Compression-Drawing of Moisturized Paperboard: Experiments on Moisture and Temperature Dependencies

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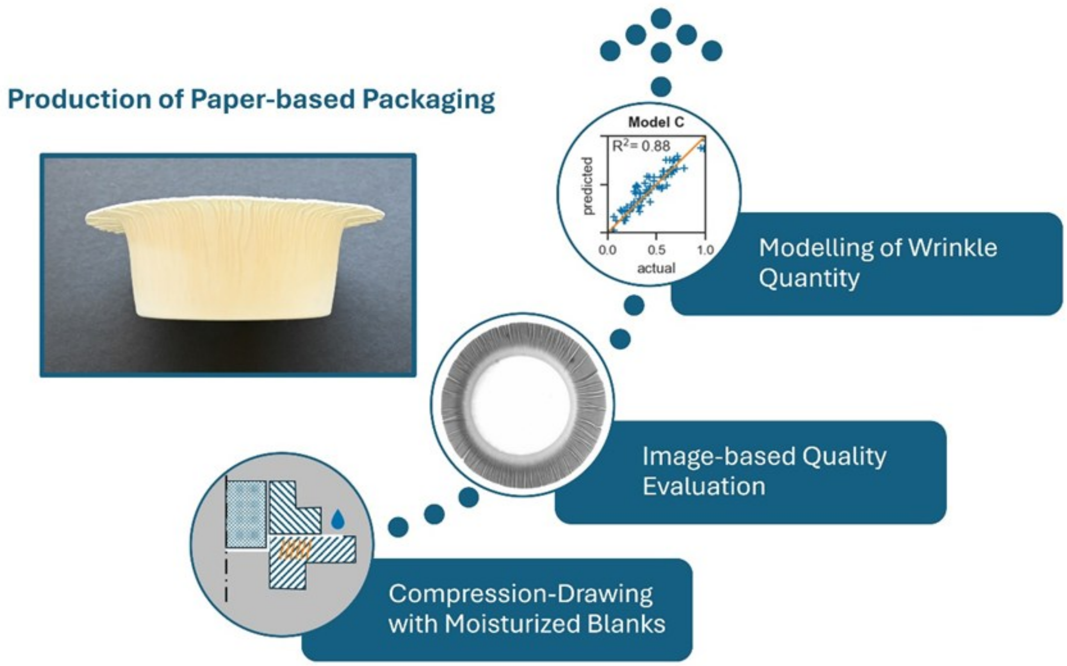
GRAPHICAL ABSTRACT



Compression-Drawing of Moisturized Paperboard: Experiments on Moisture and Temperature Dependencies

Lena Berthold,* Georg Steinert, and Jens-Peter Majschak

For the industrial production of paperboard packaging, knowledge about the process window of the forming operation is crucial information. This study presents how blank moisturization shifts the process window of a compression drawing process. A hydraulic press was utilized to draw circular cups, and their quality was evaluated by counts of defects and wrinkles. The experimental part further includes measurements of the materials' friction and tensile properties. It was found that both blank moisturization and increased blankholder force increased the wrinkle count and therefore improved the forming quality. However, the combination of high blankholder force and blank moisturization did not lead to superior forming quality. Rather, there were structural defects in the samples. A multilinear regression model was developed to predict wrinkle quantity based on tool temperature, material moisture content, and blankholder force.

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Keywords: Paper forming; Packaging; Bio-based materials; Water; Moisture; Friction

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INTRODUCTION

Fiber-based packaging is an ongoing trend in the food sector. Talia Goldman, ESG director of Colpac said in an interview with Packaging Insights: "Every material has its place in the packaging ecosystem, but there is a real power to paperboard, and we are seeing this growing wave of fiberization. It's been happening for a very long time, but it's definitely been in the zeitgeist at the moment" (Wang 2025). Legislation supports this development with restrictions of plastic use. The Packaging and Packaging Waste Regulation (Regulation (EU) 2025/40) was recently published and encourages the use of recyclable and biodegradable packaging materials in the EU. Alternative materials, such as fiber-based materials, must come into place to ensure the crucial role of packaging in global food supply. Those alternative materials are often harder or at least different to process in comparison to conventional plastics. New technologies must be found and researched, or existing technologies must be adapted to match the advanced requirements.

Paperboard, as an example of a fiber-based packaging material, offers favorable end-of-life scenarios: The recycling quota for paper and board materials in Europe is 86.6% (2023), being the highest among the packaging materials (European Commission, Eurostat 2025). If the board is not properly collected and enters environment, its fiber content is inherently biodegradable. However, the very thin plastic coating would degrade to microplastic particles.

Compression drawing is a 3D-forming technology, which converts an even paperboard blank into a one side open hollow shape. The punch pushes the blank into the cavity of the desired shape – the mold, while the blankholder controls the material inflow. The tight gap between punch and blankholder and the 90° tool angle result in immediate compression of the paperboard after entering the tool. Compression drawing of paperboard is also known as drawing or deep-drawing and is closely related to other forming processes like hydroforming, press forming, or dry-molding.

Although research on compression drawing dates back to the 1930s (Scherer 1932), the main studies with modern methods and machinery started with Hauptmann (2010). In the following years, the process influences of blankholder force trajectories, forming temperature, material properties have been investigated, as well as parameters of tool design (Vishtal and Retulainen 2012; Hauptmann *et al.* 2016a,b; Müller *et al*. 2017; Leng *et al.* 2024). Lenske *et al.* (2022) achieved separation of the force components such as bending force, in plane compression force, and friction force experimentally, which sum up to the overall forming force in compression drawing.

The influence of moisture on the paperboard properties, caused by its hygroscopic nature, is widely known (*e.g.*, Salmen 2018). In general, moisture reduces the tensile strength and stiffness of paperboard while increasing the elongation ability. The softening of the material is further enhanced when combined with heat, provided that thermal degradation or charring does not occur.

The influence of moisture on the compression drawing process wasn’t researched until recently, probably because of the cross influence of moisture to most of the before-listed parameters. Niini *et al.* (2022) and Berthold *et al.* (2024) both studied the effects of blank moisturization on press-forming and in the first case also involve compression drawing. The study of Berthold *et al.* (2024) is limited to forming with tools at room temperature to prevent excessive drying of the blanks before forming.

Steam is another method to moisturize paperboard before forming. A study by Afshariantorghabeh *et al.* (2024) applied an inline steam treatment to a thermoforming process of plastic-coated paperboard, which elevated the material moisture content by 2% to 4%. They observed a better fit to the mold contour, in some cases side effects like spring back increased as well.

Franke (2021) applied steam to a deep-drawing process *via* steam outlets in the blankholder surface to simultaneously insert moisture and heat to the paperboard blank. The moisture content in paperboard blanks of initially standard moisture content increased within 7 s of steaming to 23%. The steam treatment improved the shape accuracy (reduced ovality of the circular cup) and improved precepted visual quality. Although a drawing process was applied, it seems to lack compression in the forming gap, and thus limiting the overall sample quality.

Orlik *et al.* (2024) formulated a numerical model to investigate the effects of inner structure, moisturization, and evaporation on moisture distribution in a paperboard sheet. Orlik *et al*. (2025) extended their findings to coupled heat and moisture transport in moist paperboard. The work was validated with temperature profiles of real boards upon heating. Results suggested the application of their finding to the drawing process.

This study focuses on the experimental examination of the influences of temperature, moisture content, and surface coating of paperboard on both material behavior and the results of compression-drawing processes. It is an insight on the complex inter-dependencies of different material properties within the process of compression-drawing.

Since material moisture content, among other process parameters, has been little researched to date, two major research questions arise based on the literature mentioned above:

1. Will additional moisturization increase the formability of fiber materials and lead to higher quality of the produced cups?
2. Will additional moisturization weaken the structure of fiber materials and lead to an increased risk of material failure?

An important distinction relative to previous research is praxis-orientated moisturization with spray application instead of time-consuming sample preparation in varying climate conditions. This research shows the impact of process parameters and material conditioning measures and therefore allows conclusions for industrial production setups.

EXPERIMENTAL

Materials

All experiments were executed on the material Trayforma™ PE from Stora Enso Oyi (Helsinki, Finland). It is a three-ply fresh fiber paperboard material (baseboard grammage of 310 g/m^2) with 15 g/m^2 single-side polyethylene (LDPE) coating. The liquid used for moisturization was tap water at 23 °C from a single source. Therefore, the properties were assumed comparable throughout all experiments. The LDPE-coated material was selected to mimic industrial forming processes, in which the polymer layer functions as a barrier and facilitates heat sealing.

Moisturization

A surface moisturization was applied to the blanks or material samples to achieve varying moisture states. A two-substance spray nozzle "Module System Range 970 Form 5" from Düsen-Schlick GmbH (Coburg, Germany), sprayed air and water onto the paperboard side of the samples (see Fig. 1). The LDPE surface was not moisturized because the LDPE is water repellent. Moisturized samples were processed at consistent timing within the first minute after spraying.

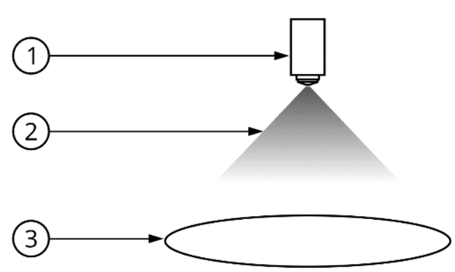

Fig. 1. Moisturization setup. A nozzle ① sprays a water cone ② to a paperboard sample ③, at a defined distance and for a definite time

To assess the samples' moisture content at standard conditions, a modification of EN ISO 287:2017 oven dry method was used, with drying for 60 min at 130 °C using moisture analyzer "MT-C" from Brabender GmbH & Co. KG (Duisburg, Germany). The moisture content of the paperboard at standard climate could then be calculated according to Eq. 1:

$$w_{\mathrm{St}} = \frac{m_0 - m_1}{m_0} \tag{1}$$

In Eq. 1, m_0 is the mass (g) of the paperboard at standard climate and m_1 is the mass (g) after the drying process. Additional moisturization leads to an increase of moisture content. If the initial moisture content is known, then the moisture content w of the moisturized material could be calculated according to formula 2,

$$w = 1 - \frac{m_0}{m_2}(1 - w_{\mathrm{St}}) \tag{2}$$

where m_0 is, again, the mass (g) of the paperboard at standard climate, m_2 is the mass after additional moisturization, and w_{St} is the moisture content (%) at standard climate. That way, weighing the moisturized samples was sufficient to determine the moisture content.

For this study, three different levels of moisturization were specified:

- ST (standard): No additional moisturization was performed. This leads to a standard moisture content of 7.1%. This value was chosen as a reference.
- ME (medium): A medium amount of moisturization was performed. This leads to an increased moisture content of 11% to 12%. This value was chosen to fit within the other points.
- HI (high): A high amount of moisturization was performed. This leads to a high moisture content of 16% to 17%. This value was chosen as the maximum amount of moisturization possible with the presented setup and in a reasonably short time (1.0 s).

These levels were used for both material characterization and compression-drawing experiments. Since the sample geometries differed for the various experiments, an alternation of the spraying parameters (distance between sample and nozzle, spraying time) was necessary. To ensure the adequate moisture content of the samples, gravimetrical measurements were performed before each test series.

Material Characterization

All testing for material properties took place in a standard test climate for paperboard with 23 °C and 50% r.h. (ISO 187:2022). First, the basic properties were identified according to (ISO 534:2011; ISO 287:2017; ISO 536:2019) as shown in Table 1. These parameters were necessary for the following tensile and friction tests.

Table 1. Basic Material Properties at Standard Conditions (23 °C, 50% r.h.)

Property	Value	Unit
Thickness	446	µm
Density	0.74	g cm^{-3}
Specific Volume	1.39	cm^3 g^{-1}
Grammage	322	g m^{-2}
Moisture content	7.6	%

The dynamic coefficient of friction (*cof*) between the paperboard material and a polished stainless steel (Type 1.4301) surface was determined with the double strip test method as described by Lenske *et al.* (2018). The setup allows testing of both sides of the paperboard material (LDPE-coated and non-coated side) independently from each other, and with defined speed, tool temperatures, and set surface pressure or constant normal force.

$$cof = \frac{1}{b-a}\int_a^b \frac{F_F(s)}{F_N(s)} ds \quad (3)$$

Equation 3 shows the calculation of *cof*, with a and b being the first and last position, where the whole samples is in between the tools, F_F (N) being the friction force at the given point and, F_N (N) being the normal force applied at this point. The external test parameters are held constant in the region of interest between points a and b. As Blume and Stecker (1967) showed, the velocity dependency of friction tests for paperboard is significant. The velocity of 80 mm/s was used, which was based on a hypothetical processing machine, forming 40 mm deep paperboard cups at a rate of 60 cups per minute while forming time at each cycle is 500 ms. Lenske (2023) describes furthermore, that certain adhesive interactions between metal and paperboard surfaces effect the frictional behavior significantly. This occurs especially at the start of a test series or after cleaning the tool surfaces. To reduce the impact of this phenomenon, at the start of each test series, experiments of the same parameter setup were performed, until the experimental data did not change further. No tool cleaning was performed within each test series to maintain constant conditions. The measurements at each parameter combination were repeated 3 times.

Tensile tests were performed according to ISO 1924-2 (2008) standard to determine tensile strength and elongation at break, and each experimental point was repeated 5 times. To examine temperature influences, a heat chamber was installed around the test rig. To ensure the heat was transmitted to the paperboard sample, the samples were placed in the test rig, and the test was started one minute after the chamber reached the aimed temperature. Table 2 summarizes the fixed and variable parameters of the material characterization.

Table 2. Fixed and Variable Parameters for Material Characterization

Properties	Tensile Test	Friction Test
Fixed Parameters		
Standard	ISO 1924-2 (2008)	-
Velocity (mm/s)	20	80
Climate conditions at test	23 °C, 50% r.h.	23 °C, 50% r.h.
Variables		
Tool temperature (°C)	23 | 50 | 80 | 120	23 | 50 | 80 |120
Moisturization	No | medium | high	No | medium | high

Forming Experiments

The sample geometry was chosen as a circular base shape, with 80 mm diameter, 40 mm forming height, resulting in a height to diameter ratio (sometimes called forming ratio) of 0.5. The TUD Dresden University of Technology paper-forming test rig (Hauptmann 2010) with hydraulic axes for blankholder and punch motion was used to perform the compression drawing. Müller (2023) gives a useful summary of this machine. Figure 2 depicts the tool geometry and some major measures. The three-part tooling consisted of mold, punch, and blankholder. All of them are made of stainless steel (Type 1.4301) with polished surfaces on the mold and blankholder, but not on the punch.

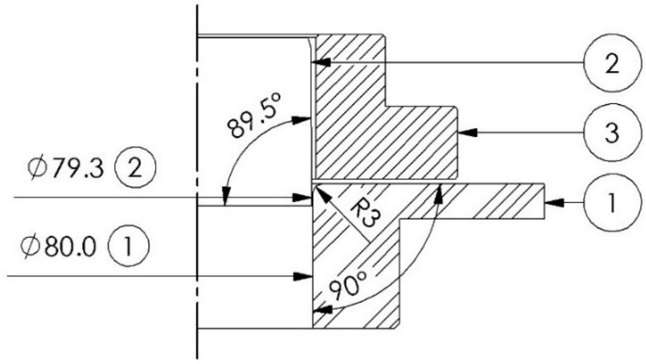

Fig. 2. Compression-drawing toolset (quarter section) and main dimensions. ① mold, ② punch, ③ blankholder

A variation of both temperature and moisture content as before seemed reasonable. Furthermore, the blankholder force was varied, since this has a crucial influence on forming paperboard (Hauptmann 2010). The parameters used for experiments are shown in Table 3. Tool temperature was applied only at the mold, since influence of a heated punch is limited (Müller *et al.* 2017) and to prevent the LDPE-coating from sticking to the punch. To avoid unwanted heat transfer prior to forming, the blank was attached to the punch. Thus, the conditioned paperboard blank touched the hot surface of the mold only just before the forming started. The mold temperature may be referred to as 'tool temperature' or 'temperature' in subsequent paragraphs. Decreasing blankholder force trajectories as shown in Fig. 3 were chosen to compensate for the reduction of blank area under the blankholder during forming.

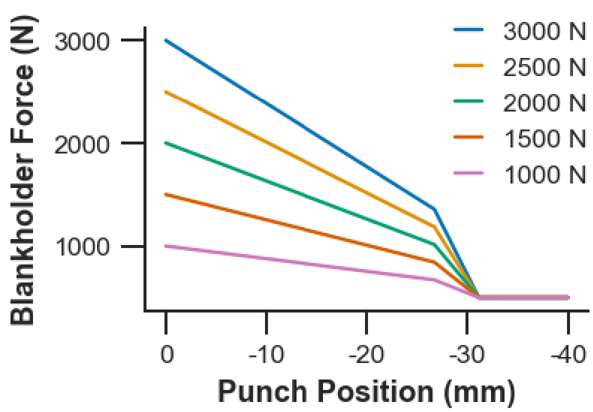

Fig. 3. Blankholder force trajectories for different nominal blankholder forces

Table 3. Fixed and Variable Parameters for Forming Experiments

Properties	Value
Mold temperature (°C)	20 | 50 | 80 | 120
Moisturization	No | medium | high
Blankholder force (N)	1000 | 1500 | 2000 | 2500 | 3000

The evaluation of the forming results consisted of two steps. First major defects (ruptures) were detected and excluded manually. The defect samples were later considered outside the process window. Second, the remaining intact parts were further evaluated regarding their wrinkle pattern. With a setup as shown in Fig. 4, top view images of the sealing rim area are taken as the base for wrinkle evaluation. Two examiners counted wrinkles along the circumferences independently and the average of their counting was used as a quality parameter. If the number of identified wrinkles deviated more than 10%, a third examiner was consulted.

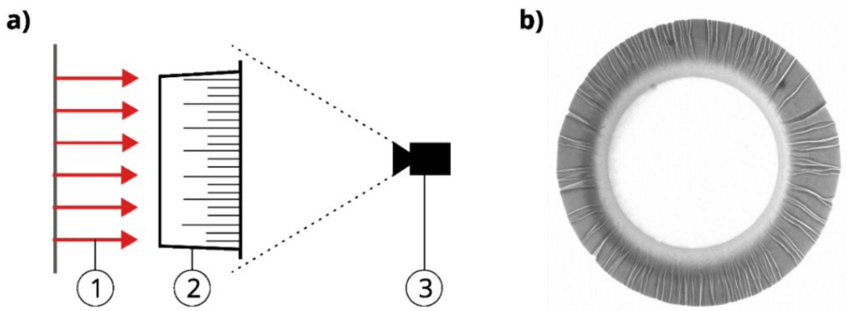

Fig. 4. a) Schematic view of imaging setup with ① infrared light source (750 nm), ② sample, ③ camera. b) Example of top view image taken with this setup

The forming results were additionally analyzed with multilinear regression models. All modelling was based on the *python statsmodel* module (Seabold and Perktold 2010).

RESULTS AND DISCUSSION

Material Characterization – Friction tests

Both the coated and the non-coated surface showed temperature dependencies but in different directions. Figure 5 presents the related data. While the *cof* for the LDPE-coated surface increased with rising temperature, the *cof* of paperboard surface decreased. The results of the non-coated surface aligned very well with the known literature (Lenske 2023).

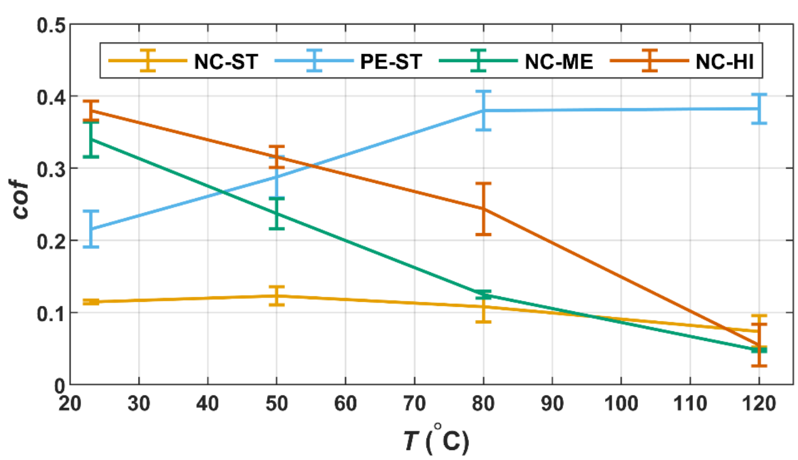

Fig. 5. Dynamic coefficient of friction *cof* of the tested paperboard depending on tool-temperature. Distinction between non-coated surface (NC) and LDPE-coated surface (PE) and the moisture levels no additional moisturization (ST), medium (ME) and high (HI) additional moisturization

The increase of the LDPE-coated surface, however, seems to be contradictory at first glance (West and Senior 1971). Voll (2016) states that the *cof* of thermoplastics are highly dependent on the friction partners, the load and velocity. The test results show that the *cof* of the LDPE-coated surface increased with temperature. Between 80 and 120 °C, there was no further increase of the *cof* of the LDPE-coated surface. While this does not fit with the proportional behavior of lower temperatures, a valid explanation could be that the melting temperature of LDPE was surpassed, resulting in a significant change of viscosity and elasticity (Eyerer and Schüle 2020).

As mentioned before, only the non-coated side was moisturized. As can be seen, the frictional coefficient increased with moisture content. This confirms the results from (Berthold *et al*. 2024). A dependency on the fiber orientation was not detected during preliminary tests.

Material Characterization – Tensile tests

In contrast to the friction tests, where the heat was transmitted through contact, the heat chamber used for the tensile tests transmitted the heat through radiation. Since that is slower, a high influence on the moisture content is expected. This was shown by gravimetrical measurements. Therefore, no combined moisture and temperature dependencies were examined.

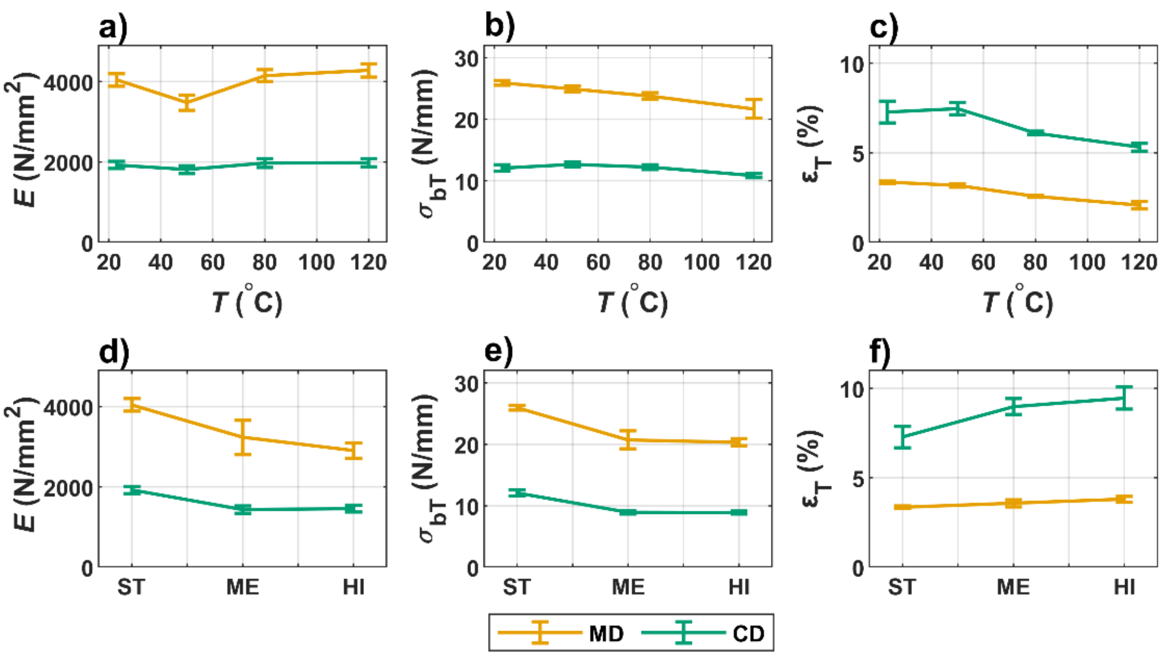

Fig. 6. Results of tensile tests: a) and c) E-Modulus (E); b) and e) width related Breaking Force (σ_{bT}); c) and f) Breaking strain (ε_T). Graphs a) - c): standard moisture with different temperatures and graphs d) - f): room temperature (23 °C) with different moisture levels (standard (ST), medium (ME), and high (HI) moisture level.). Fiber orientations in both machine direction (MD) and cross direction (CD)

As shown in Fig. 6, increasing temperature led to decreasing breaking force and elongation at break. The elastic modulus (*E*-modulus) appeared to be independent of the temperature and showed only minor deviations. Increasing moisture led to a decrease in breaking force and *E*-modulus, while the elongation at break increased. All experiments showed the anisotropic behavior of the material since fiber orientation has a dominant influence on the tensile characteristics. The findings on tensile strength and elongation at break align well with the related literature (Salmen 1982; Franke 2021; Berthold *et al*. 2024). Salmen (1982) reports for dry paperboard, that the *E*-modulus for dry paperboard is temperature-dependent but the influences is strongest at high temperatures above 200 °C where cellulose and hemicellulose soften.

Forming Experiments

The first objective was to find the process window. Therefore, every formed cup was evaluated regarding major structural defects such as ruptures or extraordinary deformations. Figure 7 shows the results, by depicting non-compliant areas in black and suitable areas in beige color. A parameter combination is considered inside the forming window when at least two out of three samples were intact. As can be seen, moisturization decreased the maximal blankholder force which still allowed for quality compliant cups. Moisture also limited the forming success at low temperatures. Medium moisturized blanks could only be formed with heated tools. This study investigated parameter range, moisturization seemed to narrow the forming window, especially regarding the blankholder forces. A shift of the forming window towards even lower blankholder forces should also be considered here. Note that in this study, the parameter range was limited by the forming equipment and could not have been extended towards lower force while maintaining the shape of the earlier presented force trajectory.

Forming of cups at 50 °C with low (1000 N) blankholder force was peculiarly only possible under medium moisture conditions. However, forming at other temperatures and the same 1000 N blankholder force was possible under both standard and high moisture conditions.

The application of surface moisture increased the *cof* (see Fig. 5), and resulted in a larger proportion of blankholder force that acted as normal force being transformed into material strain. This aggravated load in combination with reduced strength (see Fig. 6) caused material failure and reduced the forming window.

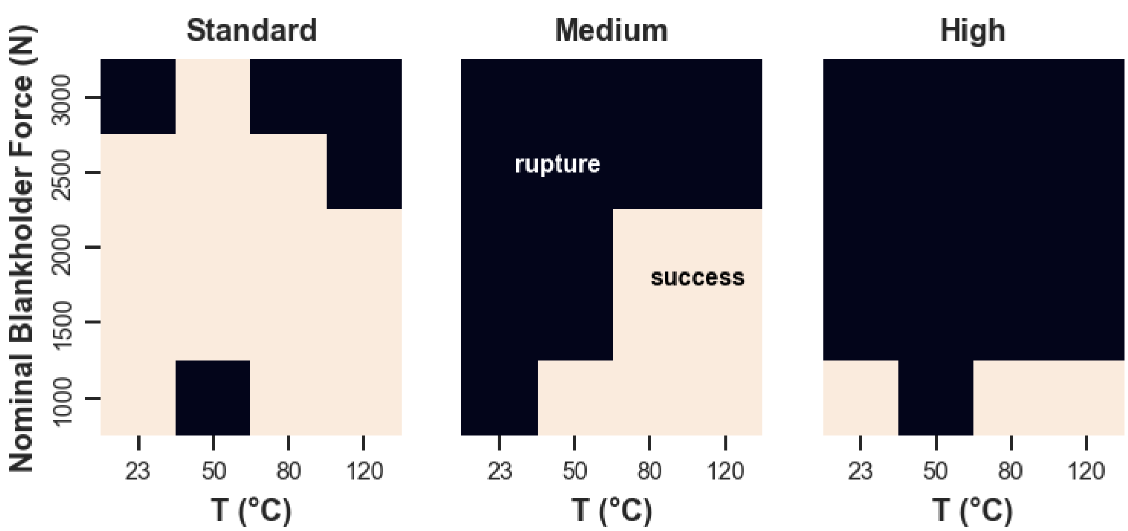

Fig. 7. Process window for forming cups with conditioned material at three moisturization levels (Standard – Medium - High)

The second objective was a quality assessment of the successfully formed cups, where the quantity of wrinkles q_w served as the governing criterion. All cups with structural defects were excluded from the upcoming discussion. As can be seen in Fig. 8, both blankholder force and moisturization had an influence on the wrinkle quantity. Large numbers of wrinkles indicate finer wrinkles and therefore high quality. In total, the lowest observed wrinkle quantity q_w at an individual cup was 75.5, occurring at standard moisture level, 1000 N blankholder force, and 80 °C tool temperature. The cup with the highest wrinkle quantity q_w (174 wrinkles, at high moisture level, 1500 N, 120 °C) had more than twice as many wrinkles. Moisturization encouraged the formation of multiple fine wrinkles. This finding corresponds to Marin *et al.* (2020), who performed a short-compression-test (SCT) on paperboard materials with varying moisture contents. The SCT-values dropped with increased material moisture content, suggesting lower resistance to in-plane compression.

A threshold of q_w=130, representing 75% of the maximum observed wrinkle quantity, could serve as criterion for determining acceptable forming quality. Such quality was achieved by eight parameter combinations in total, of which four occurred at standard moisture level, two at medium moisture level, and two at high moisture level. The influence of tool temperature on the forming quality was less pronounced than expected. A possible explanation is the parameter choice of forming temperature at max. 120 °C. When considered separately, the general trends were a positive influence on the quantity of wrinkles for nominal blankholder force, moisturization and tool temperature. High sample qualities can be achieved at the border of the process window. This underlines the importance of process knowledge for the industrial application of the compression-drawing process to balance a robust production with high product quality standards.

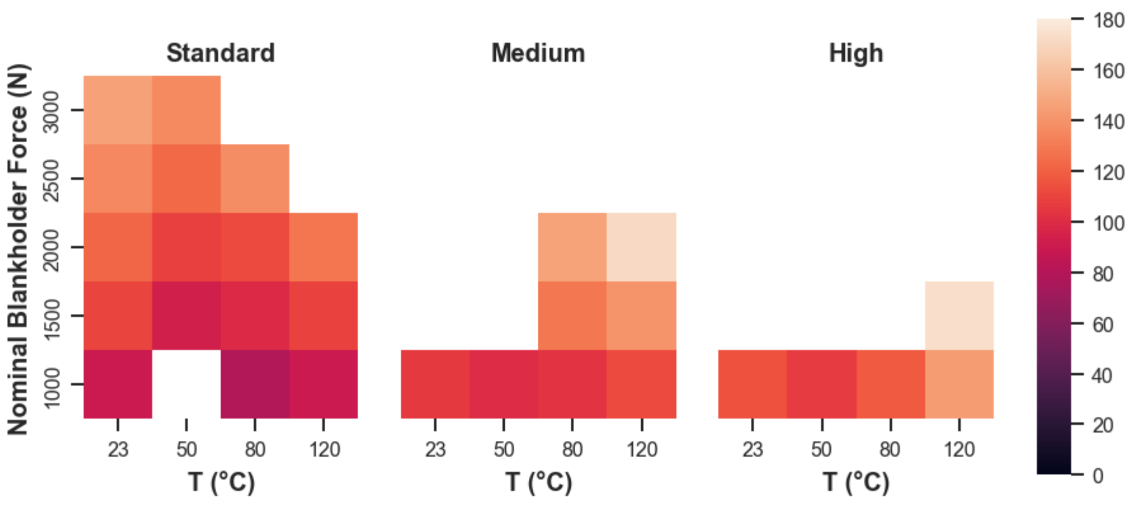

Fig. 8. Mean wrinkle quantity of successfully formed samples for different combinations of tool temperatures (*T*), nominal blankholder force, and moisturization. Blank areas occur where no intact samples were obtained.

The influence of material moisture content (by moisturization) *w*, tool temperature *T*, and nominal blankholder force *F* on the wrinkle quantity q_w was additionally analyzed with multilinear regression models. These models subsequently enabled quality predictions across the entire parameter space. The influence of moisturization was modeled as the numerical parameter of material moisture content and not the categorical parameter of moisturization level (standard – medium – high). From different approaches, four models were derived, and their nomenclature is presented in Table 4. All those models used the ordinary linear squares method for their regression. The results were evaluated using $\alpha = 0.05$ as threshold for significant correlation. The linear approach included all linear terms, their twofold interactions, and the threefold interaction. The extended approach additionally included the quadratics of the influencing variables but no interactions with those quadratics. Full dataset models included all successfully formed part in the model. Note, that the data were not evenly distributed over the parameter range (see Fig. 8). For example, for high moisture conditions, the number of samples was much smaller than for standard moisture conditions. Models B and D included only data for standard and medium moisturization, with blankholder forces up to 2000 N at all temperature levels. In this parameter range, the data points were more evenly distributed and only a few were missing. The scale of the parameters and the target strongly diverged from approx. 10^{-2} for moisture content w, T, and q_w around 10^2 to F at 10^3. To compensate, all variables of the datasets were scaled to the range of 0 to 1 using their minimum and maximum values. The reduced dataset was also scaled with minimum and maximum of the full dataset to enhance comparability. In the model representations, the authors include three meaningful digits for the intercept and the effects.

Table 4. Nomenclature for Modelling Approaches

	Full Dataset (n = 75)	Reduced Dataset (n = 53)
Linear Approach	Model A	Model B
Extended Approach	Model C	Model D

Model A considers all linear terms and their interactions for the full dataset. The influence of moisture content ($P < 0.001$), blankholder force ($P < 0.001$), and the interaction of temperature and moisture content ($P = 0.001$), as well as the three-fold interaction ($P = 0.026$) were significant to the chosen level. The resulting scaled model is formulated by Eq. 4:

$$q_w = 0.117 + 0.236\,w + 0.556\,F + 0.323\,w \cdot T + 1.637\,w \cdot F \cdot T \tag{4}$$

Model B is based on the reduced dataset. All linear terms and their interactions were calculated. After removing insignificant effects, only the effects of moisture content ($P = 0.046$) and blankholder force ($P < 0.001$) remain, and the resulting scaled model is formulated by Eq. 5:

$$q_w = 0.113 + 0.256\,w + 0.552\,F \tag{5}$$

Model C includes the full dataset and extends the model approach by adding quadratic terms but no interactions with the quadratics. The significant influences are by temperature ($P < 0.001$), moisture content ($P = 0.002$), their interaction ($P < 0.001$), blankholder force ($P = 0.000$), the interaction between temperature and blankholder force ($P = 0.018$), and the quadratic temperature ($P < 0.001$). The scaled model is shown as Eq. 6:

$$q_w = 0.165 + 0.347\,w + 0.626\,F \\ -0.532\,T + 0.346\,w \cdot T + 0.266\,F \cdot T + 0.493\,T^2 \tag{6}$$

In **Model D**, the reduced dataset is analyzed with the extended approach. After removing insignificant effects, only the influence of the blankholder force F ($P < 0.001$) and the squared temperature T^2 ($P < 0.001$) remain. The scaled model is shown in Eq. 7:

$$q_w = 0.149 + 0.717\,F + 0.486\,T^2 \quad (7)$$

Figure 9 presents the results of the four scaled models as actual-by-predicted-graphs and includes the coefficients of determination R^2 as measure for the quality of the model. Data points not represented in the charts were still included in the calculation of R^2. The models B and D, which were calculated with the reduced dataset, both displayed poorer fits than their equivalent Models A and C, which were based on the full available data. The authors deduce, that the excluded data of high moisturization levels and high blankholder force contain valuable information and should not be excluded.

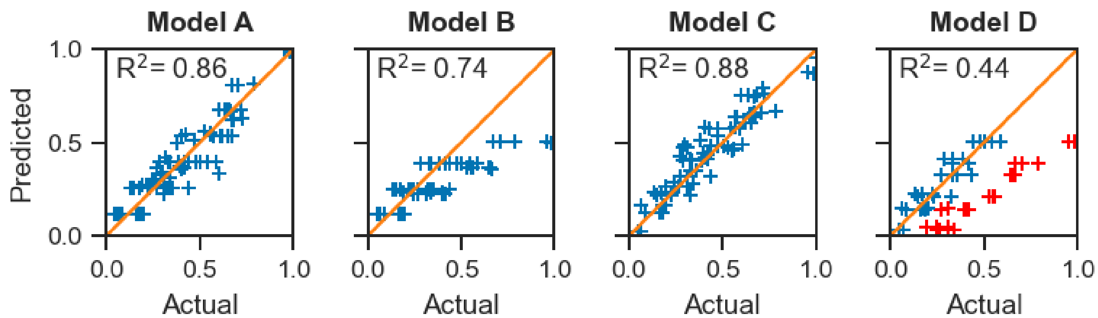

Fig. 9. Actual-by-Predicted-Graphs for four modelling approaches (A, B, C, D) and their coefficients of determination R^2. For Model D, the results are colored for no moisturization (blue), and medium moisturization (red).

The Model C (Eq. 6) performed best, measured by $R^2 = 0.88$. It included an intercept and six effects of variables or their interactions. The large number of terms resulted in a very accurate modeling of the presented data but can also contain the risk of overfitting. The even scale of all coefficients provided a stable model behavior, meaning that small changes in input will not dramatically change the output. The differences between actual and predicted data were uniform over the prediction range. The blankholder force had a large positive influence, indicating that a higher blankholder force resulted in higher numbers of wrinkles. Based on this data, the temperature had a large negative influence. A possible explanation is the observed the loss in strength with increasing material temperature (see Fig. 6). This is noteworthy, since it is generally believed (Hauptmann 2010) that compression drawing benefits from increased temperatures. This negative influence is mitigated by the positive influence of its quadratic and the interactions of temperature T with moisture content w and blankholder force F.

Model A attained a good fit ($R^2 = 0.86$) as well. However, the very strong three-fold interaction is not easy to explain. Moisture and heat had a coupled effect firstly on the friction properties of paperboard (see Fig. 5), and secondly on the softening of cellulose fibers (Gustafsson and Niskanen 2012), and thirdly on the strength of the fiber network (Coffin 2012). This may partially explain the three-fold interactions of w, T, and F. However, the scale of the effect, being three times largest than the largest individual effect makes it suspicious for overfitting. In Model A, no significant influence of temperature T was detected.

Model D was distinctly weaker than the other three models. By coloring groups that include samples with low and medium moisture content (see Fig. 9) it becomes evident that the exclusion of moisture from the model equation resulted in a noticeable deviation. Although moisture content was not found to be significant, this grouping was the cause of the poor fit.

In all models, the blankholder force *F* had the largest individual effect on the wrinkle quantity. This strong influence is confirmed by earlier literature, such as Hauptmann (2010) or Müller *et al.* (2017). A higher moisture content also increases the number of wrinkles in intact cups and thus forming quality.

Moisture did have a relevant influence on the deep drawing of paperboard. However, the experiments showed limitation when applying surface moisture. From the viewpoint of process control, it might be more promising to adjust the blankholder force levels based on material moisture content, rather than applying moisture to the paperboard.

As mentioned before, large wrinkle quantities are desirable, because they indicate fine wrinkles and therefore good quality. A high material moisture contents requires lower blankholder force, due to increased friction and reduced strength, while still achieving a high number of wrinkles. On the other hand, a dryer paperboard blank can bear higher blankholder forces, which also result in more wrinkles and therefore higher forming quality. In practice, acceptable forming qualities highly depend on the intended use case.

The authors suggest using Model C to model the wrinkle quantity of the resulting cups: A goal of future work can be to obtain a model that is more accurate inside the process windows and includes significant influences of all three parameters material moisture content, blankholder force, and tool temperature.

CONCLUSIONS

The results of this study confirmed that moisture content had a significant influence on the forming behavior of paperboard in the compression drawing of paperboard. Moreover, the constraints when using blank moisturization and the need to adjust other process parameters accordingly became evident. Further research should include more elaborate quality criteria, and investigations into the rupture mechanisms of moisturized paperboard. A first clue could be to examine the homogeneity of the moisture across the surface in question. It would be interesting to see to what extent any inhomogeneities correlate with the occurrence of ruptures. The authors conclude:

1. Temperature and moisturization influence both material properties and forming results of paperboard.
2. Temperature and moisture have analogous influence on material strength but converse influence on friction coefficient.
3. The application of moisture to the blank surface narrows the process window considerably. Though, the best forming quality was achieved at high moisture conditions.
4. With rising temperature, the friction coefficient decreases. The paperboard furthermore loses strength and gains stiffness. However, as the wrinkle quantity increases the quality of formed cups improves.
5. Higher moisture levels lead to a significant increase in friction coefficient. The material loses stiffness and strength.
6. The authors suggest using a multilinear regression model (Model C) to model the wrinkle quantity of the resulting cups. It performs accurately inside the process windows and includes significant influences of all three parameters material moisture content, blankholder force, and tool temperature.

7. The use of surface moisturization is limited by the narrowing of the process window. When applying surface moisture, it is of great importance to adjust blankholder force and tool temperatures accordingly.
8. Due to the smaller process window with only a slight improvement in cup quality, based on current knowledge, moisturization is only recommended if the process behavior is sufficiently well known. Otherwise, it may well be appropriate to refrain from moisturization.

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