PHENOMENS OF ROLLING CONTACT IN PAPER CALENDERING

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ABSTRACT

In soft calenders synthetic roll covers are “state of the art”, without knowing their detailed rolling contact behavior and their phenomenological effects to gloss and smoothness of paper. Complex interactions of process and material parameters lead to time consuming adjustments of the machine settings. Regarding the interacting material parameters the mechanical paper properties are as important as the elastomer cover properties of the rollers. This challenged coupling of the threesome paper, cover and process typifies a limit for new innovations in calendering. That is why present development objectives in calendering for example to higher calendering temperatures and higher process velocities have to be tested in practice as black box solutions concerning their effects.

Present research activities are focusing on the thermo mechanics in the interaction of process and material parameters of the rolling contact of the calendering nip. With advanced knowledge on the paper properties [2, 4], with the theory of rolling contact and with the knowledge of the influence on runnability and printability parameters, it is possible to discuss phenomenological rolling contact effects on a macroscopic level. The results point out that the physical attributes of roll cover material and of paper material have to be analyzed along with the process parameters in order to achieve improvements in calendering.

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The investigated interactions motivate a new evaluation of the calendering process under consideration of mechanic, thermal, hygroscopic, visco-elastic and rolling contact effects. This point of view is close to reality and permits the detection of physical interactions in the calender nip. From these detected dependencies we can formulate conclusions to gloss and smoothness behavior as well as to the other printability and runnability parameters.

To reduce time consuming process optimization in production, precise details on optimal machine settings in the process can be delivered. Although details to paper and roll cover properties for calendering can be given by identifying the physical interactions in the rollers' nip. Knowledge of these interactions will reveal the basic calender processes.

INTRODUCTION

The calendering process is defined as a thermo-mechanical compression treatment of paper which is performed by rollers under high velocities. Processing causes deformation heating and moistening of paper at its run through the calender.

Present research work is successfully done on calendering [5] to find the complex interactions of material and process parameters.

Throughout the years the paper mechanics reach an excellent state in mapping the uni-axial [6, 7,8] and in and out of plane the non-linear multi-axial paper properties [9, 10, 11, 12, 13, 14, 15] up to formulations coupling the physical interactions in ZD-compression[4] with MD[5]-ZD- respectively CD[6]-ZD-shear [2, 4, 13, 16, 14]. In the latest formulations plastic effects, loading and unloading behaviour and yield and hardening conditions are considered.

Material research on the elastomer covers is missing in present literatures. Especially structural mechanical analyses of the applied highly filled and restrained elastomers are not jet published. There is only some basic information by Gamsjäger [17] to get a rough idea on the thermo-mechanics of roller covers for calendering.

The advanced theory of rolling contact [18] has not yet reached calendering. This has its reason in the effort for specific continuum mechanical approaches for calendering modeling which are not implemented in common finite element systems. Furthermore the calendering specific boundary, geometric, contact and loading conditions and the missing material properties prevent from applying these tools onto the thermo-mechanical calendering process. This status will not change very soon, as multi-physical interactions (mechanical, rheological, thermal and hygroscopic) [3] and numerical scaling phenomena have to be solved parallel, before applying them on the runnability and printability parameters.

Despite of this gap there are multiple possibilities to forward calendering research and to discuss phenomenological rolling contact effects on a macroscopic level with analyzes of the calendering technology, with advanced knowledge on the paper properties [1, 2], with the fundamental theory of rolling contact and with the knowledge of the influence on runnability and printability parameters. This will help increasing process velocities and reducing energetic efforts of calendering.

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[4] ZD: thickness direction (radial), compare Figure 4Figure

[5] MD: main direction (tangential), compare Figure 4

[6] CD: cross direction (axial)

STATE OF CALENDERING TECHNOLOGY

There are two basic technologies for paper calendering. In the hard nip, the surface is leveled by constant thickness at fluctuating density. In a soft nip, the density is leveled constant at fluctuating thickness [19]. In addition new calendering methods as shoe and metal belt calenders were developed.

At equal geometries (outer radius) and loadings (line-loads) the soft-nip produces lower plastic deformation in thickness direction of paper than the hard-nip. The differences between soft-nip and hard-nip calendered paper in its optical properties is remarkable. The hard-nip can produce mottling and fatty gloss [20], as the soft-nip results in irregular profiles, less gloss values and printing irregularities (blotches, mottling) [21]. Regarding line loads is insufficient to physical calendering analyzes. Depending on the rollers structure, rollers materials and contact partners the produced stresses in the nip differ of more than 60%, as analyses at the LMK show [5, 22].

At soft-calenders soft-rollers are rolling against thermal hard-rollers. The main effect on paper surface is determined on the heated rollers side, especially leading to gloss and smoothness. In the complex calendering system the stress distribution in the nip is primarily determined by the geometrical roller dimensions, the structure of roller and the physical (thermal, mechanical, dynamic) characteristics of the reference materials, and secondarily by the dimension, structure and physical characteristics of the paper web [6, 23]. The applied line loads causes a three-dimensional force-deformation state inside the nip, whereby sliding and sticking apply tensile, compression and shear stresses on the paper web surface. Depending on rollers and calendering details, changes of the line-loads affect the stress-strain-state in the nip zone during transient processes. These over the linear loads indirectly applied stresses are strongly dependent on the paper and its characteristics, the passing nips and their configurations as also on the desired quality.

Especially in elastomer covers, coating and paper, energetic loss occurs during loading and unloading through the cyclic deformations in calendering by hysteresis [24]. With the time, the hysteresis effects abate to a constant level which is a measure for the inner damping behavior of the materials. It will be transformed into heat.

Soft calenders are produced with a single or multiple nips. The process's innate two-sidedness can be annihilated by a changing nip or with the installation of two calenders with inverse roller setup [6].

Calendering Rollers

In multi nip calenders **hard rollers** are used to apply heat onto the paper web. As calenders advance in the soft-nip technology to higher loadings, temperatures and velocities, materials used to make the hard rollers must improve with them. Based on chilled cast iron, chrome carbide and tungsten carbide, advanced surface layers are developed [22, 26] to ensure excellent hardness, surface wear resistance, strength necessities, and heating performance [25].

Thermo rolls can be peripherally drilled rolls with one or two sets of peripheral holes to perform the surface temperatures. Present research is done on external heating with induction. Hard rollers can be produced with a deviation in roll shape of less than 1 μm and with surface temperature variance below 2°C. Hot grinding during manufacture eliminates concentricity faults and edge area distortions [27].

The rollers surfaces wear through friction and strain induced slip [25]. Therefore the rollers have to be ground, with hard rollers less frequently then soft rollers whose surface has to be worked over after a few weeks in use. These roughening behavior proofs the existence of wear phenomenon between the paper and rollers surfaces by rolling contact.

The long recovering intervals of hard rollers display the good contact paring against friction in calendering.

The described surface recreation is done with specialized grinding and turning procedures using to up to four referential points to eliminate geometric errors in MD and CD [1].

Elastomer covers of **soft rollers** are industrially used since 1997 (first application in the multi nip calender “Oulu Mill”, Finland). With raising soft-calendering technology, they substitute cotton and paper covered soft rollers [28].

The development of composite materials for soft rollers initiates an amount of important advantages for paper production and finishing. High-end composites have a great thermal stability and high strength resistance. They can be designed and produced individually with specific properties [22], as for example resistance against baring, vibration, wear and abrasion. Some of them even behave antistatic. In the industries they are defined by their application and their prominent property.

In calendaring, rollers are loaded by radial compression loads, high rolling velocities, and vibrations induced by irregular paper thickness, material inhomogeneities and geometric imperfections during rolling.

The elastomer covers themselves are micro composite materials. They base on a matrix consisting of epoxy resin or polyurethane [29] with high ratio of embedded fibers or powders. Depending on the production process (winding or casting) and the inner structure, orthotropic mechanical properties are superposed to the anisotropic behavior. Nowadays fiber or powder reinforced elastomer covers are considered as standard in the elastomer cover technology. The fiber reinforcements are executed as woven (i.e. glass, carbon) or non woven (i.e. aramid, cellulose) structures.

Phenomenological Effects on Gloss and Smoothness

The rolling contact behavior affects the printability parameters of paper, especially gloss and smoothness (respectively roughness). This influence bases on the complex interactions of force, deformation, time, heat and moisture dependent physical properties to the inner structure and surface expression.

The visual sense of **gloss** depends on physically optical, physiological, and psychological influences. Most important gloss properties are height and width of the gloss peak [31, 32]. Different measurement principles (DIN, Tappi) and angles (75°, 60°, 45°) complicate the comparability of measures. In calendering gloss changes with the specific force deformation behavior of the elastomer covers, the amount of passing nips, their temperature level and gradient, line loads, micro slip effects, velocities and coating. All these parameters interact in a so far qualitatively and quantitatively unknown manner.

So far there is no complete formulation for neither the emphasis of gloss nor its synthesis or prediction. Present research activities at the University of Toronto (Canada) [30] work on the development of a paper gloss model to describe paper gloss with an optical and geometrical approach. At the LMK the prediction of gloss depending on the physical calendering properties is performed.

In opposite to the optical phenomenon gloss, **smoothness** and roughness are structural properties. They are complementary to each other and measured indirectly by optical (Laserprofilometer [33]) or pneumatic (PPS) setups. Smoothness describes the evenness of a surface as measure compared to an ideal plane and roughness its irregular or regular deviation. Smoothness and roughness are expressed by the same calendering parameters as gloss. Additional parameters are the paper composite structure and manufacturing influences from forming, heating and coating section. Smoothness itself is one of the major properties for the papers value in use [31].

First predictions of calendering effects to the runnability effects are developed by Crotogino [34, 35, 36, 37] through phenomenological analyses. New approaches in the prediction of printability parameters through calendering are performed at the LMK [5] on a physical and process related basis to optimize calendering in paper quality, energy consumption and production.

The analyses of the present state in calendering research displays very clearly that a more intensive view on the nip mechanics is necessary to increase quality and productivity of calendering. Regarding these necessities, focus is given to the coupling of initial physical and structural paper properties with the calendering parameters leading to printability and runnability properties after calendering.

TOOLS AND METHODS FOR ANALYSING ROLLING CONTACT IN CALENDERING

Process specific physical parameters for gloss and smoothness production in calenders have to base on detailed knowledge on the stress-strain formation, temperature gradient and surface properties in the nip zone. At best, the mechanical forces and deformations in the nip can be measured experimentally and transformed to the corresponding stress-strain state. Analytical calculations and numeric computations complete and support the evaluations.

Experimental Methods

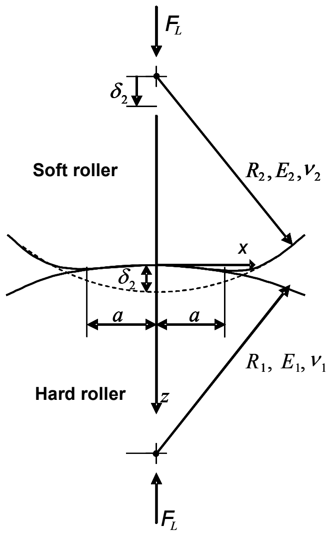
In calendering, the direct experimentally detection of the appearing forces and deformations is only possible for the static case of two identical rollers without a paper web in-between. It can be performed by strain gates (e-nip) [1] or special pressure sensitive papers. As a paper is inserted, and as the rollers contains different materials or structures, the geometric properties of the nip change non-symmetrically. With its own thickness (in the range of paper), stiffness and force-deformation behavior (in the range of the elastomer covers) a strain-gate can give estimations to the real nip-mechanics concerning the static case to detect existing phenomena and verify analytical or numerical calculations. For running processes experimental setups aren't developed so far.

Analytical Methods

Hertz theory [38] is origin of analytical sphere and cylinder contact calculations, on which the fundamental analytical work of Johnson [39] and multiple calendering analysis [17, 40] bases on. Direct analytical calculation of the rollers' and paper's mechanical behavior inside the nip are prevented from nonlinear material behavior (physical nonlinearity), discontinuous geometries (geometric nonlinearity) and nonlinearities caused by boundary conditions [39]. They are only valid for free rolling, where no tangential shear appear – this can be the changing nip and the hard nip when identical rollers are driven with identical angular velocities with neglecting elastic, viscous, plastic and kinematical effects.

Therefore simplifications are used for analytical approaches, which produce differences to the existing nip width $2a$. Mostly it becomes smaller, when hard rollers are assumed as rigid or the rollers' design is neglected. Regarding the thick walled hollow soft rollers with cover thicknesses of 10 mm to 20 mm at radii of about 600 mm, these analytical calculations give a first estimation of the force deformation behavior inside the nip.

In calendering nip width, nip pressure and surface shear are the contact determining measures.



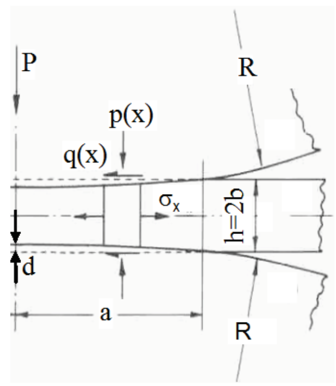


Figure 1 – General soft nip (left) and half a nip of identical elastic rollers with an elastic web in-between by Johnson [39].

To get an analytical solution for the **nip width** $2a$ an equation was build up by Johnson [39] (eq 10.5)

$$\left(\frac{a}{a_0}\right)^2 = 1 + C\frac{b}{a} \qquad \{1\}.$$

Therein C denotes the material related factor (compare Johnson [39] eq 10.1) and $h = 2b$ is the undeformed web thickness. This formulation is valid for elastic rollers, elastic web material and plane deformation. It contains the change in the roller's arc through an adapted radius R' (compare [39] eq. 10.3). Under assumption of the contact width a_0 of an infinitesimal thin web width with $a_0 = \sqrt{4P_L R(1-\nu_2^2)/E_2}$ ([39] page 314) equation 1 was developed. Analytically, this equation was unsolved so far.
Using computational solvers, we determine two complex solutions of Johnson's differential equation and the non complex physical solution of the **resulting contact width** a of the nip:

$$\begin{aligned} a = &\frac{1}{6}\left[108a_0^2Cb + 12\left(-12a_0^6 + 81a_0^4C^2b^2\right)^{1/2}\right]^{1/3} \\ &+ 2a_0^2\left[108a_0^2Cb + 12\left(-12a_0^6 + 81a_0^4C^2b^2\right)^{1/2}\right]^{-1/3} \end{aligned} \qquad \{2\}$$

Assuming that the compression of the roller is much smaller than the web compression the **maximum nip pressure** $p_{\max} = p_0 = p(x=0)$ compare ([39] eq. 4.45) can be calculated with the normal contact of elastic solids

$$p(x) = \frac{2P}{\pi a}\sqrt{\left(1 - \frac{x^2}{a^2}\right)}$$ {3} ([39] eq. 10.2),

containing the average radius R and the average elasticity modulus E^*.

The **tangential traction** $q(x)$ is assumed as upper limit when no friction can take place with the material related variables α and β as

$$q(x) = \left(1 - \frac{4\beta}{1+\alpha}\right)\frac{b}{2a} p_0 \frac{x}{\sqrt{(a^2 - x^2)}}$$ {4}([39] eq. 10.9).

In this formulation the tangential forces $q(x)$ become zero at the contact border $x = \pm a$.

The transferred tangential forces in the contact zone depend on the friction coefficient for sticking and slipping. Exceeding the frictional stick coefficient, frictional slipping and micro slip occur.

In rolling contact of cylindrical bodies slip zones are located at the inlet and outlet of the nip [38, 39, 23, 18]. In this area the existing contact pressures are small compared to the tangential forces, so the slip conditions are fulfilled. For models meeting the calendering requirements, these analyses need to be analyzed discretely and iteratively. Therefore numerical methods have to be applied. The analytical methods are used to validate the numerical results.

Computer Aided Methods

The basic nip mechanics confirm the appearing of micro slip and strain induced slip, if rollers of different deformation properties and geometries directly or indirectly roll on each other. A web in between dealing as lubricant increases this effect [38, 39, 23].

In opposite to this theoretical physics of the nip, experiments with different roughnesses at different position inside the rollers stack attest the major effect of compression to smoothness and gloss. The effects from slip at the inlet and outlet are assumed as neglectable small and effectless [20].

Particularly regarding the physical contact background of strongly different behaving rollers [39] in addition to the paper mechanical behavior [2] great slip zones have to occur in machine direction at the inlet and outlet from the micro-contact-mechanical focus [5]. As experimentally proved [20] these micro and/or extension slip zones affect themselves as secondary influence on the printability characteristics.

Therefore the numerical method of finite elements appears as sole method to visualize the mechanics of inhomogenious thick shells including the mechanical phenomens inside the nip. Especially the non-linear visco-elastic-plastic material behavior [20] of the participating roller covers and paper materials force the use of numerical calculations. To perform appropriate simulations for gloss and smoothness related nip properties the exact mechanical material properties have to be determined in experiments primarily.

Presently nonlinear dynamic modeling of an inhomogenious two roller model containing nonlinear elastic-visco-plastic materialproperties under frictional contact reach the limit of technchnical simulation possibilities, especially if thermal, gyroscopic and mass dependent effects are regarded. In calendaring these effects play a major role effecting the nip's non-symmetric stress-strain expressions [20, 23].

ANALYTICAL PARAMETRIC STUDY TO THE HERZIAN CONTACT

An analytical parameter's study on the influence of the elastic modulus as representative of the roller's material property majorly expresses the contact properties in the calendaring and displays the importance of a detailed knowledge on the roller materials (hard roller: $E = 210\, kN/mm^2$, soft roller: $E = 10\, kN/mm^2$ respectly $E = 2{,}7\, kN/mm^2$). Afterwards the results of the general material influence onto the normal compression and shear stresses are pointed out for hard nips and changing nips.

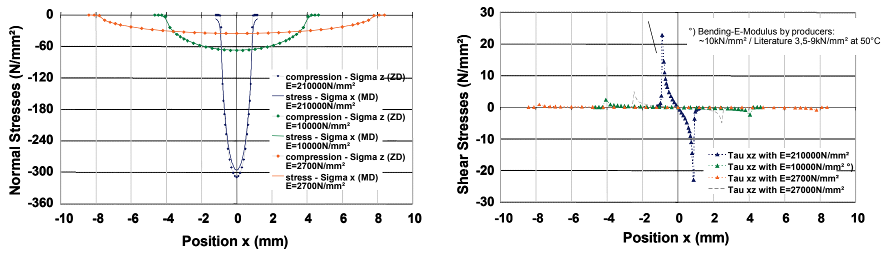


Figure 2 – Analytical calculated Hertzian nip stresses of two identical rollers ($R_1 = R_2 = 330mm$, $E_1 = E_2$, $\nu_1 = \nu_2 = 0{,}3$, and $F_{lineload} = 430\, N/mm$) located at the depth $z = 0{,}02mm$ below the surface at varying elasticity modulus.

The reduction of the elasticity modulus performs a flattening of the nip pressure as the nip length 2a increases. The influence on the calendaring results into longer contact time. Calendering becomes more carefull and the appearing streses at equal line loads reduce extraordinarily. For compression and shear they averagely decrease by a factor of 10 when the elastic modulus decreases by a factor of about 100. The maximal appearing compression and shear stresses behave nonlineary on the elasticity modulus.

Analysing a soft nip the results are comparable to the symmetric material paaring. Of course the nip width results smaller compared to the calculation with identical mechanical soft material behaviour. The difference is found with a factor of $1/3$. Compared to the symmetric soft changing nip, the compression stresses of a general soft nip appear about 1.75 times bigger and the shear stresses on factor 1.5 bigger.

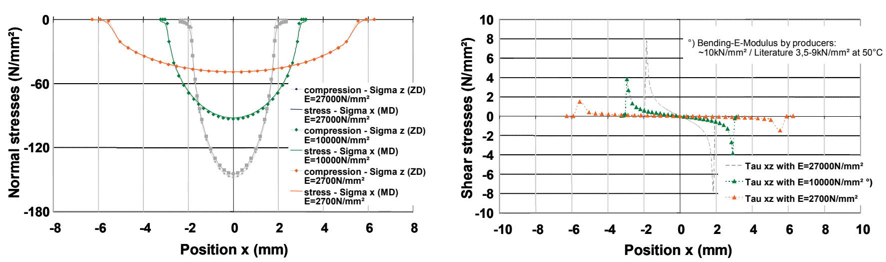


Figure 3 – Analytical calculated Hertzian nip stresses of a soft nip ($R_1 = R_2 = 330mm$, $E_1 = 210\, kN/mm^2$, $\nu_1 = \nu_2 = 0{,}3$ and $F_{lineload} = 430\, N/mm$) with different elasticity moduli E_2 located at the depth $z = 0{,}02mm$ below the surface at varying elasticity modulus.

QUASI-STATIC CONTACT ANALYSES OF A CALENDERING NIP

Finite-Elemente-Simulations are performed at partial nip models with quarter rollers and single nip models. The comparison of analytical and numerical basic models without paper show that the complex roller's behavior and the singularity at the initial contact lead to non physical stress-strain behavior at the partial nip models [44]. Compared to them the single nip models show a good quality [22]. They allow the analyzation of stress and strain inside the nip and can be enhanced to dynamic models.

Numerinal analyzes are performed on hard nips, soft nips and changing nips using the finite element program Marc-Mentat by MSC-Software. Aim was to determine the general behavior of the tangentional forces between the rollers, to forward the linkage between calendar settings, runnability and prontability parameters.

Modelling

Modeling a calender nip for mechanical analyze efforts a structural 2D-model which allows deformation in machine direction MD and in thickness direction (CD) of the paper web. The presented model illustrates the analysis of a stress-strain status at a single nip in calendering process. The details of the Finite Element model are presented in Figure 4 to calculate the stress-strain-behavior in the contact zones accurately and to identify the frictional slip areas. Therein those properties were considered, which influence compression and shear deformation behavior in the nip zone. The hollow cylinders, the layered elastomer covers, the boundary conditions, the loading and the orthotropic material behavior of paper and elastomer are modeled close to reality.

The **mesh density** has to be adapted to the efforts of the rolling contact. A fine mesh must exist at the outer surface, especially in contact. Therefore element faces with 4,3mm are chosen for the outer surface, refined up to 0,32mm in the contact zones.

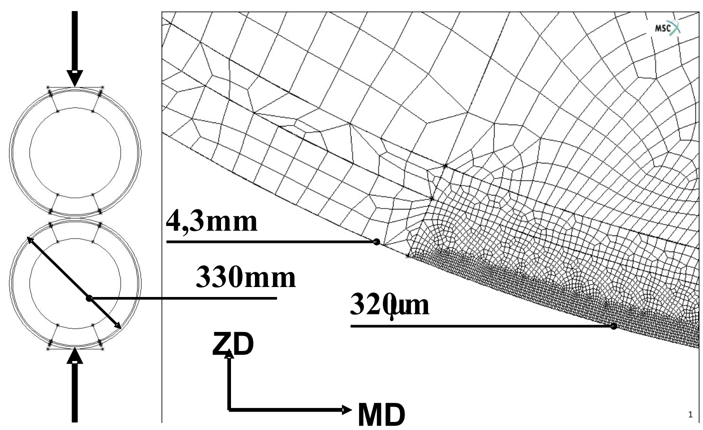


Figure 3 – Geometry (left) and detailed discretisation of the finite element model.

The **material properties** define the mechanical behavior of the model. The soft roller's inner **steel** cylinders and the hard rollers give the general cylinder behavior. They are assumed to be isotropic with standard iron properties. Their surface cover materials are neglected as chilled cast iron is also used as structural and surface material.

The orthotropic **elastomer** behavior of the soft roller's cover is determined from experimental analysis (E-Modulus) and estimated from literature values (ν [41,42, 43] and G), (Table 1Table).

	Orthotropic			Isotropic		Thickness
	E (N/mm²)	ν	G	E (N/mm²)	ν	h_0 (mm)
1st layer (Function layer)	900	0.35	500	–		11.2
	800	0.35	500			
	800	0.35	500			
2nd layer (Base layer)	900	0.4	500	–		6.3
	1200	0.35	500			
	800	0.32	500			
3rd layer (steel layer)	–			210000	0.3	140

Table 1 – Material properties of the analyzed elastomer roller in the soft nip.

Due to the rare information on the specific elastomers developed for calendaring rollers [5], literature values for elastomer covers [17] were analyzed. Most of the literature values are experimentally analyzed using bending tests over the whole height of the composite structure. Compared to them, the experimentally determined elastic moduli appear to be too soft. Therefore a parameter study for the elastomers is performed covering a wide range of stiffness values (900 N/mm² up to 10000 N/mm²). Present studies on the elastomer cover material show nonlinear stress-strain behaviour in each layer. The soft cover material shows orthotropic behaviour which nonlinearily depends on the strain. These results could not be considered in the presented numerical models. To display the wide range of the modulus of elasticity it is displayed in Table 2Table. Therein the modulus is given for the stress rate of 50N/mm² which is the load limit given by the manufactures.

E-modulus at 50 N/mm²	**Function-Layer**	**Base-Layer**
MD (tangential)	**4.000 N/mm²**	**> 10.000 N/mm²**
CD (axial)	**5.000 N/mm²**	**≈ 12.000 N/mm²**
ZD (thickness)	**4.000 N/mm²**	**> 6.000 N/mm²**

Table 2 – E-Modul of calendering soft-cover material at a compression rate of 50N/mm² (load limit).

If a **paper** web is inserted into the nip, the paper material is modeled by an implemented user subroutine [22] to generate the orthotropic material behavior. The specific material properties are taken from experimental analysis [2, 22].

The **boundary conditions** have to be set in accordance to the mechanics and kinematics of the calender's roller stack. The line load has to be applied to the rollers from the opposite side of the nip as distributed load. They are applied with a maximum of 430 N/mm from the upper roller and beard at the bottom of the lower roller. Application and bearing are performed through frictionless contact by a rigid line. For quasi-static mode, the rollers are prevented from moving out of the symmetry axis.

In the modelling case with a paper web in-between, the paper web with a thickness of 0,159 mm is loaded with tension in accordance to real calendering settings. The tensile load is applied as symmetrical deformation of 0.3081 mm in MD direction determined from general the force-deformation behaviour.

Rollers and paper are declared as deformable bodies which surfaces can come into contact. The friction coefficients is assumed to be $\mu = 0.3$.

Validating the Numerical Model

Numerical modeling includes unestimatable numerical influences as there can be inappropriate boundary conditions, improper mesh density, element locking, scaling, or contact definition problems.

To ensure the physical accurance of the general model a single hard nip model is calculated analytically and compared with the numerical results. The hard nip is most suitable for this purpose, as it only consists of stell rollers, which causes acceptable errors compared to the necessary assumptions of the Herzian contact. The idealizations for the analytical model are homogenious full[7] bodies, steady surfaces, contact surfaces may deform different, small deformations and frictionless surfaces. Except the full cylinder and the steady surface all assumptions are compared. Regarding the line loads, the bending through the center hole can be regarded as small and therefore acceptable.

Generated by the stiff contact bodies, the narrow nip produces local irregularities basically caused by the discretisation. For the hard nip modeling the discretisation should be refined below the selected mesh density with 0,1mm edge length. The validation of the soft and changing roller nip is not mapped, as it matches excellent without artifacts.

The single nip model is also taken to model the paper web inbetween the rollers. For the hard nip huge differences are found in the nip compression. The compressive contact stresses are 3.3 times higher at an increasing contact width from 2mm to 12mm without paper compared to the simulation with paper. This behaviour is expectable against the background of the progressive compression behavior in thickness direction of paper.

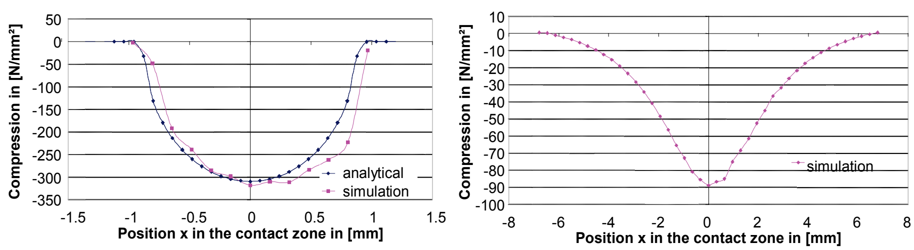


Figure 5 – Compression at frictionless contact ($\mu = 0$): numerical and analytical hard nip without paper (left) and the numerical results with paper web in between (right) without analytical validation.

Structural Results on the Rollers Behavior

A parameter study was performed to discus the structural behavior on a macroscopic level between the quasi-static single nip analysis with and without paper, based on hard, soft, and changing nip models. Therein the material properties of the elastomer coveres are modeled orthotropic, compare Table 1Table. The results of normal and shear stresses are analysed at a line load of 430 N/mm. The qualitative stress distribution of the calculated models in ZD is close to each other, but MD and MD-ZD-shear are different.

[7] without void volume

In general, a paper web in-between the nip decreases the normal stresses in the contact zone (compare Figure 5). This effect increases the harder the nip is performed. In structural roller analyses (Figure 6) this can only be analysed indirectly by the decreasing stress maxima and better stress distribution, so the contact zone is analyzed directly in the next chapter to display the content clearly.

At each nip the compression stresses in the thickness direction ZD show a single spherical stress zone per roller, performed by the line loading in the calendar. Its maximum stress is located in the contact zone itself. The hard and changing nips give symmetrical stress distribution. In the soft nip the influence zone of the compression stresses is bigger at the elastomer roller than at the hard roller, compare Figure 6Figure .

The line loads cause bending of the roller walls. This lead to MD-compression zones at the nip facing surface and MD-tensile zones at the inner cylinder surface. The bending is not uniform. Even in the hard nip model there are two spherical stress zones which merge in the roller's symmetry axis. In the soft nip three stress zones are detected with alternating algebraic sign, as they also exist in the changing nip, but there they are very small and therefore they cannot been displayed.

The MD-ZD-shear behaves antisymmetrically, with two alternating deformed spherical stress zones per roller and nip at hard and changing nip. If the rollers are covered, the covers cause depending on the loading two or four alternating spherical stress zones affecting the contact area. If the rollers have one or more layer, it depends on the inner structure and material composition, whether there are more than two alternating spherical stress zones. In the examined model we get four alternating spherical stress zones for the soft nip elastomer roller and four for the changing nip rollers (not visible in the presented resolution).

The spherical stress zones in MD correspond with the shear stresses in MD-ZD. Especially poisson ratio, deformation and normal-shear-stress interactions transfer the stresses and reduce stress-strain peaks in the three axial stress-strain-state. This interaction of normal and shear stresses has to be included in the surface evaluations.

Below the stress distribution of the ZD, MD and MD-ZD-shear in the rollers nip influencing zone is depictured.

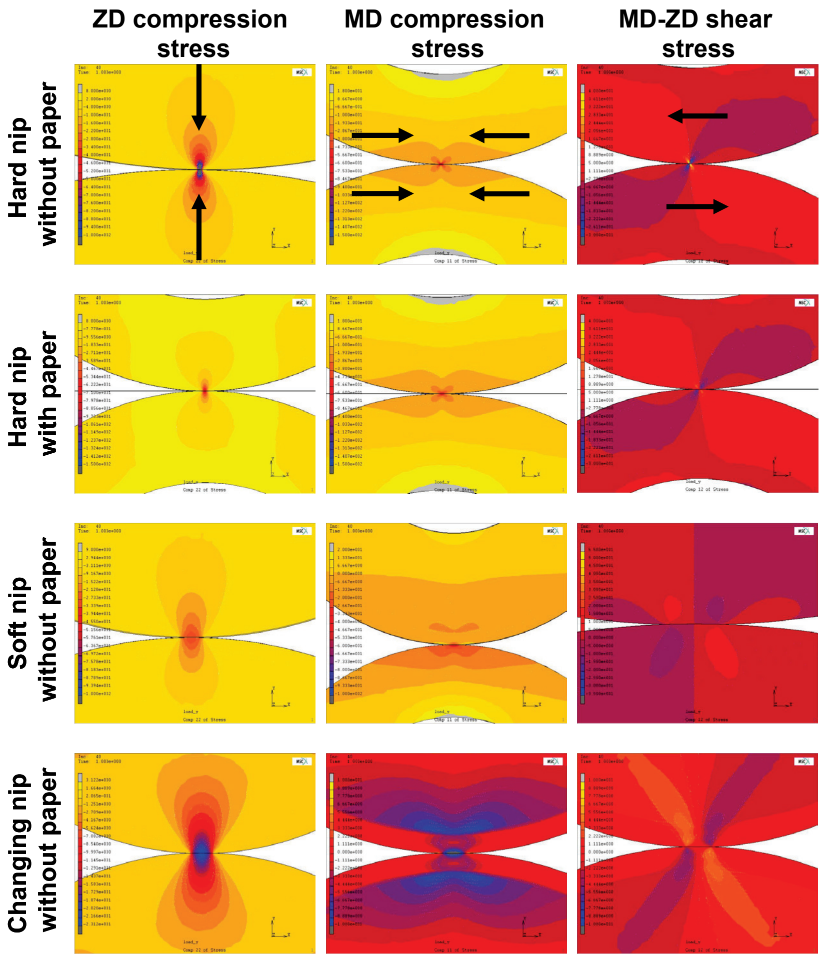


Figure 6 – Simulation results of different numerical nip-models for the normal stresses in ZD and MD as well as for MD-ZD-shear stress at quasistatic contact with calender rollers at 430 N/mm.

The analyses of hard and changing nips give a detailed impression on the general calendaring mechanics and helps validating the more important soft-nip results [22].

For calendaring analysis the structural results have to be evaluated through their effects onto the contact zones of the models. The alternating shear stress zones imply alternating tangential contact forces (traction zones), which cause alternating shear force directions inside the nip. Therefore a significant possibility exists that alternating slip and stick zones are expressed in the contact between roller and paper.

Contact Mechanical Results

The following contact mechanical results are extracted from the presented structural analysis, compare Figure 6. The surface stresses of the hard nip model are displayed in Figure 5 for compression. They qualitatively and quantitatively match the analytical results of Johnson [39] for normal stresses and tangential contact forces. This is an indication that the determined results for the soft and changing nip analysis can be ensured as close to reality, although the general analytical validation of these models is not possible, due to the strong idealizations for analytical calculations and the specific non-linearities of the nip-design in material and 3d-structure.

As expected, a paper web in-between the rollers increases the width of the slip zones inside the contact area. Table 3Table contains the analysis results for the three analyzed nip constructions. It is found that the softer the nip becomes, the lower is the increase of the nip width caused by paper.

	Nip width without paper	Nip width with paper web	Nip width difference
Hard nip	2 mm	13 mm	11 mm
Soft nip	18 mm	22,4 mm	5 mm
Changing nip	25 mm	28 mm	3 mm

Table 3 – Nip width for calender nips with rollers of 330mm outer diameter, 159µm paper thickness, line load of 430N/mm and with a friction coefficient of µ=0.3.

As most important for calendaring, the nodal stress-strain-state is displayed for a soft-nip in the quasi-static mode using an elastomer covered roller (outer diameter 330 mm) with the material properties displayed in Table 1Table under 430 N/mm line load. They are determined for the normal stresses in main direction (MD resp. 11) and in z-direction (ZD resp. 22) as well as for the tangential shear in the MD-ZD-shear-plane (12).

The contact zone is longer when a paper web is inserted. This leads to reduced stress values in the contact zone. The **ZD** compression **stress** show a parabolic shape for the pure rollers' contact at a soft nip, compare Figure 7Figure. With a paper web in-between the maximum nip pressure in ZD reduces only a little (Figure 8) in opposite to the hard nip (Figure 5 right) but the nip pressure's shape changes its shape in the inlet and outlet. At the inlet and outlet a lower stress gradiant is expressed when a paper web is inserted. This reduced stress gradient is the first hint that slip effects increase in case of a web in-between the rollers. The ZD contact stresses at the roller's surface (Figure 8) do not differ from the contact stresses at the paper web (Figure 9).

In the nipzone the **MD stresses** are interpretable as normal stresses in tangential direction to the rollers surface respectively in the web's tensile direction. They perform a nearly constant stress level at the rollers surface which becomes wider under absence of a paper web in the nip (14 mm without paper versus 9 mm with paper), but a little lower in its absolute value (17 N/mm² without paper versus 15 N/mm² with paper). The transformation of tangential traction forces and bending stresses of the rollers' wall to normal MD stresses and MD-ZD-shear stresses lead to big differences in the expression of the tangential normal and shear stresses between hard (not displayed) and soft (Figure 7) roller surface as well as between paper (Figure 8) and soft roller (Figure 9) surface. The MD-stresses of the paper web are defined by the web tension outside the nip, the web's poisson ratio and the tangential traction forces onto the papers' surface by the rollers deformation. They are much smaller than the rollers tangential stresses (compare Figure 8 with Figure 9).

Analyzing the **MD-ZD-shear stresses** of the sole rollers contact the expected antisymmetric curvature is found (Figure 7). They are inflatedly displayed with the factor of $1/\mu = 3{,}33$ against the normal stresses. With the help of this the expected width of the slip zone in the inlet and outlet can be estimated. The course of the shear stresses at the inlet and outlet points out to a slip zone of about 2 mm width at a Softnip without paper and of 3,5 mm with paper. If the surface shear stresses meet the Coulomb friction conditions, adhesion zones can be expressed even in-between the nip.

The course of the ZD-compressive stresses on the contact width is almost equal for the elastomer and hard roller. There are no significant stress rearrangements in ZD. This behavior also appears between the contact partners soft roller and paper. Inserting of a 0.157 µm thick sheet of paper in the roller's nip leads in the investigated case to an increased nip about 4mm to 22.4 mm. This reduces the maximum pressure by about 3%. The stress course changes only slightly. At the inlet and outlet a smaller increase of the ZD contact forces can be found, as in the case without a web. While the tangential contact forces generate a W-profiled course in the nip width 2a without a paper web, the presence of a paper web particularly effect the inlet and outlet zones and reduce the stress increase so that a parabolic course of the tangential contact forces is generated.

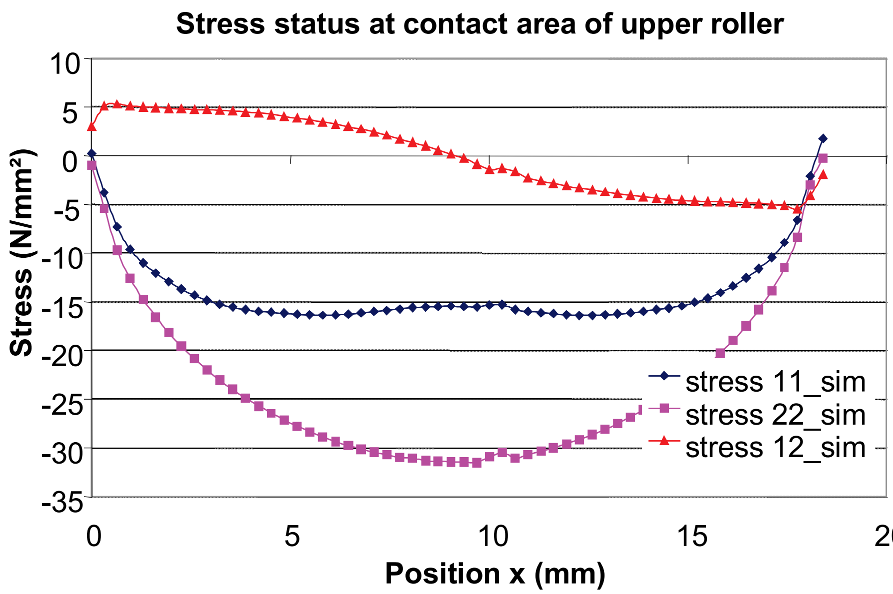


Figure 7 – Stress status of the soft nip at the soft rollers' surface without paper web with friction $\mu = 0{,}3$.

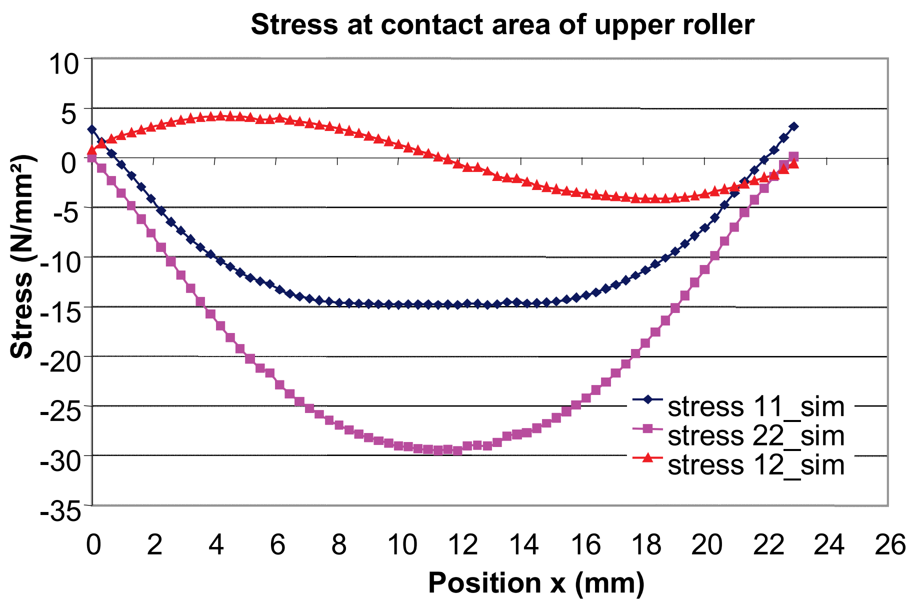


Figure 8 – Stress status of a soft nip at the soft rollers' surface with the paper web between elastic rollers with friction $\mu = 0{,}3$.

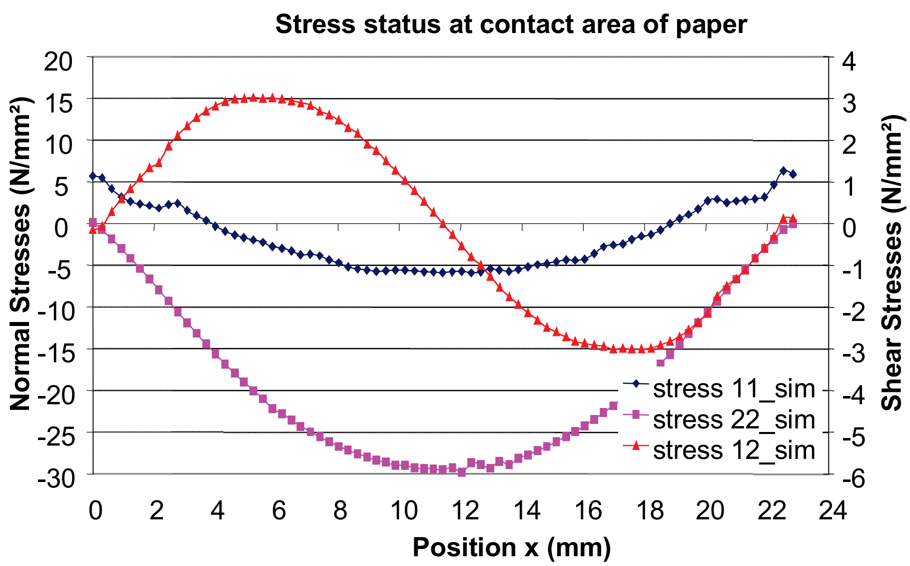


Figure 9 – Stress status of the elastic paper web in a softnip with friction $\mu = 0{,}3$.

Further parameter studies consider the influence of the E-modulus on the normal forces and shear forces in the contact area. Below the results for the nip width is displayed for the numerical model of Figure 4. The change of the cover modulus leads to an logarithmic approach for the calender relevant nip width.

The lack of knowledge about the mechanical properties of the soft rollers' cover material will be closed by present experimental investigations performed within the INFOR-project nr 104 with the aim to find a complete mechanical formulation for the production of the physical properties of paper in the calendar.

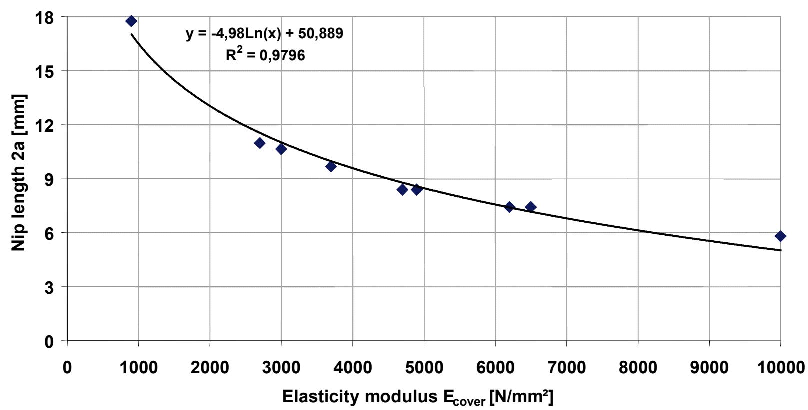


Figure 10 – Nip width of a soft nip without paper depending on the elasticity modulus of the elastomer cover.

Limits in Rolling Contact Simulation for Dynamic Calender Models

The loading of the rolls in the stack of a calendar is characterized by rotating bending stresses in circumferential direction of a thick-walled cylindrical body. The dynamic modeling shows fundamental difficulties concerning the consideration of the inherent flexural deformation of the calender roller's walls under rotation, in particular to the nip width in the replacement systems for dynamic simulation, compare Figure 11Figure .

The quasi-static loading case models the unmoving calender system in its mechanical boundary conditions exactly. The dynamic models, calculated at low speed, ie quasi static, require so-called "links" which meat like spokes in the rolling center or "Rigid Curves ", a sort of rim, to perform the rotation. In both cases, the bending deformation of the calender roller walls are constrained, so that the nip width become too small. For the use of "links" there is an error of 5% to 11% and for the "Rigid Curves" its 7% to 18% error. This indicates that in the calendering process - unlike in the simulation of car tires – steel core and elastomer cover have strong interaction with each other, so that despite the factor of 30 to 70 larger Young's modulus of the steel core cannot assumed as rigid and it has an effective rate of more than 5% to 10% (possibly up to 20% at the hard nip) to the stress strain relations, the nip width and the nip shape.

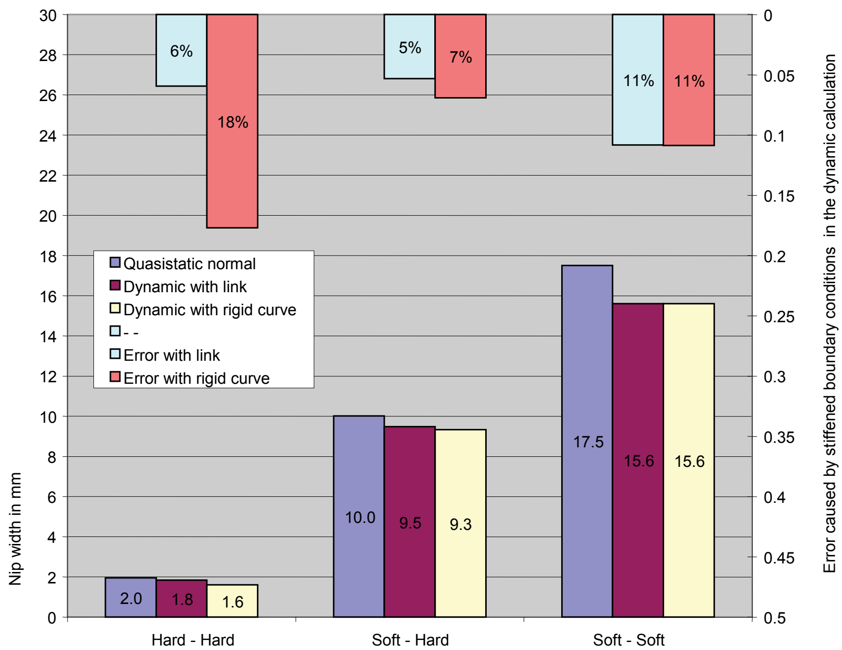


Figure 11 – Nip widths and modelling error, by using links or rigid curves for rotational movement. (ATTENTION: New model with 660 mm outer diameter, 150 mm[8] inner diameter, 10 mm function layer with E ~ 3500N/mm², 5 mm base layer with E ~ 7100N/mm², 75 mm steel wall.)

This problem can only be displayed in the current paper. A study on the applicability of the Eulerian and Lagrangian approaches (fundamental theoretical FEM investigation) for the simulation of the rolling contact at paper calendering suggests other possibilities, however, that problem was not fundamentally solved. The difficulty for the case of the Lagrangian approach is a superposition of bending and rotational movement to the calendar system to be modeled accurately. So far, only in experimental finite element programs the ALE-method (Arbitrary Lagrangian Eulerian Method) is implemented. Despite this possibility, it has to be regarded, that a new sort of error is inserted by this methode, as every material in the ALE-method is viscous, and flow through the FEM-grid. A sufficient solution requires extensive intervention in the finite element system Marc-Mentat, as so far there is no other workaround to this problem.

CONCLUSIONS

It is possible to discuss phenomenological rolling contact effects on a macroscopic level. The results point out that the physical attributes of roll cover material and of paper material have to be analyzed along with the process parameters in order to achieve improvements in calendering.

The investigated interactions motivate a new evaluation of the calendering process under consideration of mechanic, thermal, hygroscopic, visco-elastic and rolling contact

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[8] Calculated by Voith Paper (Krefeld, Germany) corresponding diameter to the given outer diameter.

effects. This point of view is close to reality and permits the detection of physical interactions in the calender nip. From these detected dependencies we can formulate conclusions to gloss and smoothness behaviour as well as to the other printability and runnability parameters. Further results on these contents will be published in the dissertation of Mr. Niebuhr.

To reduce time consuming process optimization in production, precise details on optimal machine settings in the process can be delivered. Although details to paper and roll cover properties for calendering can be given by identifying the physical interactions in the rollers' nip. Knowledge of these interactions will reveal the basic calendar processes.

Numerical evaluations are necessary to understanding the nip mechanics and to determine the necessary measures. They assume the physics inside the nip.

OUTLOOK

Further work has to be done to improve the numerical and analytical models. Especially the problem of the rolling contact modeling is important to solve. Then we can model calendering dynamically.

Another task for the future is the determination and classification of the physical material properties of the participating materials: elastomer, coating and paper. In this field lots of chemical knowledge is build up. But to use structure models forprocess analyse, the mechanical parameters have to be known with its standard deviation. The paper properties are also important for the future trends in machine concepts and machine design.

ACKNOWLEDGEMENTS

On February 1st, 2009, Professor Ewald Georg Welp has unexpectedly been torn from the life at the age of 64 years. We mourn with great sadness to our chief and Ph.D. supervisor.

Professor Welp is gone too soon. Many of his plans are still unfinished. We often notice that we miss him during our dayly work. His employees thank him for his scientific impulses to their dissertations and many students thank him for the care of their academic work. We feel great respect for his life's work and we will always remember him with great honor.

The authors would like to thank the German Pulp and Paper Association (VDP-Verband deutscher Papierfabriken e.V.) for supporting this research. Further thanks are given to the involved manufactories (StoraEnso – Reisholz, UPM-Kymmene – Augsburg and UPM-Kymmene – Dörpen) for supplying the needed materials and the students Ms Schmidt, Ms Niermann, Mr. Ebert and Mr. Dinh for their student works.

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Phenomens of Rolling Contact in Paper Calendaring

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Name & Affiliation	Question
Hongbing Lu, Oklahoma State University	This question concerns the property data for paper. Usually paper is considered a nonlinear material. It may be linear for very small strains but as strain increases the stress strain curve becomes nonlinear. Sometimes you witness nonlinear behavior when moving from tensile to compressive stresses. In your case I don't know what your strain range is. If we employ a modulus, what nonlinear modulus values are actually used? Do we choose a modulus associated with a small deformation or a large deformation? What is the strain range and what modulus values are used?
Name & Affiliation	**Answer**
Michael Desch, Technical University of Darmstadt	Contact V. Niebuhr for the answer.
Name & Affiliation	**Question**
Tim Walker, T. J. Walker & Associates, Inc.	Does the model predict the feed rate of the paper? What is the length of paper that is exits the calendar versus the length of paper that entered the calendar? Is there length increase?
Name & Affiliation	**Answer**
Michael Desch, Technical University of Darmstadt	Contact V. Niebuhr for the answer.