

# Modelling and numerical simulation of the wrinkling evolution for thermo-mechanical loading cases

Georg Haasemann<sup>1</sup>

VON ARDENNE GmbH, Plattleite 19/29, 01324 Dresden, Germany

## Abstract

The initiation and propagation of wrinkles during the handling process of thin polymers inside of coating machines results in a loss of product quality and down time of the manufacturing operation. The design of a web coater, which reduces the wrinkling problem as far as possible, requires a profound understanding of the mechanisms and causes behind this undesired web deformation. At VON ARDENNE GmbH this important challenge has been successfully mastered through years of experience and the support of numerical simulations. The modeling and simulations based on Finite Elemental Modeling (FEM) of this highly nonlinear wrinkling process will be presented. The results help to identify the geometric and process parameters, which have a significant influence on a web handling in order to avoid wrinkling.

## Introduction

One of the most serious problem during the web handling process is the occurrence of wrinkles. Thus, many companies and research centers invest substantial time and effort to gain a deeper understanding of the formation process in order to improve the web handling technology. As a result of these investigations, there are many books and publications in scientific journals (see e.g. [1] [2] and [3]). These publications discuss various topics such as the deformation and stress states of the web, tribology, wrinkles, dynamics, and tension control. In addition to the general discussion of these topics, there are many analytical models created to describe the relationships between different parameters and state variables of the web. These models are important tools for the design of the web transport system. In some cases, however, no analytical model exists and the problem is too complex to be solved. Therefore, numerical methods like the finite element analysis are applied. However, the numerical solution process is time consuming depending on the model size and requires extensive experience. This is due to the strong nonlinearity which is inherent in the web handling. Therefore, it is necessary to consider large displacements, contact with friction, nonlinear material behavior, etc. Finally, a stable and convergent solution of the numerical problem requires a suitable adjustment of parameters that are part of the numerical method. If these problems are managed, many advantages can be gained including a better understanding of the process, derivation of new solutions, and the design of an improved handling system. According to this, the paper describes the nonlinear modeling and simulation based on the finite element program ANSYS [4] in order to investigate the formation and development of wrinkles.

## Nonlinear modelling of web transport

### Geometry, FE-Model and boundary conditions

In the following report, the investigations focused on a configuration consisting of a web, which is fed by two rollers as shown in the sketch of Figure 1. The dimensions of the geometry can

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<sup>1</sup> Corresponding author, VON ARDENNE GmbH, Plattleite 19/29, 01324 Dresden, Germany. Tel.: +49 351 2637 494; Fax: +49 351 2637 308; E-Mail address: [Haasemann.Georg@vonardenne.biz](mailto:Haasemann.Georg@vonardenne.biz)

be controlled by the parameters representing: (i) the radius  $r$  of the rollers, (ii) the distance between the rollers  $L$ , which is equivalent to the web span, and (iii) the web width  $W$ . Since the friction between web and rollers as well as the bending of the web around the rollers may have an influence on the web deformation and movement, the initial state of the web is defined as a plane touching both rollers on the topside. As described below, the displacement boundary conditions will change the initial plane shape of the web into the U-shape as shown in Figure 1. In addition to this geometry, there are two modified models where the straight rollers are replaced by crowned or concave rollers. They can be characterized by the radius of curvature or the deviation  $c = r_{max} - r_{min}$  between the largest and smallest radius.

The geometry is symmetric with respect to the  $xz$ -plane in the middle of the web. In general, this gives the possibility to reduce the FE-model. However, the stability problem may lead to non-symmetric deformations, e.g. the shape of the wrinkles can be non-symmetric even if the initial geometry is symmetric. Furthermore, some of the applied boundary conditions, such as a transverse shift of the web, are in conflict with the assumption of a symmetric model. Hence, the entire geometry is used to generate an FE-model.

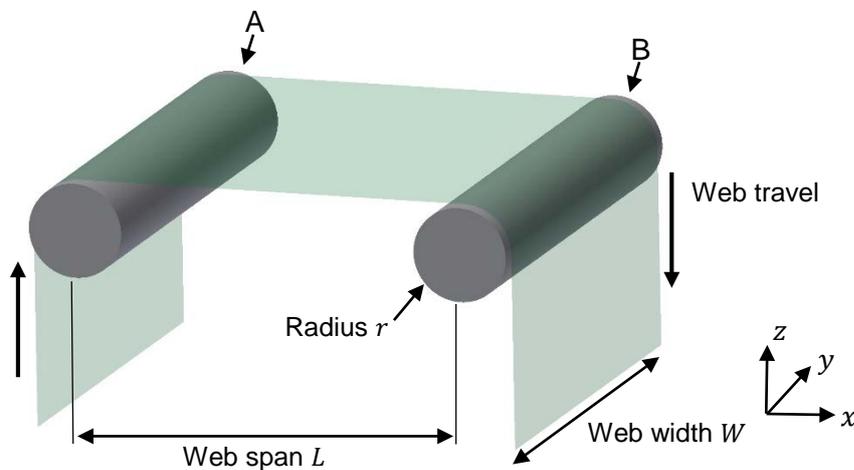


Figure 1: Illustration of a web fed by two rollers

For the FE-mesh of the elastic web, shell elements are suitable to model the thin structure since the thickness dimension is significantly smaller than the width and length. Thus, the stress in direction of thickness is negligible. It was observed that reduced integration, which is set as default, is not beneficial regarding the numerical convergence during the solution process. Hence, a full integration procedure is used.

A comparison of the roller stiffness with that of the web material shows that the rollers are very stiff. In order to reduce the numerical size of this model, the rollers are assumed to be rigid. This reduces the numerical representation of each roller to one node having three translational and three rotational degrees of freedom (DoF).

An important step as part of the model preparation is the definition of suitable boundary conditions. With respect to the rollers, it can be assumed that they exhibit no translational movement with only a free rotation around the  $y$ -axis. Accordingly, all displacement DoF and the rotation around  $x$ -axis and  $z$ -axis of the nodes representing the rigid rollers are set to zero. However, the free rotation of the rollers around the  $y$ -axis causes a serious convergence problem for the model. This problem is due to the free body rotation at the beginning of the simulation where the web and the rollers do not interact. With increasing surface area of the rollers where the web is in frictional contact, this problem disappears. In order to solve this problem, a torsion spring is attached to the rotational DoF. This provides a numerical stability since the free rotation is suppressed. However, with increasing rotation of the rollers, the moment of the linear torsion spring is increasing as well. In order to prevent an undesired level of this moment,

a bi-linear behavior, as shown in Figure 2, is assigned to the spring element. Essentially, this behavior corresponds to a serial combination of a linear spring with stiffness  $k$  and a slider characterized by the sliding moment  $M_{\text{slide}}$ . After the specification of an appropriate torsional stiffness  $k$ , the moment  $M_{\text{slide}}$  is computed such that the element starts sliding if a rotation of one degree is reached.

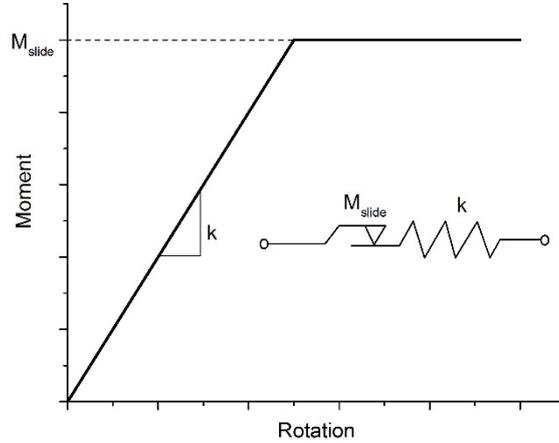


Figure 2: Bi-linear behavior of the spring element

The next group of boundary conditions are applied in order to bring the initially flat web into the U-shape as shown in Figure 1. In general, this can be accomplished by assigning displacements or loads at the ends of the web. In this context it is well known that displacement boundary conditions provide a better numerical convergence if the behavior of the model is highly nonlinear. An additional reason to prefer displacement boundary conditions is the subsequent step where the web travels from roller A to B upon which the rollers remain passive. This movement can only be controlled by appropriate displacements at the ends of the web and thus this type of boundary condition will remain consistent with the previous step. Otherwise, an unfavorable switching from load to displacement boundary conditions would be necessary. The derivation of the time-dependent displacement boundary conditions are based on the variables defined in Figure 3. Here the web is shown in its initial horizontal position and at an arbitrary wrap angle  $\varphi$ . The initial length between the right end of the web and  $x = 0$  is given by  $L_0 := s + L$ , where  $s = \varphi \cdot r$  is the arc-length of the web in contact with the roller.

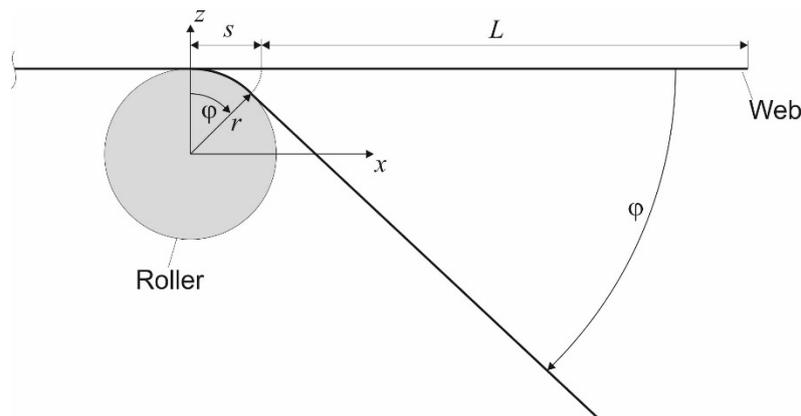


Figure 3: Schematic sketch of the web deformation

Analyzing the angle-dependent movement of the right end of the web gives the following relations for the displacement  $u_x(\varphi)$  and  $u_z(\varphi)$ .

$$\begin{aligned} u_x(\varphi) &= (L_0 - r \cdot \varphi) \cos \varphi + r \sin \varphi - L_0 \\ u_z(\varphi) &= -(L_0 - r \cdot \varphi) \sin \varphi + r(\cos \varphi - 1) \end{aligned} \quad (1)$$

If the final wrap angle is  $90^\circ$ , the course of motion is subdivided into nine load steps. The displacement at the end of each load step is assigned based on Equation (1). Since the displacement is ramped linearly during each load step, a small deviation from the ideal movement occurs. This is the only disadvantage of displacement boundary conditions. However, in the case that the deviation becomes too large, the number of load steps can be increased.

The interaction between the web and rollers is represented by contact elements. The relative sliding is characterized by the frictional coefficient, which depends on the surface finish of the roller and the web material. In order to evaluate this parameter, some tests are performed whereby the moment required to rotate the roller at different web loadings was measured. In general, the friction characteristic can be influenced significantly by air trapped between the web and roller. However, since the application here is focused on web handling in a vacuum environment, this influence can be neglected.

The numerical adjustment of the contact formulation is a very crucial point regarding the convergence behavior of the simulation. A large number of tests have shown that the Pure Penalty formulation reduces the number of necessary iterations in comparison to the Augmented Lagrange type. Another important parameter is the correction of the normal stiffness. Due to the very low stiffness of the web, the default normal stiffness that is used to include the interaction between both contact surfaces needs to be reduced by a factor between  $10^{-3}$  and  $10^{-4}$ . Further details about contact formulations and techniques in FE-simulations can be found elsewhere [4].

The main objective of the investigations here was the development of wrinkles where the initial formation is closely connected to the buckling problem. Meanwhile, inside a perfectly plane web a compressive force reaches a critical or bifurcation point, where the solution splits into two or more stable or non-stable load-deflection paths. However, the real web is not perfectly plane and may have a small variation of the material thickness as well. These so-called imperfections lead to another load-deflection path. As the imperfections become smaller and smaller, the equilibrium paths of the imperfect structure approaches the bifurcation point but never reaches it [5]. In order to simulate the post-critical behavior of the web based on finite elements, it is required to change the perfect geometry into such an imperfect one. Otherwise, the ideal shaped FE-model fails to buckle. A technique to solve this problem is to perform a linear eigenvalue buckling analysis prior to the nonlinear simulation. The displacement result obtained from the buckling analysis is applied as a slight distortion of the unloaded mesh.

An example of the deformation obtained from a linear buckling analysis is shown in Figure 4. It should be noted that the domain of the web outside the span between the rollers is forced to remain flat. This boundary condition improves the convergence behavior since these areas of the web belong to the initial contact regions.

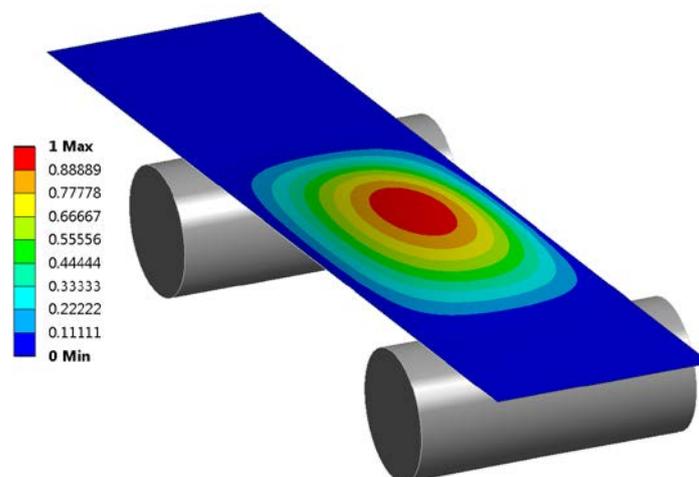


Figure 4: Deformation of the web obtained from a linear buckling analysis

The result, as shown in Figure 4, is normalized regarding the maximum displacement. Finally, the actual amount of distortion is reduced by a factor of approximately 0.01.

In most applications with web handling, there is a process unit, e.g. a thin film deposition system, which changes the temperature of the web. Then it is important to know the sensitivity of the web to generate wrinkles. In order to incorporate this influence into the simulation, the web temperature is assigned as boundary condition. The temperature distribution is obtained from another FE-computation that simulates the heat flow due to heat sources and heat transfer.

### Thermo-mechanical properties of the web material

The investigations here are focused on PET. Depending on the highest load and strain rate, the material deformations can be affected by elastic, viscous, and plastic processes, which may include a high sensitivity to the temperature. For the simulations, it is assumed that the strain rate remains in a small range where the viscoelastic behavior is nearly unchanged. Furthermore, the load does not reach a critical value where significant plastic deformation occurs. Thus, it is sufficient to use a thermo-elastic material model. This model can be described by a temperature-dependent YOUNG'S modulus as shown in Figure 5. It is to be noted that the value of the modulus is reduced if the temperature exceeds 60°C. This is due to approaching the glass transition temperature where the state of the material becomes more rubber-like. Eventually, the complete elastic characterization requires a further material parameter. Here, the POISSON'S ratio where  $\nu = 0.3$  is considered as independent of the temperature.

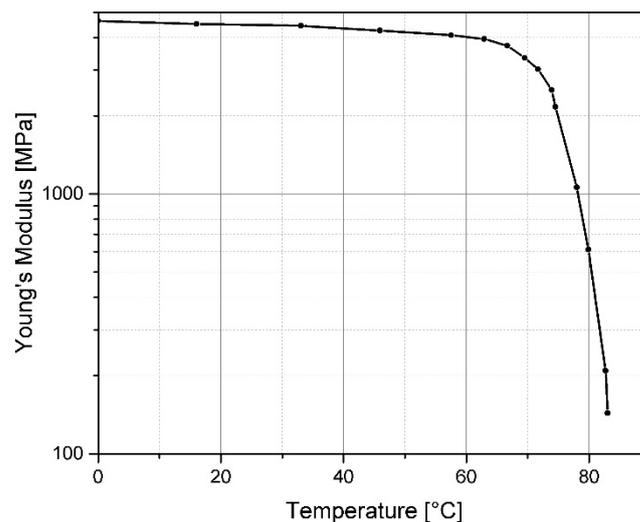


Figure 5: Dependency of YOUNG'S modulus on temperature

Another material behavior is the expansion due to the change of temperature. A standard test to evaluate this property is the thermo-mechanical analysis (TMA) where the deformation of the material is measured in machine direction (MD) and transverse direction (TD) depending on the actual temperature. An example of respective strain curves are shown in Figure 6. These curves can be used to compute the coefficient of thermal expansion (CTE) as shown in the diagram as well. The values of the strain in MD and TD varies significantly if the temperature of 70°C is exceeded. In this case, the stiffness drops down as mentioned before. Thus, such temperatures should not be used in a real world process and will not be assigned as boundary conditions.

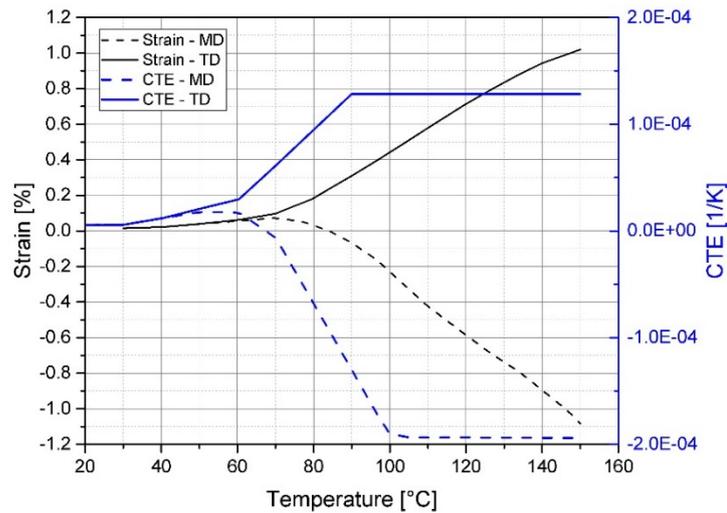


Figure 6: Strain measured during TMA and CTE derived from strain-temperature dependency

## Results and discussion

In the following, some of the models and results will be presented. In general, there is a broad spectrum of data to be analyzed, evaluated and compared. The information given subsequently is only a selection of the results, but provides an impression about the possibilities.

The dimensions of the models are as follows:  $L = 500$  mm,  $W = 200$  mm and  $r = 60$  mm. In comparison to the web handling of a typical coating plant at VON ARDENNE GmbH, these dimensions are very small. However, since the computation of larger models becomes very time consuming, it is best to analyze the general behavior of smaller models first. Eventually, the experience gained from these models can be transferred to a model based on the final design.

### Model with crowned or concave rollers

The following is a description of results obtained from two models with concave and crowned rollers, respectively. Such rollers can be used to control the web tracking or web spreading. It is well known that the application of crowned rollers increases the risk of longitudinal wrinkles in the center of the web. These can be seen on the left side in Figure 7 which shows the distribution of the  $u_z$ -displacement. During the nonlinear simulation, the shape of the wrinkles changes as shown in the diagram on the right side of the figure. There, the displacement across the web between both rollers is given at different time increments. It is shown that the wrinkles move to the left so that the three waves are flipped and the minimum at 100 mm becomes a maximum. The reason for this phenomenon is the changing conditions of the contact between web and roller during the transport of the web.

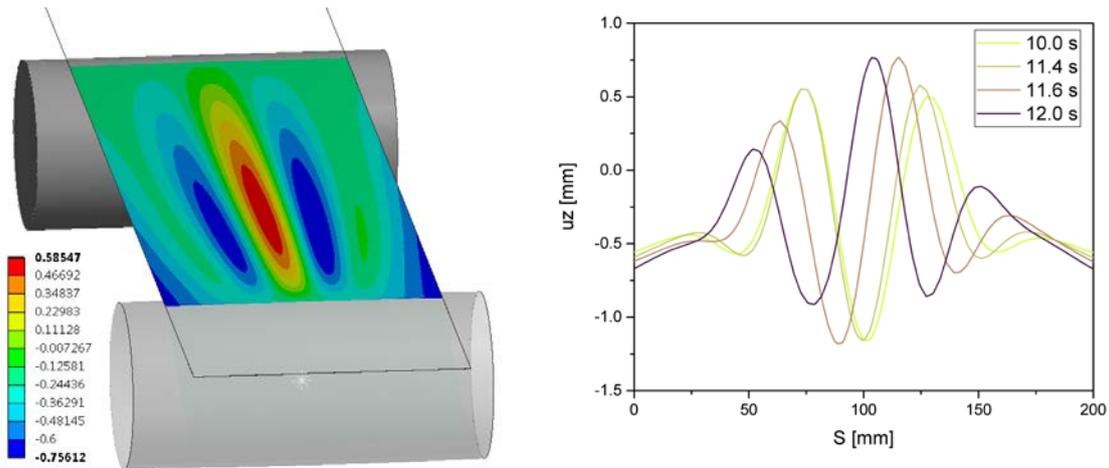


Figure 7: Displacement in mm of a model with a crowned roller, Left: displacement across the web at different time steps, Right: displacement distribution in the free span of the web

The analysis of quantities such as pressure and sliding distance in the contact domain are an important advantage of such numerical simulations. An example is shown in Figure 8. The color distributions of these images represent the pressure between web and roller. The roller has a concave shape at the left side and a crowned shape at right side.

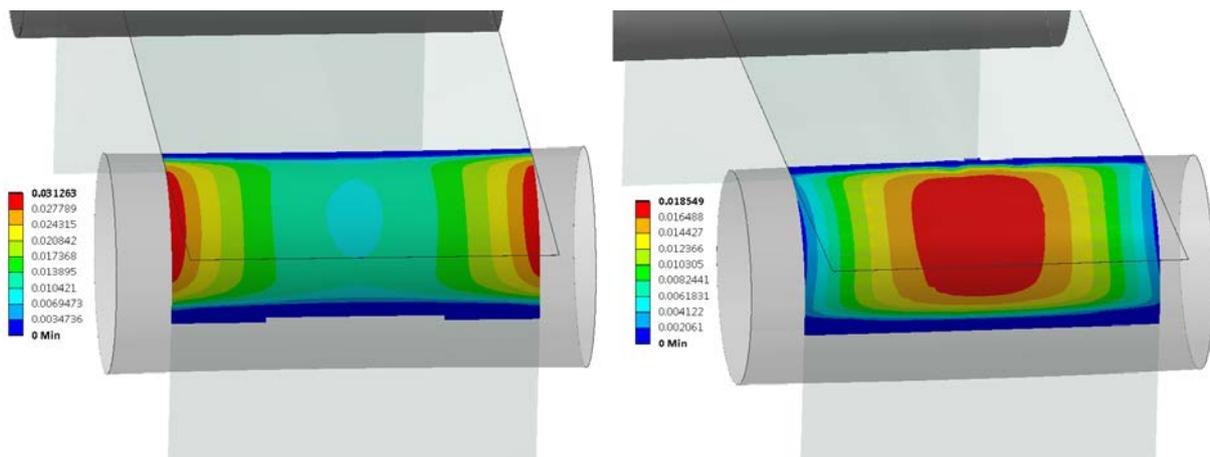


Figure 8: Comparison of the pressure in MPa between roller and web, Left: for a concave roller, and Right: for a crowned roller

### Model with transverse shift of the web

A typical source of wrinkle formation is a transverse shift of the web. There are some reasons why such a shift might occur. The following Figure 9 shows the results of a model where the web has a misalignment angle of  $0.2^\circ$ . The color distribution on the left side represents the out-of-plane displacement. As expected, the wrinkle alignment is not parallel to the web. Since the transverse shift induces a shear deformation, the principle axes change their orientation. The orientation of the minor axis in combination with the smallest principle stress are shown at the right side of Figure 9. It can be seen that the absolute value of the negative stress and the rotation of the principle axes increases from the outside toward the middle of the web. This stress defines the orientation and location of the wrinkles.

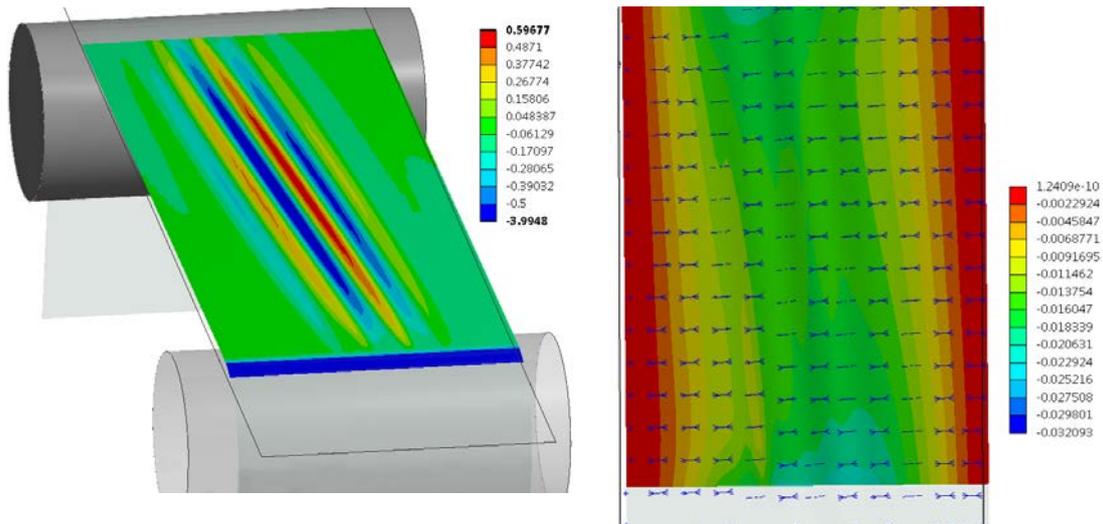


Figure 9: Model with transverse shift of the web; Left: out-of-plane displacement of the web, Right: Distribution and orientation of the smallest principle stress

### Model with inhomogeneous temperature distribution

The following model provides the possibility to investigate the influence of a plasma coating process on the web deformation. A separate FE-simulation which includes the energy source of the process, both radiation and thermal conduction, provides the temperature distribution as boundary condition. Since the heat is transferred continuously from the plasma to the web, the temperature is increasing from roller A to B. Accordingly, the distribution reaches the maximum close to roller B. As a result, the wrinkles arise in this domain as shown in Figure 10.

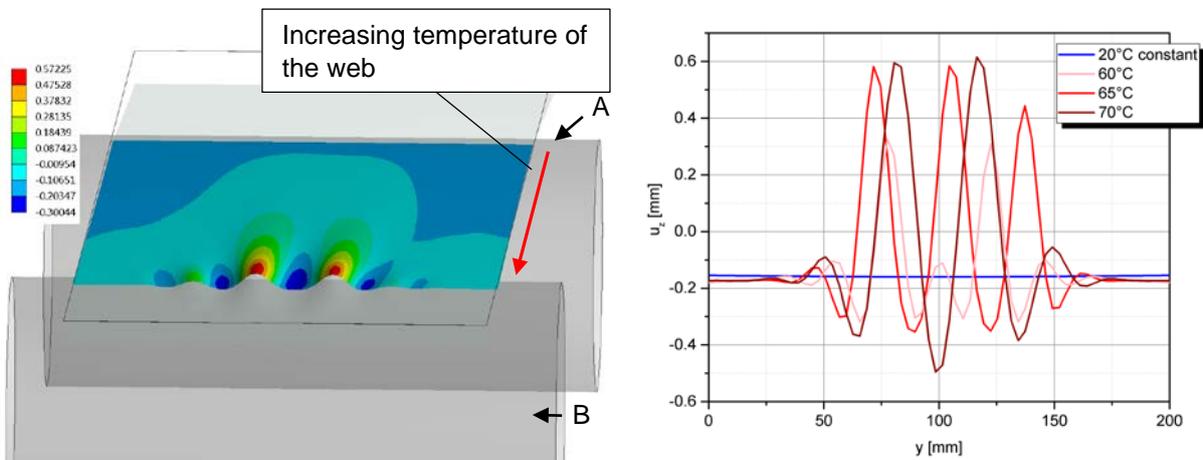


Figure 10: Wrinkles and distribution of the displacement  $u_z$  in mm due to increasing temperature of the web

At the right side of the diagram, the displacements across the web depending on the maximum of the temperature distribution are shown. It can be concluded that the wrinkles indeed grow with increasing temperature.

### Summary

The thermo-mechanical modeling of wrinkle generation and development based on the finite element method was presented. The simulation of such a highly nonlinear problem requires an adapted set-up of the finite element model, boundary conditions, and material properties. The successful application of the modeling technique was shown based on a model with different boundary conditions and load cases.

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