical mechanisms, in submicronic spaces, coupled with problems of non-linear solid mechanics. The model proposed here is an extension of the existing model in order to incorporate the effects of air entrainment and exhaust. Under these assumptions, all the main parameters which govern the winding process are taken into account: nip force, velocity, tension, foil mechanical properties and surface topography. Note that the effects due to the other parameters such as nip roll diameter or nip roll mechanical properties can be studied.

Good agreement exists between the experimental data (average residual air layer thickness, residual tension) and the theoretical predictions for a large range of parameters. A few possibilities offered by the model are presented: evaluation of the stress field like the other classical models do, but also evaluation of new parameters such as distribution within the roll of entrapped and residual air layer thickness values, residual tension...

On the basis of the new approach presented in this publication, several improvements can be done in order to take into account axial disymetries: widthwise foil thickness non-uniformities, wound foil or nip roll bending... These studies are in progress.

## ACKNOWLEDGEMENTS

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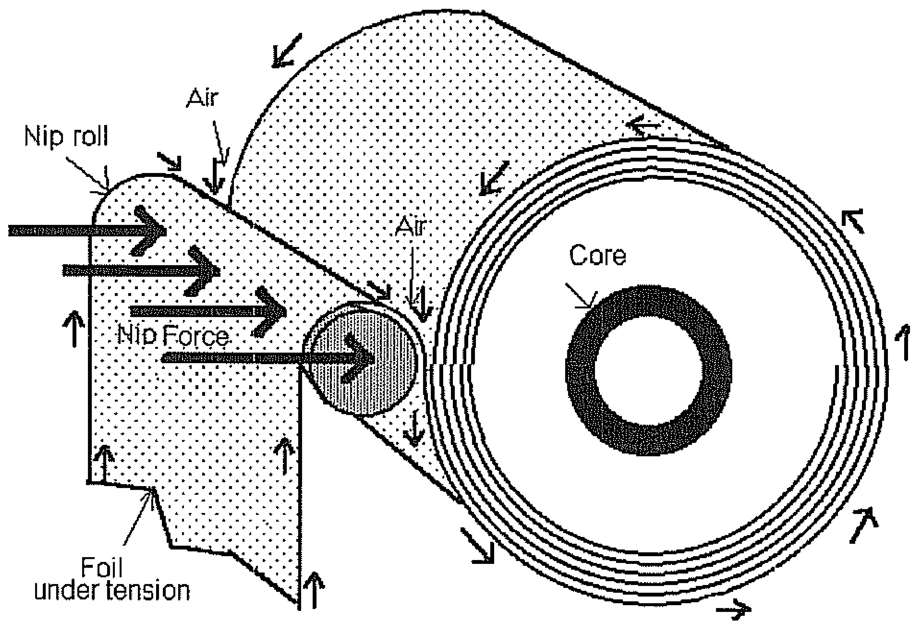


**Fig. 1 Basic configuration of center winding**

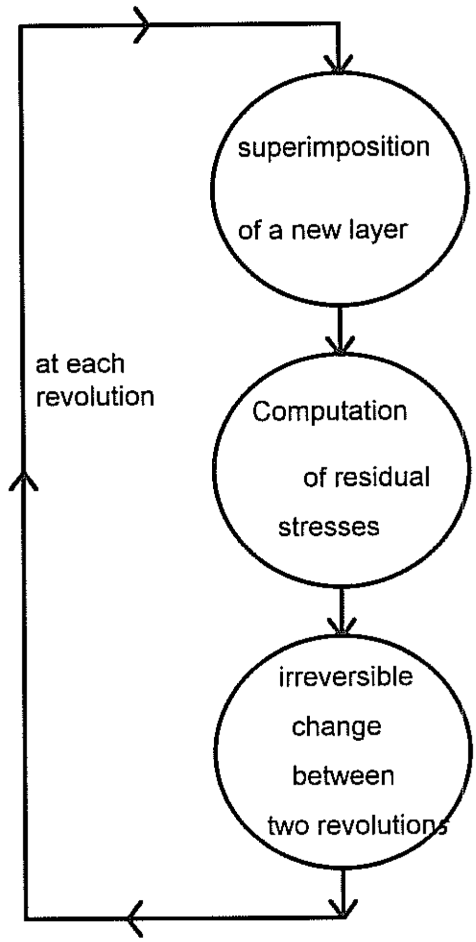


**Fig. 2 Principle of the global approach**

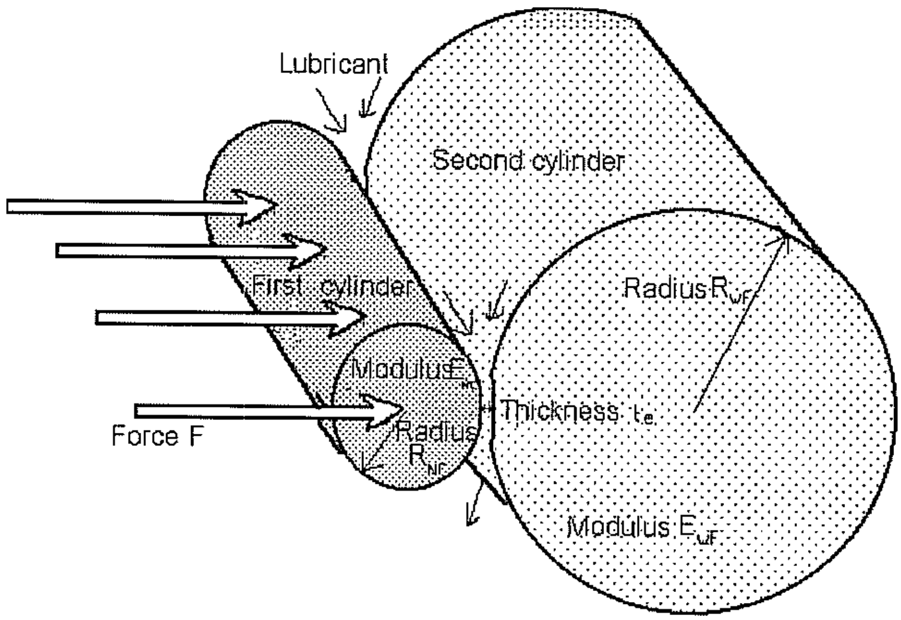


**Fig. 3 Elasto hydrodynamic lubrication of two rolling cylinders**

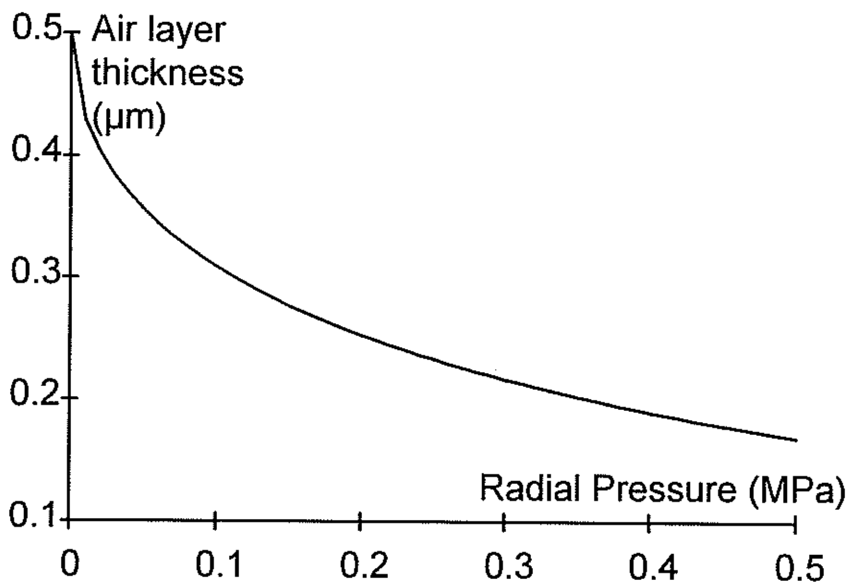


**Fig. 4 Air layer thickness versure pressure**

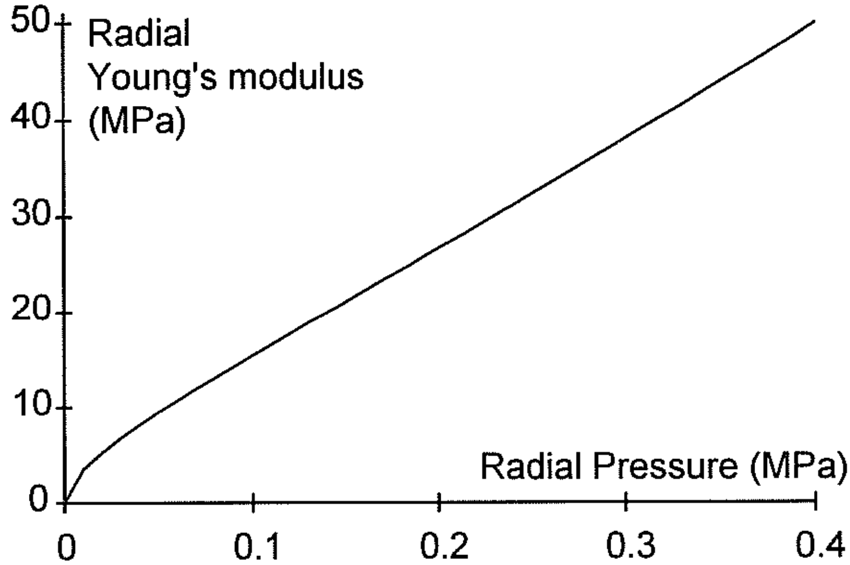


**Fig. 5 Radial Young's modulus versus pressure**

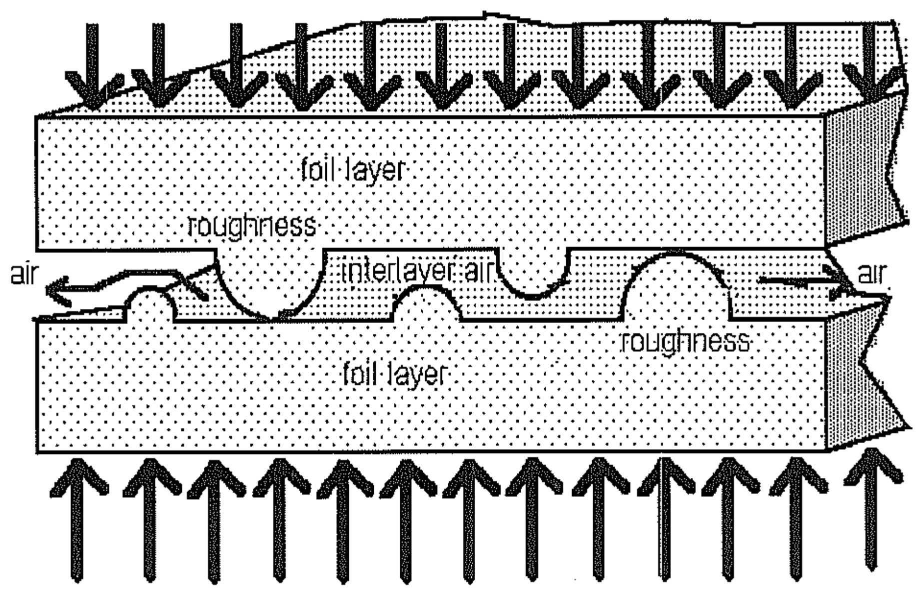


**Fig. 6 Air exhaust phenomenon**

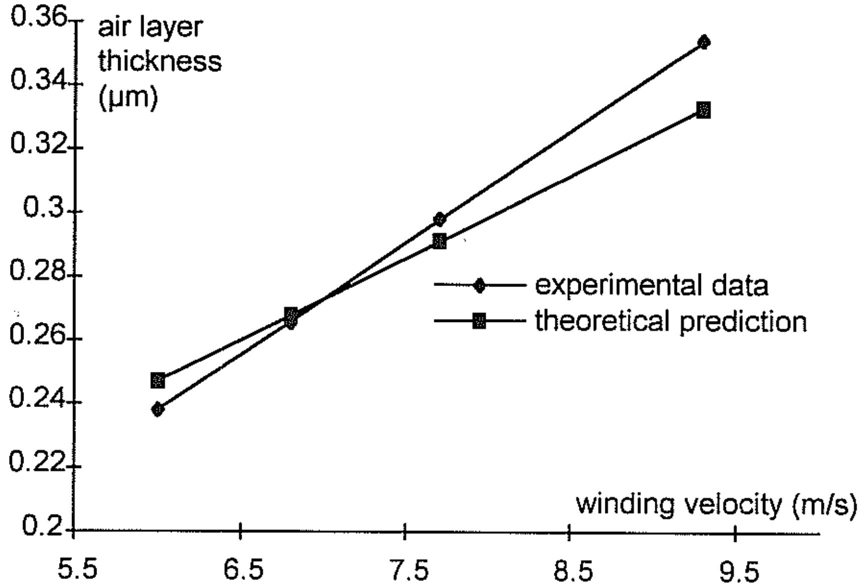


**Fig. 7 Average air layer thickness versus winding velocity**

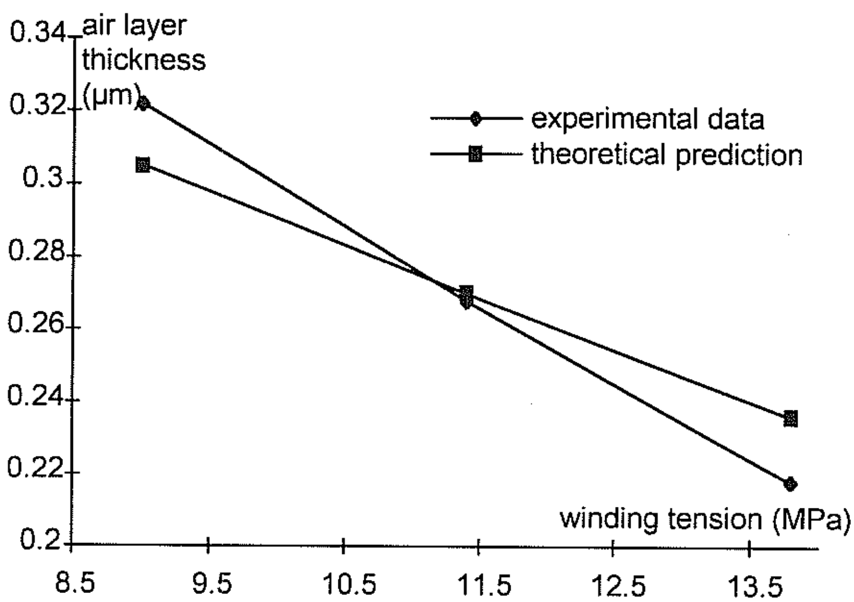


**Fig. 8 Average air layer thickness versus winding tension**

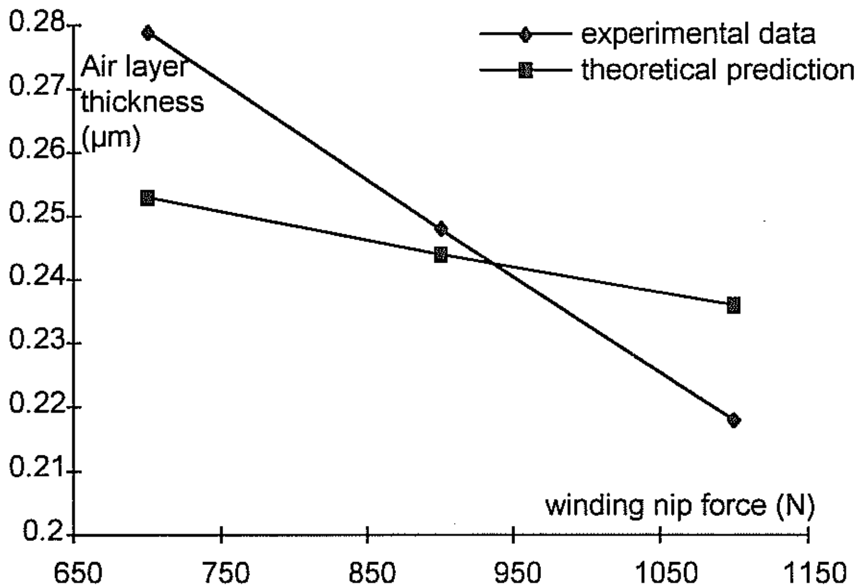


**Fig. 9 Average air layer thickness versus winding nip force**

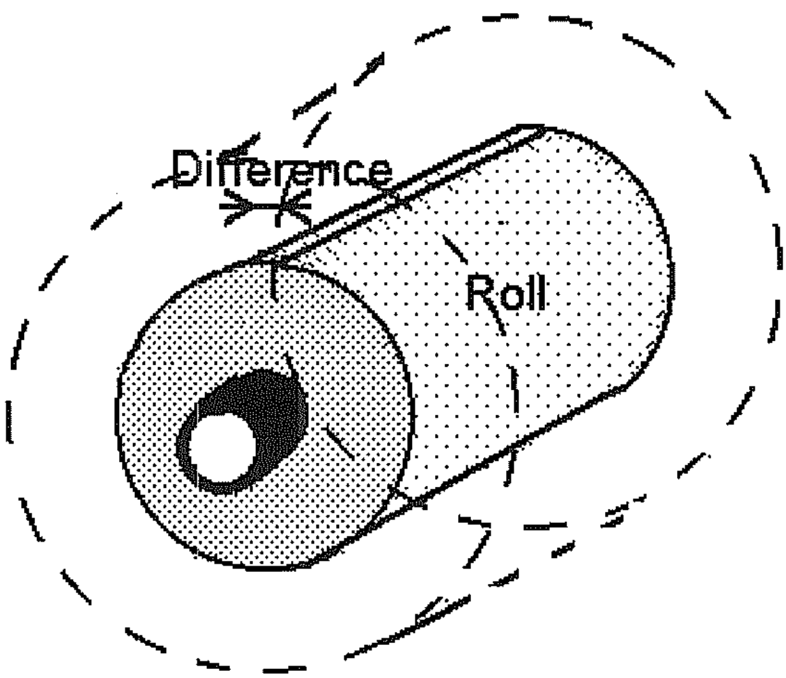


**Fig. 10 Principle of the measurement of the residual tension**

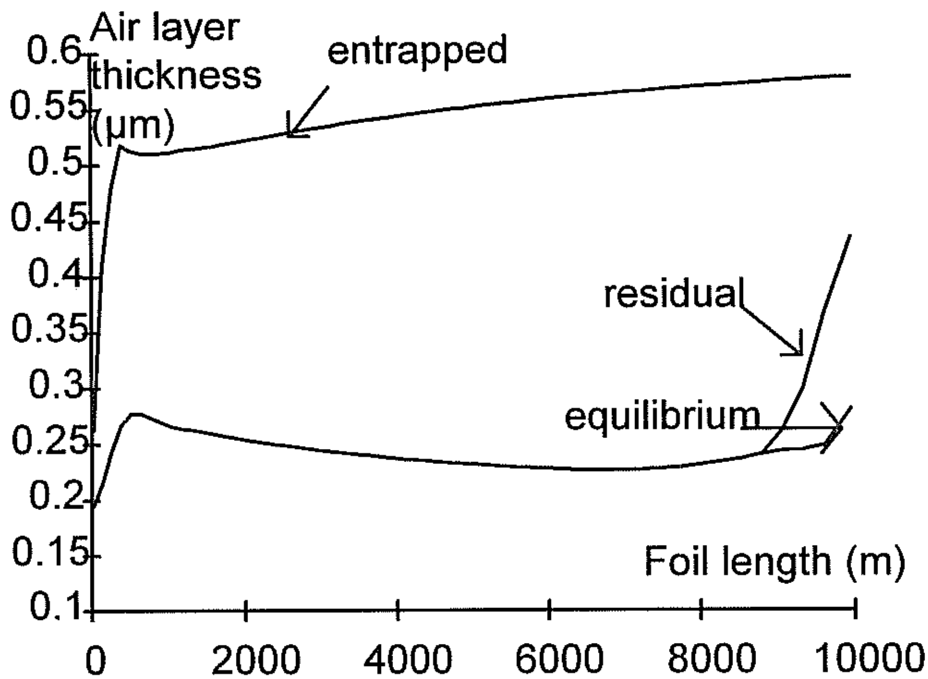


**Fig. 11 Entrapped, equilibrium, exhaust and residual air layer thickness distribution versus foil length**

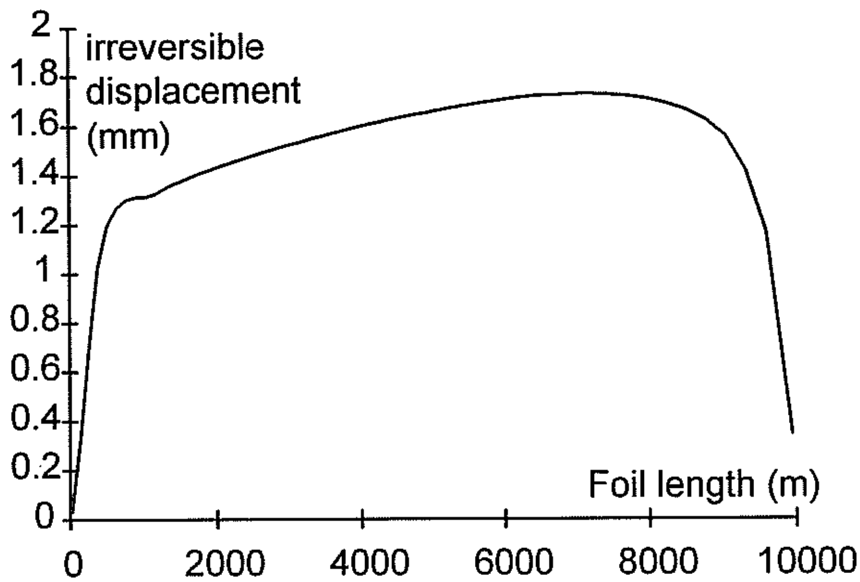


**Fig. 12 Radial irreversible displacement distribution versus foil length**

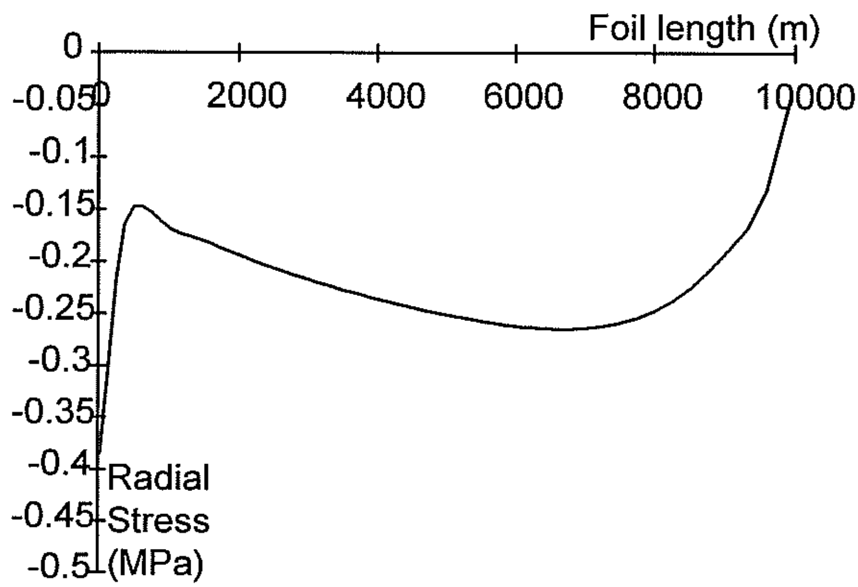


**Fig. 13 Compressive radial stress distribution versus foil length**

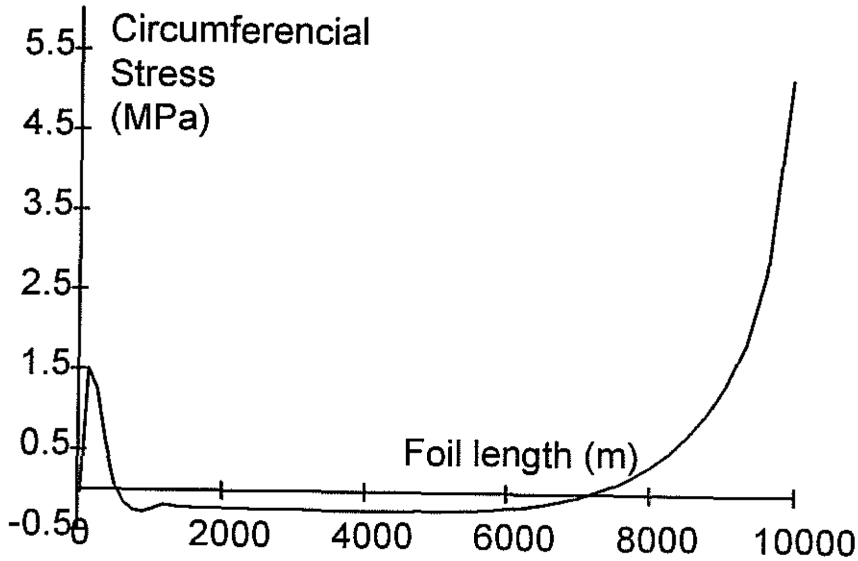


**Fig. 14 Circumferencial stress distribution versus foil length**

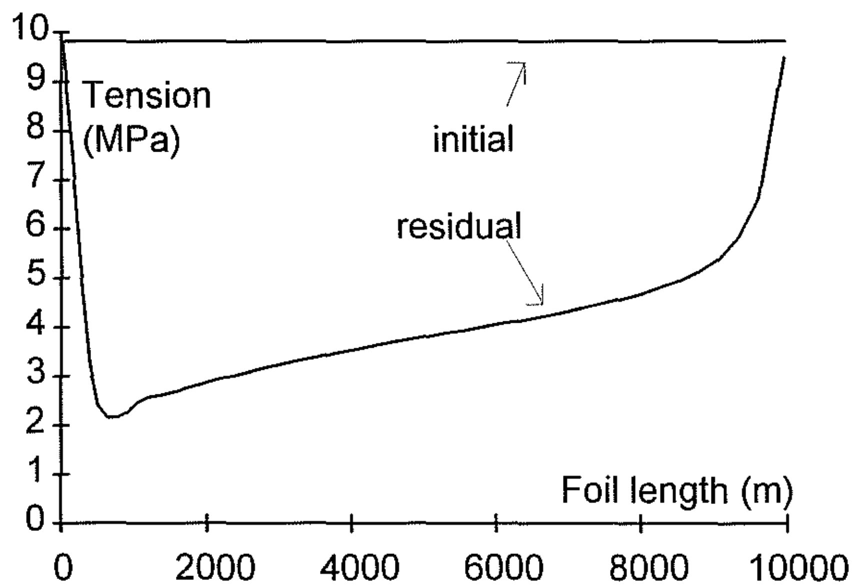


**Fig. 15 Residual tension stress distribution versus foil length**

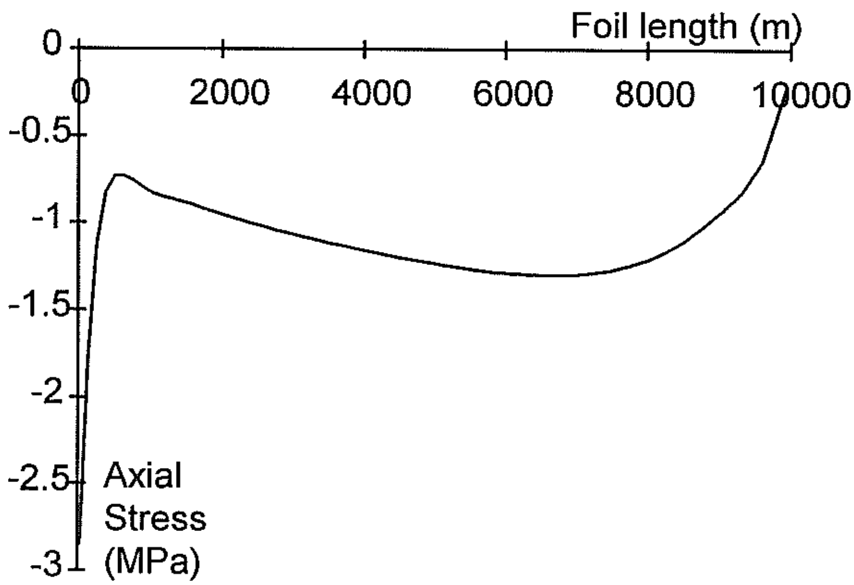


**Fig. 16 Axial stress distribution versus foil length**

**Table 1**

**Foil residual tension**

| Winding tension (MPa) | Measured residual tension (MPa) | Estimated residual tension (MPa) |
|---|---|---|
| 13.2 | 6.7 | 4.8 |
| 9.0 | 4.2 | 4.0 |

## QUESTIONS AND ANSWERS

Q. Can you precise the order of magnitude of the main parameters used in your model?

A. The typical web thickness is 12 micro meters and typical width is 1 1/2 meters. The winding process is done on a pilot machine. The web tension is 10.MPa. The Young's modulus is about 4.5 gpa.

Q. Can you give us more information about your apparatus meaning the ability of the film to exhaust air?

A. As I understood you wanted to know how we measured the time required to reduce the initial air layer of thickness and our given compression conditions. Actually, we measured that on a specific device using samples of films, basically, by optical ways. So, under given compression we measure the time required to reach the equitable value. You see, by optical ways, you see the Newton rings and you can measure the progression of this through Newton rings during your experiment. After that, of course, it's necessary to model this experiment in order to extrapolate these results to the actual situation.

Q. Have you considered verifying your model on air layer thickness value? Did you use wound roll density as a roll structure to evaluate your model?

A. We have done a lot of measurements of roll density as a function of velocity, nip force and winding tension for various thickness, and t hand length.

A. I think I have here a few slides which were presented at the ASME Winter Annual Meeting in November, which was focused on density measurements and various processing conditions, if I can find them. The first curve represents the nominal velocity versus the average value of the air inner layer of thickness which is obtained through the upper density measurement which is reduced, knowing the film thickness and so forth, it is very easy to obtain the average value of the air interior density and the dark square, the black square corresponds to the experimental data for lower roughness value. So, these results have been obtained for various types of film, topographies, either rough or smooth. So, this dark square corresponds to experimental data for lower roughness values. Now, for high roughness values and corresponds to the white rectangle and the other one for vertical experiments. So, basically, the upper curves correspond to the nominal value of the velocity plotted versus the average value of the air thickness. The lower curve would correspond to the nominal value of the tension plotted versus the average value of the air interior thickness. For rough or smooth films. And you see the correlation is fairly good based on these measurements and people of the art know well that the upper roll density, specifically in polyester film manufacturing, is a very good indication of the actual process conditions. If you have, for some reason, a change in the nominal tension or the nip force, then you would first observe the wrinkles of the effects and you can detect that through the measurement of the upper end of the roll. So, this is a good indicator of the stress state you have in your roll, and we use it because, as I said before, it's difficult to have other experimental results on the roll. So, we use it as a pertinent way to validate the model.

Q. The elastro hydrostatic equation that you solved was very complex, but in this application it is even further complex because of the radial modulus in the winding rolls. I wonder if the logical step was first taken to a simpler case where you looked at hydro dynamic equations rather than elastro type of equations.

A. I think, considering hydro dynamic equations would overestimate the value of the air layer between the nip roll and the roller, and I think that the fact that the EHD theory can not be applied directly here due to the elastic behavior has been taken into account in the model by modifying each step the value, by considering that each step it is tangent to an equivalent elastic model. The Young's modulus being calculated at each step and being readjusted at each step. So, we know that it's not the right way, but we tried by simply assuming that the rolls would be rigid and then we obtained an over value of the value of the film thickness. But we were sure that we had to improve this and to take into account, of course, the radial variation of this radial modulus.