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Tailoring Thermal Energy Supply Towards the Advanced Control of Deformation Mechanisms in 3D Forming of Paper and Board

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Abstract: The temperature of the tools and the moisture content of the material play a significant role in the 3D forming of paperboard in terms of the degree of forming and the quality of the formed part. It is known that different forming mechanisms act within the paperboard in different areas of the deep drawing tools during the deep drawing of paperboard and that the success of the forming process is also based on a dynamic interaction between material moisture and tool surface temperature. However, it has not yet been investigated how the forming parameters can be influenced by an individually adjustable temperature for the individual tool areas and how they influence the complex interaction with the moisture content of the paperboard during the forming process. Due to the inhomogeneity of the natural fiber network of paperboard, rapid and directed temperature changes of the tools are also of interest in order to be able to react quickly to variations of material properties in order to prevent frequent process failure within a continuous production. In this paper, test tools with individually controllable heating zones were developed and the use of different heating technologies to improve the rate of temperature change was analyzed. These tools were used to investigate the influence of temperature in the individual sections of the deep drawing process and how the moisture content can be specifically controlled during the process. It was found that with modern heating technology, the deep-drawing tools can be tempered significantly faster and that a temperature difference between the blank holder zone and the drawing cavity zone has a positive influence on the formability and the fixation of the shape of the part produced. This effect was further enhanced by the fact that, thanks to the temperature tailored tool, it was possible to work with a very high moisture content of the paperboard.

Keywords: paperboard; deep drawing; tool modification; temperature and moisture control



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1. Introduction

Due to increasing demand and new legislative requirements [1], companies are increasingly looking for ways to replace plastic packaging with packaging made from natural fiber materials such as cardboard. The geometries that can be produced and the production speed play a major role when considering processes for producing packaging from cardboard in comparison with the plastic packaging to be substituted. One way of producing cylindrical shaped parts from cardboard at high speed is deep drawing. To improve the cardboard thermoforming process, there are various influencing factors.

A significant factor is the temperature of the drawing tools. The temperature serves to soften the cardboard and fix the forming result. The drawing tools consist of a blank holder, a punch and a drawing cavity. In the conventional process, these components are each heated to a uniform temperature by installing several heating elements in the tool components, depending on the size and geometry. This process requires a lot of energy and time until a uniform temperature is reached, since the components are usually solid steel bodies [2]. Furthermore, Vishtal has put forward the theory that a uniform temperature for the entire deep drawing tool is not ideal, but rather that the temperature should be adapted to the individual stages of the deep drawing process [3].

Tanninen et al. introduced a tool to improve the temperature distribution and heat input by hollowing out the mold components instead of using heating elements and filling them with oil as a heat-conducting element, which in turn is brought to temperature by a heating spindle [4]. In this way, the surface area for heat input is larger and more uniform. However, the study focused only on improving heat distribution at a homogeneous target temperature. Efficiency and rate of temperature change were not considered in detail.

A fast and highly focused application of thermal energy was part of the research conducted by Löwe on ultrasonic-assisted deep drawing tools for cardboard [5]. It was shown that by vibrating the tools at an ultrasonic frequency, temperatures of around 200 °C can be reached in the cardboard within a few seconds. This variant is very efficient, since the tool components do not have to be heated. However, it has the disadvantage that the temperature is difficult to control according to the current status. On the one hand, heating is one of several effects generated by the ultrasonic vibration, which is why changing the vibration parameters always leads to a complex change in the conditions during the deep drawing process and it is not possible to influence the temperature independently from the other effects. On the other hand, heating occurs so quickly that it is difficult to set a specific temperature at specific stages of the forming process in specific tool areas [5].

Another approach to heat the board without actively heating the tools is to introduce steam through channels in the deep drawing tool. However, the steam not only leads to heating of the board, it also increases the moisture content. This combined influence on the workpiece parameters can be advantageous, since the moisture content is also an important factor for the formability of cardboard, but it also makes it difficult to control the individual factors [6].

A first attempt to divide the drawing sleeve of a deep drawing tool into temperature zones was made by Franke et al. by dividing the drawing sleeve into two edge areas and a strip-shaped middle section by a special positioning of the heating elements in combination with a system for active cooling [7]. The aim of the setup was to heat different areas of the paper, which due to its anisotropy, has different physical properties along (MD) and across (CD) the fiber direction, which also has an effect on the forming behavior. It could be shown that the different behavior of the areas can be adjusted by different tempering of the sections oriented in MD and CD. However, due to the low temperatures of 30 °C and 40 °C and the resulting small difference of 10 Kelvin, only a small effect on the behavior of the molded part can be seen and it is not explained in detail whether the test setup is also suitable for larger temperature differences.

Techniques for introducing high-resolution temperature profiles are already known from other areas of processing technology, e.g., digital heating and sealing systems for plastics processing. In these special flat preheating and sealing tools, a large number of individually controllable heating elements are mounted under a thin metal plate made of a tungsten and copper alloy. This alloy has a high strength to protect the heaters, but is also a very good conductor of heat. The individual heating elements allow a two-dimensional temperature pattern to be created on the tool surface comparable to pixels which form a

picture. Also, high temperature change rates are possible, due to the high power of the heaters and the low thermally relevant mass. However, these heating systems have not yet been tested for three-dimensional deep drawing tool surfaces [8].

The methods used so far are therefore not yet capable of setting a defined temperature on a specific component of the deep drawing tool in a specific phase of the deep drawing process. In this paper, a concept of a tool for deep drawing cardboard is introduced with which this is possible. Further, it is investigated which effects can be generated with this ability.

The possibility of achieving a high thermal energy input into the board in a short time with the new tool also enables the processing of the material with elevated moisture content. This is of interest because the moisture content of the board has a strong influence on the forming behavior. A higher moisture content makes the board softer and more flexible [9]. However, the moisture must also be reduced again within the forming cycle to an equilibrium moisture content at standard climate conditions in order to ensure the shape retention of the workpiece after forming. In this context, it is not only the temperature input through the tool contact that is important, but also whether the resulting water vapor can escape from the tool. If this is not the case, steam bubbles form in the board and damage it [10].

With conventional drawing cavities, a compromise had to be found in which the cardboard blank is heated before forming but not yet dried out too much and then subjected to sufficient temperature in the drawing cavity to regulate the moisture to the desired value and ensure the shape retention of the molded part [10–12].

2. Methods and Materials

The developed tool is used for deep drawing of cardboard (cf. Hauptmann [13]). The basic deformation of paperboard to 3D shapes is based on the mechanism of wrinkling while a flat blank is drawn into the drawing cavity by a punch and the folds are then compressed between the wall of the drawing cavity and the punch. The number, distribution and compression of the folds are characteristics for assessing the quality of the molded part. The Trayforma 310 board from Stora Enso is used for testing the tool. It consists of three layers of virgin fiber paper made out of sulphate pulp. To achieve better formability, a chemi-thermomechanical pulp is added to the middle layer. For this reason, Trayforma is a frequently used material in the production of deep drawing or press forming. The fiber board has a total basis weight of 310 g/m² and a thickness of 420 µm. The deep drawing tool is designed to be operated in an experimental drawing press. This test rig was developed for deep drawing cardboard and paper and has a range of force and movement which can be used to carry out a wide range of investigations [2,13].

Based on the requirements resulting from the design of the test rig, a tool set consisting of a drawing cavity, blank holder and punch was designed. Particular attention was paid to thermal separation of the tool surfaces of the individual heating zones in the drawing cavity in order to reduce mutual interference between the temperature zones. This was done by fully enclosing the heated elements in thermally insulating material and by keeping a gap of 10 mm between the heated zones. In addition, the masses of the heated components were kept as low as possible in order to increase the rate of temperature change. Figure 1 shows the final tool assembly. The three modules punch, blank holder and drawing cavity each consist of basic components and functional components with fitted or mounted tubular heating elements. The base parts are made of thermoset plastic with fabric reinforcement and thus serve to thermally insulate the heated functional parts. Due to the high strength of the insulating material, no additional steel parts are required to support the load. Only the adapter ring for inserting the drawing cavity into the frame plate is a steel part, since

critical shear forces can occur briefly at the mounting in the base plate when the die pushes into the drawing cavity.

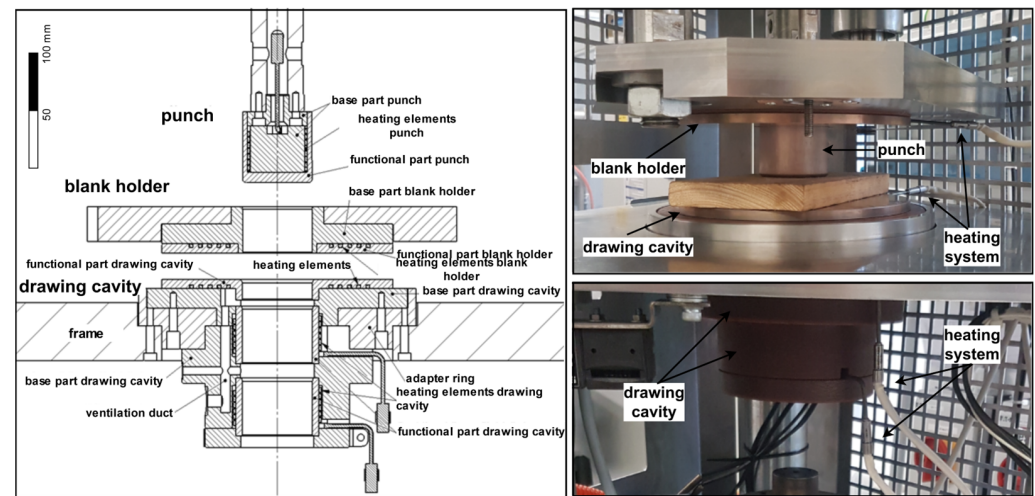


Figure 1. (Left): Cross-section of the experimental deep-drawing tool. (Right): Mounted tool in the test rig.

Only the functional parts are in direct contact with the board and are heated individually. Depending on the position in the deep drawing process, the cardboard is clamped between the blank holder and the drawing cavity or between the punch and the drawing cavity. Due to the surface contact, the temperature of the cardboard is equalized to the respective temperature of the heated tool section with which it is currently located. The material used here is the tungsten–copper alloy (WCu) also used by Watttron [8], which has high strength, good thermal conductivity and low thermal expansion at the same time. The comparatively low density of WCu also favors the heating rate. For this reason, the functional parts are kept as thin-walled as possible. Tubular heating elements with a rectangular cross-section are used, which are in contact with the functional bodies in tight spirals so that the contact surface is as large as possible to achieve the best possible heat transfer. In the case of the functional part of the blank holder and the counterpart of the drawing cavity, the strand-shaped heating elements are fitted into grooves that are slightly deeper than the height of the heater cross-section in order to protect them from mechanical stress. With a heating power of 1000 watts per heating element, it is estimated that the tool can be heated to 250 °C in less than a minute. The heaters are controlled by self-tuning control units with proportional, integral and differential behavior (PID) which adapt the PID coefficients to the system during the first heating cycles. The actual temperature for controlling the heater output is recorded by a Pt100 sensor in the tip of the heater, which measures the temperature of the sensor and the material in the immediate proximity.

To test another heating system and to investigate the generation of temperature patterns within a functional part, another version of the drawing cavity was developed in cooperation with the Watttron company (Freital, Germany). In this version, the tubular heating elements, which uniformly heat the respective section, are replaced by a pattern of pixel heating elements. The drawing die in which the pixel heaters are used otherwise corresponds to the cavity design with the tubular heating elements, so that a direct comparison can be made between the homogeneously heated zone and the zone that is further subdivided by the separate control of the individual heaters. The heaters are individually assigned a setpoint in the software interface of the control unit developed by Watttron and made available for the duration of the project. The control unit regulates the output of the heaters depending on the individual temperature sensors. The temperature of the sensors

is also recorded. Another difference to the first cavity design is the thin design and the higher heating rate of the heaters, favored by a smaller wall thickness of the functional bodies in the drawing cavity. This is possible because the heaters do not completely cover the outer circumference of the sleeve, thus creating free areas on which the sleeve can be supported by a second steel sleeve. A total of 20 heating elements are attached to such a heating sleeve in two rings (see Figure 2). In the flat surface of the drawing cavity, 68 heaters are arranged in circles. This offers various possibilities for creating temperature patterns. The heaters are divided into five rings, one of them around the vertical sleeve at the round opening of the functional part. The main task of the heaters in the blank holder is to adjust the temperature of the flat sheet prior to forming. Due to the possibility of generating a radial temperature curve or heating specific areas more or less strongly, areas that are likely to be subject to greater stress can be specially treated.

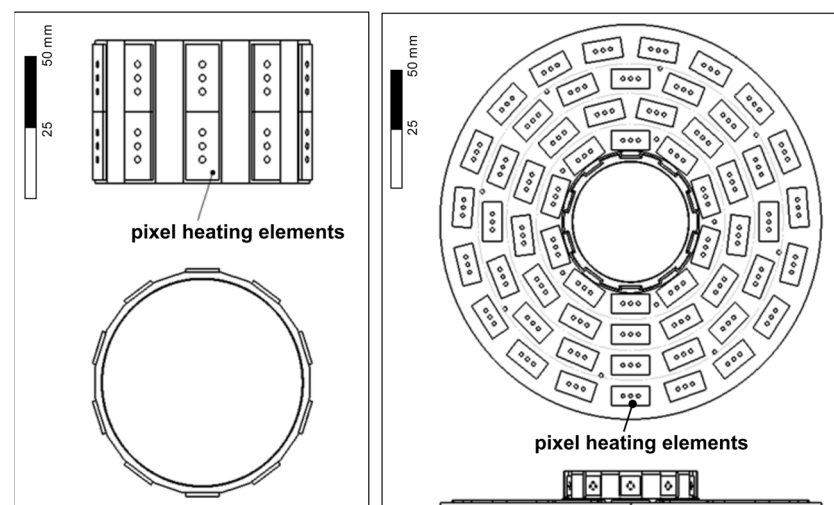


Figure 2. Functional parts of the tool variant with Watttron heating elements (variant 2).

The possibility of achieving a high thermal energy input into the board in a short time with the new tool also enables the processing of the material with elevated moisture content. As described in the Introduction, processing of material with elevated moisture content can lead to problematic steam generation. To counteract this, vent holes are provided in the tool developed here. However, since the functional bodies are occupied by the heating elements over their entire surface, it is only possible to provide circumferential grooves between the heating zones, which are ventilated by a system of channels and an active vacuum system. Although the steam cannot escape directly at the point where it is generated, the distance it has to travel through compressed cardboard is significantly reduced compared to a draw box without gaps.

When testing the tools, the focus is on the one hand on the question of the maximum possible rate of temperature change and the generation of temperature patterns on the tool surface. On the other hand, there is the question of how the forming result can be positively influenced by the different heating of the zones. To determine the temperature acting on the cardboard blank when it comes into contact with the tool, a workpiece dummy made of several layers of cardboard is used. In the surface of the dummy the measuring tip of a Pt100 thermal sensor is located which is connected to a temperature measuring device (Voltcraft PL-120-T1). The measuring dummy is clamped between the blank holder and the drawing cavity, so that the sensor is pressed onto the drawing cavity. The tool temperature profile at the contact surface is measured there and compared with the sensors integrated in the heating elements. A measurement inside the cylindrical passage of the drawing cavity is not possible due to poor accessibility. The measurement on the horizontal surface

is considered representative for the entire tool since the material thicknesses and heater powers hardly vary. A thermal imaging camera is used to observe temperature profiles on the tool surface. However, this is not suitable for measuring absolute values, since the surfaces are polished metal surfaces and the measurement result therefore has an offset.

The division into heating zones allows a heating of the paperboard blank in the blank holder area at a different temperature than it experiences in the vertical part of the drawing cavity. The individual heating zones in both tool variants are shown schematically in Figure 3. The flat functional part of the drawing cavity, which is the counterpart for the blank holder, includes the round drawing edge where the punch dives into the cavity. This is necessary because a division of the functional body at this point leads to an interruption perpendicular to the direction of movement of the cardboard in the surface of the tool. If the cardboard is pulled over such an interruption under pressure, it can be damaged as a result. When testing the effects of the different temperature zones, the boundary needs to be defined between the areas before and after three-dimensional forming. For this reason, the vertical ring of Watttron heaters in tool variant two is assigned to zone Z1 in the control software (see Figure 3 right).

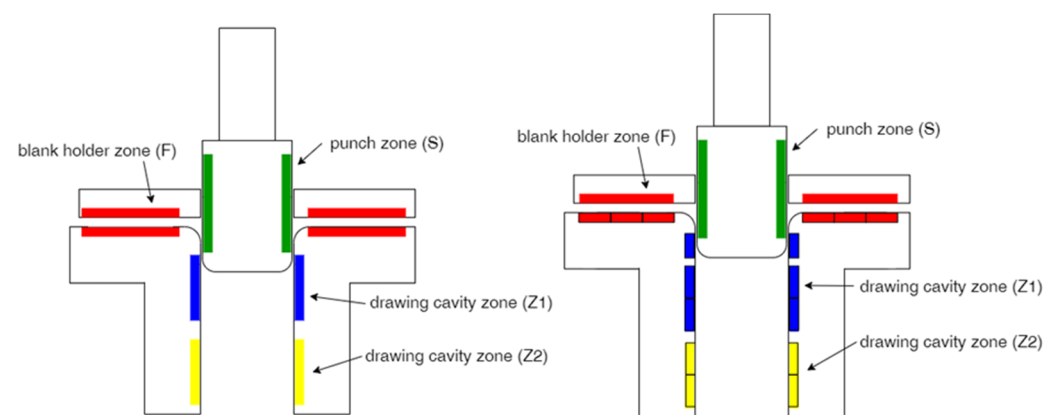


Figure 3. Heating zones of the tools, variant 1 (left) and variant 2 (right).

In the first place, the influence of different temperatures in the blank holder zone on the formed part is investigated. Since the wrinkles are formed in the blank holder zone, the number of wrinkles is used as the measured variable. The folds are recognized with the help of an optical measuring device by taking images of the surface while shadows are created in the folds by illuminating them from the side. The images are automatically evaluated with a grey value analysis and contiguous linear areas of a certain length are detected as folds [14].

The possible influence of different temperatures in the area of the drawing cavity zones 1 and 2 cannot be determined by the number of folds, since it does not change after forming the drawing edge. However, it can be assumed that different temperatures in the drawing cavity have an influence on the shape retention of the formed part, i.e., on the extent to which the formed part deviates from the ideal cylindrical shape after forming. To determine this deviation, the shape wall is scanned using an optical distance sensor and the measurements are used to form a 3D model. In this way, the deviation of the formed part from the ideal cylindrical shape can be determined. Due to the production of the paper as continuous sheet, the physical properties are subject to an anisotropic effect, as the cellulose fibers tend to align themselves predominantly in the direction in which the sheet moves through the paper machine. The two extremes of the property differences are therefore in the paper machine direction (MD) and perpendicular to it (CD). This is also noticeable in the formed part, since the board tends to bulge more in the MD direction than in the CD direction, causing the formed part to warp into an oval in the case of poor shape retention.

To obtain a measure of the shape accuracy the deviation of the sidewall angle of the formed part from the vertical alignment is considered. Then, the difference in the deviation at MD and CD is determined. A higher difference indicates a strong deformation. If the difference is zero, the part is perfectly round.

In addition to the measurement of the geometry of the formed part, it is also investigated whether an increased initial moisture content has an influence on the cohesion of the pressed folds. For this purpose, random samples of formed parts are subjected to a wall tensile test as described by Hauptmann [15]. In this test, horizontal strips are cut from the upper part of the wall, clamped in a material testing machine and stretched until tearing occurs. The stretching initially pulls the folds apart until the force is higher than the maximum load capacity of the fiber network and the board tears apart. The sample strips are removed from the wall in a way that they are oriented along MD, since the load capacity is higher in this direction. For this purpose, the formed parts are cut in half in MD and the upper 10 mm of the wall is cut off from both halves. This results in two 90 mm long strips. The strip width is fixed at 10 mm because the number of folds decreases the closer it is located to the bottom of the cup. A wider strip has too much inhomogeneity in the number of folds across the strip width. The samples are then clamped in the materials testing machine with a clamp distance of 50 mm and the tensile test is performed. For each tensile test, the testing machine delivers a curve of force versus elongation. The sharp increasing force right before the tearing can be explained by the onset of fiber elongation. This area is not relevant for the fold stability investigation. Since it is not possible to determine exactly when the length of the folds changes to material strain, only force values of the first 10 mm are used (see Figure 4). The first 10 mm elongation of a total of six samples is used to determine an average.

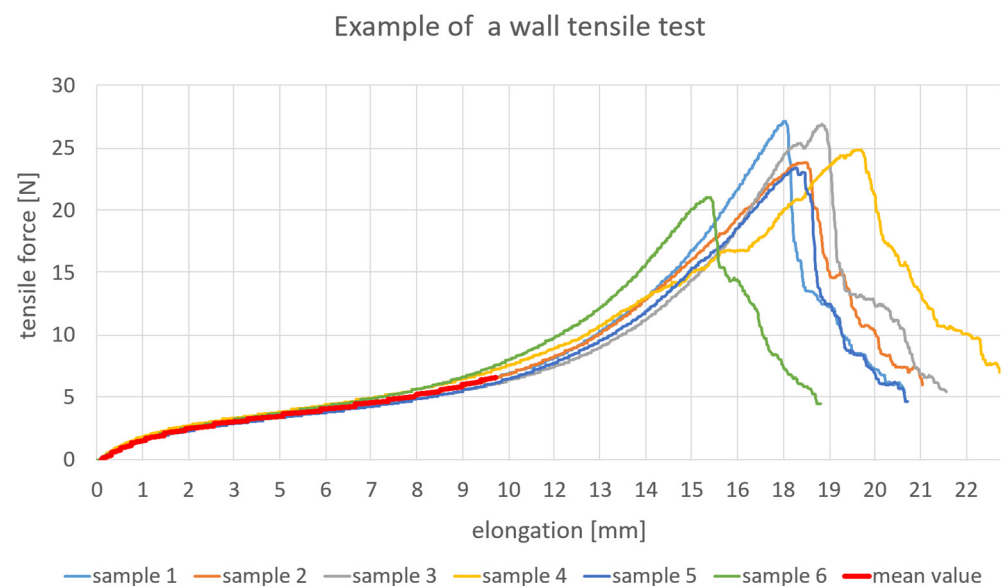


Figure 4. Example for the averaging of the load–extension curves.

The temperature in the considered zone is increased in 10-Kelvin steps to investigate the effects. The plan is shown in Table 1. Afterwards, the water content of board samples is increased in 5% steps to test the steam removal system, starting with the equilibrium moisture content of approx. 5%, which occurs in the board at standard climate. Subsequently, the temperature settings in the tool are investigated to enable deep drawing of the sample so that it again has the equilibrium moisture content after the forming process. The tests with increased moisture content are carried out at a drawing speed of 25 mm/s in order to

reproduce production-like conditions. The blank holder force is reduced as required, since the durability of the cardboard decreases with increasing moisture content.

Table 1. Testing plan for the zonal heating.

Drawing Speed	Blank Holder Force	Temperature			
		Zone S	Zone F	Zone Z1	Zone Z2
mm/s	N	°C	°C	°C	°C
5	1200	100	80, 90, ..., 170	120	120
5	1200	90	90	100	90, 100, ... 160
5	1200	90	90	100	200

3. System Behavior of Heater Technologies

The temperature response of the two tool variants is determined by recording the surface temperatures and the sensor temperatures of the heating system in comparison. Additionally, the surface temperature of a conventional steel drawing cavity is recorded as a reference. This is done by reading the temperatures of the sensor from digital real-time displays during the experiment and noting them with the corresponding time stamp. The sensors are integrated into the heaters or, as with the conventional design, are mounted as a cylindrical pin next to the heaters in a corresponding hole in the tool. Due to the proximity to the heater source and due to the internal position, both a temporal difference in the course of the temperature value and a difference in the absolute value compared to the surface measurement can be expected. The comparison of the temperature curves of the heating system sensor (nominal temp.) and surface temperature (actual temp.) can be seen in Figure 5. The two concept tools and the conventional steel tool are each heated from 25 °C to 100 °C. The target temperature is set at 100 °C because at this temperature a significant change in the forming behavior of paper can be observed as the boiling point of the water in the fiber network is reached.

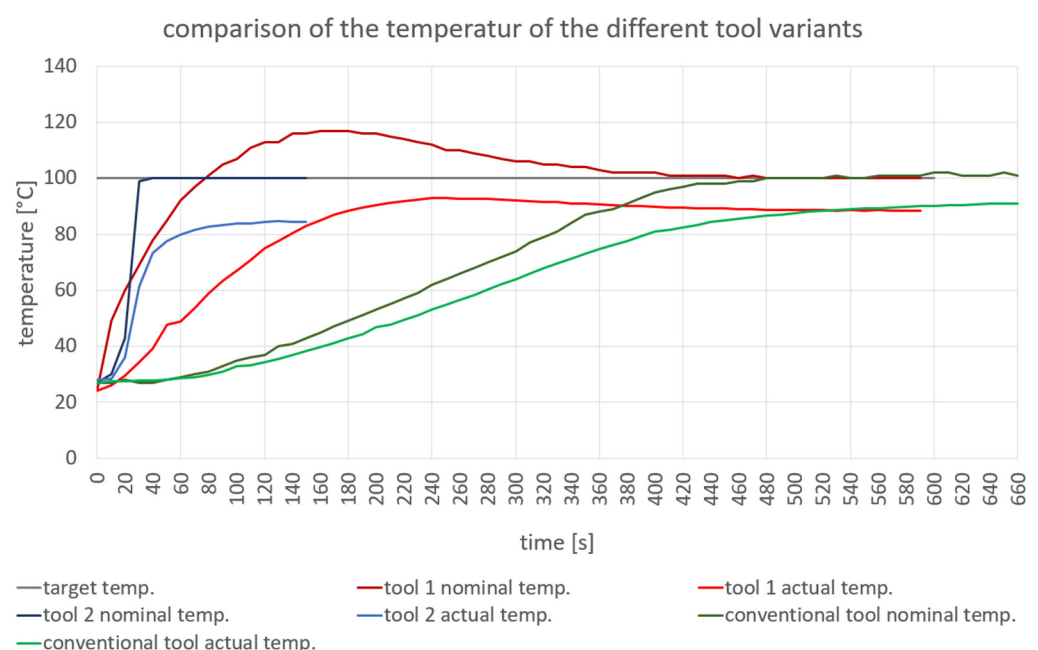


Figure 5. Comparison of the heating process of the tool variants.

The end of the heating process is defined as the time at which the surface temperature no longer increases significantly (less than 0.01 Kelvin per second). The conventional

drawing cavity requires 10 min 40 s for the heating process and reveals an offset of 9 K to the target temperature. The segmented tool with the tubular heaters (tool 1) is heated up in about one-third of the time (3 min) due to the lower thermal mass, the better insulation and the higher heating power. The time could be reduced again by about 50% to 1 min 40 s with the tool equipped with Watttron heaters (tool 2). Therefore, this tool heats up nearly ten times faster than the conventional tool. The termination criterion is reached at 88 °C for the tool with tubular heaters and 84 °C for the Watttron tool. These differences between temperature at the sensor and temperature on the tool surface can have various reasons. Different climate conditions could be an explanation, but mainly the different setups have to be considered as a possible cause. The masses of the heated elements differ remarkably. In addition, the position of the sensor in relation to the heating element is different for all three tools. Also, the temperature controls use different hardware and are not ideally programmed, since optimizing the parameters of the control for the individual tool is very complex and is not an objective in this project. In general, however, the maximum difference in the tool surface temperatures at the end of the heating process of 7 Kelvin is sufficiently small to be ignored in the evaluation of the heating rates.

The cooling of all three tools takes place exclusively by free convection, since there is no active cooling in any of the systems. The only influencing factor is therefore the mass of the heated tool part and the associated specific heat capacity of the tool. The cooling behavior of the different tools is shown equivalent to the heating behavior in Figure 6.

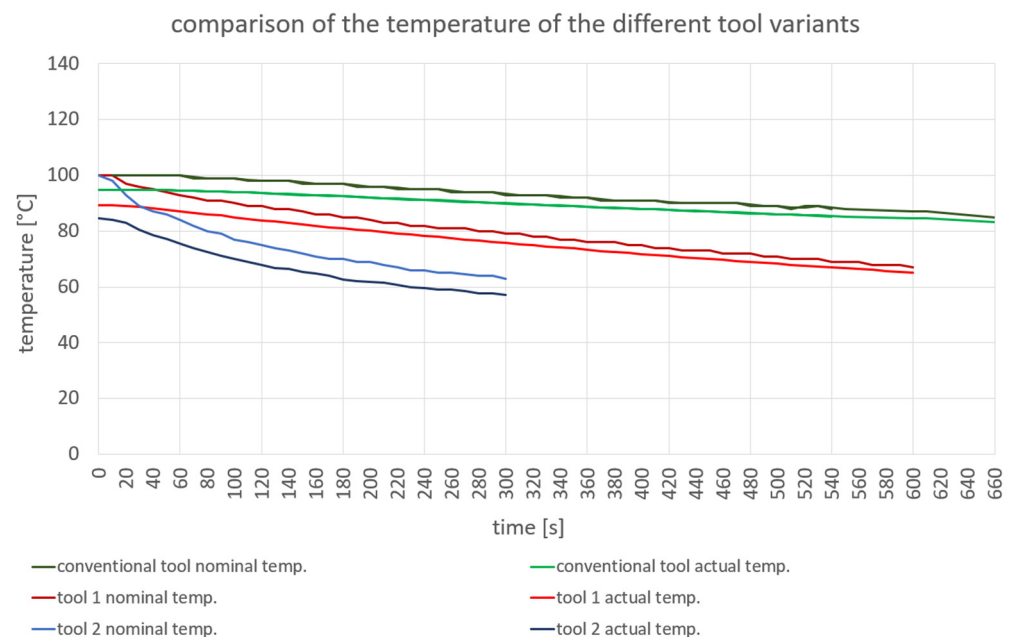


Figure 6. Comparison of the cooling process of the tool variants.

The speed of the cooling process is exponentially decreasing and thus takes a very long time since the cooling process is a passive temperature equalization of two systems (tool and ambient air). A holistic consideration of the temperature range 100 °C to 25 °C is therefore not useful. For this reason, the drop of the first 10 Kelvin is considered for the determination of the cooling rate. The conventional drawing cavity requires 10 min 30 s for cooling by 10 Kelvin, which is a similar time to the previous heating by 75 Kelvin. The temperature of the tubular heater tool has dropped by 10 Kelvin after 4 min 10 s, and the Watttron tool takes 1 min 10 s to do the same. This shows the rate of temperature change is significantly lower for all tools compared to the heating process, but it can be seen that the Watttron tool cools noticeably faster, especially at the beginning, and is therefore best suited

for rapid changes in temperature by a few Kelvin during the running process. Nevertheless, even at the start of the cooling process, the rate of temperature change is six times lower than for heating due to the described passive cooling process. Active cooling would be necessary to achieve the same rate of temperature change as during heating.

The improvement of heating times with new toolsets gives rise to the assumption that changes in moisture content can be addressed with temperature adaptations during the running machine operation. The reaction to for instance reduced moisture content of materials or on-reel changes with different material grammages by an increase in temperature needs remarkably less time than the reduction in temperature, which might be necessary in case of higher material moisture. Referring to the typical output range of machines with a cycle time of 3 s, a reduction by 10 K starting from 100 °C requires about 27 cycles with the tubular heater toolset and six cycles with the Watttron toolset in heating. In cooling, respectively, 243 cycles with the tubular heater toolset and 23 cycles with the Watttron toolset would be required to achieve a reduction of 10 K. The cooling would probably be faster starting from higher temperatures and it was not taken into account how much thermal energy is taken out of the tool by the paper each cycle. This typically reduces the temperature of the tools each cycle and reduces cooling time but increases heating time in the running machine operation. Even small temperature changes are therefore probably not possible within one cycle. However, an application for the regulation as a reaction to changing moisture values of the layers of a paper roll, caused by fluctuating storage conditions, at constant draw-off in a converting machine is conceivable.

In addition to the short heating and cooling times, the Watttron drawing cavity also theoretically allows temperature patterns to be generated on the tool surface. To test this function, the surface was divided into four areas in the control panel, with the same temperature setting selected for the diagonally opposite areas. Two areas should be heated to 100 °C and the other two areas are set to 150 °C. The change in surface temperature is then observed using the thermal imaging camera. Extracts from the recording are shown in Figure 7.

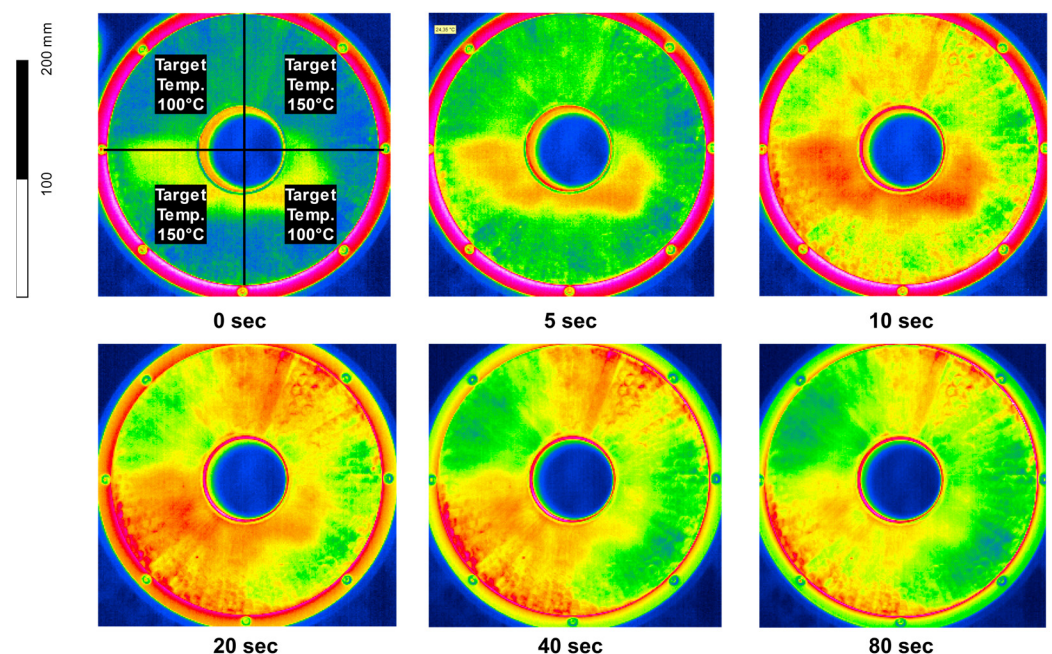


Figure 7. Images from the thermal camera during the zonal heating of the drawing cavity with Watttron heating elements.

The thermal imaging clearly shows that the surface initially heats up differently. However, an equalizing effect can already be seen after 20 s. Since the heating power flows quickly into the entire tool surface, the heaters in the areas with a higher temperature specification continue to heat until the entire surface has reached the high level. Thus, temperature equalization already occurs before the desired temperatures are reached. To divide the tool surface into individually heatable plots, an insulating layer would have to be provided between them. However, this would interrupt the closed surface, which could have an effect on the sliding behavior of the board on the tool.

4. Effect of Temperature Variation in the Blank Holder Zone

The tests were carried out with both die variants (with tubular heaters and with Watttron heaters). In certain cases, the complete set of tests was not repeated with the Watttron tool, but only individual comparative tests were implemented. The influence of the varied test parameters can be measured not only on the drawn parts according to the procedures described above, but also directly on the reaction forces of the deep drawing system, in particular on the force required by the system to push the punch through the drawing cavity. The force curve allows to draw conclusions about the properties of the formed material and to see whether they change.

As can be seen in Figure 8 on the left, the system requires a higher force at low temperature to pull the cardboard over the drawing edge from the blank holder into the drawing cavity. This force decreases continuously with increasing temperature up to 130 °C. From this point on, no change in force can be seen as the temperature is increased further. It should be considered that the temperature specification is the sensor temperature. The actual surface temperature is likely to be between 100 °C and 110 °C, based on the findings of the preliminary tests. It can therefore be assumed that the thermal softening of the board reaches a maximum when heated to approx. 100 °C and can no longer be increased by further thermal energy intake. Since this temperature is also the boiling point of water, it can be assumed that the fibers of the cardboard are softened by the high temperature, but the water molecules between the fibers have not yet evaporated. When the boiling point is reached, the water begins to evaporate. Drying occurs and thus the cardboard solidifies. The time that elapses between insertion of the cardboard blank and drawing of the cardboard also has a significant influence and offers potential for further investigations.

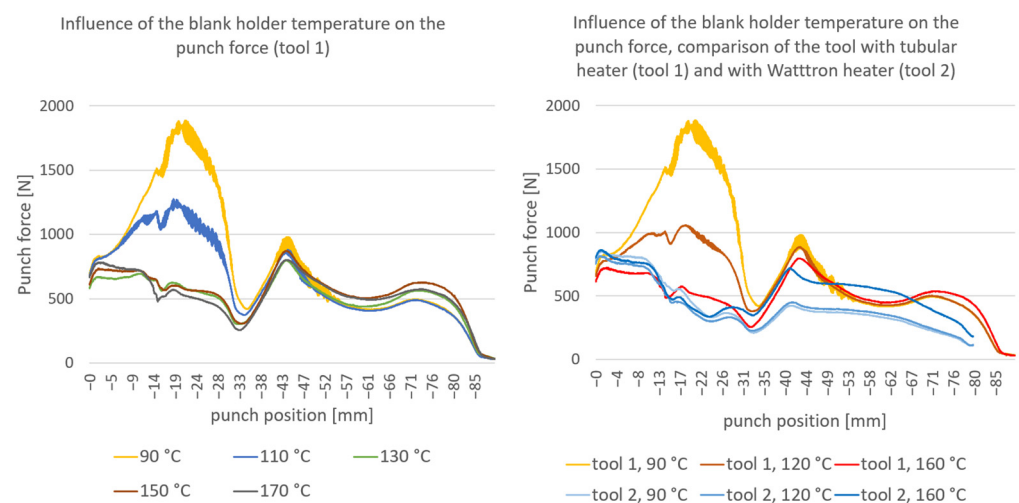


Figure 8. (Left): Reaction of the punch force to the variation of the temperature in the blank holder zone. (Right): Comparison of the punch forces of the two tool variants in the same setting.

Lenske et al. found a similar effect of temperature on the punch force curve. According to them, the drop in force at higher tool temperatures is caused by reduced friction between the tool and the cardboard [16]. However, according to Lenske, this effect mainly plays a role in areas of the tool where folding no longer takes place and the punch force results to a large extent from friction. The influence of the blank holder temperature can therefore only be observed to a limited extent on the basis of the punch force, as the force curve is probably largely dependent on the friction that occurs when the punch is immersed in the drawing cavity. Comparative measurements with tool variant 2 surprisingly show no effect of the blank holder temperature on the punch force (see Figure 8 right). One possible explanation is a different temperature at the drawing radius, which occurs in the constellation with the Watttron heaters due to the row of heaters at the lower edge of the drawing edge, since this is assigned to the heating zone Z1, which is kept at a constant 100 °C, but is materially connected to the plank holder zone. However, if one considers the findings from Figure 7, the actual temperature difference is likely to be minimal. The cause could not be conclusively determined.

Of main interest is the effect the blank holder temperature has on the number of folds, since this determines the quality of the wall surface of the formed part. The measurement of the parts results in the following fold distribution over the height of the wall (see Figure 9). As expected, the number of folds increases towards the upper edge of the wall, since more and more material has to be placed in folds. Independently of this, however, there is also an increase in the number of folds at 110 °C to 130 °C. But no further increase can be seen within temperatures above 130 °C. The results lead to the assumption that the maximum softening of the cardboard is reached at around 100 °C tool surface temperature. Comparative measurements with tool variant 2 principally reflect this result. This effect was also observed by Östlund. He heated a drawing cavity to 100 °C and 180 °C and obtained a fold curve over the wall height that is of the same order of magnitude as the results shown here. He assumes that the increased temperature softens the material [17]. Hauptmann et al. describe the forming process during deep drawing of cardboard in three phases [18]. In phase 1, the fiber network is stretched and in phase 2, wrinkling occurs. They classify the results of determining the number of folds in such a way that with a long phase 1, a low number of folds indicates good formed part quality. With a short phase 1, on the other hand, a low number of folds indicates an uneven distribution of folds, which is negative for the quality of the formed part. As the length of phase 1 was not considered in the tests carried out here, the measured fold distribution must be used to classify the quality according to Hauptmann et al. [18].

In addition to the number of folds, the fold distribution also includes the distances between the folds. If the mean value of the distances is calculated, the standard deviation of the mean value provides information about the uniformity of the fold distribution. If the standard deviation is low, the folds are evenly distributed across the wall of the formed part. Looking at the standard deviation of the pleat spacing at the upper edge of the formed part, it can be seen that the standard deviation is lower from a blank holder temperature of 130 °C, the same temperature at which the number of folds also increases (see Figure 10). This supports the assumption of better formability and consequently better part quality at a tool surface temperature of 100 °C and above. The standard deviation stagnates at temperatures above 130 °C. Hauptmann et al. also came to this conclusion. In their experiments, they found that an increase above 400 K (126.85 °C) did not result in a further reduction in the standard deviation. This is probably due to the fact that a certain minimum deviation is given by the inhomogeneity of the natural fiber material [19].

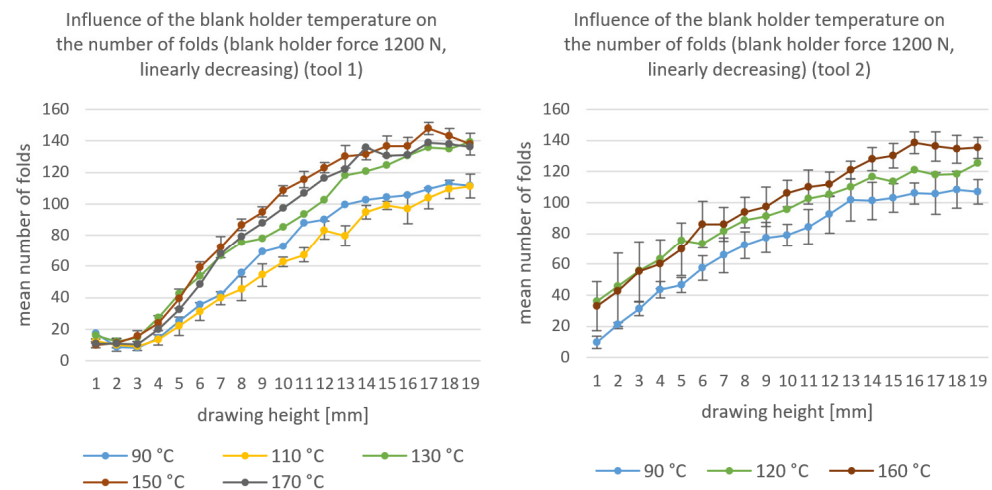


Figure 9. (Left): Reaction of the number of folds over the wall height to the variation of the temperature in the blank holder zone (tool 1). (Right): Sample test with tool 2 for the same setting (with standard deviation of the highest and lowest results).

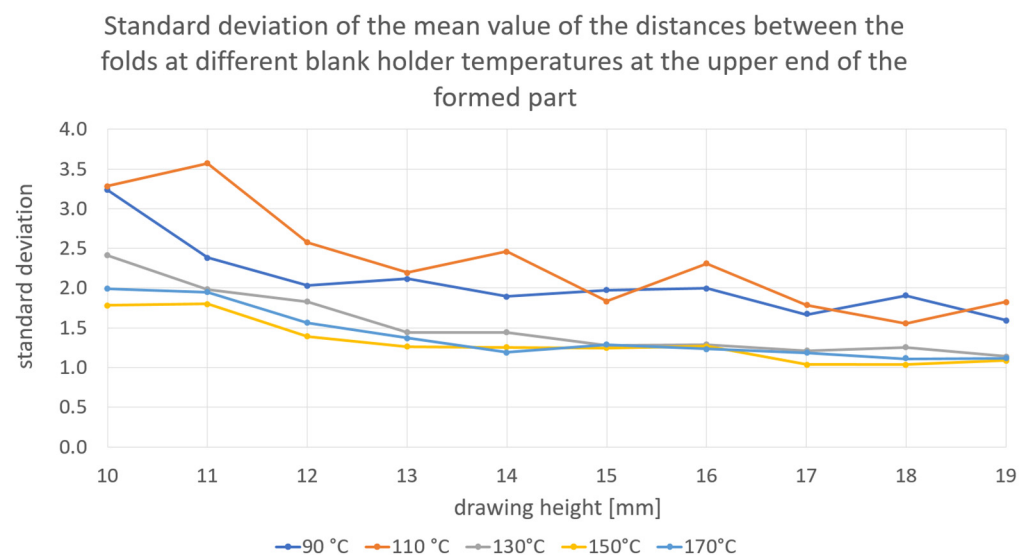


Figure 10. Standard deviation of the distances between the folds of parts formed with different blank holder temperatures.

Hauptmann et al. also describe that paperboard with lower binding forces in the fiber network has better forming properties in phase 2 of the deep drawing process [18]. The isolated influence of temperature on the fiber network of paperboard was described by Salmén and Back [20]. They found that the stretchability of the paperboard increases continuously as the temperature rises. This is in contrast to the stagnating number of folds at approx. 100 °C in the tests carried out in this work. One possible explanation for this is that the paperboard begins to dry out, which in turn leads to poorer formability. Vishtal discovered that in an open system where moisture can evaporate the best temperature for formability of chemical pulp is 60 to 70 °C and at temperatures of 100 °C and higher the formability decreases, probably due to drying [3].

During the production and subsequent measurement of the formed parts for this series of tests, it was found that the formed parts warp more with increasing blank holder temperature and that the wall shows increased spring back (see Figure 11).

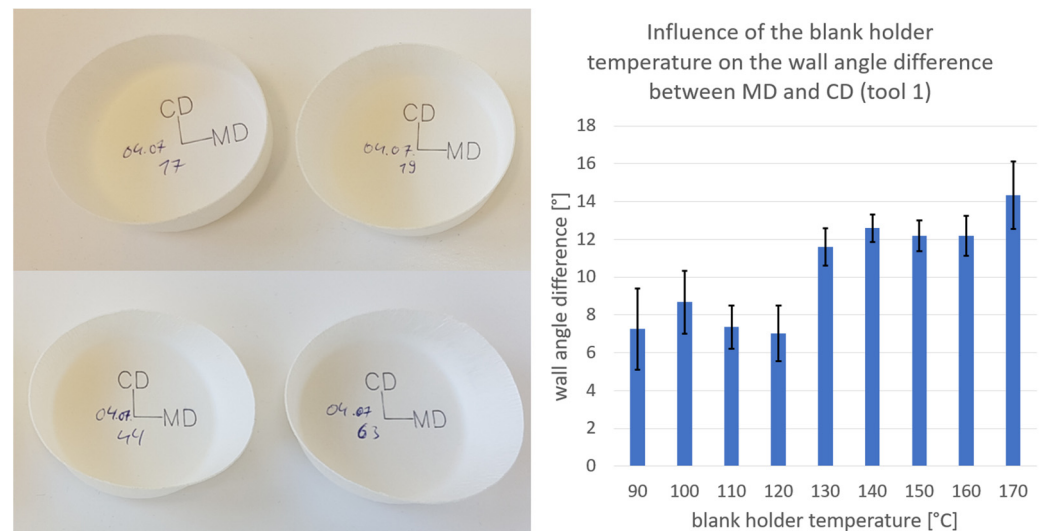


Figure 11. (Left): Formed parts with increasing blank holder temperature from top left to bottom right. (Right): Reaction of the wall shape of the formed parts to the rise of the temperature in the blank holder zone.

In order to investigate this effect more closely, a wall shape determination was carried out for all formed parts. The curvature of the frame increases in both board web directions and the distortion of the circular shape also increases at 130 °C blank holder temperature (see Figure 11). This in turn corresponds to an actual surface temperature of 100 °C. The boiling point of water seems to mark a limit above which the forming properties of the board change. The poorer shape retention of the forming result at higher blank holder temperature is probably due to the significant reduction in water content within the fiber network structure before forming.

If the water content in the cardboard is reduced too much, no new hydrogen bonds can form when the folds are compressed in the drawing cavity, which ensure greater stability of the wall after the forming process [15]. However, this is contradicted by the result of the fold count. A high number of folds leads to many contact surfaces of the fold flanks where bonds can form. A high number of folds therefore actually has a positive influence on the stability of the formed part wall. A more detailed examination of the influences on part stability is necessary in future research.

Looking at the results of the wall tensile force test, a tendency towards better fold cohesion shows due to both a high blank holder temperature and a high blank holder force. However, the blank holder force seems to have less influence than the temperature as the sample with a high blank holder force is stretched at lower tensile forces than the sample formed with a high blank holder temperature. The sample with both high temperature and high blank holder force shows no difference to the sample with only high temperature (see Figure 12). This contradicts the results of Hauptmann and Majschak [15]. They came to the conclusion that an increased temperature only leads to better results in the tensile strength of the formed part wall in combination with a high blank holder force. However, the tests were carried out with conventional tools in which only a uniform temperature can be set for the tool. The effect of the temperature in the blank holder area can therefore also be superimposed by the effect in the drawing cavity. In addition, the increase in tensile force occurs with increasing elongation, starting at about 2 to 3 mm elongation. In the first millimeters, no difference can be seen in the tensile force curves. The adjustment of the temperature in the blank holder zone therefore seems to have no influence on the initial strength of the folds. The influence that can be observed concerns the subsequent expansion required to smooth out the folds. This correlates with the number of folds. A high number

of small folds requires a higher force to be smoothed than a few large folds [15]. A possible positive influence of the increased pleat holder temperature on the initial fold stability is possibly revised as described by the simultaneous reduction in the moisture content before forming. Further investigation is necessary here.

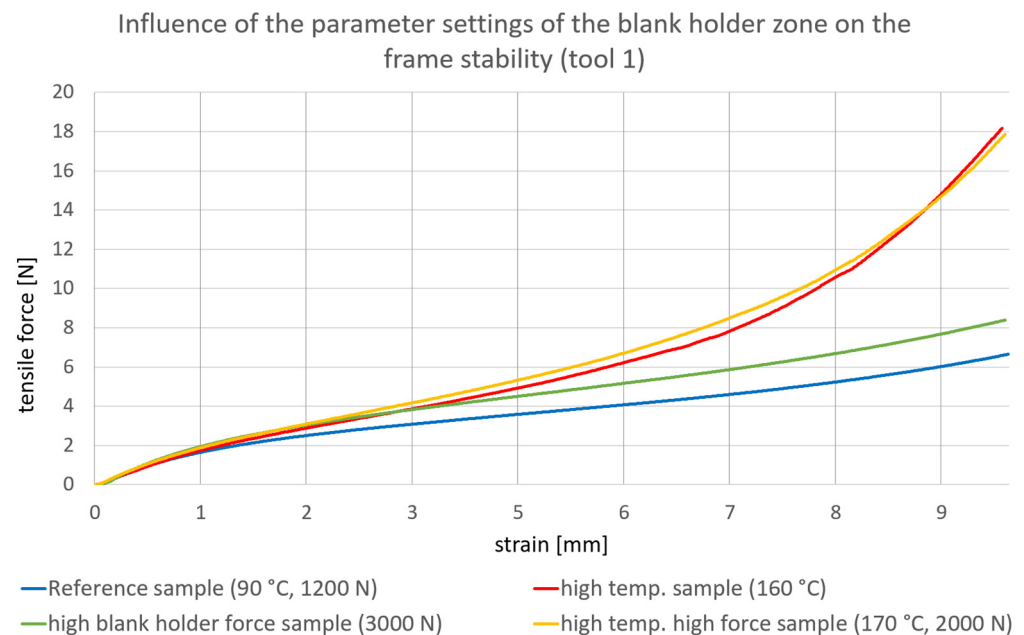


Figure 12. Reaction of the wall stability of the formed parts to the variation of the settings in the blank holder zone.

To summarize, it can be said that the surface temperature in the blank holder zone should not exceed 100 °C. For further investigations, it would be interesting to revise the division of the heating zones and find a solution to thermally separate the drawing edge from the blank holder zone to investigate it as a separate zone.

5. Effect of Independent Temperature Variation in the Cavity

It is assumed that a surface temperature of over 100 °C is useful within the drawing cavity in order to fix the shape of the workpiece. To investigate this assumption, the temperature setting of drawing sleeve zone 2 is increased in 10-Kelvin steps from 90 °C to 150 °C. As the temperature increases, the required punch force decreases compared to the constant heated drawing cavity zone (see Figure 13). With a decrease in the peak of more than 50%, the effect is not negligible. One possible cause is the thermal expansion of the tools. If the functional bodies of the heating zones in the drawing sleeve expand and widen as a result, the distance between the cavity wall and the punch increases, which reduces the compression of the cardboard and ultimately the force required by the punch to draw the formed part through the drawing sleeve. The tungsten–copper alloy was chosen here specifically for the functional parts of the tool due to its low thermal expansion. Such a large effect through expansion of the tool is therefore unlikely. Another possible cause is the reduced friction between the tool surface and the cardboard as the temperature rises [16]. They found that by increasing the temperature of polished steel deep drawing tools to 120 °C, the dynamic coefficient of friction between the tool and the cardboard decreased significantly.

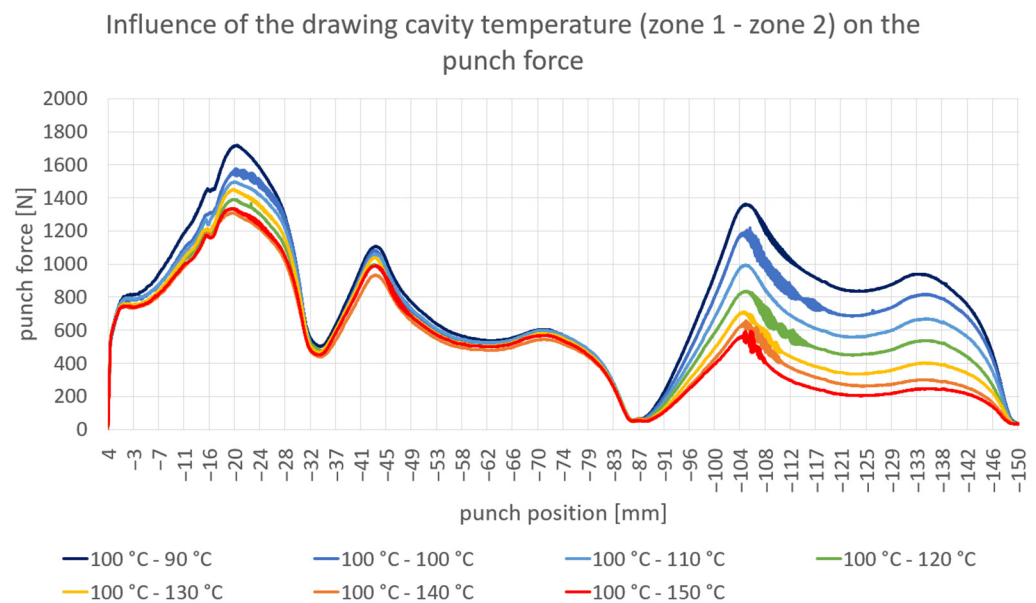


Figure 13. Reaction of the punch force to the rise of the temperature in the cylindric area of the drawing cavity.

It is not necessary to consider the number of folds for this series of tests, as the folds are only formed in the area of the blank holder and are just compressed in the vertical part of the cavity. The focus is on the shape accuracy of the formed parts. It is again calculated by measuring the walls and determining the frame angles. The angle difference between the CD angle and the MD angle is determined directly after forming (approx. 2 s after removal from the thermoforming line) and a second time after 24 h of storage in a standard climate. This double consideration is important because in industrial processing it is possible that the formed part is filled and sealed in a form–fill–seal line directly after forming, but there is also the possibility that the packages are produced for empty sale and then filled and sealed by a different supplier. The result of the measurements shows a slight but not significant improvement in the angular difference both immediately after forming and after storage (see Figure 14).

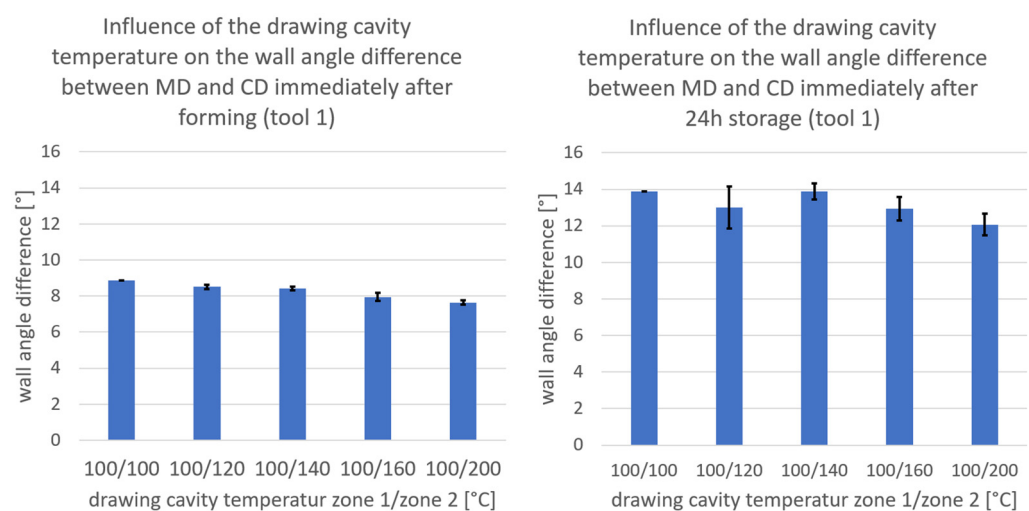


Figure 14. Reaction of the wall stability after forming and after storage to the rise of the temperature in the cylindric area of the drawing cavity.

As expected, the distortion increases with storage time. Although a slightly smaller increase in angular difference is seen at the higher temperature setting, this difference is

only a 4° increase instead of 5° at 100 Kelvin temperature difference. Furthermore, a higher statistical error can be seen in the values of the measurement after storage. Since cardboard is an inhomogeneous material, it interacts with the environment to varying degrees over the surface area, i.e., it exchanges moisture with the ambient air to varying degrees locally. As a result, the formed parts warp differently over time and the average value shows higher deviations.

The determined influence of the temperature in the drawing cavity is comparatively low. Hauptmann and Majschak [19] come to the conclusion that the initial moisture content of the cardboard has a greater influence on the dimensional stability. As described in Section 2, the heating of the deep drawing tools also has the purpose of drying moistened cardboard back to an equilibrium moisture content during the passage through the drawing cavity in order to improve the shape accuracy. The increased heating capacity in combination with the system for removing the developing water vapor should enable the reliable application of paperboard blanks with elevated moisture content and to still reduce the water content back to 5–6% of the total mass within the forming process. The main influencing factors are the tool temperature and the forming speed. The forming speed determines how long a section of the cardboard material is in contact with the individual heating zones and therefore how long the respective temperature can act on the material to dry it. The speed is kept constant at 25 mm/s, as a lower speed means a longer contact time but also a lower output. Higher speeds have led to an increase in the failure rate in previous tests with this process. At the set forming speed, each point of the cardboard blank, except for the area forming the base of the formed part, is in contact with zone F for 3.5 s and with zones Z1 and Z2 for 2 s each. According to a one-factorial experimental design, it is investigated how much the initial moisture content of the material can be increased and which temperatures are required in the zones of the tool (cf. Figure 3 in the Methods and Materials Section) in order to dry the formed parts. The experiments are shown in Table 2. The drawing tests were carried out at the beginning with a blank holder force of 2500 N. However, this had to be lowered as the moisture content increased, since the strength of the cardboard decreased. It was not possible to increase the moisture content above 25%, as the strength of the board decreased to a point where non-destructive deep drawing was no longer possible. The tests show that steam is successfully removed in the drawing cavity during deep drawing.

Table 2. Results of the experiments with cardboard with different moisture contents.

Zone S	Temperature [°C]				Moisture Content [%]		Evaporation [g]
	Zone F	Zone Z1	Zone Z2		Before	After	
100	100	100	120		15	8	0.14
100	100	120	140		15	3	0.19
100	100	120	140		20	9	0.22
100	100	120	160		25	14	0.22
120	100	140	170		25	6	0.44

It is known from previous test series with conventional deep drawing toolsets that bubble formation occurs at initial moisture content of 11% [19]. The reason is that moisture cannot escape from the fiber network structure during the way through the cavity. A stronger increase in the quality of the formed parts can be seen with increasing initial moisture both in the wall stability and in the appearance of the folds. In addition to an apparently very high number of folds, the compression of the folds is significantly better than with the unmoistened specimens. However, this also has the consequence that the

measuring system for detecting the folds fails. The surface of the wall is so uniform and smooth that the folds no longer cast shadows and thus cannot be recognized as such by the evaluation software (see Figure 15 left). The red dots represent a transition in the greyscale of the image, which is recognized by the software as a possible fold. A linear group of points is defined as a fold. If no groups are recognizable to the software, no fold is counted. Figure 15 on the right shows a frame section from the tests with high blank holder temperature for comparison.

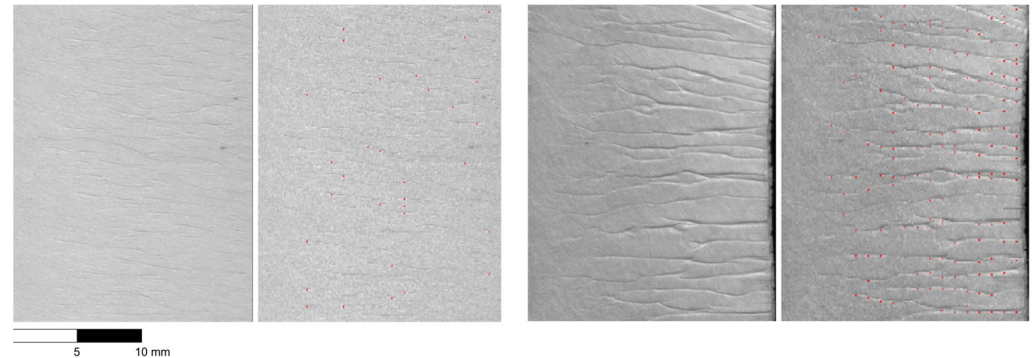


Figure 15. Results of the wrinkle detection: (Left): moistened cardboard, (Right): unmoistened cardboard.

The measurement results of the automatic fold counting indicate a decreasing number of folds with increasing moisture and are also below the samples from the tests with the high blank holder temperature (see Figure 16). Since it has been noticed that the measuring system is no longer able to detect the folds correctly, it is assumed that this result is falsified. In order to verify this assumption, the wrinkles of individual samples are counted by hand. The manual evaluation of five parts with an initial moisture content of 25% showed an average of 308 folds at the upper edge of the wall. A detailed manual evaluation is not possible due to the high time required. However, the sample clearly suggests that a significantly greater improvement in the fold appearance can be achieved by moistening than by regulation temperature alone. However, the high temperature in the drawing cavity zone is required to dry material with a high initial moisture content quickly enough. The use of moisture is therefore directly linked to the use of high temperatures.

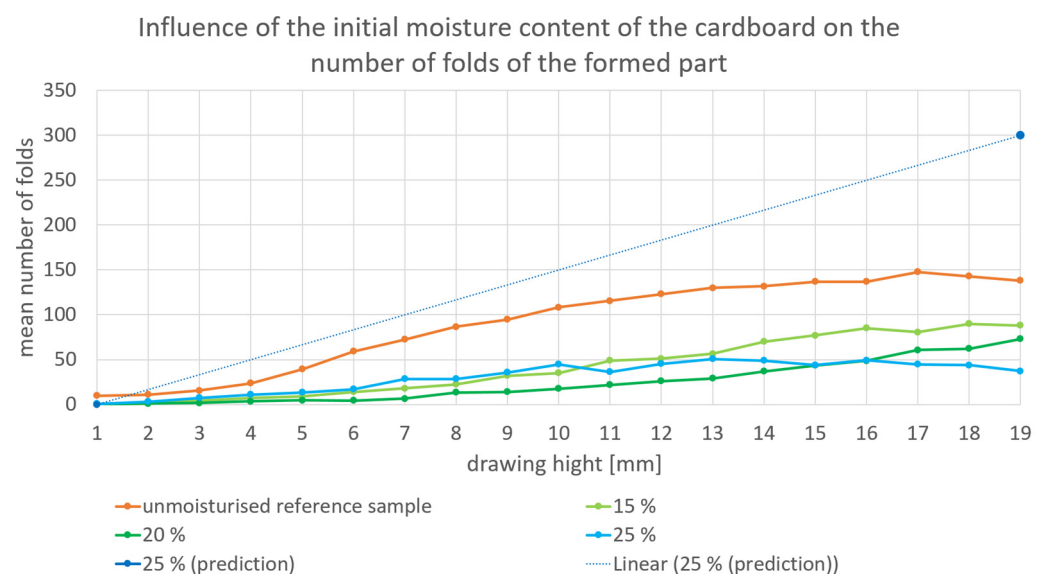


Figure 16. Reaction of the number of folds to the increase in the initial moisture content of the cardboard.

In the case of wall stability, it can be seen that although the warpage of the formed parts decreases with increasing relative water content, again only a few degrees could be gained on the results of the temperature tests in the draw cavity zones. The big difference to the dry tests, however, is the constant warpage after 24 h of storage. In the samples with low moisture content, a change still occurs, but at 25% it disappears nearly completely (see Figure 17). Hauptmann and Majschak came to the idea that material with increased moisture, dried out by increased thermal heat, forms new hydrogen bonds in its fiber network, which provide new contacts between the fibers. It is plausible that this higher number of fiber bonds can better compensate for the stresses in the fiber network due to its anisotropy, resulting in less distortion of the formed part [15].

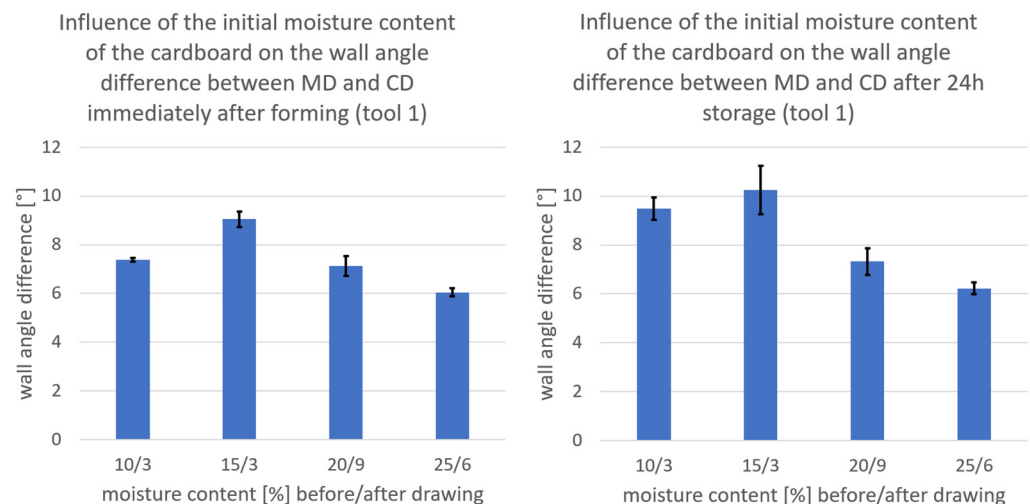


Figure 17. Reaction of the wall stability after forming and after storage to the rise of the initial moisture content of the cardboard.

The influence of moisture can also clearly be seen when examining the wall tensile strength. The increase in the draw cavity temperature alone has only a minor effect on the wrinkle cohesion. Increasing the initial moisture content of the material, on the other hand, results in a more stable wall (see Figure 18). Hauptmann and Majschak found that even when using increased moisture, a positive effect of an increasing blank holder force on the strength of the formed part wall can still be observed [15]. However, only moisture values of up to 12% were used. The use of a high blank holder force was not possible with the moistened specimens up to 25%, since otherwise the cardboard would tear when drawn into the drawing cavity due to the reduced strength.

In summary, it can be said that a high tool temperature in the area of the drawing cavity where folds are no longer formed but only compressed has only a very minimal influence on the quality of the formed part. The major advantage over conventional tools is the processing of material with a high initial moisture content. The adjustable temperature difference between the blank holder zone and the drawing cavity zone ensures that the material is only dried after forming, thus utilizing the maximum formability of the fiber network.

Since the forming with the highly moistened samples yielded very good results in terms of quality, additional samples of cardboard grades were formed with the test tool in order to create an outlook for further test possibilities. In particular, cardboard grades were selected which have been shown to be difficult to form by deep drawing because their physical properties are comparatively poor. These include recycled board, but also alternative board grades made from agricultural residues or grass stalk fibers. According

to an apparent assessment, good molded parts could be produced with all tested board grades (see Figure 19).

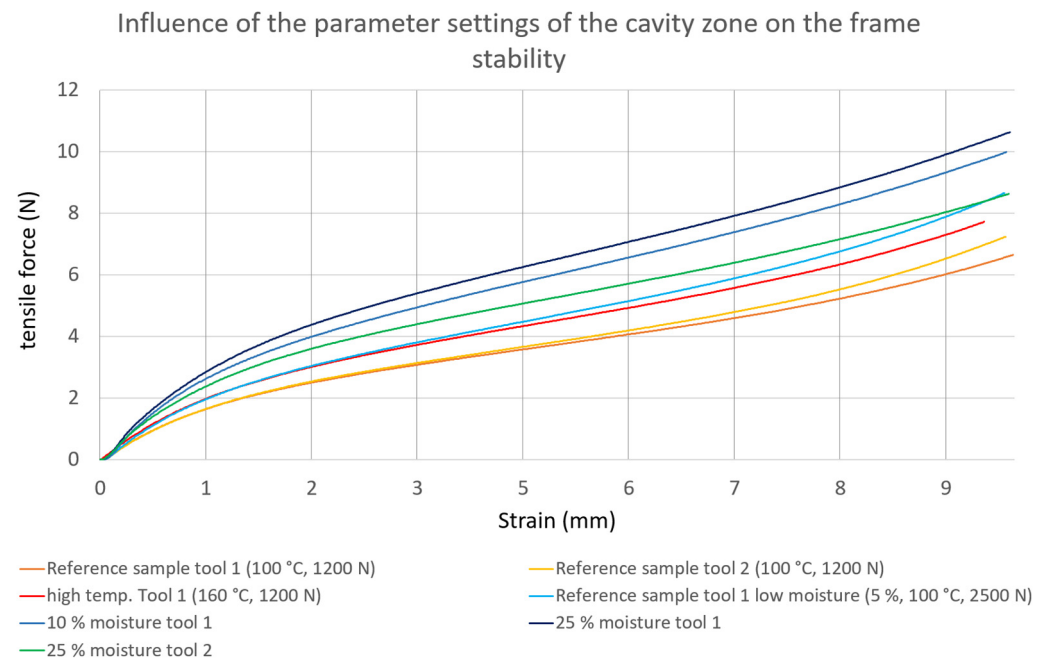


Figure 18. Reaction of the wall stability of the formed parts to the variation of the temperature in the cylindrical drawing cavity zones and the initial moisture content of the cardboard.



Figure 19. Different samples of cardboard grades (from left to right: virgin fiber, recycled fiber, agricultural residues, grass fiber).

6. Conclusions

1. The use of a digital heater enables the tool temperature to be changed more quickly. This makes it possible to react to fluctuations in the moisture content of the cardboard during the process. The deep drawing process of cardboard can thus be made less error-prone;
2. A maximum tool surface temperature of 100 °C in the blank holder zone is sufficient for softening of the board and favorable fold formation, but at the same time prevents excessive drying before forming and thus severe distortion of the mold after forming;
3. Stronger heating during the compression of the folds leads to slightly increased dimensional stability and fold resistance;
4. The zonal tool allows the implementation of the use of a low temperature in the blank holder zone and a separately controlled higher temperature in the drawing cavity

- zones. This leads to the best possible forming result in terms of shape accuracy and folds fixation;
5. By using material with an initial moisture content of up to 25% water content in relation to the total mass, significantly increased wall stability and high dimensional accuracy are achieved;
 6. Overall, it could be shown that the formed part quality and dimensional stability are more strongly influenced by the use of moisture than by the pure use of heating zones in the deep drawing tool. However, this use of high material moisture is only possible due to the heating zones and the venting channels;
 7. The results are apparently transferable to other materials and offer approaches for forming more demanding grades of board.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MD	Machine Direction
CD	Cross Direction
WCu	Tungsten–Copper alloy

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