

Analysis of wrinkle formation and propagation during paperboard deep drawing

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ABSTRACT: Paper-based packaging is becoming increasingly important as a sustainable alternative to plastics. Among forming processes, deep drawing is particularly promising due to its high cost-effectiveness, short processing times, and suitability for large-scale production. A major challenge, however, lies in the formation of wrinkles, which impair the visual quality, functional performance, and dimensional stability of the packaging, thereby affecting subsequent processes such as filling, printing, and sealing.

This study focuses on analyzing the occurrence and propagation of wrinkles during the deep drawing of paper-based materials to derive fundamental insights and strategies for prevention. The wrinkles arise from tangential compressive stresses in the flange and the material's limited thickening, leading to local stability failures once a critical stress threshold is exceeded.

A combined approach of experimental investigations, numerical simulations, and analytical considerations was used to examine a rotationally symmetrical part. A transparent die enabled spatial observation of wrinkle initiation and growth. First, wrinkles were found to typically initiate in the cross direction (CD), while most wrinkles develop in the machine direction (MD). By comparing analytically and numerically determined stress distributions, the mechanisms of wrinkle formation can be understood both locally and temporally, thereby enabling the prediction of wrinkle occurrence.

Application: This paper presents findings on the formation and propagation of wrinkles during the deep drawing of paperboard. Using experimental, numerical, and analytical approaches, the location and timing of the first wrinkles can be roughly predicted.

In response to the growing environmental concerns surrounding plastic waste, paper-based packaging has emerged as a promising alternative due to its renewable origin, recyclability, and biodegradability. In this context, deep drawing is a particularly suitable process, as it is characterized by high cost-effectiveness, short process times, and suitability for mass production [1]. One major challenge, however, is the formation of wrinkles, which can impair the visual quality of the packaging, affecting its advertising design and its functionality [2]. These wrinkles result from tangential compressive stresses and low flowability in the flange area during deep drawing.

Previous research has shown that the wrinkling can be influenced by multiple process and material parameters. Increased blank-holder forces lead to more but finer wrinkles, which was extensively examined [3,4]. Similarly, an increased water content in the material and additional heating of the forming tools result in less rough wrinkling [5,6]. Depending on the deep drawing settings and geometric constraints, a certain drawing depth without wrinkles is described in literature between 1–2 mm [7] and up to 4 mm [8]. At this so-called initial wrinkle height, the first wrinkles are initiated and become visible on the wall of the deep-

drawn part. Based on the paperboard's porosity, Hauptmann et al. derive a formula to calculate the initial height. It is assumed that porosity provides the capacity to reduce tangential compressive stresses. Once this capacity is exhausted, wrinkles form [9]. Most wrinkles form parallel to the machine direction (MD) due to paperboard anisotropy.

Since wrinkling is caused by tangential compressive stresses, the phenomenon can be described as a stability issue. This has been investigated both experimentally and through numerical simulations. Lenske et al. developed an experimental method to evaluate in-plane compression behavior during deep drawing. Using multiple specially tailored sample geometries, the tangential compressive force in the flange area can be estimated and isolated from other influences. Using a special "in-plane compression testing method," they further analyzed compression until a compression factor adapted to the deep-drawing process was achieved. Compression forces between 80 and 200 N were measured. Given the geometric measures and paperboard thickness, the average tangential compressive stress ranges from 9 to 16 MPa. While fiber orientation strongly influenced the compressive force, the effect of applied normal pressure was negligible [10].

The in-plane compressive behavior of paperboard can be analyzed using the short-span compression test (SCT). As described in ISO 9895 “Paper and board — Compressive strength — Short-span test,” a one-dimensional in-plane compression is applied by compressing a paperboard sample between two clamps with a free length of 0.7 mm. Borgqvist et al. used the SCT to analyze the compression behavior of paperboard and found that, compared to tensile tests, the stiffness of paperboard under compression is significantly lower. Additionally, they employed a continuum model to simulate the SCT. The simulation and post-mortem X-ray tomography images were analyzed, revealing that the material exhibited an unstable response after reaching a maximum out-of-plane stress, resulting in severe delamination [11].

The wrinkling behavior of paperboard was described by Linvill et al. using an idealized model of a perfectly plastic hinge. In a one-dimensional model, wrinkling occurs under compressive loading if it requires less energy than non-wrinkling deformation. This concept was implemented as a subroutine to a three-dimensional numerical simulation of the deep-drawing process, showing a comparable number of wrinkles to experimental observations [12].

The most recent research on wrinkling behavior in deep drawing is presented by Sanjon et al. [13]. They compared different approaches to material modeling in a numerical simulation to connect in-plane and out-of-plane behavior. In the deep-drawing process, they concluded that a composite model with cohesive interfaces exhibits more realistic delamination and wrinkling than a single-continuum model. The disadvantage was that the simulation time increased with more complex models.

As presented, the phenomenon of wrinkle formation during deep drawing, resulting from tangential compressive stresses, can be explained in general terms. The wrinkling behavior of paperboard and the resulting delamination have also been studied using one-dimensional approaches, with a focus on SCT [11]. During deep drawing, the flange area experiences complex loading with locally and temporally varying stresses. Therefore, the exact timing and location of wrinkle formation, as well as the subsequent development after initiation, are not yet sufficiently known or predictable. Knowledge of wrinkle initiation and development from a process perspective would help to derive strategies for targeted intervention.

This study investigates wrinkle initiation and propagation during paperboard deep drawing by combining depth-resolved experimental observations with analytical and numerical stress analysis. The aim is to identify the stress mechanisms governing wrinkle formation in a rotationally symmetric deep-drawn part. Using a transparent die, the initiation of the first wrinkles and their propagation directions are observed under varying process parameters. In addition, a simplified analytical description of the stress state in paperboard deep drawing is developed and com-

pared with numerical simulations. By relating the effective compressive stresses in the flange area to the critical compressive stress, the initiation of wrinkle formation can be predicted.

METHODS AND MATERIALS

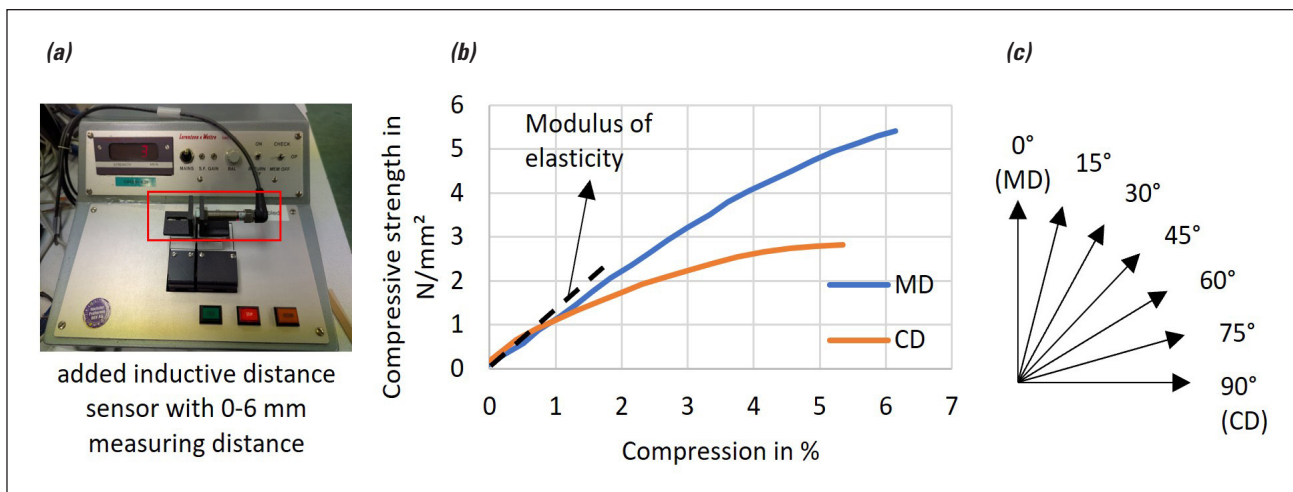
An industrial virgin-fiber paperboard, trademarked Trayforma (350 g/m²) from Stora Enso (Helsinki), consisting of a three-layer structure with a chemithermomechanical pulp core and chemical pulp outer layers, was used. Two material moisture contents of approximately 5% and approximately 15% were investigated. The target moisture contents were achieved by conditioning the paperboard samples in a climate cabinet (Binder KMF115; Binder GmbH, Tuttlingen, Germany) and were determined gravimetrically based on the sample weight in accordance with ISO 287:2017 “Paper and board — Determination of moisture content of a lot — Oven-drying method.” Higher moisture content resulted in increased elongation and reduced tensile strength in both the machine and cross directions. A more detailed description of the material used, including its stress-strain diagram in machine direction (MD) and cross direction (CD), is presented in [14].

Experimental setup

The deep-drawing experiments are conducted using a laboratory tool consisting of a transparent die with an optical camera system. A circular punch with a diameter of 100 mm is used during deep drawing. The drawing gap is 0.5 mm, and the punch conicity is 1°. Laser-cut blanks with defined fiber orientation markings are used to ensure precise sample positioning. Deep drawing is performed at a punch speed of 2.5 mm/s. The experimental setup and the optical evaluation concept are only briefly summarized here; for a detailed description of the forming system, tooling, and measurement methodology, the reader is referred to [14,15].

Due to the transparent die and video recordings, flange draw-in and wrinkle formation can be observed during the deep-drawing process, as presented in [15]. Wrinkle detection was performed by manual evaluation of the video recordings, supported by an automated wrinkle detection algorithm. The relevant detection procedure and its limitations are described in the present manuscript; additional details are provided in [16]. With a camera frame rate of 20 fps and a punch speed of 2.5 mm/s, one frame corresponds to a drawing depth increment of 0.125 mm. Thus, the determination of wrinkle initiation is limited by this temporal resolution. Clearly visible wrinkles can be detected reliably, whereas very fine wrinkles, particularly at high moisture content and high blank-holder force, may be more difficult to identify. Consequently, the reported wrinkle initiation refers to the first optically detectable wrinkle, while the actual onset may occur slightly earlier. Each parameter combination was repeated at least three times.

In addition to the deep drawing test, a short-span com-



1. (a) Device used for short-span compression test (SCT); (b) stress-strain curve obtained with derived modulus of elasticity in the compression direction; and (c) fiber orientations examined (MD: machine direction; CD: cross direction).

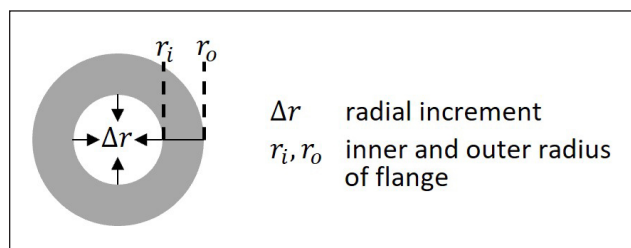
pression test was performed to determine the compressive strength of the paperboards used. In accordance with ISO 9895, a paperboard specimen with a width of 15 mm is positioned between two pneumatic clamps, leaving a free clamping length of 0.7 mm. The paperboard is then compressed in the sheet plane until failure. For the investigations, the Compressive Strength Tester by Lorentzen & Wetre (Kista, Sweden) was used, with a slight modification that added a contactless displacement sensor, as shown in **Fig. 1a**. By continuously recording force and displacement until failure, the gradient in the first phase of compression, hereafter referred to as the modulus of elasticity in the compression direction, can be calculated, as shown in Fig. 1b. For gradient calculation, the first 15% of the maximum strain for each individual sample was used. Samples are cut at angles of 0° (MD) to 90° (CD) in increments of 15°, as Fig. 1c shows. According to the ISO standard, the compression strength is usually specified as a force per sample width in kN/m. Due to its subsequent use, it is calculated as an area-related value in N/mm² based on the material thickness of 0.465 mm. Each parameter combination was repeated ten times.

Numerical model

In the investigation, a numerical finite element simulation of the deep-drawing process was used to analyze the stress state in the flange. The numerical simulation was set up in Abaqus (Dassault Systèmes Simulia; Johnston, RI, USA) using an explicit solver and an existing orthotropic material model from Jessen et al. [17]. Since the focus of this research is describing flange stresses up to the formation of the first wrinkles, only the first 10 mm of the deep-drawing process were modeled in the simulation. Experimental pre-tests revealed that the first wrinkles formed at this drawing depth. For a more detailed description of the material model, the reader is referred to Jessen et al. [17].

DEVELOPMENT OF AN ANALYTICAL DESCRIPTION OF THE STRESS STATE

To describe the stress distribution in the flange area during the deep-drawing process, the paperboard was idealized as a flat, homogeneous circular ring with inner radius r_i and outer radius r_o , as shown in **Fig. 2**. The material was modeled using a linear-elastic continuum approach. Although paperboard exhibits orthotropic material behavior, an equivalent isotropic representation with elastic modulus E and Poisson's ratio ν was employed, enabling a closed-form analytical solution while capturing the dominant mechanical response relevant to stress development and instability formation. Directional material properties were incorporated through the selection of effective parameters corresponding to the investigated material orientation. Due to the rotational symmetry of the geometry and loading, an axisymmetric stress state was assumed. Thus, all mechanical quantities depended solely on the radial coordinate r . The mechanical loading was represented by an evenly distributed intake at the inner radius, which accounts for the reduction of the inner flange radius during forming. These assumptions and their validity for paperboard, which is characterized by its inhomogeneity and anisotropy, will be discussed in a later section.



2. Assumptions for the analytical description of the flange as a circular ring disc.

Based on these assumptions, the stress state is described using the equilibrium conditions of plane elasticity for a rotationally symmetric disc, leading to the radial equilibrium relations for the radial and tangential stress components σ_r and σ_φ , respectively (see also [18]):

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\varphi}{r} = 0 \quad (1)$$

The general solution to this differential equation has the form:

$$\sigma_r(r) = A - \frac{B}{r^2}, \quad \sigma_\varphi(r) = A + \frac{B}{r^2} \quad (2)$$

with constants A and B, which follow from boundary conditions.

In a displacement-based formulation, the kinematic relations and the linear-elastic constitutive law are combined to derive a differential equation for the radial displacement of the ring disc:

$$\varepsilon_r = \frac{du}{dr}, \quad \varepsilon_\varphi = \frac{u}{r} \quad (3)$$

For isotropic linear-elastic material in a plane stress state, the strain-stress relations are given by:

$$\varepsilon_r = \frac{1}{E}(\sigma_r - \nu\sigma_\varphi), \quad \varepsilon_\varphi = \frac{1}{E}(\sigma_\varphi - \nu\sigma_r) \quad (4)$$

The radial displacement field is obtained from the kinematic relations and the linear elastic constitutive law for plane stress, yielding:

$$u(r) = \frac{1}{E} \left((1-\nu)Ar + \frac{(1+\nu)B}{r} \right) \quad (5)$$

Appropriate boundary conditions were introduced to uniquely determine the solution. At the outer radius r_o , a stress-free boundary condition in radial direction was assumed to reflect the free edge of the flange. At the inner radius r_i , a prescribed inward radial displacement was applied, representing the reduction of the inner radius during the forming process:

$$u(r_i) = -\Delta r \quad (6)$$

$$\sigma_r(r_o) = 0 \quad (7)$$

By solving the displacement differential equation with these boundary conditions, analytical closed-form expressions as a function of the radial position for the stress distribution within the ring disc were obtained:

$$\sigma_\varphi(r) = -\frac{\Delta r \cdot r_i E}{(1-\nu)r_i^2 + (1+\nu)r_o^2} \cdot \left(1 + \frac{r_o^2}{r^2} \right) \quad (8)$$

$$\sigma_r(r) = -\frac{\Delta r \cdot r_i E}{(1-\nu)r_i^2 + (1+\nu)r_o^2} \cdot \left(1 - \frac{r_o^2}{r^2} \right) \quad (9)$$

This formulation provides a simplified analytical description of the effective tangential compressive stresses in the flange and serves as a basis for assessing the tendency toward wrinkling during deep drawing.

The previous formulation does not account for the blank-holder force, a fundamental process parameter in deep drawing. The assumption of a disc in the sense of elastostatics does not allow normal forces on the disc plane. Therefore, the blank-holder force was simplified and assumed to be a Coulomb friction force acting in the feed direction. Its effect is to generate an in-plane shear traction opposing material draw-in. The blank-holder force F_{BH} was converted into an average contact pressure, with the contact area given by the flange geometry.

The resulting frictional shear traction is $\tau_{BH}(r) = 2\mu p$ for two-sided contact. In a membrane representation with sheet thickness t , this shear traction is introduced as an equivalent distributed in-plane load term $b_0 = \frac{\tau_{BH}}{t}$, which appears as an additional term in the radial equilibrium equation. For the calculations including the blank-holder force, a constant Coulomb coefficient of friction of $\mu = 0.2$ was assumed.

This leads to a modified differential equation:

$$\sigma_{\varphi,BH}(r) = A_{BH} + \frac{B_{BH}}{r^2} - b_0 r \quad (10)$$

with

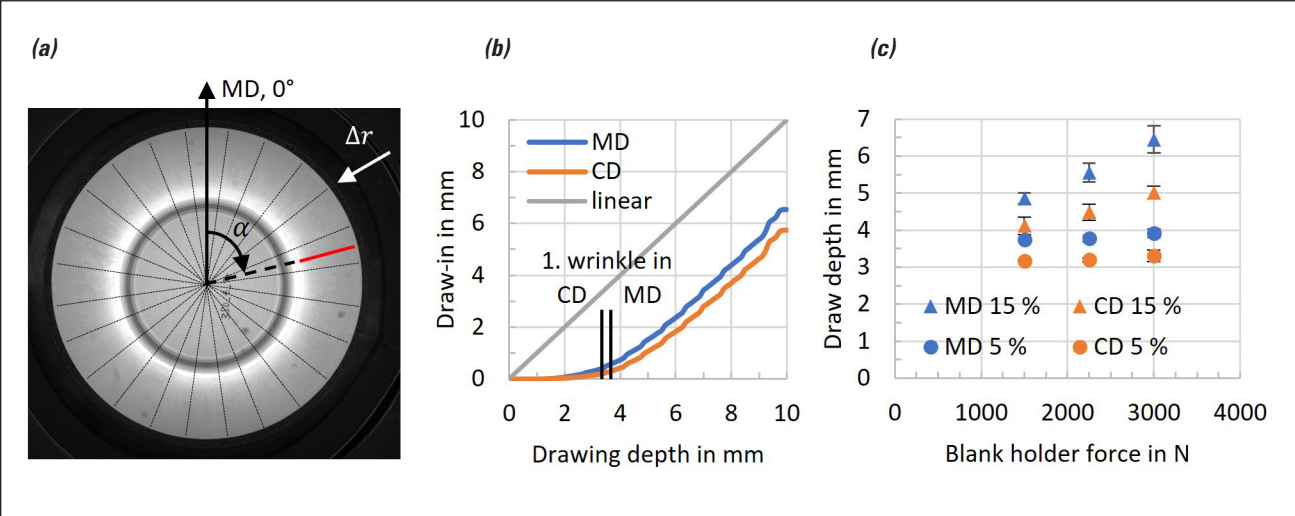
$$b_0 = \frac{\tau_{BH}}{t} = \frac{2\mu F_{BH}}{t\pi(r_o^2 - r_i^2)} \quad (11)$$

The constants A_{BH} and B_{BH} are derived directly from the boundary conditions.

Paperboard exhibits pronounced orthotropic mechanical behavior due to its fibrous microstructure, with distinct properties in MD and CD. A rigorous description would therefore require an orthotropic constitutive model with direction-dependent elastic moduli and Poisson's ratios, resulting in coupled stress-strain relations. Combined with the axisymmetric equilibrium equations in polar coordinates, this leads to a system of coupled differential equations without a closed-form analytical solution.

In addition, the orthotropic material axes (MD, CD) are defined in Cartesian coordinates, whereas the present problem is formulated in polar coordinates. Transforming the constitutive relations introduces further coupling between radial and tangential deformation modes, preventing a simple analytical solution for the orthotropic case with distributed frictional loading.

Therefore, an equivalent isotropic formulation with effective elastic parameters was employed. This approach enables a closed-form analytical solution while capturing the dominant mechanical effects relevant for stress distribution and wrinkle initiation.



3. (a) View of the flange through a transparent die with indicated wrinkling and (b) its occurrence depending on the drawing depth; and (c) initial wrinkling depending on the blank-holder force and material moisture.

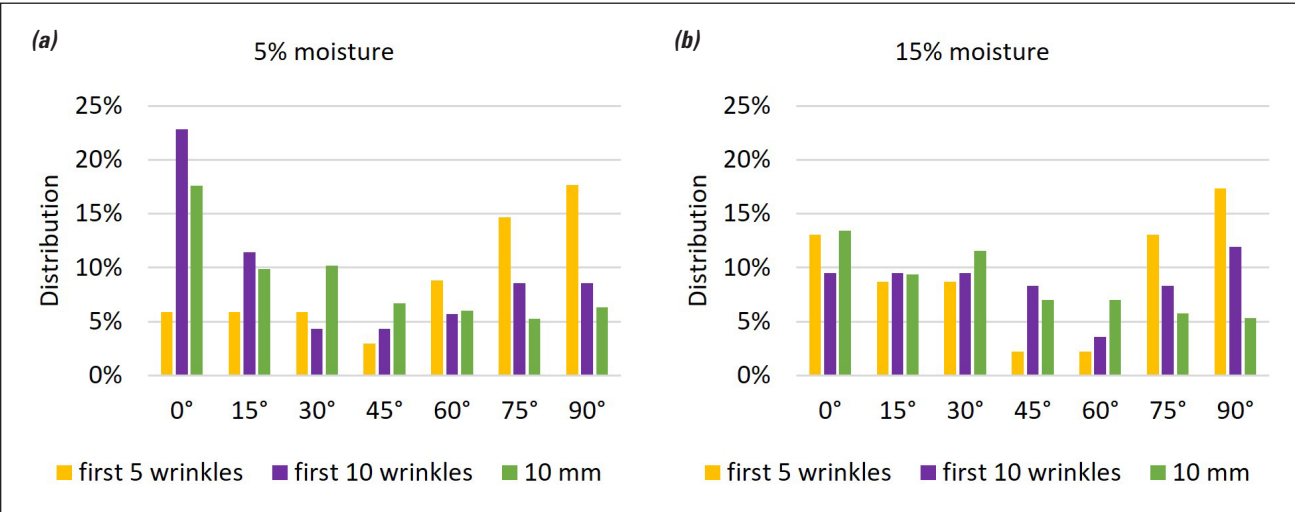
RESULTS AND DISCUSSION

Experimental: Wrinkling in deep drawing

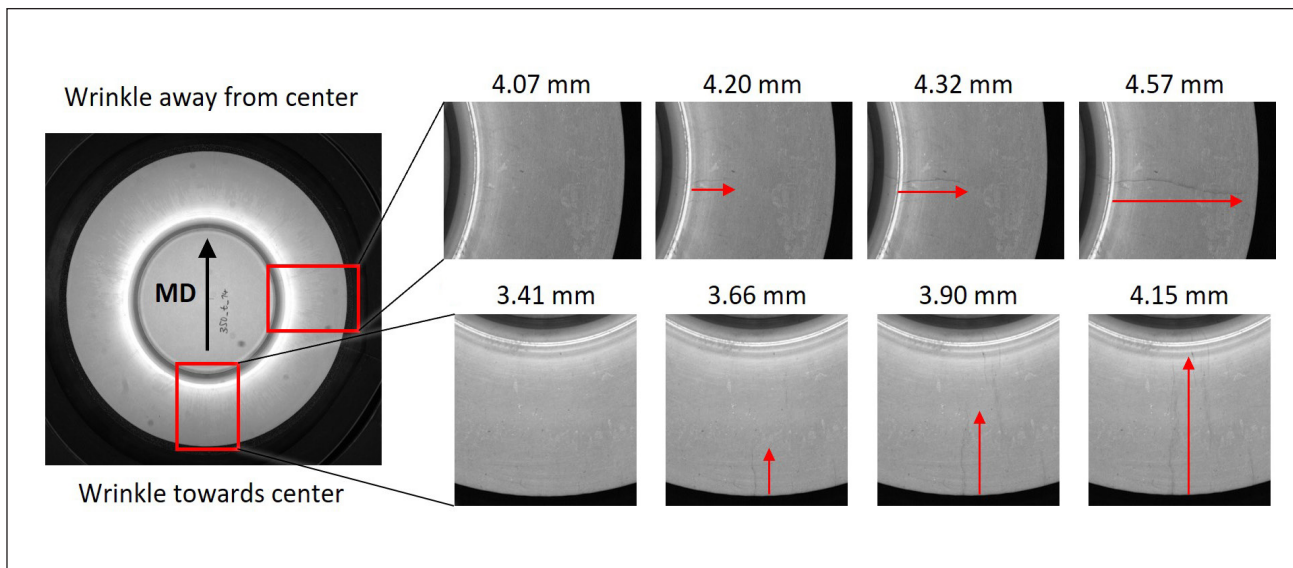
The visual accessibility of the flange allows determining the drawing depth and the angle relative to MD at which the wrinkles occur, as shown in **Fig. 3a**. As indicated in the figure, the flange area is divided into equal intervals with an angle width of 15° for the subsequent analyses. For deep drawing with 5% moisture content and 1500 N blank-holder force, **Fig. 3b** shows the radial indentation measured at the outer edge in MD and CD relative to the drawing depth specified by the punch. No radial draw-in is visible in the initial phase up to a drawing depth of approximately 2 mm, due to the paperboard's elongation. From a drawing depth of approximately 5 mm, the difference between radial draw-in and drawing depth remains constant. The draw-in in MD is greater than in CD, due to the material's lower elongation in MD. At a drawing depth of approximately 3.2 mm, the first wrinkle is visible in CD. At a drawing depth of approx-

imately 3.8 mm, the first wrinkle appears in MD. **Figure 3c** shows the drawing depth of the first wrinkle in MD and CD for different process parameters. The standard deviation of the detected wrinkle initiation depth is visible as error bars. The drawing depth of the first wrinkle depends on the material moisture and the blank-holder force, but regardless of the parameters, the first wrinkle always occurs in CD before wrinkles occur in MD. With higher blank-holder force and increased material moisture, wrinkles are only visible at greater drawing depths. It should be noted that very fine wrinkles can occur, especially at high moisture and blank-holder force, and their image-based detection can be prone to error. Therefore, wrinkles can occur even at lower drawing depths that the setup cannot detect.

In addition to the appearance of the first wrinkle, the subsequent wrinkles were also considered. The distribution of the angle of appearance at the beginning of the deep-drawing process is shown in **Fig. 4** for different ma-



4. Distribution of wrinkle formation by direction at a constant blank-holder force of 1500 N for (a) low and (b) high moisture content.



5. Direction of wrinkle propagation away and towards the center (the contrast in the images has been increased).

terial moisture contents. A distinction is made between the first five and the first ten wrinkles, and a drawing depth of 10 mm, at which approximately 50–70 wrinkles occur. In low-moisture content, most wrinkles occur in the areas around CD during the initial phase. After the first wrinkles in CD, only a few new wrinkles form there; instead, further wrinkling occurs in MD. As the drawing depth increases, the majority of the wrinkle distribution shifts to the area around MD. Humid papers exhibit similar behavior, but to a lesser extent. The center of wrinkling is also in CD at the beginning and shifts to MD as the process progresses. The less pronounced differences between MD and CD can be explained by the paperboard's lower anisotropy at higher moisture levels, as described in the following sections.

The high temporal resolution of the image data also allows the direction of wrinkle propagation to be determined. This shows that wrinkle development can be observed both from the inside to the outside and from the outside to the inside. Both cases are shown in **Fig. 5**. The wrinkle development from the inside to the outside accounted for the majority of the observed wrinkles and was evident across all fiber orientations. In some samples, the spread of individual wrinkles from the outside to the inside could also be observed, but this was evident only in some of the wrinkles parallel to the MD.

Experimental: Short-span compression test

The compressive strength in newtons per square millimeter (N/mm²) examined for different fiber orientations and material moisture contents is shown in **Fig. 6a**. Paperboard with low moisture content shows a clear directional dependence with higher strength in MD than in CD. At higher moisture contents, a significant reduction in strength can be observed. In MD, increased strength compared to CD can still be seen. Figure 6b shows the modulus of elasticity

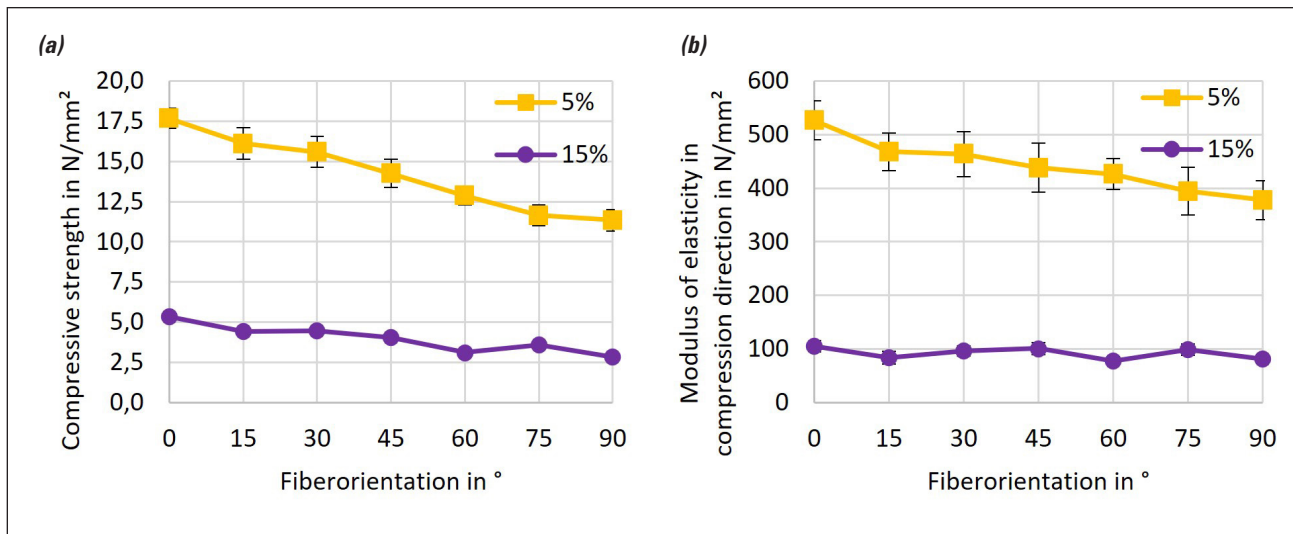
in the direction of compression derived from the force-displacement curve. For dry paperboard, this shows a similarly strong directional dependence as the compressive strength. When looking at the humid paperboard, it is noticeable that, in addition to the lower stiffness values, the directional dependence is less pronounced, caused by moisture-induced softening of the fiber network.

The modulus of elasticity in the compression direction is significantly lower than the modulus of elasticity in the tension direction. For example, for the paperboard examined, the modulus of elasticity in the MD direction is 526 N/mm² in compression and 6590 N/mm² in tension, corresponding to approximately 11.5 times higher in tension. In the cross direction, the difference compared to the factor of approximately 6 is smaller (377 N/mm² vs. 2650 N/mm²), which can be attributed to the lower number of fibers in the direction of stress.

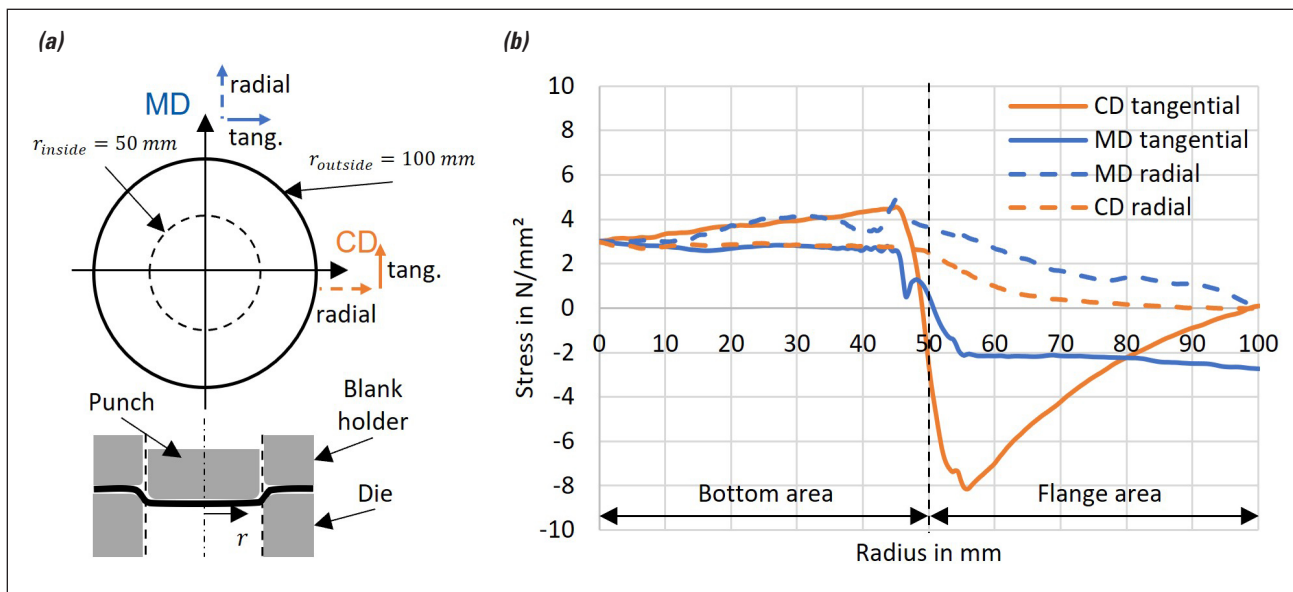
Numerically derived stress distribution

The stress distribution is derived from the numerical simulation separately for MD and CD and in the radial and tangential directions, as described in **Fig. 7a**. The curves for paperboard with 15% moisture content, a blank-holder force of 1500 N, and a drawing depth of 2 mm, are shown in Fig. 7b. As expected, tensile stresses are observed in the bottom region of the round blank. At approximately 50 mm, there is a transition area between the radii of the punch and the die.

In the flange area, tensile stresses occur in the radial direction, reaching zero at the edge of the blank, as required by theoretical considerations. In MD, the stresses are higher than in CD, which can be explained by higher strength and lower elongation. In the tangential direction, negative stresses, i.e., compressive stresses, occur throughout the flange. Here, the pressure curves in MD and CD



6. (a) Compression resistance and (b) modulus of elasticity in compression direction obtained from SCT for different fiber orientations.



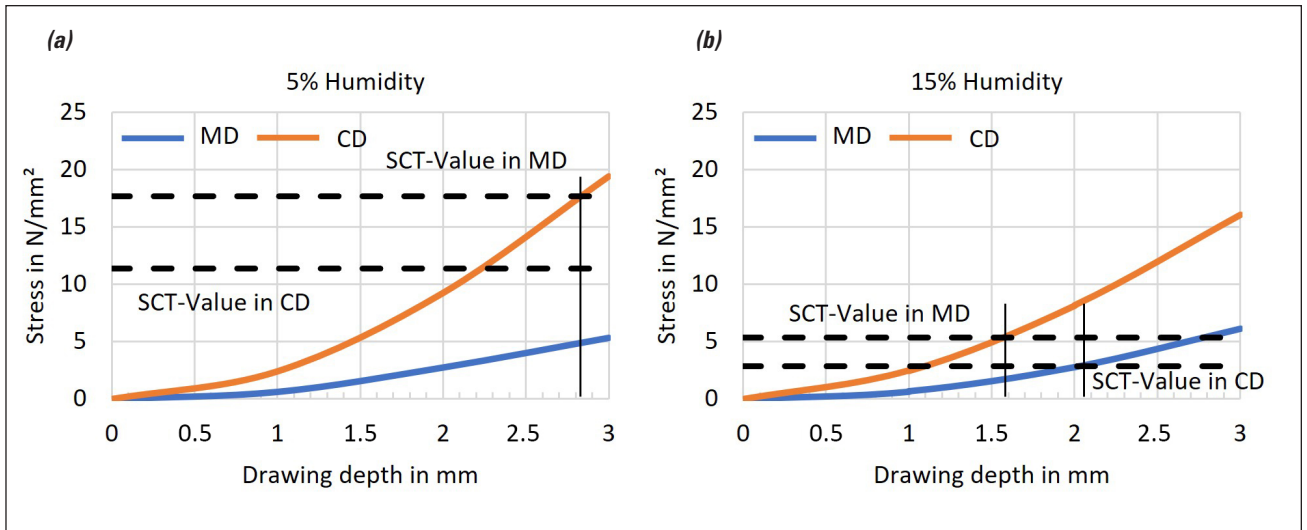
7. (a) Analyzed radial and tangential stresses in MD and CD in the flange, and (b) exemplary stress distributions

differ significantly. In MD, there is an almost linear increase in compressive stress towards the outside. In CD, the curve is different: the greatest tangential compressive stresses occur at the die radius, decrease towards the outside of the blank, and approach zero at the outer edge.

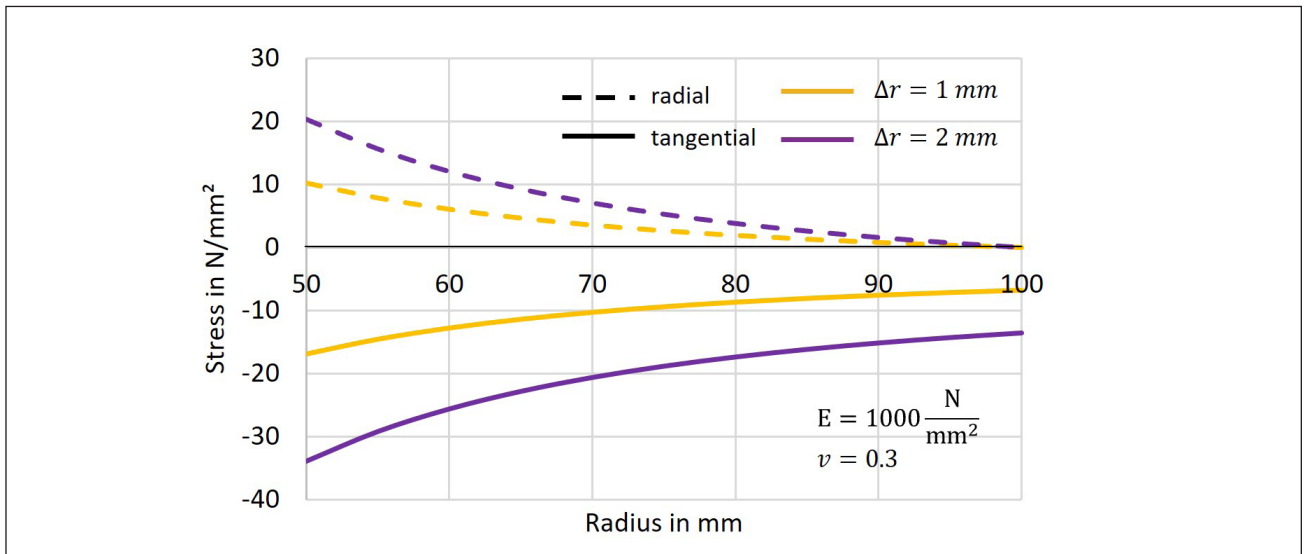
As the drawing depth increases, the tangential compressive stresses increase in magnitude, with the maximum remaining at the die radius in CD and at the outer edge of the blank in MD. **Figure 8** shows the maximum stress magnitude for MD and CD across the drawing depth, with dry paperboard on the left and humid paperboard on the right. In addition, the SCT limit values for MD and CD (Fig. 6a) are shown as dashed lines.

As described previously, the occurrence of wrinkles can

be checked by comparing the critical compressive stress with the effective compressive stress. The effective compressive stress increases quadratically with drawing depth. Based on the numerically determined effective compressive stresses, the first wrinkle in the dry sample will occur at approximately 2.8 mm in CD, where the critical compressive stress is exceeded. For wrinkling in CD, tangential compressive stresses must be taken into account with the critical compressive stress perpendicular to the wrinkling direction, i.e., in MD. A comparison of these results with the experimental observations shows a basic agreement. The first wrinkles can be detected in CD at a drawing depth of approximately 3.2 mm. Given the distribution of compressive stresses across the flange, wrinkles are expected



8. Numerically derived maximum tangential compressive stresses in the flange area as a function of drawing depth, shown for (a) low and (b) high moisture content. Absolute values of the negative stresses are shown.



9. Radial and tangential stress distributions from analytical estimation for two drawing depths.

at the inner radius (Fig. 7), which is also demonstrated experimentally (Fig. 5). Due to the lower compressive stress, wrinkling in MD is expected at a drawing depth of approximately 5.5 mm. In the experimental investigations, wrinkles in MD appear at a drawing depth of approximately 3.7 mm. The numerically determined stress curves show a higher compressive stress at the outer edge of the blank, so that wrinkle initiation would be expected there. This was experimentally confirmed for some of the wrinkles, as shown in Fig. 5. It should be noted that no stress reduction due to wrinkle formation is accounted for, as would be expected in reality. Additionally, no porosity is captured, potentially reducing compressive stresses, as described in [9].

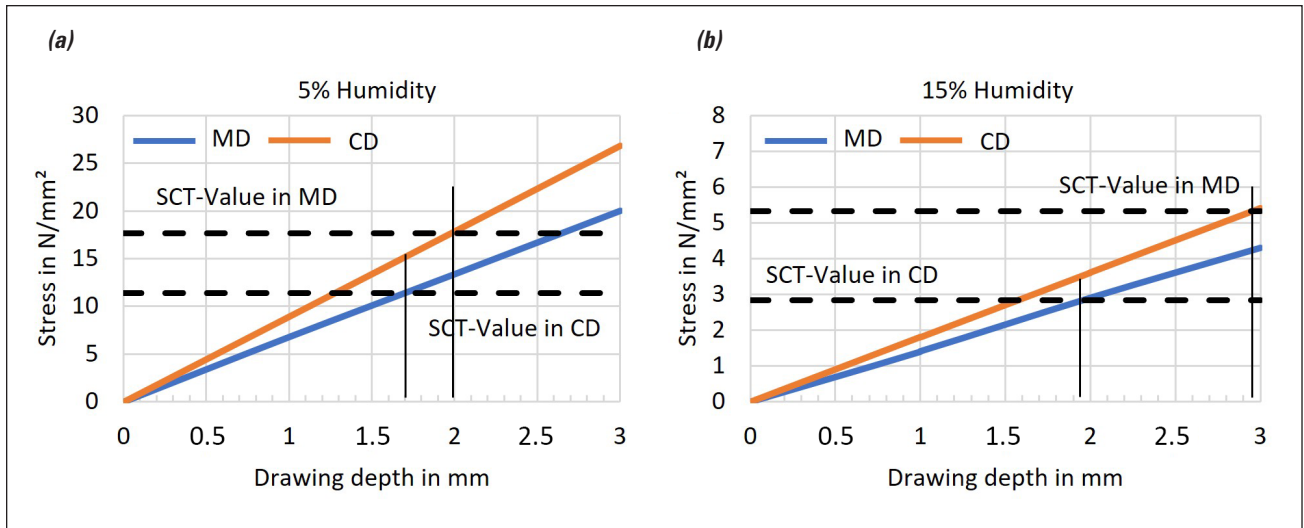
For humid paperboard, the numerically determined maximum compressive stresses in CD are lower than in dry paperboard, but slightly higher in MD. Significant differ-

ences are observed in the compressive strength determined in the SCT. As a result, wrinkling can be expected at a drawing depth of approximately 1.6 mm in CD and 2.05 mm in MD. In the experimental observations, the first wrinkles appear in CD at approximately 4.1 mm and in MD at approximately 4.8 mm.

As described in [11], the values determined from the SCT are strongly influenced by the clamping due to the relatively short free buckling length. The load scenario differs greatly from the SCT in terms of superimposed blank-holder forces and the clamping scenario.

Analytically derived stress distribution

Figure 9 shows the distribution of stresses in the flange in the radial and tangential directions, obtained from the analytical estimate, without taking the blank-holder force



10. Analytically derived maximum tangential compressive stresses in the flange area as a function of drawing depth, shown for (a) low and (b) high moisture content. Absolute values of the negative stresses are shown.

into account. The radial stresses are positive, with the highest value at the inner radius and similar to the numerical results. Towards the outer edge, the value approaches zero, as specified in the boundary conditions. The tangential stresses are negative across the entire flange area and progress at $1/r^2$. The highest stresses in terms of magnitude, therefore, occur at the inner radius, as obtained for CD in the numerical simulation. The tangential stresses remain less than zero towards the outer radius of the disc.

The derived analytical model is based on the assumption of isotropic material behavior and therefore cannot fully capture the anisotropy of industrial paperboard. Despite the fundamental assumption of isotropy, an investigation was conducted into how the tangential compressive stresses in MD and CD can be determined using the formula when direction-dependent material properties are applied.

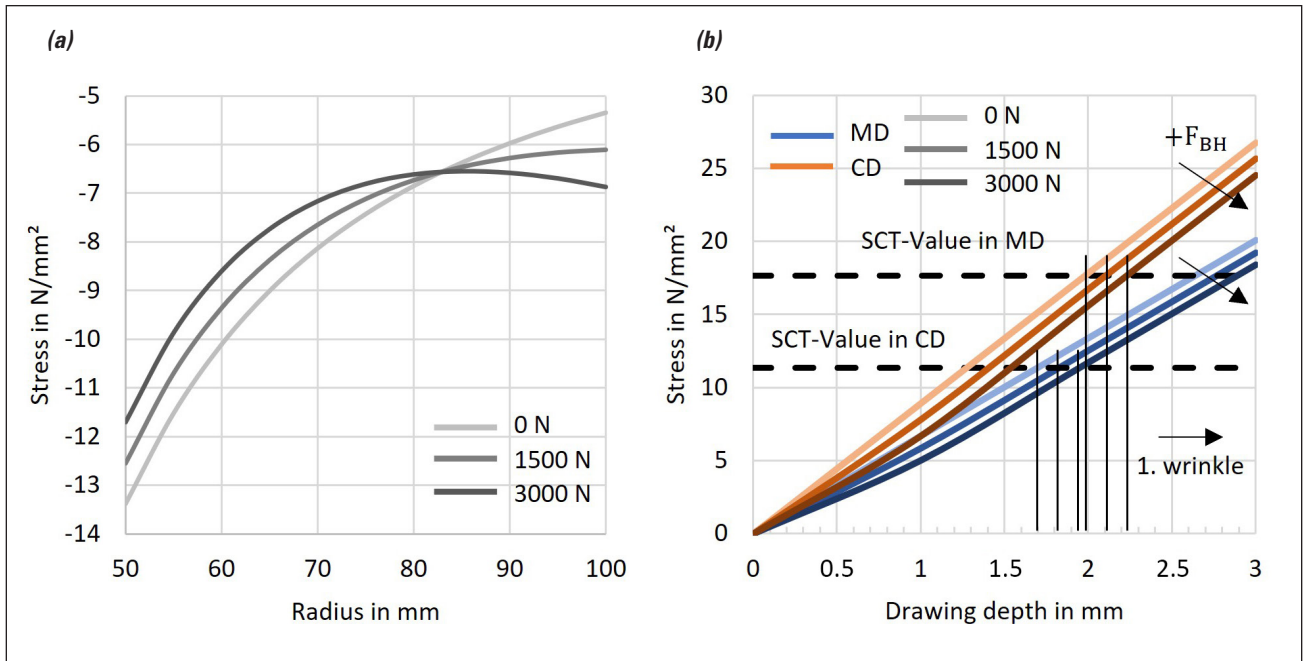
The direction- and moisture-dependent compressive elastic moduli obtained from the SCT measurements were used as effective elastic parameters. The Poisson's ratio was not measured experimentally. Therefore, ν_{12} was assumed to be 0.3 for the MD-to-CD direction. The reciprocal value ν_{21} was calculated according to $\nu_{21} = \nu_{12} \cdot E_{CD} / E_{MD}$.

The largest tangential compressive stresses, in terms of magnitude, are shown in **Fig. 10** for MD and CD at both moisture contents over the drawing depth. To calculate the tangential compressive stresses in MD, the material behavior in CD, described by the modulus of elasticity in the compression direction in CD as in **Fig. 6**, must be used. Likewise, this must be adjusted in the opposite direction. As shown in **Eq. 8**, the maximum compressive stress increases linearly with the drawing depth. A comparison with the compressive strength determined in the SCT shows that, for dry paperboard, the first wrinkle in MD would occur at a drawing depth of approximately 1.7 mm, and the

first wrinkle in CD would be expected at approximately 2 mm. This estimate differs from the experimentally determined values in terms of sequence and values (first wrinkle in CD at 3.2 mm; first wrinkle in MD at 3.7 mm).

In the case of moist papers, the significantly lower modulus of elasticity results in a later estimated initiation of wrinkling, despite the lower SCT values. Initial wrinkling would be expected at around 1.9 mm in MD and around 3 mm in CD. Here, too, the values and sequence deviate more strongly from the experimentally determined values (initial wrinkle in CD at 4.1 mm; initial wrinkle in MD at 4.8 mm).

Including the blank-holder force via friction introduces an additional radius-dependent load component. This component modifies the tangential compressive stress distribution and affects the outer flange area in particular. However, since the integration constants are determined from the boundary conditions, the resulting total stress is not uniformly increased. Instead, the superimposed frictional contribution leads to a redistribution of the tangential compressive stresses and to a reduction of the compressive stress magnitude in parts of the outer flange area, as shown in **Fig. 11a**. This leads to a shift of the area of maximum compressive stress towards smaller radii. The effect of the superimposed frictional force on the expected wrinkle formation is shown in **Fig. 11b** as an example for low material moisture. With increasing blank-holder force, a lower tangential compressive stress is observed at the same drawing depth. Compared to the compressive strength from the SCT, this leads to expected wrinkle formation at a later stage of the process. For example, the first wrinkle would be expected to appear at a depth of approximately 1.9 mm in MD with a blank-holder force of 3,000 N rather than at a depth of 1.7 mm without one. Although this value still deviates from ex-



11. (a) Analytically derived tangential compressive stresses with superimposed blank-holder force, exemplary in MD for low material moisture, and (b) maximum absolute compressive stresses derived from them over the drawing depth in MD and CD (shown in different colors) for different blank-holder forces (shown in different color intensities).

perimental values (3.7 mm), the correct tendency is evident, namely that the first wrinkle occurs later as the blank-holder force increases, as in Fig. 3c.

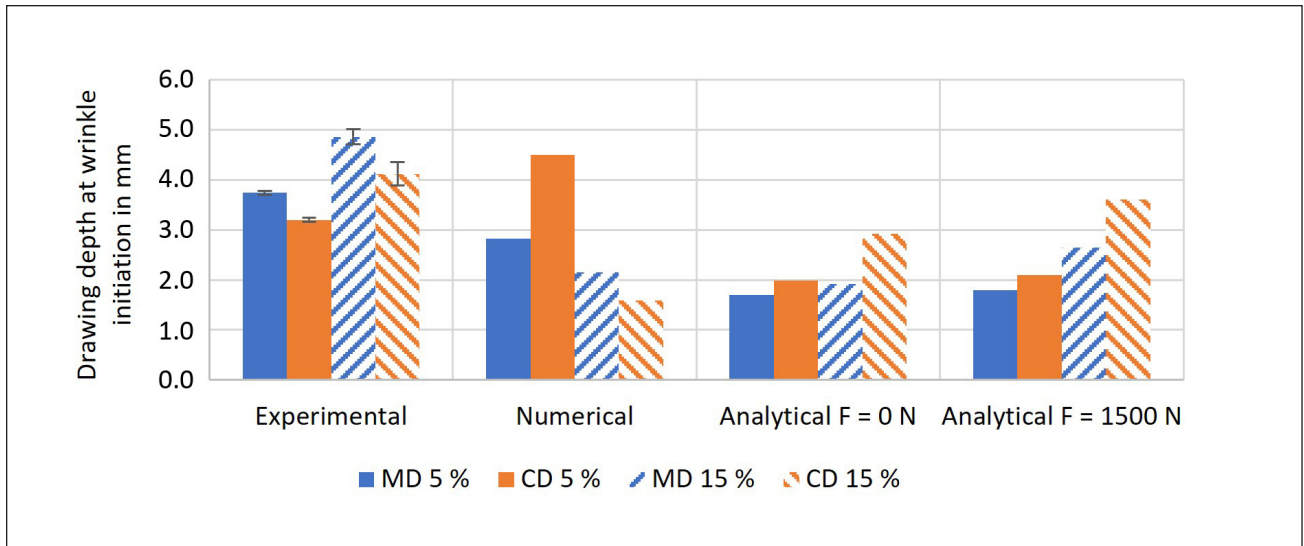
Despite taking into account the blank-holder force in the form of a frictional force acting over the surface, there are still deviations from the experimentally visible wrinkles. The analytically estimated drawing depth is consistently below the experimental values. A possible explanation is that the analytical model assumes that the drawing depth acts directly on the inner radius of the flange. No elongation in the bottom area and in the already deep-drawn wall area is considered. As can be seen in Fig. 3b, the radial indentation at the outer edge of the blank at the beginning of deep drawing deviates significantly from the drawing depth. The indentation at the inner radius of the flange used in the analytical consideration cannot be directly measured, but is expected to lie between the value of the drawing depth and the indentation at the outer radius. Consequently, the effective radial contraction of the flange is overestimated in the analytical model. Since the analytically derived tangential compressive stresses scale directly with the imposed radial displacement, the critical stress level is reached too early, and wrinkle initiation is predicted at smaller drawing depths than observed experimentally. Further deviations arise from the simplifying assumptions of the analytical model, including the equivalent isotropic material description, the idealized representation of blank-holder friction, the neglect of stress relaxation after wrinkle formation, and structural effects such as porosity and delamination. In addition, the critical com-

pressive stresses derived from the SCT represent only an approximation of the actual failure condition in the flange during deep drawing.

The assumption of equivalent isotropic material behavior enables a closed-form solution, but it does not fully capture the pronounced orthotropic behavior of paperboard. Since the local radial and tangential directions in the flange area continuously change their orientation relative to MD and CD, an orthotropic formulation would lead to angle-dependent stiffnesses and stress distributions. This could affect both the magnitude and location of the maximum tangential compressive stresses as well as the predicted sequence of wrinkle initiation, particularly at low moisture content where anisotropy is more pronounced.

Therefore, the analytical model should be interpreted as a simplified approximation for identifying the dominant stress mechanisms rather than as a fully quantitative prediction model. Future work should include an orthotropic formulation with direction-dependent elastic parameters, Poisson's ratios, and critical compressive stresses, as well as experimentally measured radial draw-in, a more detailed description of friction and blank-holder pressure, and out-of-plane instability or delamination mechanisms.

To facilitate the comparison between the model-based estimates and the experiments, **Fig. 12** summarizes the wrinkle-initiation depths obtained experimentally and those predicted by the numerical and analytical approaches for MD and CD at both moisture levels. The comparison shows that the numerical approach provides a closer esti-



12. Comparison of wrinkle-initiation depths obtained experimentally and predicted by the numerical and analytical approaches for MD and CD at low and high moisture content.

mate for some parameter combinations, but does not reproduce the experimentally observed sequence and absolute wrinkle-initiation depths in all cases. The analytical model consistently predicts wrinkle initiation at lower drawing depths than observed experimentally. Including the blank-holder force in the analytical model shifts the predicted wrinkle initiation to higher drawing depths, but the values remain below the experimental results. This deviation is mainly attributed to the simplified boundary condition of the analytical model, in which the imposed drawing depth is directly converted into radial flange displacement.

SUMMARY AND CONCLUSION

The transparent die used in this study enables process-accompanying analyses of wrinkle formation. An observation of deep-drawn components reveals that most wrinkles occur in MD. When detecting the formation of wrinkles across the drawing depth, it was observed that the first wrinkles form in the CD direction. A larger number of wrinkles only appear in MD at a later stage of the process, at a drawing depth of approximately 10 mm. Individual wrinkles are oriented parallel to the MD form from the outside in, whereas the majority of wrinkles, especially those in other orientations, spread from the inside out.

An estimate of the critical and effective compressive stresses in the flange was carried out to more precisely understand the occurrence of the first wrinkle. The critical compressive stresses were determined using a short-span compression test for different material moisture levels and fiber orientations. The effective compressive stresses were derived using two approaches. Pressure curves obtained from numerical simulations exhibit a strong directional dependence due to anisotropy. This is reflected in the mag-

nitude and qualitative course of the tangential compressive stresses across the flange. A comparison with the compressive strength from the SCT shows fundamental agreement between the expected and experimentally determined wrinkling: the first wrinkle is expected in CD, with wrinkles in MD following at a later drawing depth. The wrinkles, some of which are visible from the outside to the inside in MD, can be explained by the larger tangential compressive stresses at the outer radius. Quantitative deviations between the estimated and experimentally observed wrinkling can be explained in particular by influences on the determined compressive strength arising from the clamping situation in the SCT, as shown in [11].

In addition, a simplified analytical estimate of the effective compressive stresses was derived and also compared with the critical compressive stresses. Despite the simplifying assumption of isotropic material behavior, the present analytical model captures the primary mechanical mechanisms governing stress development during deep drawing. By assigning orientation-specific elastic parameters for MD and CD loading, the model incorporates the most relevant anisotropic effects in an averaged sense. This approach enables a physically meaningful and computationally efficient evaluation of stress distributions and critical regions prone to instability, while maintaining a closed-form analytical solution. Due to the strong idealizations, significant deviations between the estimated and experimentally visible wrinkle formation are observed despite accounting for the blank-holder force. Future work should address these limitations by extending the analytical description toward an orthotropic formulation and by incorporating experimentally measured draw-in and more detailed instability mechanisms.

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ABOUT THE AUTHORS

We chose this topic because wrinkle formation is one of the major challenges in the deep drawing of paperboard, and it directly affects the quality and functionality of paper-based packaging. In this study, we analyzed wrinkling during the deep drawing of paperboard using multiple approaches. With a transparent die, wrinkle formation and development could be made visually accessible. Using numerically and analytically determined tangential compressive stresses, wrinkling can be predicted within a specified range. This research complements previous work on paperboard deep drawing by focusing specifically on the location, timing, and propagation of wrinkle formation using experimental observations combined with numerical and analytical stress analysis.

The most difficult aspect of this study was observing wrinkle initiation during the forming process, since wrinkles can be very small and occur dynamically. We addressed this by using a transparent die and video-based evaluation with a high-resolution camera.

Through this work, we discovered that the first wrinkles typically initiate in the cross direction, while the majority of wrinkles at later drawing depths develop in the machine direction. The most interesting finding was that wrinkle initiation and wrinkle propagation are not uniform, but depend strongly on ma-

terial direction, moisture content, and the stress distribution in the flange area.

Mills may benefit from this information by better understanding how material properties, moisture content, and process parameters influence wrinkle formation during the conversion of paperboard into three-dimensional packaging.

The next step in this research is to improve the prediction of wrinkle formation by extending the analytical model toward orthotropic material behavior and by further linking process observations with numerical and experimental stress analyses.

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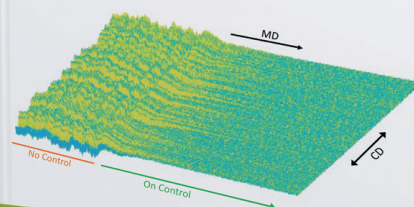
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